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INSTITUTE OF NATURAL AND APPLIED SCIENCE**

PhD THESIS

K. Çağatay BAYINDIR

MODELING OF CUSTOM POWER DEVICES

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

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FEN BİLİMLERİ ENSTİTÜSÜ

MODELING OF CUSTOM POWER DEVICES

K. Çağatay BAYINDIR

DOKTORA TEZİ

ELEKTRİK ELEKTRONİK MÜHENDİSLİĞİ ANABİLİM DALI

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ÖZ

DOKTORA TEZİ

ÖZEL GÜÇ CİHAZLARININ MODELLENMESİ

K. Çağatay BAYINDIR

ELEKTRİK ELEKTRONİK MÜHENDİSLİĞİ ANABİLİM DALI

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Özel Güç, dağıtım şebekelerinde kalite ve güvenilirliğin artırılması amacıyla güç elektroniği temelli cihazların uygulanması bazlı bir konsepttir. Bu tez Özel Güç Cihazlarının modellenmesine odaklanmıştır. Modellemede üst seviye bilgisayar dilleri kullanarak matematiksel modellerin kodlanması yerine grafiksel bir yaklaşım kullanılmıştır ve tüm modeller açık ve detaylı şekilde sunulmuştur.

Matlab / Simulink modelleri sunulan Özel Güç Cihazları şunlardır: Şönt Aktif Güç Filtresi, Statik Transfer Anahtarı (STS), Dinamik Gerilim İyileştirici (DVR) ve Birleştirilmiş Güç Kalitesi Düzenleyici (UPQC). Bulanık mantığın güç elektroniğinde uygulanması son zamanda artmaktadır. Bulanık mantık kontrolcülerin klasik kontrolcülere göre üstünlüğü kesin matematiksel modellere ihtiyaç duymaması, hassas doğrulukta giriş sinyalleri gerektirmemesi ve lineer olmayan durumlarla başa çıkabilmesidir. Bu tezde Özel Güç Cihazlarının güç elektroniği kalbini oluşturan PWM eviriciler için bulanık mantık tabanlı akım ve gerilim kontrol metotları geliştirilmiştir. Geliştirilen metotlar benzer diğer evirici kontrol uygulamalarında kullanılabilir.

Her modellenen cihazın performansını değerlendirmek amacıyla vaka çalışmaları yoluyla kapsamlı sonuçlar sunulmuştur. Vaka çalışmalarında, endüstri için tipik olan güç sistemi parametreleri kullanılmıştır.

Anahtar Kelimeler: Özel Güç, Aktif Güç Filtresi, STS, DVR, UPQC.

ABSTRACT

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Custom Power is a concept, based on the application of power electronics based devices aimed at enhancing the reliability and quality of power in distribution networks. This thesis focuses on modeling and analysis of Custom Power Devices. The modeling approach adopted is graphical in nature, as opposed to mathematical models embedded in code using a high-level computer language and all models are presented clearly and in a detailed manner.

Matlab/Simulink based models for the following Custom Power Devices are presented: Shunt Active Power Filter, Static Transfer Switch (STS), Dynamic Voltage Restorer (DVR) and Unified Power Quality Conditioner (UPQC). The application of fuzzy logic is recently growing in power electronic systems. The advantages of fuzzy logic controllers over conventional controllers are that they do not need an accurate mathematical model; they can work with imprecise inputs and can handle non-linearity. In this thesis fuzzy logic based voltage and current control methods are developed for PWM inverters which form the power electronic heart of the new Custom Power Devices. Developed methods can also be utilized in other similar inverter control applications.

Comprehensive results through case studies are presented to evaluate the performance of each modeled device. In the case studies, characteristic values for power system parameters are taken which are typical for industry.

Keywords: Custom Power, Active Power Filter, STS, DVR, UPQC.

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CONTENTS	PAGE
ÖZ	I
ABSTRACT	II
ACKNOWLEDGEMENTS	III
CONTENTS	IV
LIST OF TABLES	VIII
LIST OF FIGURES	IX
LIST OF SYMBOLS	XIV
LIST OF ABBREVIATIONS	XVIII
1. INTRODUCTION	1
1.1. Motivation for the Work	3
1.2. Objectives of the Work	4
1.3. Content	4
2. POWER QUALITY AND CUSTOM POWER	6
2.1. Introduction	6
2.2. Power Quality Problems	14
2.2.1. Customer Load Profiles	17
2.2.1.1. Heavy Industry	17
2.2.1.2. Manufacturing Industry	18
2.2.1.3. Commercial Business	18
2.2.1.4. Domestic Environments	19
2.2.2. Sources of Power Quality Problems	20
2.2.2.1. Power Electronic Devices	20
2.2.2.2. IT and Office Equipment	20
2.2.2.3. Arcing Devices	21
2.2.2.4. Load Switching	21
2.2.2.5. Large Motor Starting	22
2.2.2.6. Embedded Generation	22
2.2.2.7. Sensitive Equipment	23
2.2.2.8. Storm and Environment Related Damage	24

2.2.2.9. Capacitor Switching	25
2.2.3. Interruption	25
2.2.4. Sags	27
2.2.5. Swells	28
2.2.6. Voltage Flicker	29
2.2.7. Harmonics	30
2.2.7.1. Harmonic Distortion	31
2.2.7.2. Harmonic Sources from Commercial Loads	33
2.2.7.3. Harmonic Sources from Industrial Loads	34
2.2.8. Transients	34
2.2.9. Magnetic Field Interference Problems	36
2.2.10. Power Quality Standards	37
2.3. What is Custom Power?	37
2.4. Custom Power Devices	41
2.4.1. Static Current Limiter	41
2.4.2. Static Transfer Switch	43
2.4.3. Active Power Filters	46
2.4.3.1. Shunt Active Power Filters	48
2.4.3.2. Series Active Power Filters	49
2.4.4. Dynamic Voltage Restorer	50
2.4.5. Unified Power Quality Conditioner	53
2.5. Custom Power Park	54
2.5.1. Custom Power A	58
2.5.2. Custom Power AA	59
2.5.3. Custom Power AAA	59
3. MODELING OF THREE-WIRE SHUNT APF	63
3.1. Introduction	63
3.2. System Description	65
3.2.1. Mains Supply	67
3.2.2. Nonlinear Load	67
3.2.3. Voltage Source Inverter	67

3.2.4.	Interface Reactor	69
3.2.5.	Reference Current Generator	70
3.2.6.	PWM Current Controller	76
3.2.6.1.	Single Fuzzy Logic Controller Based Active Power Filter and Problem Definition	76
3.2.6.2.	Proposed Hierarchical Neuro Fuzzy Controller for Shunt Active Power Filter	83
3.3.	Simulation Results	89
4.	MODELING OF FOUR-WIRE SHUNT APF	97
4.1.	Introduction	97
4.2.	Proposed Three-Phase Four-Wire Active Power Filter Configuration	99
4.3.	Reference Current Generation	101
4.4.	Voltage Source Inverter Current Control	104
4.4.1.	DC Link Voltage Imbalance Problem	104
4.4.2.	Fuzzy Logic Current Controller	109
4.5.	Simulation Results	117
5.	MODELING OF STATIC TRANSFER SWITCH	125
5.1.	Introduction	125
5.2.	Static Transfer Switch Circuit Topologies, Operation and Controls	126
5.2.1.	STS Circuit Topologies	126
5.2.2.	STS Operation	128
5.2.3.	STS Controls	129
5.2.3.1.	Zero Current Gating Strategy	129
5.2.3.2.	Commutation Gating Strategy	130
5.3.	Proposed STS Controls	131
5.3.1.	Sag Detection Logic	133
5.3.2.	Transfer and Gating Strategy	135
5.4.	Simulation Results	140
5.4.1.	Three Phase Balanced Fault	141
5.4.2.	Three Phase Unbalanced Fault	146

5.4.3. Single Phase to Ground Fault	150
6. MODELING OF DYNAMIC VOLTAGE RESTORER	154
6.1. Introduction	154
6.2. DVR Power Circuit and Operation Principles	157
6.2.1. VSI	158
6.2.2. Filter Circuit	158
6.2.3. Injection Transformers	158
6.2.4. Energy Storage and DC Converter	160
6.3. Proposed DVR Controls	160
6.3.1. Sag Detection	161
6.3.2. Reference Voltage Compensation	165
6.3.3. Fuzzy Logic Controller and PWM Generator	167
6.4. Simulation Results	171
6.4.1. Single Phase to Ground Fault	172
6.4.2. Three Phase Balanced Fault	173
6.4.3. Three Phase Unbalanced Fault	175
6.4.4. Voltage Sag Associated with Phase Angle Jump	175
7. MODELING OF UNIFIED POWER QUALITY CONDITIONER	178
7.1. Introduction	178
7.2. UPQC Configurations	179
7.3. Proposed UPQC Model	180
7.3.1. DC Link Regulator	180
7.3.2. Series Connected DVR	182
7.3.3. Shunt Connected Active Filter	182
7.4. Simulation Results	183
7.4.1. Case 1	184
7.4.2. Case 2	186
8. CONCLUSIONS AND FUTURE WORK	190
REFERENCES	195
CURRICULUM VITAE	205

LIST OF TABLES

Table 2.1	Typical power quality problems	16
Table 2.2	Some power quality standards of IEC and IEEE	37
Table 3.1	Magnitudes of harmonics in % of fundamental component in the currents for the hysteresis control scheme and the single fuzzy controller scheme for the case firing angle is 10° .	81
Table 3.2	Simulation details table for the single fuzzy controller scheme.	82
Table 3.3	Magnitudes of harmonics in % of fundamental component in the currents for the single fuzzy controller scheme and hierarchical neuro-fuzzy controller scheme for the case firing angle is 10° .	91
Table 3.4	Magnitudes of harmonics in % of fundamental component in the source currents for the single fuzzy controller scheme and hierarchical neuro-fuzzy controller scheme for the case firing angle is 30° .	93
Table 3.5	Comparison of magnitudes of harmonics in % of fundamental component of compensated source currents for the single fuzzy controller scheme and hierarchical neuro-fuzzy control scheme for the cases where firing angle is 10° , 30° , 45° and 60° .	95
Table 3.6	Magnitudes of harmonics in % of fundamental component in the source currents for the single fuzzy controller scheme and hierarchical neuro fuzzy controller scheme for the case firing angle changed from 10° to 40° .	96
Table 4.1	Rule table of proposed fuzzy logic controller	115
Table 4.2	System parameters	118
Table 4.3	THD values for load currents , active filter currents with hysteresis control and fuzzy logic control.	118
Table 5.1	Truth table of transfer and gating process	137
Table 5.2	Truth table of counter logic.	140
Table 6.1	Fuzzy decision table	170
Table 6.2	Simulation parameters	172
Table 7.1	Power Circuit Parameters	182

LIST OF FIGURES

Figure 2.1	Classical model of the power system.	10
Figure 2.2	Modern model of the power system	11
Figure 2.3	Typical disturbance caused by the energization of a capacitor bank.	25
Figure 2.4	Interruption	26
Figure 2.5	Custom power distribution system	40
Figure 2.6	Basic structure of SCL	42
Figure 2.7	Basic configuration of a Static Transfer Switch	44
Figure 2.8	STS structure	45
Figure 2.9	Generalised block diagram for active power filter	48
Figure 2.10	Compensation characteristics of shunt active power filter	49
Figure 2.11	Series active filter configuration	50
Figure 2.12	Operation of DVR	52
Figure 2.13	Schematic diagram of a typical DVR	52
Figure 2.14	Schematic diagram of UPQC	54
Figure 2.15	Custom Power Park concept	60
Figure 3.1	Diagram illustrating components of the shunt connected active power filter with waveforms showing cancellation of harmonics from a nonlinear load.	66
Figure 3.2	Matlab/Simulink model of designed system	66
Figure 3.3	Matlab / Simulink model of the nonlinear load.	67
Figure 3.4	Matlab / Simulink model of voltage source inverter	68
Figure 3.5	Matlab / Simulink model of interface reactor.	69
Figure 3.6	Compensation scheme	74
Figure 3.7	Calculation circuit of p^* .	74
Figure 3.8	Block diagram of reference current generator.	75
Figure 3.9	Single fuzzy logic controller based PWM current controller.	77
Figure 3.10	Generation of switching signals.	78
Figure 3.11	Input and output membership functions.	79
Figure 3.12	Load current and compensated source currents for the hysteresis control	

	scheme and single fuzzy logic controller scheme respectively.	81
Figure 3.13	Interface of the program written for generating the data in Table 2.	83
Figure 3.14	Hierarchical system employed in the model.	84
Figure 3.15	Hierarchical neuro-fuzzy PWM current controller.	87
Figure 3.16	Input membership functions for the second group fuzzy logic controllers.	87
Figure 3.17	Structure of ANFIS.	88
Figure 3.18	Load current and compensated source currents for the single fuzzy controller scheme and hierarchical neuro-fuzzy control scheme for the case firing angle is 10° .	90
Figure 3.19	Reference compensating currents and active power filter output currents for the single fuzzy controller scheme and hierarchical neuro-fuzzy control scheme for the case firing angle is 10° .	92
Figure 3.20	Load current and compensated source currents for the single fuzzy controller scheme and hierarchical neuro-fuzzy control scheme for the case firing angle is 30° .	93
Figure 3.21	Reference compensating currents and active power filter output currents for single fuzzy controller scheme and hierarchical neuro-fuzzy control scheme for the case firing angle is 30° .	94
Figure 3.22	Load current and compensated source currents for the single fuzzy controller scheme and hierarchical neuro-fuzzy control scheme for the case firing angle changed from 10° to 40° .	96
Figure 4.1	Block diagram of the proposed three-phase four-wire shunt active power filter	100
Figure 4.2	Control block diagram of the Sinusoidal Current Control Strategy	102
Figure 4.3	Fundamental positive sequence voltage detector	102
Figure 4.4	Injected current by leg a in hysteresis current control	106
Figure 4.5	Block diagram of the proposed fuzzy logic current controller	110
Figure 4.6	MODE 1 operation	111
Figure 4.7	MODE 2 operation	111
Figure 4.8	MODE 3 operation	112

Figure 4.9	MODE 4 operation	113
Figure 4.10	Membership functions used in fuzzification	116
Figure 4.11	Matlab / Simulink model of fuzzy logic based current controller	117
Figure 4.12	A, B and C phases nonlinear load currents and neutral current.	119
Figure 4.13	Source currents and neutral current with hysteresis control	120
Figure 4.14	Source currents and neutral current with fuzzy logic control.	121
Figure 4.15	VC1 and VC2 with hysteresis control	122
Figure 4.16	VC1 and VC2 with fuzzy logic control	123
Figure 4.17	Dynamic response of active power filter for hysteresis current control.	124
Figure 4.18	Dynamic response of active power filter for fuzzy logic control.	124
Figure 5.1	Single line diagram of single load bus configuration.	127
Figure 5.2	Single line diagram of split bus configuration.	128
Figure 5.3	Static Transfer Switch System	129
Figure 5.4	Block diagram of zero-current transfer logic	130
Figure 5.5	Block diagram of commutation gating strategy	131
Figure 5.6	Block diagram of the control circuit of a STS.	132
Figure 5.7	Matlab/Simulink Model of Static Transfer Switch	132
Figure 5.8	Block-diagram of the voltage-detection circuit.	134
Figure 5.9	(a) Transfer logic for phase A, (b) direction and zero current detection for preferred source phase A.	138
Figure 5.10	Preferred source Phase A Thyristor switches.	139
Figure 5.11	Counter logic	140
Figure 5.12	Preferred source voltage	142
Figure 5.13	Alternative source voltage	142
Figure 5.14	Load voltage	143
Figure 5.15	Preferred to alternative source transition for voltage during fault	143
Figure 5.16	Alternative source to preferred source transition for voltage 10 cycles after the fault is cleared	143
Figure 5.17	Preferred Source Current	144
Figure 5.18	Alternative Source Current	144

Figure 5.19	Load Current	145
Figure 5.20	Preferred to Alternative source transition for current during fault	145
Figure 5.21	Alternative source to preferred source transition for current 10 cycles after the fault is cleared	145
Figure 5.22	Preferred source voltage	146
Figure 5.23	Alternative source voltage	146
Figure 5.24	Load Voltage	147
Figure 5.25	Preferred to alternative source transition for voltage during fault	147
Figure 5.26	Alternative source to preferred source transition for voltage 10 cycles after the fault is cleared	148
Figure 5.27	Preferred Source Current	148
Figure 5.28	Alternative Source Current	148
Figure 5.29	Load Current	149
Figure 5.30	Preferred to alternative source transition for current during fault	149
Figure 5.31	Alternative source to preferred source transition for current 10 cycles after the fault is cleared	149
Figure 5.32	Preferred source voltage	150
Figure 5.33	Alternative source voltage	151
Figure 5.34	Load Voltage	151
Figure 5.35	Preferred to alternative source transition for voltage during fault	151
Figure 5.36	Alternative source to preferred source transition for voltage 10 cycles after the fault is cleared	152
Figure 5.37	Preferred Source Current	152
Figure 5.38	Alternative source Current	152
Figure 5.39	Load Current	153
Figure 5.40	Preferred to alternative source transition for current during fault	153
Figure 5.41	Alternative source to preferred source transition for current 10 cycles after the fault is cleared.	153
Figure 6.1	Main configuration of DVR	158
Figure 6.2	VSI and filter circuit	159
Figure 6.3	Matlab / Simulink model of proposed DVR.	160

Figure 6.4	Matlab/Simulink model for sag detection	163
Figure 6.5	The block diagram of reference voltage compensation block of proposed DVR controller	167
Figure 6.6	Membership functions for inputs	170
Figure 6.7	Membership function for output	171
Figure 6.8	Generation of PWM switching signals	171
Figure 6.9	Case 1: The supply, injected and load voltages	173
Figure 6.10	Case 2: The supply, injected and load voltages	174
Figure 6.11	Case3: The supply, injected and load voltages	176
Figure 6.12	Case 4: The supply, injected and load voltages	177
Figure 7.1	(a) Right-Shunt UPQC and (b) Left-Shunt UPQC	179
Figure 7.2	Matlab / Simulink model of UPQC	181
Figure 7.3	Block diagram of reference current generator	183
Figure 7.4	Case 1: The supply voltages	184
Figure 7.5	Case 1: The supply currents	185
Figure 7.6	Case 1: The load voltages	185
Figure 7.7	Case 1: The load currents	185
Figure 7.8	Case 1: DC link voltage	186
Figure 7.9	Case 2: The supply voltages	187
Figure 7.10	Case 2: The supply currents	187
Figure 7.11	Case 2: The load voltages	187
Figure 7.12	Case 2: The load currents	188
Figure 7.13	Case 2: DC link voltage	188

LIST OF SYMBOLS

T_1	Thyristor 1
T_2	Thyristor 2
R_{on}	Ideal switch resistance
L_{on}	Ideal switch inductance
e_α, e_β	voltages on α, β orthogonal coordinates
i_α, i_β	currents on α, β orthogonal coordinates
p	instantaneous power
q	instantaneous imaginary power
p_L	load instantaneous power
q_L	load imaginary power
v_a, v_b, v_c	three phase bus voltages
i_{La}, i_{Lb}, i_{Lc}	three phase load currents
\bar{p}_L	dc component of p_L
\tilde{p}_L	ac component of p_L
\bar{q}_L	dc component of q_L
\tilde{q}_L	ac component of q_L
$i_{refa}, i_{refb}, i_{refc}$	a,b,c phase reference currents
P_{av}	instantaneous real power corresponding to the loss of the active power filter
V_{DC}	DC link voltage
K_p	Proportion constant
K_I	Integral constant
I_{inv}	Inverter current
I_{ref}	Reference current
x, y	Inputs

A_i, B_i	Membership functions
p_i, q_i, r_i	Consequent parameters
i	Node number
$\mu_{A_i}(x)$	Bell shaped membership function
O_i^1	Output of layer 1 for node i
\bar{P}_{loss}	Active power filter loss
V_α, V_β, V_0	$\alpha, \beta, 0$ axis voltages
i_α, i_β, i_0	$\alpha, \beta, 0$ axis currents
p_0	Zero sequence power
i_0	Zero sequence current
V_α', V_β'	Fundamental positive sequence component of the system voltage transformed into α - β axis
$i_{ca}^*, i_{cb}^*, i_{cc}^*$	a,b,c phase reference currents
V_{C1}	DC voltage of C1
V_{C2}	DC voltage of C2
V_{ref}	Reference voltage
T_a	Full switching period
t_{1a}	Period during switch 1 is ON
t_{2a}	Period during switch 1 is OFF
I_{Fa}	Injected current
δ_a	Instantaneous error in reference current tracking
I_{Fa}^*	Reference current for phase A
L_F	Interface reactor inductance
h	Hysteresis band
d_a	Duty cycle
\bar{P}_{Fa}	instantaneous power developed by the voltage source inverter.

I_{C1}, I_{C2}	Currents for capacitor C1 and C2
e	Error
ce	Error rate
V_L	Interface reactor voltage
V_{dq0}	Voltages in d,q,0 axis
K_s	Park Transformation matrix
$V_{ab_p}, V_{bc_p}, V_{ca_p}$	Preferred source voltages
$V_{d_p}, V_{q_p}, V_{0_p}$	dq0 components of the preferred source voltage
E_{tot}	Sag tolerance limit
f_c	Filter cut-off frequency
w	Rotating frame angular frequency
V_P	rms value of V_{d_p} and V_{q_p}
i_{ZCT}	Zero current threshold limit
V_0	Zero sequence voltage
V_{dp}	Positive sequence voltage component of d axis
V_{dn}	Negative sequence voltage component of d axis
V_{qp}	Positive sequence voltage component of q axis
V_{qn}	Negative sequence voltage component of q axis
V_{dpref}	Positive sequence reference voltage of d axis
V_{qpref}	Positive sequence reference voltage of q axis
err_A	Error for phase A
Δerr_A	Error rate for phase A
V_{S_A}	A phase supply voltage
V_{PLL_A}	PLL data for phase A
U	Crisp value of output
y_i	Normalized controller output

$\mu(y_i)$	Membership grade
X_F	Fault line impedance
R_F	Fault line resistance

LIST OF ABBREVIATIONS

DVR	Dynamic Voltage Restorer
STS	Static Transfer Switch
UPQC	Unified Power Quality Conditioner
AF	Active Filter
DG	Distributed Generation
UPS	Uninterruptible Power Supply
VSI	Voltage Source Inverter
PQ	Power Quality
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
SVC	Static Var Compensator
CAD/CAM	Computer Aided Design/Computer Aided Manufacturing
TV	Television
IT	Information Technology
SMPS	Switched Mode Power Supply
EN	European Norm
rms	Root Mean Square
ASD	Adjustable Speed Drive
IEEE	Institute of Electrical and Electronics Engineers
et al.	And Others
PLC	Programmable Logic Controllers
AC	Alternative Current
DC	Direct Current
CPU	Central Processing Unit
LAN	Local Area Network
CRT	Cathode Ray Tube
IEC	International Electrotechnical Commission
GTO	Gate Turn-Off Thyristor
IGBT	Insulated Gate Bipolar Thyristor

VAR	Volt Amper Reactive
SCL	Static Current Limiter
ZnO	Zinc Oxide
kV	Kilo Volt
MVA	Mega Volt Amper
PWM	Pulse Width Modulation
kWh	Kilo Watt Hour
CP	Custom Power
CP-A	Custom Power A
CP-AA	Custom Power AA
CP-AAA	Custom Power AAA
APF	Active Power Filter
ANFIS	Adaptive Neuro-Fuzzy Inference System
THD	Total Harmonic Distortion
N	Number of membership functions
FIS	Fuzzy Inference System
PI	Proportional-Integral
PLL	Phase Locked Loop
KVL	Kirschoff's Voltage Law
D-STATCOM	Distribution Static Compensator
SSTC	Solid State Tap Changer
BBM	Break before make
MBB	Make before break
LPF	Low pass filter
NN	Neural network
FL	Fuzzy Logic
FLC	Fuzzy Logic Control
pu	Per-Unit
SRF	Synchronous Reference Frame
SVPWM	Space vector pulse width modulation
SPLL	Software phase locked loop

PCC

Point of Common Coupling

pf

Power factor

1. INTRODUCTION

Power quality phenomena include all possible situations in which the waveform of the supply voltage (voltage quality) or load current (current quality) deviate from the sinusoidal waveform at rated frequency with amplitude corresponding to the rated rms value for all three phases of a three-phase system. The wide range of power quality disturbances covers sudden, short duration variations, e.g. impulsive and oscillatory transients, voltage sags, short interruptions, as well as steady state deviations, such as harmonics and flicker. One can also distinguish, based on the cause, between disturbances related to the quality of the supply voltage and those related to the quality of the current taken by the load.

To the first class belong, among others, voltage dips and interruptions, mostly caused by faults in the power system. These disturbances may cause tripping of “sensitive” electronic equipment with disastrous consequences in industrial plants where tripping of critical equipment can bear the stoppage of the whole production with high costs associated. One can say that in this case it is the source that disturbs the load. To avoid consistent money losses, industrial customers often decide to install mitigation equipment to protect their plants from such disturbances.

The second class covers phenomena due to low quality of the current drawn by the load. In this case, it is the load that disturbs the source. A typical example is current harmonics drawn by disturbing loads like diode rectifiers, or unbalanced currents drawn by unbalanced loads. Customers do not experience any direct production loss related to the occurrence of these power quality phenomena. But poor quality of the current taken by many customers together will ultimately result in low quality of the power delivered to other customers: both harmonics and unbalanced currents ultimately cause distortion and respectively, unbalance in the voltage as well. Therefore, proper standards are issued to limit the quantity of harmonic currents, unbalance and/or flicker that a load may introduce. To comply with limits set by standards, customers often have to install mitigation equipment (Sannino et al., 2003).

In recent years, both industrial and commercial customers of utilities have reported a rising tide of misadventures related to power quality. The trouble stems from the increased refinement of today's automated equipment, whether variable speed drives or robots, automated production lines or machine tools, programmable logic controllers or power supplies in computers. They and their like are far vulnerable to disturbances on the utility system than were the previous generation of electromechanical equipment and the previous less automated production and information systems (Hingorani, 1995). A growing number of loads is sensitive to customers' critical processes which have costly consequences if disturbed by either poor power quality or power interruption (Rabinovitz, 2000).

For the reasons described above, there is a growing interest in equipment for mitigation of power quality disturbances, especially in newer devices based on power electronics called "custom power devices"(Hingorani, 1995) able to deliver customized solutions to power quality problems(Sannino et al., 2003).

The concept of Custom Power was introduced by N.G. Hingorani (Hingorani, 1995). The term Custom Power describes the value-added power that electric utilities and other service providers will offer their customers in the future. The improved level of reliability of this power, in terms of reduced interruptions and less variation, will stem from an integrated solution to present problems, of which a prominent feature will be the application of power electronic controllers to the utility distribution systems and/or at the supply and of many industrial and commercial customers and industrial parks (Hingorani, 1995).

The Custom Power devices are basically of two types – network reconfiguring type and compensating type. Static Transfer Switch (STS) belongs to network configuring type. STS is usually a thyristor based device that is used to protect sensitive loads from sag/swell. It can perform a sub-cycle transfer of the sensitive load from a supplying feeder to an alternate feeder. A STS can also be connected to a bus coupler between two incoming feeders.

The compensating devices are used for active filtering, load balancing, power factor correction and voltage regulation. The active power filters, which eliminate the current harmonics, can be connected in both shunt and series. However, the shunt

filters are more popular than the series filters because of greater ease of protection. Shunt active power filter can perform power factor correction, harmonic filtering when connected at the load terminals. The harmonic filtering approach is based on the principle of injecting harmonic current into the AC system, of the same amplitude and reverse phase to that of the load current harmonics.

Dynamic Voltage Restorer (DVR) is a series connected device. The main purpose of this device is to protect sensitive loads from sag/swell interruptions in the supply side. This is accomplished by rapid series voltage injection to compensate for the drop/rise in the supply voltage. Since this is a series device, it can also be used as a series active power filter.

Unified Power Quality Conditioner (UPQC) is a very versatile device that can inject current in shunt and voltage in series simultaneously in a dual control mode. Therefore it can perform both the functions of load compensation and voltage control at the same time (Ghosh et al., 2002).

1.1. Motivation for the Work

The next 20 years will present both technical and business opportunity challenges to utilities in their distribution of electrical energy. The evolving nature of distribution system operations and end-use equipment performance presents a mixed bag of tasks that will need to be well executed for utilities to succeed in the new highly competitive marketplace. A growing number of loads is sensitive to customers critical processes, which have costly consequences if disturbed by poor power quality (Rabinovitz, 2000).

At the moment most projects in active power filtering are concentrated in the field of harmonic current compensation. The demand on harmonic and reactive power compensation devices is increasing day by day in the world and in Turkey forced by the government regulations.

DVR is a device gaining popularity due to increasing sensitivity of industry to voltage sags/swells.

The Unified Power Quality Conditioner (UPQC) is a relatively new device and not much work has been reported on it yet.

Besides these global conditions, there is not a background on power quality issues and custom power devices in Turkey. This study will provide a strong background on these subjects.

1.2. Objectives of the Work

The objectives of this work is as follows:

To summarize the power quality definition, problems and solutions;

To describe Custom Power, Custom Power devices and Custom Power Park;

To describe the modeling of three-wire and four-wire shunt active power filters;

To evaluate the performance of the modeled shunt active power filters with case studies;

To describe the modeling of STS;

To evaluate the performance of the modeled STS with case studies;

To describe the modeling of DVR;

To evaluate the performance of the modeled DVR with case studies;

To describe the modeling of combined DVR and shunt active power filter known as UPQC;

To evaluate the performance of the modeled UPQC with a case studies;

1.3. Content

The content of the thesis is arranged as follows:

After this introductory chapter, Chapter 2 defines the power quality problem, solutions and custom power devices. The new concept Custom Power Park is introduced briefly.

In Chapter 3, modeling of three-wire shunt active power filter is presented. Three different current control techniques named hysteresis, fuzzy and neuro-fuzzy

are compared and performances are evaluated through case studies.

In Chapter 4, modeling of four-wire shunt active power filter is presented. Proposed fuzzy controls is compared with conventional hysteresis current control and performances are evaluated through case studies. The proposed current controller employs both active filter currents and DC link voltage as the control variable and has three inputs and one output for optimum control.

In Chapter 5, a fast thyristor based STS system which employs fast voltage-detection and thyristor-gating strategies is presented. Three different case studies are presented to verify the modeled and proposed STS.

In Chapter 6, a novel fuzzy logic based control method for DVR is presented. Different case studies for sag / swell and phase shift compensation are given. The proposed DVR is a multifunctional device and different than the available ones in literature.

In Chapter 7, the marriage of DVR in Chapter 6 and shunt active power filter in Chapter 3 named as UPQC is presented. A three-level voltage source converter used for maintaining DC link voltage of the common bus. The proposed UPQC with its functions is suitable for connecting at the PCC of industrial drives which are most sensitive to sags and are the main cause of harmonics.

In Chapter 8, the important conclusions of the study are explained and the future work topics on custom power devices are given. References used for this study and curriculum vitae of the author is also presented.

2. POWER QUALITY AND CUSTOM POWER

2.1. Introduction

The term power quality has many different meanings, probably as many as attempt to describe its impact on system operation. Because there is no ideal case, power quality express the degree of mutual satisfaction among the parties involved:

- The end users
- The utility providers
- The original manufacturers of electrical equipment
- The various organizations involved in developing power quality standards

(M. H. Nagrial et al., 1993)

From the energy provider's perspective, it is a measure of the level of service that provides to its customers. The ideal situation would be a unispectral voltage signal, of constant magnitude and frequency, for 365 days a year. Unfortunately this is impossible. Generally various factors cause system power quality to deteriorate, including (a) effects due to polluting loads such as motors, arc furnaces, large UPS systems, etc.; (b) Human accidents (carne accidents, traffic accidents, etc.); (c) weather and other natural-disaster-related equipment failures (lightning, ice, flooding, earthquakes); and (d) transmission and distribution equipment failures due to aging or other factors.

The end user is the party ultimately affected by power quality related problems. As the term power quality has been used as an indication of the variation of the voltage, current and frequency on the power system. Power quality usually means the degree of how closely the utility voltage approaches the ideal case of stable, reliable, zero distorted and disturbance free source. Indeed, the variation of these three parameters, up to ten years ago, had no significant effect on power equipment. It is not that utilities produced power of better quality back when, in most cases, they are supplying as good or even better quality today. Rather, the same electrical environment is too uneven for the sensitive microprocessor and power electronic equipment being installed these days to control assembly lines and to

enhance life at home. A range of different interference signals that appears on voltage supply can disrupt the operation of other devices connected to the same network. Nonlinear current consumption, switching procedures, commutations, short circuits and inrush currents cause supply interruptions, voltage swings, harmonics or brief voltage surges. However, during the last ten years, the power industry witnessed an introduction of a large amount of equipment, which is not so tolerant to variation in the earlier mentioned parameters and more susceptible to the effect of power system disturbances. A large number of these equipments are controlled by power electronics. These controllers are divided into two categories:

- Direct through power conversion such as ac and dc drives, and switch mode power supply
- Peripheral control such as computer and programmable logic controllers (M. H. Nagrial et al., 1993)

Both electric utilities and end users of electric power are becoming increasingly concerned about the quality of electric power. The term power quality has become one of the most prolific buzzwords in the power industry since the late 1980s. It is an umbrella concept for a multitude of individual types of power system disturbances. The issues that fall under this umbrella are not necessarily new. What is new is that engineers are now attempting to deal with these issues using a system approach rather than handling them as individual problems. There are three major reasons for the increased concern:

- Newer-generation load equipment, with microprocessor-based controls and power electronic devices, is more sensitive to power quality variations than was equipment used in the past. The increasing emphasis on overall power system efficiency has resulted in continued growth in the application of devices such as high-efficiency, adjustable-speed motor drives and shunt capacitors for power factor correction to reduce losses. This is resulting in increasing harmonic levels on power systems and has many people concerned about the future impact on system capabilities.
- End users have an increased awareness of power quality issues. Utility customers are becoming better informed about such issues as interruptions, sags, and switching transients and are challenging the utilities to improve the quality of power delivered.

- Many things are now interconnected in a network. Integrated processes mean that the failure of any component has much more quality important consequences.

The common thread running through all these reasons for increased concern about the quality of electric power is the continued push for increasing productivity for all utility customers. Manufacturers want faster, more productive, more efficient machinery. Utilities encourage this effort because it helps their customers become more profitable and also helps defer large investments in substations and generation by using more efficient load equipment. Interestingly, the equipment installed to increase the productivity is also often the equipment that suffers the most from common power disruptions. And the equipment is sometimes the source of additional power quality problems. When entire processes are automated, the efficient operation of machines and their controls becomes increasingly dependent on quality power. (R.C. Dugan et al., 2003)

In last years, there have been some developments that have had an impact on power quality:

- Throughout the world, many governments have revised their laws regulating electric utilities with the intent of achieving more cost-competitive sources of electric energy. Deregulation of utilities has complicated the power quality problem. In many geographic areas there is no longer tightly coordinated control of the power from generation through end-use load. While regulatory agencies can change the laws regarding the flow of money, the physical laws of power flow cannot be altered. In order to avoid deterioration of the quality of power supplied to customers, regulators are going to have to expand their thinking beyond traditional reliability indices and address the need for power quality reporting and incentives for the transmission and distribution companies.

- There has been a substantial increase of interest in distributed generation (DG), that is, generation of power dispersed throughout the power system. There are a number of important power quality issues that must be addressed as part of the overall interconnection evaluation for DG.

- The globalization of industry has heightened awareness of deficiencies in power quality around the world. Companies building factories in new areas are suddenly

faced with unanticipated problems with the electricity supply due to weaker systems or a different climate. There have been several efforts to benchmark power quality in one part of the world against other areas.

- Indices have been developed to help benchmark the various aspects of power quality. Regulatory agencies have become involved in performance-based rate-making, which addresses a particular aspect, reliability, which is associated with interruptions. Some customers have established contracts with utilities for meeting a certain quality of power delivery. (R.C. Dugan et al., 2003)

Classically, the aim of the electric power system is to generate electrical energy and to deliver this energy to the end-user equipment at an acceptable voltage. The constraint that was traditionally mentioned is that the technical aim should be achieved for reasonable costs.

The optimal level of investment was to be obtained by means of a trade-off between reliability and costs. A recurring argument with industrial customers concerned the definition of reliability: should it include only long interruptions or also short interruptions or even voltage sags. The term power quality came in use referring to the other characteristics of the supply voltage (i.e. other than long interruptions). But, immediately, the first confusion started as utilities included the disturbances generated by the customers in the term 'power quality'.

This difference in emphasis will be discussed in more detail below. The main complaint of domestic customers concerned the costs that were perceived too high, especially where cross subsidizing was used to keep prices low for industrial or agricultural customers.

This classical model of the power system, as it can be found in many textbooks, is found in Figure 2.1. The customers are traditionally referred to as loads.

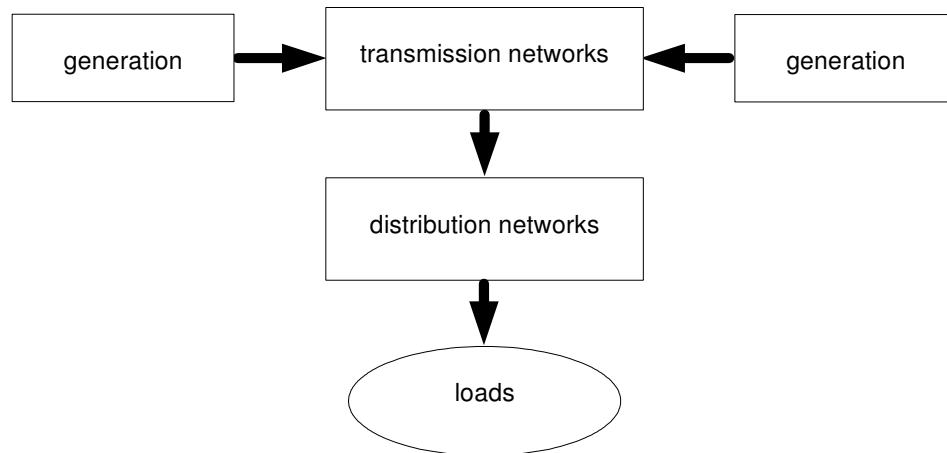


Figure 2.1 Classical model of the power system. (M.H.J. Bollen et al.,2003)

Various developments have led to a different view at the power system. These developments are strongly interrelated, but the three main ones are:

- The deregulation of the electricity industry makes that there is no longer one single system but a number of independent companies with customers.
- Electricity customers have become more aware of their rights and demand low-cost electricity of high reliability and quality, where the priorities are different for different (types of) customers. Customers are certainly no longer willing to accept their position as merely one parameter in a global optimization.
- Generation of electricity is shifting away from large power stations connected to the transmission system towards smaller units connected at lower voltage levels. Examples are combined-heat-and-power and renewable sources of energy like sun and wind.

Because of this the power system can no longer be seen as one entity but as an electricity network with Customers. This new model is shown in Figure 2.2. Note that the physical structure of the power system/network has not changed, it is only the way of viewing it that has changed.

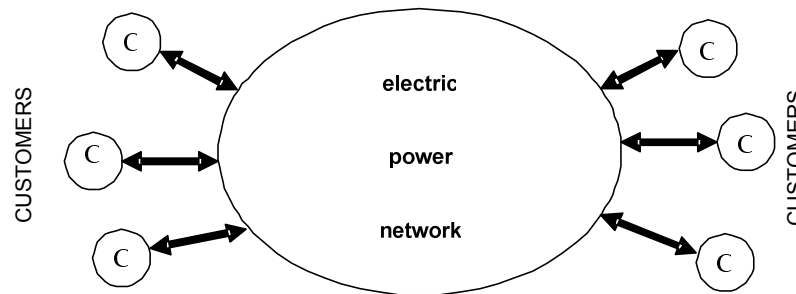


Figure 2.2. Modern model of the power system (M.H.J. Bollen et al.,2003)

In Figure 2.2 the electric power network connects some or many customers. Customers may generate or consume electrical energy or even both albeit at different moments in time. Different customers have different demands on voltage magnitude, frequency, waveform, etc. Different customers have different patterns of current variation, fluctuation and distortion, thus polluting the voltage for other customers in different ways.

The power network in Figure 2.2 could be a transmission network, a distribution network, an industrial network, or any other network owned by one single company. For a transmission network, the customers are, e.g., generator stations, distribution networks, large industrial customers (who could be generating or consuming electricity at different times, based on the electricity price at that moment), and other transmission networks. For a distribution network, the customers are currently mainly end-users that only consume electricity, but also the transmission network and smaller generator stations are customers. Note that all customers are equal, even though some may be producing energy while others are consuming it. The aim of the network company is only to transport the energy, or in economic terms: to enable transactions between customers.

The technical aim of the power network becomes one of allowing the transport of electrical energy between the different customers, guaranteeing an acceptable voltage and allowing the currents taken by the customers.

With an ideal network each customer should perceive the electricity supply as an ideal voltage source with zero impedance. Whatever the current is, the voltage should be constant. As always, reality is not ideal. Power quality concerns this deviation between reality and ideal. Note that this same model also becomes attractive when considering the integration of renewable or other environmentally friendly sources of energy into the power system. The power network is no longer the boundary condition that limits e.g. the amount of wind power that can be produced at a certain location. Instead the power network's task becomes to enable the transport of the amount of wind power that is produced. It will be clear to the reader that the final solution should be found in co-operation between the customer and the network operator considering various technical and economic constraints. (M.H.J. Bollen et al., 2003)

It is important to know the residential and commercial customers. Load curve and power quality level for the distribution network planning and mainly for the choice of the distribution transformers rating. Although these transformers have a low unit cost, they appear in large number, and a criterion of choose with a lower margin is desirable.

And also power quality has become a major concern to both electric utilities and consumers. The effects of the lack of PQ can be strongly felt in some countries, where billions of dollars have been wasted every year. This occurs mainly because most industries are in an endless race to upgrade their plants. In many cases, industries have their productivity indices, foreseen by projects, not achieved due mainly to PQ problems. Generally, this is caused by incompatibility between the power supply system and the operational requirements of this new generation of equipment.

Since power quality problems often involve interactions between the supply system and the customer facility and equipment, regulators should make sure that distribution companies have incentives to work with customers and help customers solve these problems.

The economics involved in solving a power quality problem must also be included in the analysis. It is not always economical to eliminate power quality variations on the

supply side. In many cases, the optimal solution to a problem may involve making a particular piece of sensitive equipment less sensitive to power quality variations. The level of power quality required is that level which will result in proper operation of the equipment at a particular facility.

Disturbances, even though short in duration, can be extremely expensive. For example, it has been estimated that at a single plant, a five-cycle interruption (an outage of less than a tenth of a second) can cost about \$200,000. Other major manufacturers indicate that an outage of two seconds can cost as much as \$600,000. In addition, the performance of most assembly line equipment is sensitive to voltage level, -transients and harmonic content. (L. L. Grigsby et al., 1994)

Power quality, like quality in other goods and services, is difficult to quantify. There is no single accepted definition of quality power. There are standards for voltage and other technical criteria that may be measured, but the ultimate measure of power quality is determined by the performance and productivity of end-user equipment. If the electric power is inadequate for those needs, then the "quality" is lacking.

Perhaps nothing has been more symbolic of a mismatch in the power delivery system and consumer technology than the "blinking clock" phenomenon. Clock designers created the blinking display of a digital clock to warn of possible incorrect time after loss of power and inadvertently created one of the first power quality monitors. It has made the homeowner aware that there are numerous minor disturbances occurring throughout the power delivery system that may have no ill effects other than to be detected by a clock. Many appliances now have a built-in clock, so the average household may have about a dozen clocks that must be reset when there is a brief interruption. Older-technology motor-driven clocks would simply lose a few seconds during minor disturbances and then promptly come back into synchronism. (G.J. Lee et al., 2004)

Technically, in engineering terms, power is the rate of energy delivery and is proportional to the product of the voltage and current. It would be difficult to define the quality of this quantity in any meaningful manner. The power supply system can only control the quality of the voltage; it has no control over the currents that

particular loads might draw. Therefore, the standards in the power quality area are devoted to maintaining the supply voltage within certain limits.

AC power systems are designed to operate at a sinusoidal voltage of a given frequency [typically 50 or 60 hertz (Hz)] and magnitude. Any significant deviation in the waveform magnitude, frequency, or purity is a potential power quality problem.

Of course, there is always a close relationship between voltage and current in any practical power system. Although the generators may provide a near-perfect sine-wave voltage, the current passing through the impedance of the system can cause a variety of disturbances to the voltage. For example,

- The current resulting from a short circuit causes the voltage to sag or disappear completely, as the case may be.
- Currents from lightning strokes passing through the power system cause high-impulse voltages that frequently flash over insulation and lead to other phenomena, such as short circuits.
- Distorted currents from harmonic-producing loads also distort the voltage as they pass through the system impedance. Thus a distorted voltage is presented to other end users.

Therefore, while it is the voltage with which we are ultimately concerned, we must also address phenomena in the current to understand the basis of many power quality problems.

2.2. Power Quality Problems

A power quality problem is defined as " an occurrence manifested in voltage, current, or frequency deviations, which results in failure or misoperation of end-use equipment" Commercial customers have become more exacting in their demand for relative 'quality' of power they purchase, variations in flow or voltage can actually damage and disrupt sensitive electronics, computers, and microprocessors. As modern society relies more heavily on high tech-processes, power quality has become even more critical.

Power quality is influenced among other factors by utility operations, customer load types, and equipment designs. Distribution utilities and their customers, along with their engineering equipment manufacturers and vendors, generate, propagate, and receive power quality problems. Electrical disturbances can ensue from problems within the customer's facility, even though the supply voltage is constant. Achieving power quality demands a united effort between the utility and the customer. (H. Kochukuttan et al., 1997)

Customers and utilities have a shared responsibility in the mitigation of voltage variation. Mitigation of the effects on consumer devices from voltage variations can be achieved only if utilities work with manufacturers in the design of consumer products so that the products function during normal utility operation. (Cherly et al., 1994)

Power quality can be evaluated by its effect on the performance of the equipment. Weather conditions and other factors may preclude utilities from providing power at constant voltage and constant frequency. The main types of voltage disturbances that occur in electrical power distribution systems include the following; Transients, Voltage sags, Voltage swells, Interruptions, Distortion, Flicker, Noise, Frequency deviations. These voltage disturbances will cause various power quality problems like electrical equipment damage, malfunction of computer and other sensitive equipment.

Power Quality problems need to be addressed in a coordinated manner since a large number of variables are involved. The different players in the power quality arena are: Distribution utilities, Commercial customers, Residential customers, Industrial customer, Equipment manufacturers, Health care facilities, Federal regulatory commission, State regulatory commission, and University researchers. (H. Kochukuttan et al., 1997) Table 2.1 gives a summary of typical power quality problems, causes and consequences.

Table 2.1 Typical power quality problems

DISTURBANCE	SYMPTOM	POSSIBLE CAUSE	CONSEQUENCE
Interruption	<ul style="list-style-type: none"> Complete loss of supply (exceeding 1 minute) 	<ul style="list-style-type: none"> Weather, storms, lightning, heavy winds, ice. Accidents, cars and excavation. Planned maintenance. Line faults, blown fuse. 	<ul style="list-style-type: none"> Affects all equipment.
Overvoltage	<ul style="list-style-type: none"> Long-term increase in supply voltage (> +6%). 	<ul style="list-style-type: none"> Light system loading. Poor regulation. 	<ul style="list-style-type: none"> Affects most equipment without internal backup facilities.
Undervoltage	<ul style="list-style-type: none"> Long-term lowering of the supply voltage (< -10%). 	<ul style="list-style-type: none"> Heavy, peak network loading. Lack of Var support. Poor power factor. 	
Momentary Interruption	<ul style="list-style-type: none"> Short-term power loss (200ms-few seconds). 	<ul style="list-style-type: none"> Circuit breaker tripping. Fault clearing. Bus transfer. 	
Voltage sag	<ul style="list-style-type: none"> Medium-term (2-10 cycles) depression in the steady state rms. voltage amplitude (-10 to -30%). 	<ul style="list-style-type: none"> Large loads being switched in. Temporary faults, circuit breakers in operation, reclosing operations. Inductive loading. 	<ul style="list-style-type: none"> Resetting of control systems and microprocessor operations.
Voltage Swell	<ul style="list-style-type: none"> Medium-term (>200ms) duration coupled with an increasing amplitude (+10 to +30%). 	<ul style="list-style-type: none"> Circuit Capacitance Switching out large loads. Load rejection. Phase fault. 	<ul style="list-style-type: none"> Protection tripping or possible damage to tabulation and windings.
Voltage Transient	<ul style="list-style-type: none"> Short-duration (sub-cycle) impulse voltage/current spikes, large amplitude high voltage gradients. 	<ul style="list-style-type: none"> Lighting/capacitive switching. Low fault current trip protection. Non-linear switching loads. Transmitted noise through the supply system. 	<ul style="list-style-type: none"> Control resetting and major damage to sensitive electronic components and insulation.
Current harmonics	<ul style="list-style-type: none"> Steady-state periodic waveforms which deform the supply signal 	<ul style="list-style-type: none"> Increased use of non-linear circuit elements. High frequency switches, TVs, computers and fluorescent lighting. Power factor correction capacitor. Negligent users unaware of signal pollution generated by equipment 	<ul style="list-style-type: none"> Overheating of transformers and motor drives, increased power loss and control command interference.
EMC & EMI effects	<ul style="list-style-type: none"> Line susceptibility and generation of e-in radiation. Radiated and conducted interference, spurious signals which proliferate on the supply. 	<ul style="list-style-type: none"> Incorrect wiring. Common: disturbances between supply and earth. Series: disturbance between supply and neutral Generated by unshielded electrical equipment. Unknown effects regarding human health matters. 	<ul style="list-style-type: none"> Interference with control signals, spurious noise and induced voltages.
Flicker	<ul style="list-style-type: none"> Series of systematic voltage fluctuations. 	<ul style="list-style-type: none"> Variable frequency voltage variation, fluorescent lights. Erratic loads, reactive power variation. 	<ul style="list-style-type: none"> Irritating light flicker and control reset
Voltage unbalance	<ul style="list-style-type: none"> 3-phase load interruptions, negative sequence and unsymmetrical voltages. 	<ul style="list-style-type: none"> Unbalanced polyphase loads, e.g. capacitor banks and motors. 	<ul style="list-style-type: none"> Interruption of 3-phase operations.

2.2.1. Customer Load Profiles

The analysis of disturbance effects and subsequent problems reveal a wide variety of customer priorities and this enables one to categorize specific user types . Faults affect load profiles in different ways, presenting different solution requirements when determining the optimum type of network support methodology and protection scheme for a customer. For industry and commerce, such an interruption can sometimes cost in excess of £100,000 per single disturbance. The precise consequences can be difficult to categorize, since system faults will affect customers to varying degrees. The more costly the potential interruption, the greater the likelihood that the customer will assign a high priority to 'improved' system protection investment. It is appropriate to consider four separate sectors, namely heavy industry, manufacturing, commerce and the domestic environment.

2.2.1.1. Heavy Industry

Traditionally, this sector includes heavy engineering and chemical process operations, e.g. steel works, refinery plants and production techniques which typically employ significant numbers of heavy duty machinery applications. These distort the supply signal, and are generally at system voltages of 3.3-11 kV with megawatt load ratings (e.g. induction motors, arc furnaces, pumps and compressors). In many cases, the system was carefully designed around the anticipated operation and generally the power quality characteristics are quite well understood. Local generation, dedicated supply feeders and isolation transformers are commonplace. These-precautions need to be taken, since it is sometimes necessary to isolate other more sensitive equipment from any harmful disturbances. Static Var Compensator (SVC) is used to counteract voltage sags encountered during heavy loading, surge arresters and fault current limiters being used to minimize switching transients and voltage surges. Continuous production processes are more susceptible to adverse power quality and reliability effects. Because these processes can involve long term process cycles, lasting for a matter of hours or even days, operating parameters such as flow rates, vessel pressure and temperature

have strict tolerances and any interruption or perturbation from the steady state conditions may result in an imperfect product. Another possible drawback, particularly for chemical processes where product flows can stop or are interrupted mid cycle, is the fact that a complete system 'clean-up' is necessary before production can continue. These consequences can be very costly, and for this reason, customers often seek safeguards to 'strengthen' the network and negotiate with the supply utility to guarantee optimal reliability of supply.

2.2.1.2. Manufacturing Industry

Manufacturing industries now employ many advanced production techniques utilising Computer Aided Manufacturing (CAD/CAM) and Just-in-time manufacturing etc., to improve output standards and production (e.g. car plants, electronics manufacturers and printing processes). Highly automated technology provides very efficient and flexible production, utilizing microprocessor controlled robot assembly lines, performing typical complex functions, including spot welding, soldering and accurate 'pick and place' operations. Once again, good power quality and supply reliability is vital. Short term power disturbances, comprising sufficiently large voltage perturbations (i.e. sags or transients) can 'reset' the controller, resulting in substandard fabrication, welding or misalignment. Clearly, if these manufactured defects go undetected the results could be disastrous. Many companies invest substantially to guarantee a minimal level of supply disturbance. Typical preventative measures include dedicated feeders, power factor correction and harmonic filters. Another option is to seek service and fiscal arrangements with the utilities, to guarantee not more than a agreed maximum number of possible interruptions. Subsequently, in the unlikely event of a problem, the customer will be compensated.

2.2.1.3. Commercial Business

Data processing and communication reflect the core commercial businesses and these are central to the success of this sector. Typical sector activities include

banking, retail, travel, communication and the emergency services. This sector includes a greater 'human element' in the office environment e.g. heating, air conditioning and lighting. The operational environment needs to be carefully controlled, since many functions include, or rely on, micro-electronic technology, and it is also vital that commercial data is not 'corrupted' due to power failure or signal distortion. Although many systems have independent emergency backup supply facilities there will invariably be some data loss, the severity of which will differ for various users. Many organizations rely on nation-wide links for information retrieval and distribution, (e.g. banks, insurance, retail stores and the travel industry). Transients, and supply surges causing 'downtime' on any of these systems can result in minutes and even hours of lost business. Since transient voltage and current surges pose a major threat, more so than voltage sags, this sector invests largely in system backup and surge suppression, because a severe transient could, not only 'reset' but could also, physically damage electronic equipment.

Hospitals and emergency services cannot tolerate a loss of supply. In critical areas such as operating theatres and intensive care units, short-term power quality problems can be potentially life threatening. Consequently, many hospitals and other organizations install dedicated uninterruptible power supplies (UPS) to protect vital activities. This solution tends to be very expensive both to purchase and maintain, but it is nevertheless essential.

2.2.1.4. Domestic Environments

Historically, household power quality concerns tended to be comparatively minor, yet they were often irritating. Clock radios 'flashing', dimming or flickering lights and the loss of supply are predominant domestic concerns, particularly for the elderly during the cold months. However, with the increasing trend towards IT, working from home (Teleworking), power quality requirements are becoming comparable to the commercial sector. Domestic appliances represent an ever-increasing source of disturbance and it is predicted that the 'harmonic pollution' level will increase markedly over the next decade. TV's, computers and fluorescent lights are major culprits and the

increasingly large number of these applications, including energy efficient devices, will actually contribute significantly to the harmonics and EMC effects present in the network, although initially, they were designed to reduce the system load demand. (Dong-Jun Won et al., 2002)

2.2.2. Sources of Power Quality Problems

2.2.2.1. Power Electronic Devices

Power electronic devices are non-linear loads that create harmonic distortion and can be susceptible to voltage sags if not adequately protected. The most common 'economically damaging' power quality problem encountered involves the use of variable-speed drives. Variable-speed motor drives or inverters are highly susceptible to voltage sag disturbances and cause particular problems in industrial processes where loss of mechanical synchronism is an issue. The ideal solution to problems of this nature would be for systems engineers to specify equipment that has a 'reasonable level' of susceptibility to voltage clips from the outset.

2.2.2.2. IT and Office Equipment

IT equipment power supplies consist of a switched mode power supply (SMPS) and are the cause of a significant increase in the level of 3rd, 5th and 7th harmonic voltage distortion in recent years. Because the third harmonic is a 'triplen' harmonic it is of zero order phase sequence and therefore adds in the neutral of a balanced three-phase system. The increasing use of IT equipment has led to concern of the increased overloading of neutral conductors and also overheating of transformers.

Recent developments have seen the use of switched mode power supplies in fluorescent lighting applications; these lighting applications typically represent in the region of 50% of a modern building's load. Many modern commercial buildings have large neutral conductors to cope with the levels of third harmonic, which can theoretically reach three times the magnitude of the fundamental.

2.2.2.3. Arcing Devices

Electric arc furnaces, arc welders and electric discharge lamps are all forms of electric arcing device. These devices are highly non-linear loads. The current waveform drawn is characterised by an increasing arc current limited only by the network impedance. Large arc furnace installations have typical current requirements of tens of thousands of amperes, welding sets draw current in the range of hundreds of amperes, individual electric discharge lamps draw only fractions of an ampere, but when it is considered that a large percentage of the domestic and commercial load requirement is contributed by lighting requirements this has a significant impact.

All arcing devices are sources of harmonic distortion and the arcing load can be represented as a relatively stable source of voltage harmonics. The effects of arc furnaces are difficult to mitigate; balancing the phases with other furnaces will not always be effective as arc furnaces are operated in various modes, leading to phase imbalance. Arc welders commonly cause transients in the local network due to the intermittent switching and therefore some electronic equipment may require protection from the impulsive spikes generated.

Because of the requirement to limit the current within fluorescent lights a ballast is fitted that can add to the level of harmonic distortion of the supply. Of particular concern is the level of the third (or higher order triplen) harmonic. Balancing the phases to have equal harmonic load is a good way to minimise the level of the triplen harmonics, but on a star-star connected transformer connection no cancellation will occur.

2.2.2.4. Load Switching

The effect of heavy load switching on the local network is a fairly common problem causing transients to propagate through to other 'electrically close' equipment. These transients can be of surprisingly large voltage magnitude, but have very little energy due to their short duration, which is normally measured in terms of milliseconds. Electronic devices that may be sensitive to these voltage impulses can

have their operation impaired. The effect of load switching on the voltage is typically encountered in the form of transient activity. This type of transient might occur as the result of switching in a heavy single-phase load, the effect seen on the voltage measured nearby. Other equipment can be protected from these switching transients by electrically isolating them from the affecting equipment.

2.2.2.5. Large Motor Starting

The dynamic nature of induction machines means that they draw current depending on the mode of operation; during starting this current can be as high as six times the normal rated current. This increased loading on the local network has the effect of causing a voltage sag, the magnitude of which is dependent on the system impedance. It can take several seconds for motors to reach their rated speed and for this reason measures are taken to reduce the level of current drawn. These measures are dependent on the type of motor and drive. Most modern motors employ a sophisticated power electronic converter 'drive', which in most cases will control the motor's starting current to a reasonable level. Some lower cost types of motors use series capacitors or resistors to reduce the starting current. These components are then switched out once the motor's rated speed has been reached. Autotransformers are used to start some older motors. These have a variable secondary winding that allows the motor stator voltage to be controlled and hence the current drawn from the supply.

2.2.2.6. Embedded Generation

Increasing levels of embedded generation predicted in the future are likely to have an effect on power quality. Although it cannot be stated that this increased level of dispersed generation on public distribution networks will degrade or improve power quality (this is an issue of some contention), it can be said that there are both advantages and disadvantages to the more widespread application of embedded generation where power quality is concerned. An increased amount of embedded

generation at substation level and below will lead to increased fault current levels in the feeders. This increased fault level is one of the major concerns when considering embedded generation issues.

2.2.2.7. Sensitive Equipment

If it were not for the use of increasing levels of sophisticated equipment, which tends to be more sensitive, power quality would not have become such an issue in recent years. Equipment manufacturers are designing and manufacturing ever more sophisticated equipment, much of which is increasingly susceptible to variations in power quality. There are many issues relating to the subject of equipment sensitivity and the effect of power quality occurrences on sensitive equipment. The main areas of concern are:

- catastrophic equipment malfunction
- data corruption
- reduced equipment operating life
- reduced process quality, hence product quality
- increased scrap material produced in production processes
- process stoppage
- equipment damage
- safety issues.

Any device that depends on a volatile memory chip for information storage is potentially at risk from power quality events. IT equipment therefore requires protection. Many processes in industry depend on automated microprocessor control systems. Solutions to the power quality problems encountered with this type of equipment often consist of protection for the control system alone, the actual process not being sensitive to the more common disturbances.

A large part of the problem with sensitive loads is down to the so-called 'standards gap'. The EMC limits EN 61000-3 series cover many electromagnetic compatibility requirements that manufacturers of equipment must meet. EN 50160

details the voltage characteristics of electricity supplied by public distribution systems. Between these two standards is a grey area, meaning that equipment, made to meet EN6100-3, can be affected by electricity supplied in accordance with EN50160.

2.2.2.8. Storm and Environment Related Damage

Lightning strikes are a cause of transient overvoltages often leading to faults on the electricity supply network. Lightning does not have to strike a conductor in order to inject transients onto the local network. Impulses can be induced if lightning strikes near a conductor. The local ground potential can be raised by a nearby strike leading to neutral current flowing to earth via a remote ground. This can have destructive effects on sensitive equipment. Lightning strikes that hit overhead lines often cause 'flash-overs' to neighbouring conductors as the insulators break down. The strike will therefore not only consist of a transient over-voltage but also fault-clearing interruptions and sags.

High winds and storm conditions cause widespread disruption to the supply networks. Where disruptions are caused by faults that can be cleared in less than one minute (e.g. by the use of auto-reclosers) the effect on the network is seen as a power quality issue. Long interruptions, above one minute, are generally seen as reliability or quality of supply issues.

Snow and ice build-up have a severe effect on the reliability of overhead lines. This has obvious power quality/quality of supply consequences. Sea mists in the vicinity of overhead lines can lead to flashover between conductors. Insulators must be cleaned on a regular basis in these areas to avoid these problems. In hot and humid climates dust and heavy dew can cause similar flashover problems, requiring non-intrusive insulator cleaning methods. Finally, damage due to wildlife, such as birds colliding with overhead lines, and tree branches touching live conductors is common in rural areas, particularly in the spring. As with any faults, these are potential causes of power quality problems. (John Stones et al., 2001)

2.2.2.9. Capacitor Switching

Figure 2.3 shows the disturbance to a waveshape during the energization of a large capacitor bank on a utility transmission substation. The capacitor bank is being switched on to compensate for reactive power losses to support the voltage and energy transmission capability of the transmission grid. Notice that this waveshape also has the waveshape disturbance occurring at the peak of the sine wave. But can we detect these capacitor switching transients by the oscillatory ringing that is characteristic of the natural frequency of the power system? (David Mueller et al.)

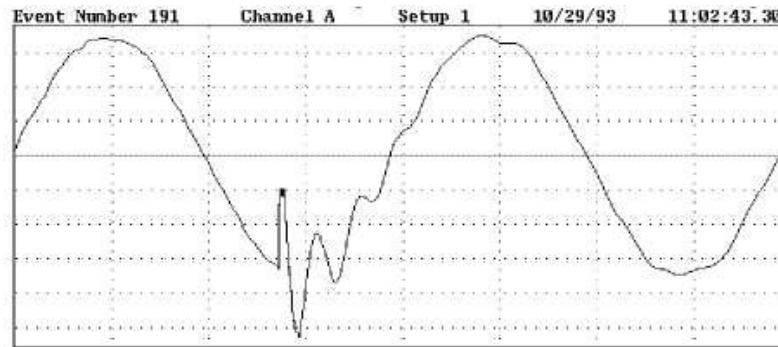


Figure 2.3 Typical disturbance caused by the energization of a capacitor bank. (David Mueller et al.,)

2.2.3. Interruption

An interruption is defined as the complete loss of supply voltage or load current. Refer to Figure 2.4 for an illustration of an interruption. Within this definition there are three types of interruptions which are characterized by their duration. The momentary interruption is defined as the complete loss of supply voltage or load current having a duration between 0.5 cycles and 3 seconds.

The temporary interruption is the complete loss lasting between 3 seconds and 1 minute; and the long term interruption or outage is an interruption which has a duration of more than 1 minute. The causes of interruptions are myriad and too numerous to outline in detail but normally result in the operation

of a system protective device, e.g., a fuse or automatic breaker, which is utilized to isolate the source of the system fault. Common sources of interruptions include lightning, animals, trees, vehicle accidents, and equipment failure.

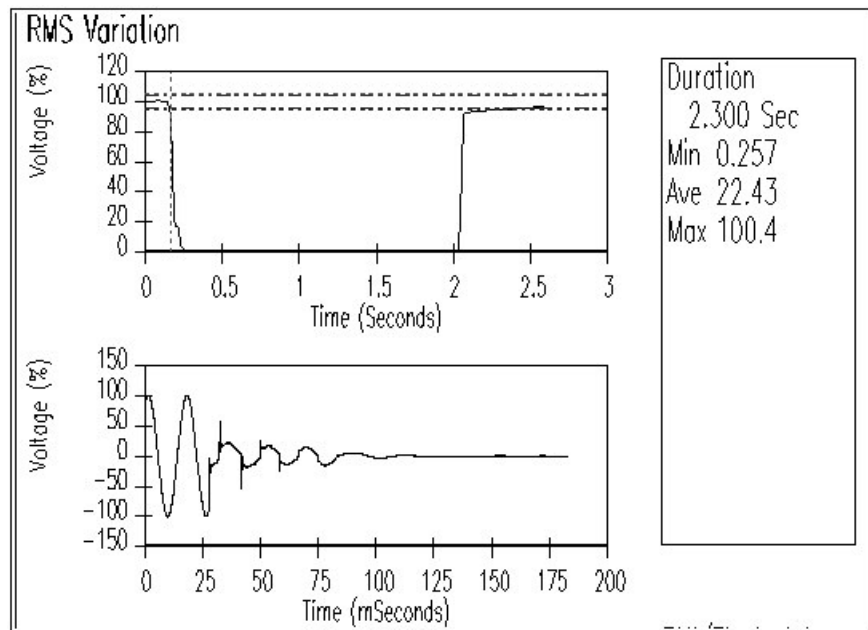


Figure 2.4 Interruption (Thomas Ackermann et al., 2001)

An interruption impacts both the electric utility and the industrial customer. The protection device serves to limit physical damage to utility equipment and reduce the negative effect on the life of utility equipment. Some reduction in useful life of equipment such as transformers can occur as the result of enduring the higher fault currents. More devastating is the loss that the industrial customer sustains in the form of lost product, equipment downtime, clean up, and restart cost. These costs can go into the millions of dollars in each instance and threaten the ability of the customer to complete or even survive in the world market.

Solutions vary both in effectiveness and cost. The first effort should go into eliminating or reducing the likelihood of potential problems. Good design and maintenance of utility systems are, of course, essential this also applies to the industrial customer's system design which is often as extensive and vulnerable as the utility system.

Once the potential for problems is reduced, additional equipment or design methods are needed to allow the customer's equipment or process to ride-through or restart after unavoidable interruptions. The most common mitigating devices employed are the uninterruptible power supply (UPS), motor generator, and the use of system design techniques which take advantage of redundant systems and energy storage. Recent advances in switch technology have allowed for standby energy storage systems to be utilized less than one half cycle. (Thomas Ackermann, et al. 2001)

2.2.4. Sags

Voltage sags (dips) are short-duration reductions in rms voltage caused by short-duration increases of the current, typically at another location than where the voltage sag is measured. The most common causes of overcurrents leading to voltage sags are motor starting, transformer energizing and faults. Also capacitor energizing and switching of electronic load lead to short duration overcurrents, but the duration of the overcurrent is too short to cause a significant reduction in the rms voltage. These events are normally not referred to as voltage sags but as voltage notches or voltage transients. Voltage sags due to short circuit and earth faults are the cause of the vast majority of equipment problems. Most of the recent emphasis on voltage sags is directed towards these fault-related sags. Voltage sags are generally seen as undesired events, but a more positive viewpoint could equally well see them as a consequence of the high reliability of the power supply. Without the widespread use of protection equipment any fault would lead to the loss of supply for a large fraction of the customers. The protection significantly limits the numbers of customers that experience a long interruption, in many cases to zero. However many customers who would experience an interruption without protection now experience a voltage sag. This way of protection has been good enough for many years, but recently more and more problems with end-user equipment are reported due to these voltage sags. Not only has, especially electronic, equipment become more susceptible to voltage sags, companies have also become less tolerant of production stoppages.

Voltage sags have been mainly associated with short circuit incidences. Fault occurrences elsewhere can generate voltage sags affecting consumers differently according to their location in the electrical system. Starting large motors can also generate voltage sags, although usually not so severe (M. F. Mcgranghan et al., 1993).

Voltage sag analysis is a very complex issue, since it involves a large variety of random factors, such as:

- *type of short-circuits* — three-phase faults are responsible for larger voltage sag magnitude than single line-to-ground faults, although these ones are more frequent;

- *location of faults* — transmission system faults are much more severe than distribution system ones, as a short circuit in a transmission grid is supposed to affect a larger area than in a distribution system;

- *protective system performance* — the duration of a voltage sag is directly related to the protective system performance, i.e. the clearing times; (Jose Maria *et al.*, 1993)

- *Atmospheric discharges* — surveys have shown that most of the voltage sag occurrences are associated with atmospheric discharges in transmission and distribution system (M. F. Mcgranaghan et al., 1993).

Every consumer is subject to a voltage sag occurrence since faults can not be totally avoided. In fact, the greatest losses will fall upon customers having sensitive equipment as PLCs (programmable logic controllers) and ASDs (adjustable speed drives). Some of the voltage sag effects on such equipment are:

- PLCs malfunction, causing industrial process totally or partially shutdown;
- ASDs disconnection with consequent shutdown and production losses;
- contactors and auxiliary relays dropout;
- unexpected tripping of undervoltage relays.

2.2.5. Swells

Swell is an RMS increase in the AC Voltage, at the power frequency, for duration

from a half a cycle to a few seconds. Voltage can rise above normal level for several cycles to seconds.

When single phasing occurs, a loss of one of three energized conductors, an imbalance in the two remaining energized conductors will result where a voltage increase can be experienced; sudden decrease in line loads; re-energizing of power after a utility power interruption, when power comes back in; open neutrals; loose wiring.

Voltage swells can originate internally in building wiring or externally on power lines. Voltage swells are the least frequent of the power line problems representing only about 2 to 3% of all power problems occurring to industry studies.

Voltage swells will normally cause damage to lighting, motor and electronic loads and will also cause shutdown to equipment. With electronically controlled equipment, voltage above 6 to 10% above normal may result in damage.

Solutions to voltage swells for motor loads include motor phase protectors, electronically controlled devices that shutdown motors before damage occurs. For sensitive computer and electronic loads, solutions include Uninterruptible Power Supplies, Voltage Regulators, Power Conditioners, Energy Storage Devices and Static Switches.

2.2.6. Voltage Flicker

Flicker is a very specific problem related to human perception and incandescent light bulbs. It is not a general term for voltage variations. Humans can be very sensitive to light flicker that is caused by voltage fluctuations. Human perception of light flicker is almost always the limiting criteria for controlling small voltage fluctuations. The sensitivity is a function of the frequency of the fluctuations and it is also dependent on the voltage level of the lighting.

Note that individual step changes in the voltage, such as would be caused by motor starting or switching a capacitor bank, are often limited separately from the continuous flicker limits. IEC 61000-2-2 specifies a compatibility level of 3% for the individual voltage variations. EN 50160 specifies a limit of 5% for these variations

but mentions that more significant variations (up to 10%) can occur for some switching events. Specific recommendations are not provided in IEEE but individual utilities usually have their own guidelines in the range 4-7%. Electric arc furnaces are the major cause of flickers in distribution and transmission systems.

2.2.7. Harmonics

A good assumption for most utilities is that the sine-wave voltage generated in central power stations is very good. In most areas, the voltage found on transmission systems typically has much less than 1.0 percent distortion. However, the distortion increases closer to the load. At some loads, the current waveform barely resembles a sine wave. Electronic power converters can chop the current into seemingly arbitrary waveforms.

While there are a few cases where the distortion is random, most distortion is periodic, or an integer multiple of the power system fundamental frequency. That is, the current waveform is nearly the same cycle after cycle, changing very slowly, if at all. This has given rise to the widespread use of the term harmonics to describe distortion of the waveform. This term must be carefully qualified to make sense.

When electronic power converters first became commonplace in the late 1970s, many utility engineers became quite concerned about the ability of the power system to accommodate the harmonic distortion. Many dire predictions were made about the fate of power systems if these devices were permitted to exist. While some of these concerns were probably overstated, the field of power quality analysis owes a great debt of gratitude to these people because their concern over this "new" problem of harmonics sparked the research that has eventually led to much of the knowledge about all aspects of power quality.

To some, harmonic distortion is still the most significant power quality problem. It is not hard to understand how an engineer faced with a difficult harmonics problem can come to hold that opinion. Harmonics problems counter many of the conventional rules of power system design and operation that

consider only the fundamental frequency. Therefore, the engineer is faced with unfamiliar phenomena that require unfamiliar tools to analyze and unfamiliar equipment to solve. Although harmonic problems can be difficult, they are not actually very numerous on utility systems. Only a few percent of utility distribution feeders in the United States have a sufficiently severe harmonics problem to require attention.

In contrast, voltage sags and interruptions are nearly universal to every feeder and represent the most numerous and significant power quality deviations. The end-user sector suffers more from harmonic problems than does the utility sector. Industrial users with adjustable-speed drives, arc furnaces, induction furnaces, and the like are much more susceptible to problems stemming from harmonic distortion.

Harmonic distortion is not a new phenomenon on power systems. Concern over distortion has ebbed and flowed a number of times during the history of ac electric power systems. Scanning the technical literature of the 1930s and 1940s, one will notice many articles on the subject. At that time the primary sources were the transformers and the primary problem was inductive interference with open-wire telephone systems. The forerunners of modern arc lighting were being introduced and were causing quite a stir because of their harmonic content—not unlike the stir caused by electronic power converters in more recent times.

Fortunately, if the system is properly sized to handle the power demands of the load, there is a low probability that harmonics will cause a problem with the power system, although they may cause problems with telecommunications. The power system problems arise most frequently when the capacitance in the system results in resonance at a critical harmonic frequency that dramatically increases the distortion above normal amounts. While these problems occur on utility systems, the most severe cases are usually found in industrial power systems because of the higher degree of resonance achieved. (R.C. Dugan et al., 2003)

2.2.7.1 Harmonic Distortion

Harmonic distortion is caused by nonlinear devices in the power system. A nonlinear device is one in which the current is not proportional to the applied voltage.

While the applied voltage is perfectly sinusoidal, the resulting current is distorted. Increasing the voltage by a few percent may cause the current to double and take on a different waveshape. This is the source of most harmonic distortion in a power system.

Any periodic, distorted waveform can be expressed as a sum of sinusoids. When a waveform is identical from one cycle to the next, it can be represented as a sum of pure sine waves in which the frequency of each sinusoid is an integer multiple of the fundamental frequency of the distorted wave. This multiple is called a harmonic of the fundamental, hence the name of this subject matter. The sum of sinusoids is referred to as a Fourier series, named after the great mathematician who discovered the concept.

Because of the above property, the Fourier series concept is universally applied in analyzing harmonic problems. The system can now be analyzed separately at each harmonic. In addition, finding the system response of a sinusoid of each harmonic individually is much more straightforward compared to that with the entire distorted waveforms. The outputs at each frequency are then combined to form a new Fourier series, from which the output waveform may be computed, if desired. Often, only the magnitudes of the harmonics are of interest.

When both the positive and negative half cycles of a waveform have identical shapes, the Fourier series contains only odd harmonics. This offers a further simplification for most power system studies because most common harmonic-producing devices look the same to both polarities. In fact, the presence of even harmonics is often a clue that there is something wrong—either with the load equipment or with the transducer used to make the measurement. There are notable exceptions to this such as half-wave rectifiers and arc furnaces when the arc is random.

Usually, the higher-order harmonics (above the range of the 25th to 50th, depending on the system) are negligible for power system analysis. While they may cause interference with low-power electronic devices, they are usually not damaging to the power system. It is also difficult to collect sufficiently accurate data to model power systems at these frequencies. A common exception to this occurs when there are system resonances in the range of frequencies. These resonances can be excited by notching or switching transients in electronic power converters. This causes voltage waveforms with multiple zero crossings which

disrupt timing circuits. These resonances generally occur on systems with underground cable but no power factor correction capacitors.

If the power system is depicted as series and shunt elements, as is the conventional practice, the vast majority of the nonlinearities in the system are found in shunt elements (i.e., loads). The series impedance of the power delivery system (i.e., the short-circuit impedance between the source and the load) is remarkably linear. In transformers, also the source of harmonics is the shunt branch (magnetizing impedance) of the common "T" model; the leakage impedance is linear. Thus, the main sources of harmonic distortion will ultimately be end-user loads. This is not to say that all end users who experience harmonic distortion will themselves have significant sources of harmonics, but that the harmonic distortion generally originates with some end-user's load or combination of loads.

2.2.7.2 Harmonic Sources from Commercial Loads

Commercial facilities such as office complexes, department stores, hospitals, and Internet data centres are dominated with high-efficiency fluorescent lighting with electronic ballasts, adjustable-speed drives for the heating, ventilation, and air conditioning loads, elevator drives, and sensitive electronic equipment supplied by single-phase switch-mode power supplies. Commercial loads are characterized by a large number of small harmonic-producing loads. Depending on the diversity of the different load types, these small harmonic currents may add in phase or cancel each other. The voltage distortion levels depend on both the circuit impedances and the overall harmonic current distortion. Since power factor correction capacitors are not typically used in commercial facilities, the circuit impedance is dominated by the service entrance transformers and conductor impedances. Therefore, the voltage distortion can be estimated simply by multiplying the current by the impedance adjusted for frequency. Typical nonlinear commercial loads are single-phase power supplies, fluorescent lighting and adjustable speed drives for HVAC and elevators.

2.2.7.3 Harmonic Sources from Industrial Loads

Modern industrial facilities are characterized by the widespread application of nonlinear loads. These loads can make up a significant portion of the total facility loads and inject harmonic currents into the power system, causing harmonic distortion in the voltage. This harmonic problem is compounded by the fact that these nonlinear loads have a relatively low power factor. Industrial facilities often utilize capacitor banks to improve the power factor to avoid penalty charges. The application of power factor correction capacitors can potentially magnify harmonic currents from the nonlinear loads, giving rise to resonance conditions within the facility. The highest voltage distortion level usually occurs at the facility's low-voltage bus where the capacitors are applied. Resonance conditions cause motor and transformer overheating, and misoperation of sensitive electronic equipment.

Nonlinear industrial loads can generally be grouped into three categories: three-phase power converters, arcing devices, and saturable devices.

2.2.8. Transients

An electrical transient is a temporary excess of voltage and/or current in an electrical circuit which has been disturbed. Transients are short-duration events, typically lasting from a few thousandths of a second (milliseconds) to billionths of a second (nanoseconds), and they are found on all types of electrical, data and communications circuits. Transient surges are corrosive disturbances that range from only a few volts, to over 20,000 volts with currents in excess of 10,000 amperes. They can occur as frequently as 180,000 to 432,000 events per hour in extremely active industrial environments. As businesses increasingly rely on electronic and electrical devices, they become highly vulnerable to problems inherent in their source of energy - electricity. The sudden loss of electricity, an unwanted surge or simply some "noisy" electricity can knock out equipment and bring business to a halt. Alternatively, it can subtly impair equipment, resulting in erratic performance or premature failure that can be hard to diagnose and expensive to repair or replace.

Sixteen years ago, transients were thought to be nonexistent figments of the imagination of persons who sold unnecessary protection for an imaginary problem. The education and experience of the last several years have clearly demonstrated that transients are anything but imaginary. With many industries moving toward automated information and reporting systems and automated material-handling systems, transients are a relevant and ever-present problem. Once the destructive transient problem is understood, solutions may be sought and implemented.

The simple act of turning on (or off) a light, motor, copy machine or any other electrical device can disturb the electrical circuit and create transients. In general, the larger the load current, the greater the disturbance when the load is switched on or off. The switching of high-capacity loads such as electric welders and electric motors is known to create transients. Studies have shown that a majority of transients (roughly 80%) in a given facility are generated inside that facility.

Transients external to the facility come from lightning (direct hits or induced transients), normal utility operation (such as grid switching, switching of power factor correction capacitors and reclosure operation), unusual power line conditions such as downed lines due to falling trees or automobiles, or squirrels shorting transformers and noisy electrical neighbors such as welding shops down the street.

Cloud-to-cloud lightning discharges or nearby lightning strikes are capable of creating electric-field intensities in the range of hundreds to thousands of volts per meter. A two-meter length of wire (i.e. a power or signal conductor) exposed to an electric-field intensity of 300 volts per meter can develop an induced transient voltage of 600 volts (2 meters x 300 volts/meter = 600 volts). If this 600-volt transient appears across an unprotected power, telephone, data or coaxial line the result can be system destruction.

Power companies have little or no control over transients induced by lightning or high-power switching at substation levels. Currents from a direct or indirect strike may directly enter or be induced in conductors of a suspended or buried cable. Either way, the surge will propagate in the form of a traveling wave bidirectionally on the cable from the point of origin.

2.2.9. Magnetic Field Interference Problems

Interference with computer or Cathode Ray Tube video display monitors is the dominant problem associated with elevated magnetic field environments. Screen interference caused by magnetic fields is of two categories: AC magnetic fields can cause the image to "jitter" on a display, while DC magnetic field monitor interference problems are manifested as stationary image tilt or color purity problems (changes or blotches of color in various areas of the screen). Thresholds for computer monitor interference will vary by different magnetic field intensities, depending upon the type, size, make and model of the monitor. In general, CRT's are much more sensitive to AC magnetic fields than to DC magnetic fields.

A wide variety of audio equipment may experience interference problems when located in an elevated AC magnetic field environment. Most notably, sensitive preamplifier sections of professional and broadcast audio mixing consoles may experience increases of audible 60 Hz "hum" or increased levels of signal-to-noise when located in areas with elevated AC magnetic field conditions. Such hum and increased signal-to-noise conditions are created by the induction of an interference voltage at 50 Hz in sensitive components of analog audio amplifiers. Similarly, sensitive or poorly shielded microphones and musical instrument audio pick-up transducers can experience undesirable levels of 50 Hz hum when used in environments with elevated levels of AC magnetic fields. Professional musicians have long been aware of this phenomenon in performance venues and have learned to shift or orient amplifiers and sensitive musical instruments to locate areas with lower AC magnetic field levels or "null" points.

Interference problems may be present in audio/video/data cabling when placed in close adjacency to conduits, bus-ducts or other electrical distribution equipment containing high AC current conductors. Magnetic fields naturally emitted from such conduits or bus-ducts may be sufficient in magnitude to induce troublesome levels of interference AC voltage on adjacent signal cabling. The potential for such interference is markedly greater when signal cable runs closely parallel AC power conduits for extended distances. Although not well documented or

understood, there have been numerous anecdotal reports of a wide variety of possible interference manifestations in CPU and digital equipment when placed in elevated AC magnetic field environments. Such interference problems have been known to affect the operation of high-speed CPU and certain computer disk drives, loss of data resulting in increased error rates and slower transmission speed of LAN digital signal networks. Most equipment manufactures including companies making CRT monitors, unfortunately do not publish AC or DC sensitivity levels for equipment.

2.2.10. Power Quality Standards

Geneva based International Electrotechnical Commission (IEC) and Institute of Electrical and Electronic Engineers (IEEE) have proposed various power quality standards. Table 2.2 lists some of these standards (Ghosh et al., 2002).

Table 2.2 Some power quality standards of IEC and IEEE (Ghosh et al., 2002).

Phenomena	Standards
Classification of power quality	IEC 61000-2-5: 1995, IEC 61000-2-1: 1990, IEEE 1159:1995
Transients	IEC 61000-2-1: 1990, IEEE c62.41: (1991), IEEE 1159: 1995, IEC 816: 1984
Voltage sag/swell and interruptions	IEC 61009-2-1: 1990, IEEE 1159: 1995,
Harmonics	IEC 61000-2-1: 1990, IEEE 519: 1992, IEC 61000-4-7: 1991
Voltage flicker	IEC 61000-4-15: 1997

2.3. What is Custom Power?

Customers are increasingly demanding quality in the power supplied by the electric company. In that way, technology, regulations and customer practices are moving forward in that direction. The most important benchmarks in the suitable technology to be used in the solution of quality problems are marked by the continuous upgrade in the characteristics of the power semiconductor devices, such as IGBTs, GTOs and thyristors. The availability of better and faster electronic

devices is followed, with some time delay, with the appearance of commercial equipment that use them.

There have been considerable changes in today's power systems in recent years, as emergence of privatization and deregulation is to provide the customer with reduced costs. The global competition between utilities leads to utility cost-cutting, downsizing and reducing maintenance on both transmission and distribution systems. Power systems that are hierarchically integrated are being separated such that tasks normally carried out within traditional organizations have been open to competition whenever practical and profitable. This process is called "unbundling", which consists of unbundling of vertically integrated utilities, unbundling of functions within a corporation and service unbundling. As the consequence, the common structure in the deregulated power industry is the separation of the generation, transmission and distribution business into separate entities. The customers, then, would be free to select their desired level of power quality. However, many technical problems must be solved to realize such an unbundled power quality service.

Power quality issues have become more important in the face of this open competition. Customers, who need high quality of power for their equipment and are becoming better informed about power quality issues, provide the principal motivation for the utility industry with unbundled services and greater reliance on competitive forces. There is opportunity for enhanced value of service through greater choice among customized and competitive services. Yet the utility industry is likely forced to offer a variety of valued-added unbundled services and prices to customers so as to increase customer satisfaction and the threat of competition. (Alvarez *et al.*, 2000)

With the ever-increasing role of electricity in improving the quality of life, productivity of manufacturing and service industries, and efficient energy use, power electronics will play a significant part. One of the growing power electronics applications is the Power Quality/Custom Power (Hingorani, 1995).

Custom power is the employment of power electronic or static controllers in medium and low voltage distribution systems for the purpose of supplying a level of reliability and/or power quality that is needed by electric power customers sensitive

to power quality variations. (D. Daniel Sabin et al.,2003). In other words custom power is intended to protect the customers from interruptions and voltage reductions originating in the utility system as well as those transferred to customers from other customers via the utility system and even internal disturbances (Hingorani, 1995). Custom power devices, or controllers, include static switches, active filters, DVRs, injection transformers, energy storage modules that have the ability to perform current interruption and voltage regulation functions in a distribution system to improve reliability and/or power quality (D. Daniel Sabin et al., 2003).

In a Custom Power system customer receives specified power quality from a utility or a service provider or at-the-fence equipment installed by the customer in coordination with the utility, which includes an acceptable combination of the following features:

- No (or rare) power interruptions
- Magnitude and duration of voltage reductions within specified limits.
- Magnitude and duration of overvoltages within specified limits.
- Low harmonic voltage.
- Low phase unbalance.

This can be done on the basis of an individual, large customer, industrial / commercial park or a supply for a high tech community on a wide area basis (Hingorani, 1995). Figure 2.5 shows a custom power distribution system.

The need for the Custom Power concept arises from the fact that:

1. Most of the interruptions and voltage reductions occur in the utility system on account of lightning faults on transmission and distribution lines, low frequency dynamic swings of the transmission system, trees touching the wires, equipment failure, switching, etc. Voltage sags may also be a consequence of large load changes affecting customers' own equipment or affecting other equipment via the utility system.

2. Impulses, switching surges and overvoltages affecting the insulation, would most likely result from lightning strikes and switching events in the transmission and distribution system.

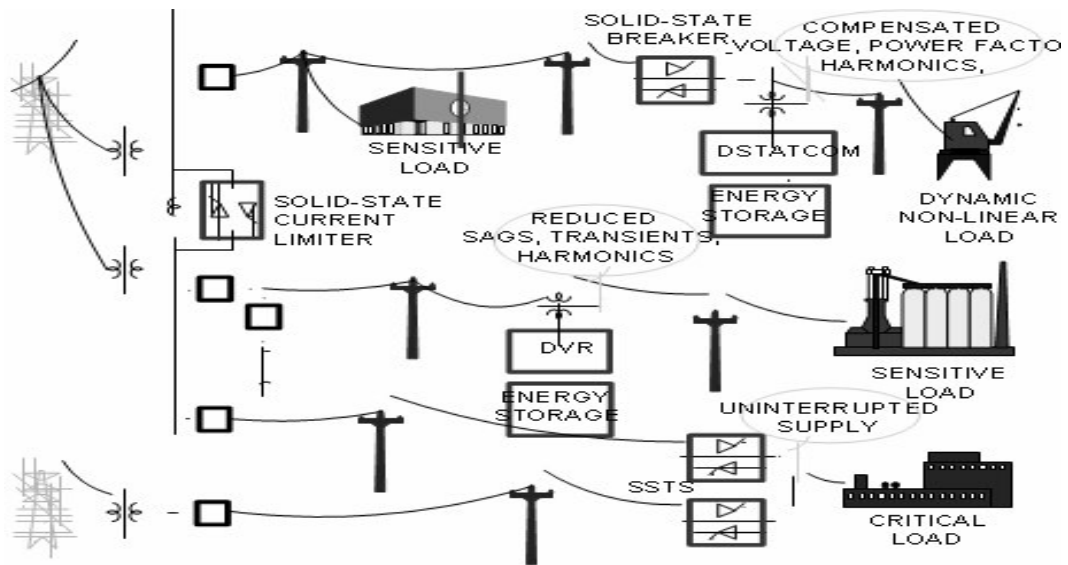


Figure 2.5 Custom power distribution system (Suresh Kumar, 2003)

3. Temporary overvoltages lasting from several cycles to several seconds would largely result from large load changes, capacitor switching, transformer switching, dynamic stability swings, excessive leading-VARs during light loads, etc. in the utility system.

4. Voltage unbalances in a three-phase supply would occur mostly due to large unbalanced loads on a utility's distribution lines and long lines with unbalanced phase impedances.

5. Harmonics would most likely be the consequence of high harmonics in the customer load, or the saturation of a utility's transformers. These harmonics would then be amplified by the natural resonances in the utility system and/or the customer system.

6. There are a number of reasons for the choice of the Custom Power concept for many customers, and on a long term basis for most customers. These reasons are:

- The customers are better served if they receive a comprehensive solution to their power supply problems from the power supply service providers
- Most of the voltage reductions and interruptions result from events that involve the utility system.

- In general, the total cost of the solutions that involve the utilities' own systems would be much less than the cost of solutions put in place by the individual customers.
- At least from the point of view of reliability, migration to the Custom Power concept seems to be inevitable.

2.4. Custom Power Devices

The power electronic controllers that are used in the custom power solution can be network reconfiguring type or compensating type.

The network reconfiguration devices are used for current limiting, current breaking and current transferring devices. These devices are:

- a) Static Current Limiter (SCL)
- b) Static Transfer Switch (STS)

The compensating devices either compensate a load, i.e., correct its power factor, unbalance etc. or improve the quality of the supplied voltage. These devices are either connected in shunt or in series or combination of both (Ghosh et al., 2002).

The devices include:

- a) Active Power Filters
- b) Dynamic Voltage Restorer (DVR)
- c) Unified Power Quality Conditioner (UPQC)

2.4.1 Static Current Limiter

Static current limiter (SCL) limits a fault current by quickly inserting a series inductance in the fault path. A SCL is a parallel connection of an anti-parallel gate turn-off thyristor (GTO) switch with snubbers, a current limiting inductor and a zinc oxide (ZnO) arrester. (Figure 2.6)

A GTO can be switched off at any time by applying a negative gate pulse. Therefore it can interrupt a current instantaneously. A thyristor switches off only when the current through it changes polarity. An anti-parallel thyristor switch is in a

current limiter will keep on conducting till the next zero crossing irrespective of the instant of occurrence of the fault. This will defeat the purpose for which a current limiter is installed.

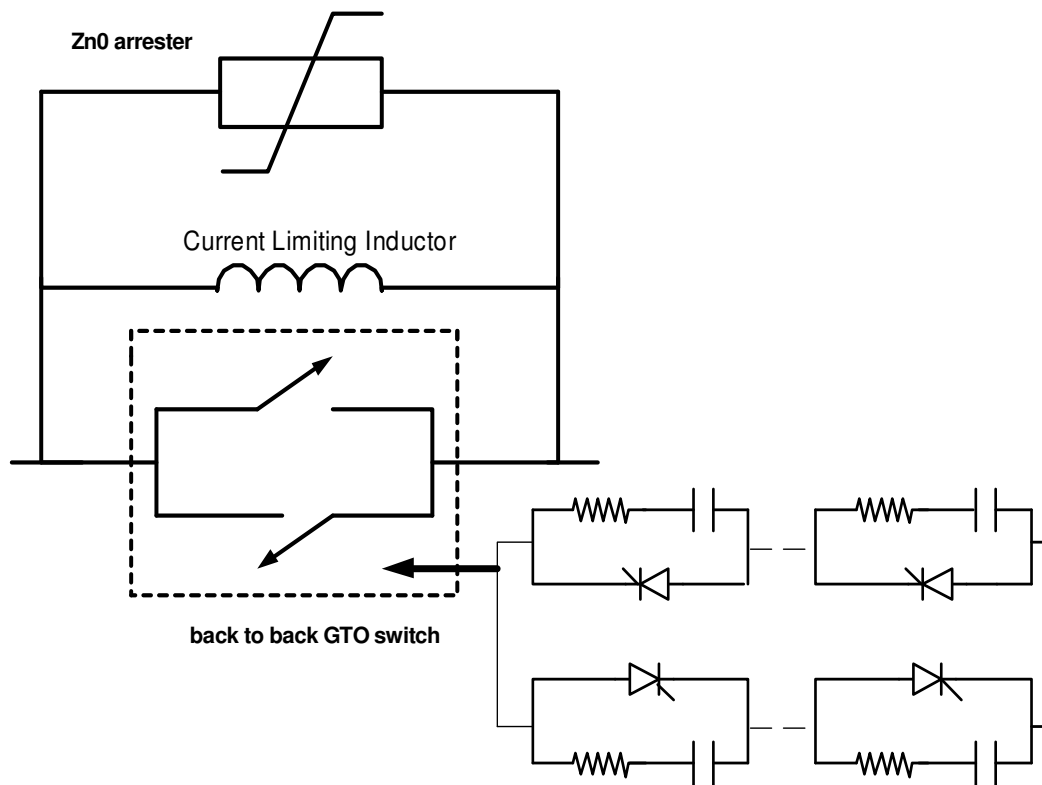


Figure 2.6 Basic structure of SCL (Ghosh et al., 2002).

Under normal (unfaulted) operating conditions, the GTOs are gated for full conduction. Once a fault occurs, the GTOs are turned off as soon as the fault is detected. A GTO can respond within a few microseconds. Once the GTOs are turned off, the fault current is diverted to the snubber capacitor that limits the rate of rise in voltage across the GTOs. The voltage across the anti-parallel GTO switch rises until it reaches the clamping level established by the ZnO arrester. The same voltage also appears across the current limiting reactor. Once the clamping level of the voltage is reached, the current across the reactor will rise linearly. This linear rise will continue till it becomes equal to the instantaneous level of current flowing in the line. Thus the

current will be limited by total effective series impedance, i.e., by a combination of the impedance of the limiting reactor and the faulted feeder impedance.

Without the snubber circuit, the limiting inductor comes in series with the feeder inductance once the GTO switch is turned off. The initial condition of the limiting inductor current is zero, while the feeder current flows through the feeder reactance. However when these two inductance come in series, the current through these two inductances must be same. Therefore the limiting inductor must be forced to instantaneously carry the feeder current. (Ghosh , 2003)

2.4.2. Static Transfer Switch (STS)

The STS can be used very effectively to protect sensitive loads against voltage sags, swells and other electrical disturbances. The STS ensures continuous high-quality power supply to sensitive loads by transferring, within a time scale of milliseconds, the load from a faulted bus to a healthy one. (Ani Gole et al., 1998), (Moschakis et al., 2003)

The STS contains two or more switches that allow transferring a load from a preferred feeder to an alternate feeder, as in Figure 2.7. The mechanical transfer switch has been used for many years to transfer industrial loads to a backup power source (e.g. alternate feeder, backup generator, etc.) as a countermeasure against interruptions on the preferred source or feeder. Due to the nature of the electromechanical switches used, a “seamless” transfer is not obtainable. Typical transfer times can range from about 100 milliseconds up to approximately ten seconds. (D. Daniel Sabin, 2003)

In the event of a voltage disturbance, the STS is used to transfer the load from the preferred source to an alternative healthy source. This results in a very effective way of mitigating the effects of both interruptions and voltage sags by limiting their duration as seen by the load. The success of the STS is mainly due to its rather low cost compared with other solutions. A requirement is that a secondary in-feed, independent from the main source (e.g. a feeder to another substation), must be

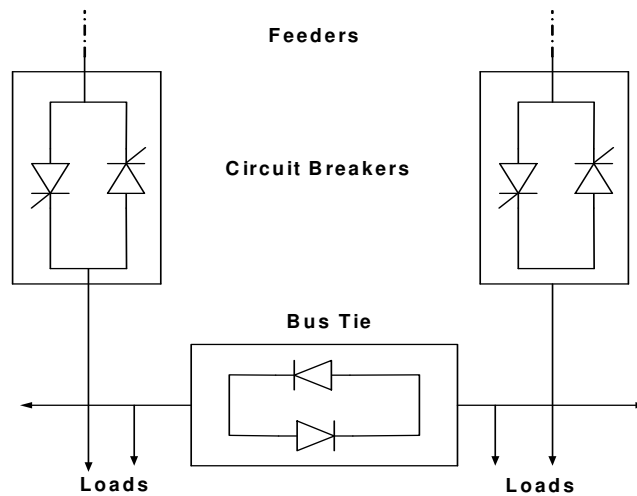


Figure 2.7 Basic configuration of a Static Transfer Switch

available. Therefore, this solution is particularly attractive for installations that already have mechanical transfer systems, where upgrading to a static system does not require major changes in the layout of the distribution system. Formerly available only for low voltages, STS systems are now advertised for higher voltages and load ratings, which make them suitable for high-power industrial applications: they would be capable to protect loads up to 35 MVA supplied at a voltage as high as 35 kV.

Figure 2.8 shows the detailed system structure of the STS. The system is composed of:

- A load which is sensitive to variations of utility supply,
- Two independent sources one of which is the preferred one and the other is the alternative one,
- Two thyristor blocks T_1 and T_2 which connect the load to the power sources,
- A control logic to monitor voltage quality of both sources, detect voltage fluctuations in the system (detection process), compare the two sources, and perform a load transfer from one source to the other one if needed (transfer process).

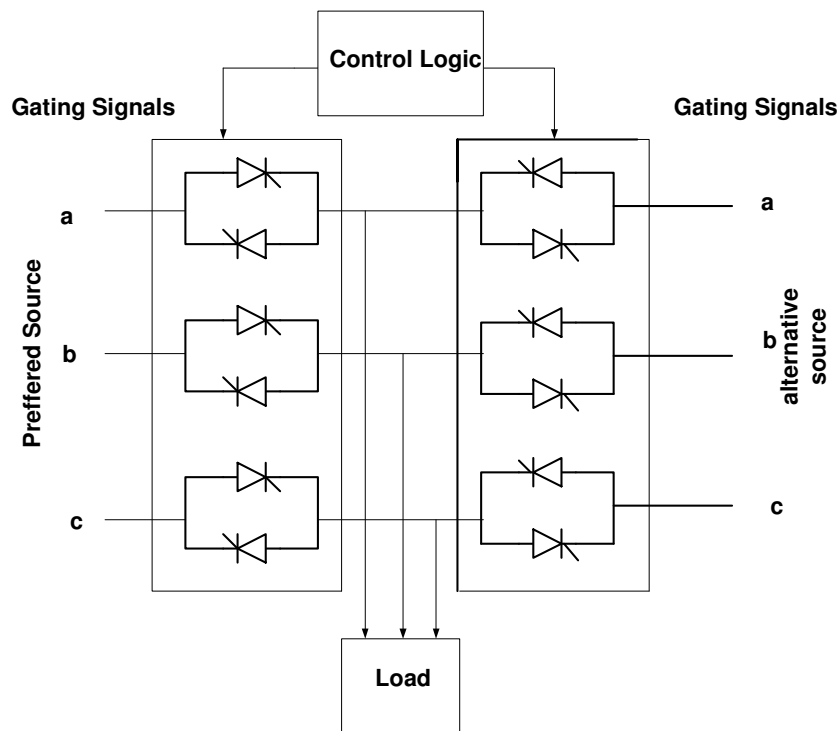


Figure 2.8. STS structure (IEEE PES TF, 2001)

Under normal operating conditions, i.e., when the preferred source meets load voltage requirements, the control logic triggers only the thyristors of T_1 . If the preferred source cannot meet voltage requirements, the control logic will transfer the load to the alternate source if it is in a better condition than the preferred one. This is achieved by removing gating signals from T_1 thyristors and triggering T_2 thyristors. In case of voltage recovery, the load is transferred back to the preferred source.

STS blocks T_1 and T_2 each contain three thyristor modules corresponding to the three phases of the system. Each thyristor module includes two anti-parallel thyristor switches.

Transfer-time estimation of a STS is not a straightforward process due to its dependence on commutation between the thyristor switches in each phase. The commutation process itself is determined by the system parameters and the component characteristics. (IEEE PES TF, 2001). To offer ride-through capability,

the load must be transferred within the shortest possible time. Therefore, the STS must meet the following requirements:

- It must detect voltage fluctuations in the system as fast as possible.
- In case the preferred source fails, it must perform a fast load transfer to the alternative source.
- The gating strategy, which controls the transfer process, must prevent paralleling the two sources.
- Detection and transfer logic must function properly for all possible operating conditions.
- Detection scheme must not be sensitive to temporary voltage transients, e.g., capacitor switchings. (IEEE PES TF, 2001)

2.4.3. Active Power Filters

The increasing use of power electronics based loads (adjustable speed drives, switch mode power supplies, etc.) to improve system efficiency and controllability is increasing the concern for harmonic distortion levels in end use facilities and on the overall power system. The application of passive tuned filters creates new system resonances which are dependent on specific system conditions.

In general, passive tuned filters have been used to minimize low-frequency current harmonics while high-pass units have been connected to attenuate the amplitude of high frequency current components. However, high-pass filters present disadvantages due to the resistance connected in parallel to the inductor, which increases the filter losses and reduces the filtering effectiveness at the tuned frequency. The most critical aspects of passive filters are related to the fact that they cannot modify their compensation characteristics following the dynamic changes of the nonlinear load, the performance dependence they present with the power system parameters, and the probability of series resonances with the power system's equivalent reactance. Another technical disadvantage of passive filters is related to the small design tolerances acceptable in the values of L and C. Small changes in the value of L or C modify the filter resonant frequency. For example, a 5% difference in

the selected value of L or C in a second-order LC filter tuned at 250 Hz (fifth harmonic) modifies the required resonant frequency in 7% with respect to the selected design value, affecting the filter current harmonic compensation performance. Also, the passive filter generates at fundamental frequency reactive power that changes the system voltage regulation, and if the filter is not designed properly or disconnected during low load operating conditions, overvoltages can be generated at its terminals. (Fang Zheng Peng et al., 1998), (Darwin Rivas et al., 2003)

Also, passive filters often need to be significantly overrated to account for possible harmonic absorption from the power system. Passive filter ratings must be coordinated with reactive power requirements of the loads and it is often difficult to design the filters to avoid leading power factor operation for some load conditions.

A flexible and versatile solution to voltage/current quality problems is offered by active power filters. Active filters have the advantage of being able to compensate for harmonics without fundamental frequency reactive power concerns. This means that the rating of the active power can be less than a conquerable passive filter for the same nonlinear load and the active filter will not introduce system resonances that can move a harmonic problem from one frequency to another.

Figure 2.9 shows the components of a typical active-power-filter system and their interconnections. The information regarding the harmonic current, generated by a nonlinear load, for example, is supplied to the reference-current/voltage estimator together with information about other system variables. The reference signal from the current estimator, as well as other signals, drives the overall system controller. This in turn provides the control for the PWM switching-pattern generator. The output of the PWM pattern generator controls the power circuit via a suitable interface. The power circuit in the generalised block diagram can be connected in parallel, series or parallel/series configurations, depending on the connection transformer used. (M. El-Habrouk *et al.*, 2003)

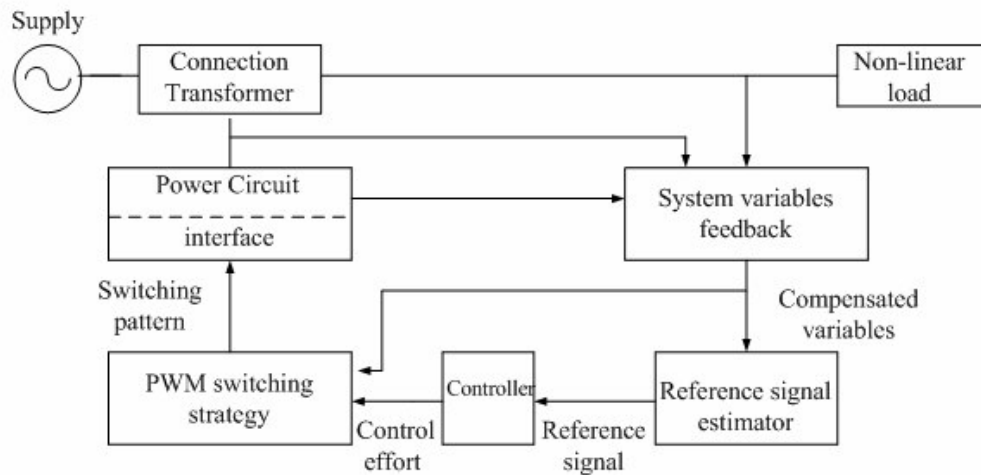


Figure 2.9 Generalised block diagram for active power filter (M. El-Habrouk et al., 2000)

2.4.3.1. Shunt Active Power Filters

The purpose of the shunt active power filters is to cancel load harmonics fed to the supply. It can also contribute to reactive-power compensation and balancing of three phase currents. (M. El-Habrouk et al., 2003) Shunt active power filters compensate current harmonics by injecting equal-but-opposite harmonic compensating current. In this configuration active power filter operates as a current source injecting the harmonic components generated by the load but phase shifted by 180° . This principle is applicable to any type of load considered a harmonic source. Moreover, with an appropriate control scheme, the active power filter can also compensate the load power factor. In this way, the power distribution system sees the non linear load and the active power filter as an ideal resistor. The current compensation characteristic of the shunt active power filter is shown in Figure 2.10 (Luis A. et al., 1999)

Parallel filters have the advantage of carrying only the compensation current plus a small amount of active fundamental current supplied to compensate for system

losses. It is possible to connect several filters in parallel to cater for higher currents, which makes this type of circuit suitable for a wide range of power ratings.

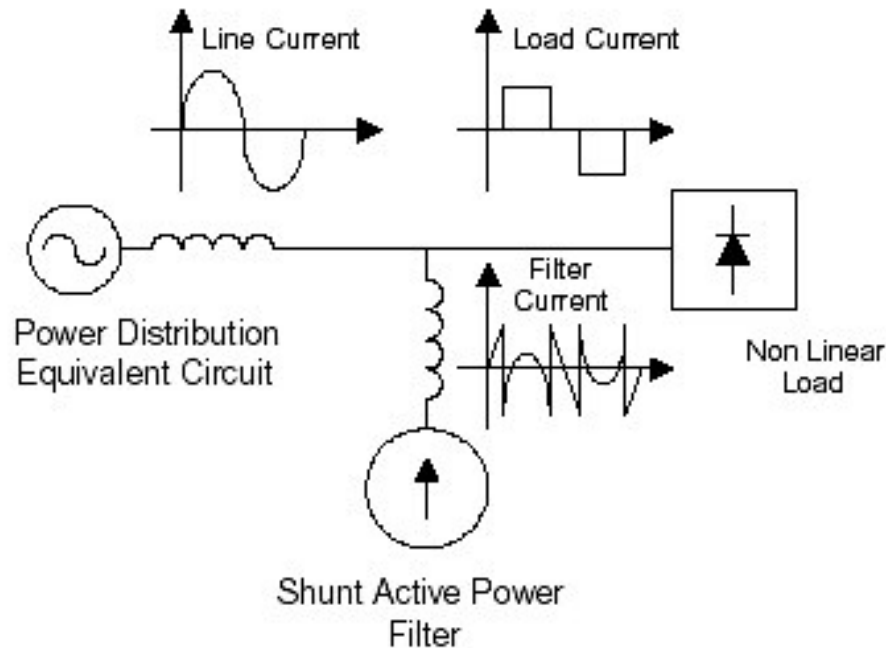


Figure 2.10 Compensation characteristics of shunt active power filter (Luis A. et al., 1999)

2.4.3.2. Series Active Power Filters

The active filter in this configuration produces a PWM voltage waveform which is added/subtracted, on an instantaneous basis, to/from the supply voltage to maintain a pure sinusoidal voltage waveform across the load (M. El-Habrouk et al., 2000). The main power-circuit configuration is shown in Figure 2.11.

Series active filter is to be placed in series between the ac source and the load (or harmonic source) to force the source current to become sinusoidal. The approach is based on a principle of harmonic isolation by controlling output voltage of the series active filter. In other words, the series active filter is to present high impedance to harmonic current, therefore blocking harmonic current

flow from the load to the ac source and from the ac source to the load side. (Fang Zheng Peng et al., 1998)

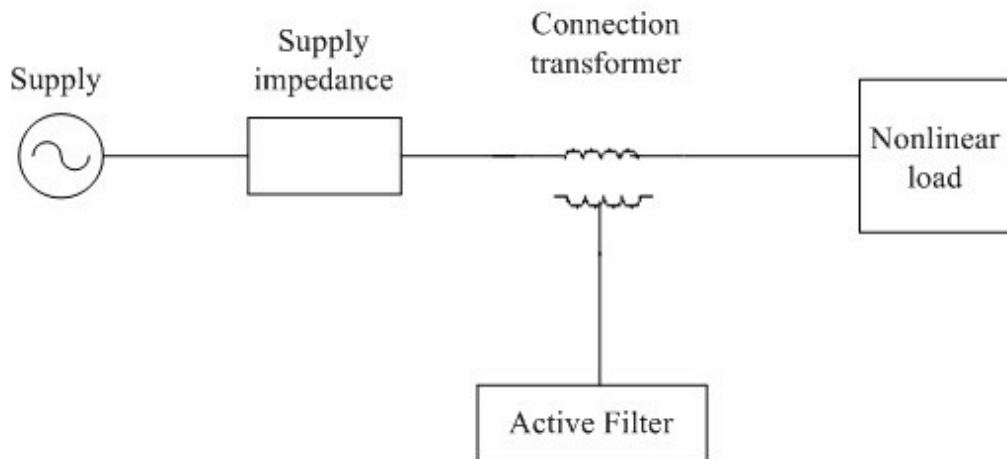


Figure 2.11 Series active filter configuration (M. El-Habrouk et al., 2000)

The main advantage of series filters over parallel ones is that they are ideal for eliminating voltage-waveform harmonics, and for balancing three-phase voltages. This, in fact, means that this category of filter is used to improve the quality of the system voltage for the benefit of the load. It provides the load with a pure sinusoidal waveform, which is important for voltage-sensitive devices. (M. El-Habrouk et al., 2000)

2.4.4. Dynamic Voltage Restorer

A Dynamic Voltage Restorer (DVR) is a power-electronic-converter based device that has been designed to protect critical loads from all supply-side disturbances other than outages. It is connected in series with a distribution feeder and is capable of generating or absorbing real and reactive power at its ac terminals. The basic principle of a DVR is simple: by inserting a voltage of required magnitude and frequency, the DVR can restore the load-side voltage to the desired amplitude and waveform even when the source voltage is unbalanced or distorted. Usually a

DVR is connected to protect sensitive loads during faults in the supply system. (Ghosh et al., 2002), (N.H. Woodley et al., 1999), (Arindam Ghosh et al., 2004)

A DVR is usually built round a dc–ac power converter that is connected in series with a distribution line through three single-phase transformers. The dc side of the converter is connected to a dc energy-storage device. The energy state of the device is regulated by taking power from the feeder. (Mahinda et al., 2002)

Voltage magnitude, waveform, and frequency are the major factors that dictate the quality of a power supply. Use of extensive nonlinear power electronic loads is one of the major reasons of deteriorating the quality of power supply. Faults at either the transmission or distribution level may also cause transient voltage sag or swell in the entire system or a large part of it. Also, under heavy load conditions, a significant voltage drop may occur in the system. Such voltage variations are not desirable for sensitive loads. (Vilathgamuwa et al., 2003)

Dynamic Voltage Restorers are used in some basic voltage disturbance correction. By correcting these disturbances, the line is said to be compensated. DVR is especially used for compensating the sags and swells. A typical operation of a DVR is shown in Figure 2.12. Figure shows that distribution system has a voltage sag and DVR is used to compensate it. The corrected output voltage waveform is purely sinusoidal at the load side.

Figure 2.13 shows the schematic diagram of a typical DVR used for voltage correction. When the supply voltage changes, the DVR injects a voltage in such a way that the desired load voltage magnitude can be maintained. The DVR is simply a voltage source inverter that produces an ac output voltage and injects in series with the supply voltage through a booster transformer. To correct a given voltage drop, not only voltage injection but also active and/or reactive power injection are needed. The DVR itself is capable of generating the reactive power, however, but the injected active power must come from the energy storage part of the DVR. Thus minimization of active power injection is essential to increase the life of the energy storage. (Vilathgamuwa et al., 2003), (Liu et al., 2003)

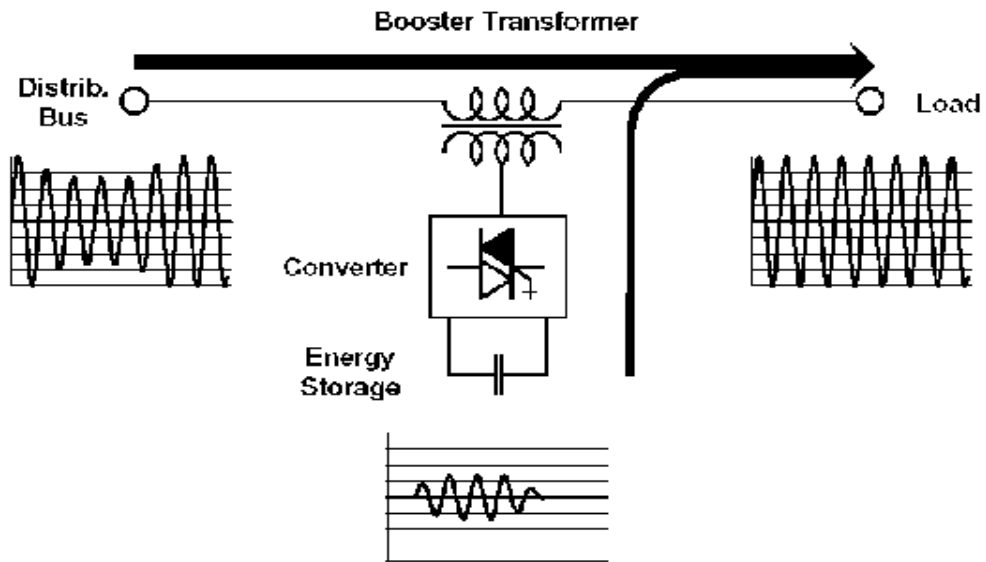


Figure 2.12 . Operation of DVR

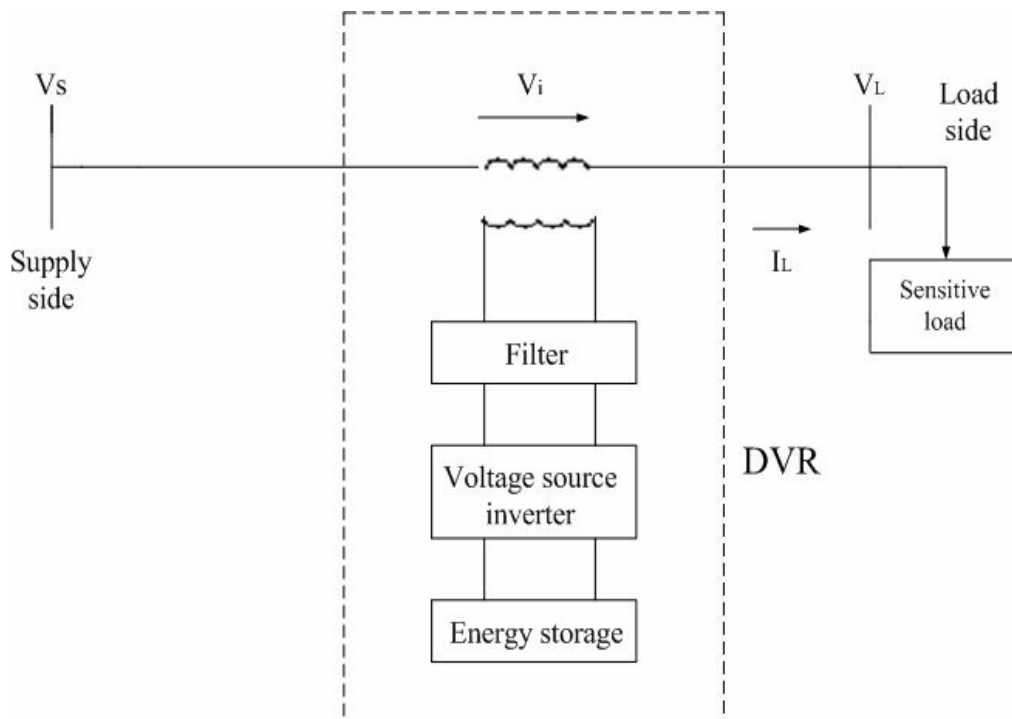


Figure 2.13 . Schematic diagram of a typical DVR (Choi et al., 2000)

2.4.5. Unified Power Quality Conditioner

Poor power quality in a system could be due to different factors such as voltage sag, voltage swell, voltage outage and over correction of power factor and unacceptable levels of harmonics in the current and voltage. Modern solution for poor power quality is to take advantage of advanced power electronics technology. Recent research efforts have been made towards utilizing a device called unified power quality conditioner (UPQC) to solve almost all power quality problems. (Vilathgamuwa et al., 1998)

The main purpose of a UPQC is to compensate for supply voltage flicker/imbalance, reactive power, negative-sequence current, and harmonics. In other words, the UPQC has the capability of improving power quality at the point of installation on power distribution systems or industrial power systems. The UPQC, therefore, is expected as one of the most powerful solutions to large capacity loads sensitive to voltage flicker/imbalance. (Fujita et al., 1998)

Unified Power Quality Conditioner (UPQC) for non-linear and voltage sensitive loads has following facilities.

- It eliminates the harmonics in the supply current, thus improves utility current quality for nonlinear loads.
- UPQC provides the VAR requirement of the load, so that the supply voltage and current are always in phase, therefore, no additional power factor correction equipment is necessary.
- UPQC maintains load end voltage at the rated value even in the presence of supply voltage sag.
- The voltage injected by UPQC to maintain the load end voltage at the desired value is taken from the same dc link, thus no additional dc link voltage support is required for the series compensator. (Malabika et al., 2002)

The UPQC consists of two three phase inverters connected in cascade in such a manner that inverter II is connected in parallel with the load. Inverter I is connected in series with the supply voltage through a transformer (Figure 2.14). The main purpose of the shunt compensator is to compensate for the reactive power

demanded by the load, to eliminate the harmonics and to regulate the common dc link voltage.

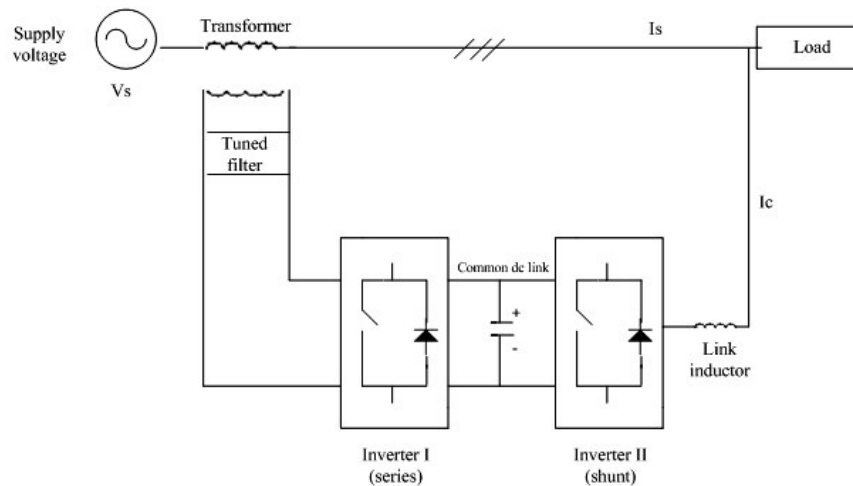


Figure 2.14 Schematic diagram of UPQC (Malabika et al., 2002)

The series compensator is operated in PWM voltage controlled mode. It injects voltage in quadrature advance to the supply voltage (current) such that the load end voltage is always maintained at the desired value. The two inverters operate in a coordinated manner. (Malabika et al., 2002)

2.5. Custom Power Park

As a new custom power concept of improving power quality, attention has been paid to Custom Power Park, which is able to offer customers high quality of power and to meet the needs of sensitive loads with an industrial/commercial business park. (Alvarez et al., 2000) The concept requires integration within the park of multiple Custom Power devices, which have previously been deployed independently. These devices compensate for power quality disturbances to protect sensitive process loads as well as improve service reliability. By integrating multiple power quality technologies and utilizing a communications network between the devices, this concept is actually distinguished from previous

technologies that only stand-alone pieces of equipment. Such an approach can actually permit business strategies whereby customer retention and acquisition becomes possible in a globe competitive environment. (Alvarez et al., 2000)

The Custom Power Park concept requires integration of state-of-the-art power quality devices within a utility's distribution system, which could provide tenants with electronically controlled, cost-effective, nearly undisturbed energy: energy corrected for major sags, swells, harmonics and other disturbances. (Christine, 1999) As mentioned in the previous sections, STS, Active Filters, DVR, and UPQC so forth are state-of the-art technologies installed to coordinate with each other and monitor the power supply so as to mitigate disturbances. The distinguished features of these devices can be combined to create a new technology that can provide improved quality of electrical service to the tenants of industrial (or commercial office) sites. The concept can be applied to either a new development or the upgrade of an existing property. The Custom Power Park combines power quality controllers with engineering services to develop and maintain integrated high-quality electric service. (Alvarez et al., 2000)

A tenant in the Custom Power Park may be able to dispense with specialized equipment to condition incoming electric power, and experience improved power quality. Functions such as power factor correction and power conditioning would become the responsibility of the Custom Power Park operators and would be achieved by proper application of power quality controllers. The Park operations center receives power from multiple distribution feeders and can even combine it with distribution sources or energy storage systems, and then distribute power to its tenants in the park. Another possible Custom Power Park design includes a utility corridor with multiple electric circuits. Electric power with different power quality specifications could be provided to tenants with different needs. Tenants would be able to connect portions of their load to appropriate classes of service. If a tenant's load characteristics later change (as detected by the monitoring system), the tenant may be switched to a different power quality rate and service level as appropriate. (Alvarez et al., 2000)

It has been pointed out that for banks, financial institutions, highly automated manufacturing and businesses, interruptions of electric power are becoming prohibitively expensive because of their heavy reliance on electronic computation and communication. These enterprises are better located in Premium Quality Power Parks which provide a total solution to power quality. The dedicated Parks are segregated from “dirty loads”. To ensure continual availability, power is taken from more than one independent source: the electric utility grid, energy storage and/or cogeneration schemes. (Weixing et al., 2002)

A major benefit to the Custom power park tenant would be that, in most cases, there would no longer be a need for power correction capacitors on the tenant’s power system. This equipment is a major cause of harmonic resonance and and overvoltage conditions. Power factor correction could be the responsibility of the Custom Power Park and would be achieved by proper application of Custom Power Controllers on the park.

Restrictions on tenants would include permission to monitor power system conditions within the tenant’s system. If a tenant’s load characteristics change (detected by the monitoring system) in such a way that requires additional enhancement by the park, the tenant may be moved to a different Custom Power rate classification since the Custom Power rate would be a function of the degree of “clean up” required by the tenant’s processes and system.

A further benefit to tenants that results from the in-plant electrical service monitoring by the park is that the tenant no longer needs power system experts or consultants on their payroll. The Custom Power Park will provide the necessary in-plant power system engineering expertise for all tenants. This seen as a very significant plus for the Custom Power Park concept. Power system engineering expertise is increasingly difficult to find when needed and surveys show that utility customers prefer a utility-supplied solution to their electrical service disturbance problems.

Alternatively, Custom Power rate classification could be determined by “levels of enhancement” in electrical service available from the utility defined simply as:

- Standard Service
- Improved Service
- Premium Service

A measure of power quality such as a Quality Factor Index, would be assigned to each class of service. Certain weightings would be identified and assigned to the parameters which define power quality, i.e., sags, swells, transients, interruptions, etc. A Quality Factor Index would be assigned to each class of service and justify the higher (premium) rates due to the improved quality of power available. Their justification for paying higher rates would be based upon their need for the selected level of service to void costly downtime as well as the savings achieved by not purchasing, operating and maintaining internal power conditioning equipment.

Any cost comparison of Custom Power service with “standard” service must include both investment and operating costs of “going it alone” versus the premium rate changes. Operating costs of conventional power conditioning includes:

- cost of losses
- maintenance costs
- communications costs
- spare parts inventory
- indirect (overhead) costs associated with equipment, e.g. floor space, air conditioning, lighting, special fire protection/monitoring, etc.

Costs would be expressed in such a manner to allow allocation over tenant energy consumption, peak demand, tenant occupied space, sale of “corrected kWh” or other measures. The cost of providing Custom Power may include a “loss of business” insurance premium to cover utility liability exposure. (Suresh Kumar, 2003)

In a Custom Power Park all customers will benefit from a basic supply which is a cut above the normal power supply from a utility. This basic supply can be obtained by provision of two incoming feeders along with Solid State Transfer switches which will reduce the duration of most voltage dips to 4-8ms by rapidly selecting the feeder with the highest voltage. (Ghosh et al., 2004) It is also clear that

most of the customers generate moderate to high harmonics, and therefore need an active filter service. Thus, the lowest grade supply should involve use of two incoming feeders, SSTs and an active harmonic filter.

The key issue is how many grades of power should be available, and how the choices are determined and managed. Consideration of the value to different type of customers suggests that three grades of qualities (CP-A, CP-AA, and CP-AAA) with appropriate value-added premium cost, can serve the need. As a minimum, all customers would receive power CP-A with a quality superior to the regular power. Custom Power Park Control system will play a key role in the real-time and off-line management of services.

As an example, the following loads are assumed for the Custom Power Park. (Figure 2.15).

<u>Max Load</u>	<u>PQ Need</u>
Semiconductor Chip Co.	10 MW CP-AAA
Biotech Co.	2 MW CP-AAA
Computer Hardware Co.	1 MW CP-A
Software Development Co.	1 MW CP-AA
Plastics Co.	3 MW CP-A
Hospital	10 MW CP-AA + CP-AAA
Data Processing Center	2 MW CP-AA + CP-AAA
Office Building	2 MW CP-A
Shopping Mall	2 MW CP-A + CP-AAA

Total	33 MW peak load

2.5.1. Custom Power A (CP-A)

This is the basic value-added power at the Park. Its higher quality, compared to the regular power, arises from the fact that the Park has two incoming feeders, which can be designed with improved grounding, insulation and arresters, and better maintenance which reduces the chance of nearby lightening and other faults. With

single phase tripping and reclose, the interruptions and major voltage dips are greatly reduced. In addition, the Solid State Transfer Switching ensures that the feeder with superior voltage is selected in less than half a cycle. There will still be voltage dips which are common to both feeders resulting from faults and dynamic swings in the transmission network. Sags from transmission line faults usually last for 4-10 cycles, and occasionally the system swings may cause 20-50 percent dips for about 1 second, and then repeated if the power system is unstable. There is also the possibility that a circuit breakers after clearing the fault will reclose into a fault, and the voltage sag and system oscillations will be repeated. Never the less, improvement over and above the normal power is substantial and may be characterized as follows:

- a) 60-80 percent reductions in voltage sags.
- b) Rare occurrence of interruptions.
- c) Active harmonic filters.

2.5.2. Custom Power AA (CP-AA)

Over and above grade CP-A, grade CP-AA receives the benefit of a standby generator which can come up to speed in about 10-20 seconds in case of a power loss.

2.5.3. Custom Power AAA (CP-AAA)

Over and above grade CP-AA, grade CP-AAA receives the benefit of DVR, which precisely adds the right amount of voltage including harmonics to the feeder voltage to ensure virtually sag free, interruption free, and harmonic free voltage to the customer.

It is assumed that under emergency conditions (loss of DVR), CP-AAA may degrade to CP-AA. For unavailability of backup power, it would still receive superior quality power and priority customer service attention.

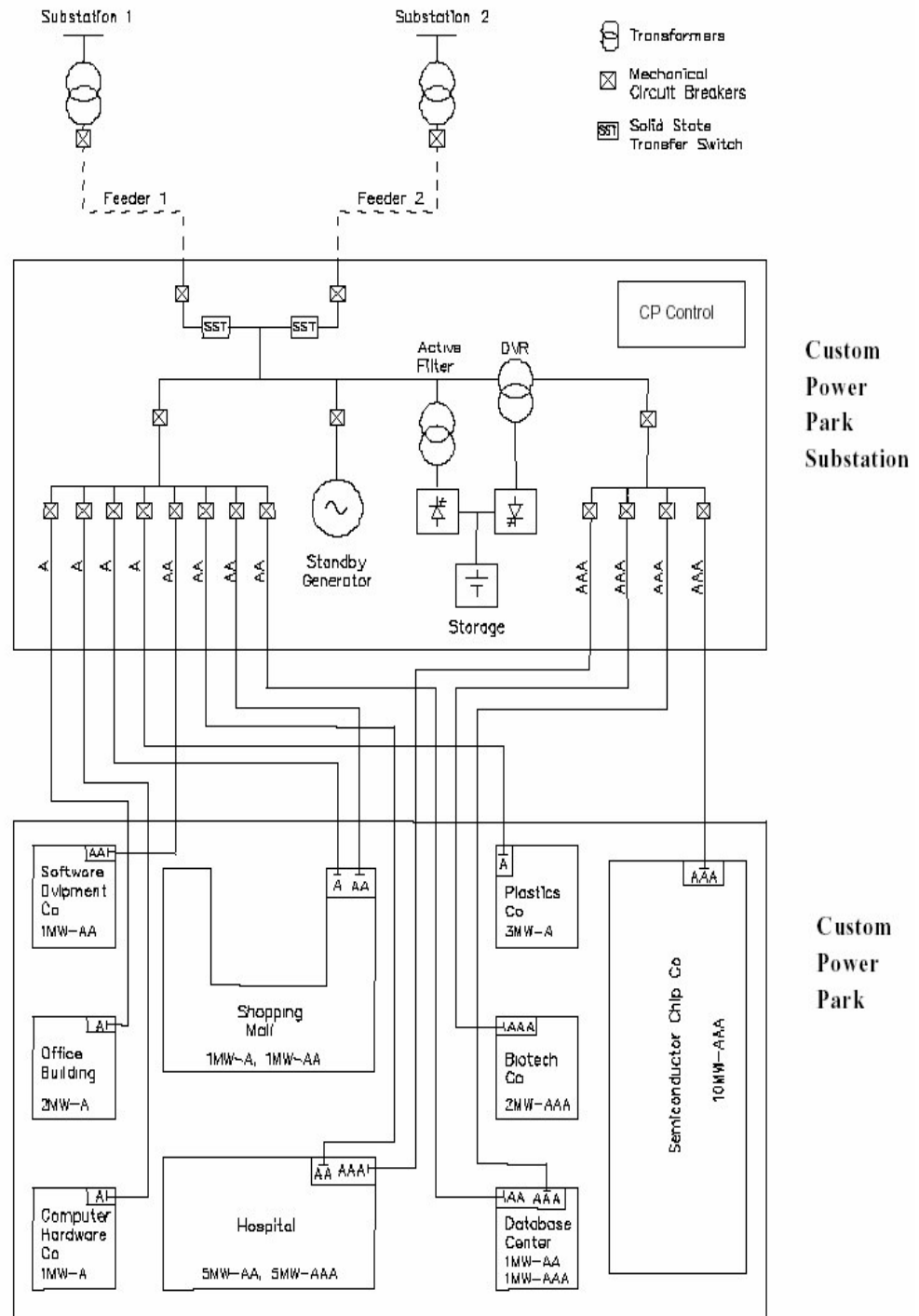


Figure 2.15 Custom Power Park concept (Hingorani, 1995)

On the left hand side of the CP bus, Figure 2.15 shows a distribution bus for Custom Power A and AA. Both receive the same service as long as either of the two feeders is available. If and when both feeders are lost, the circuits of all customers A and AA are disconnected at both ends by their circuit breakers. The differentiating feature between customers A and AA is that when the standby generator is up and running (perhaps 10-20 seconds after the loss of both feeders), the circuit breakers for customers AA are closed to restore power to those customers. This means that customers AA do not lose power for more than 10-20 seconds in the case of loss of both feeders. However the customers A do not receive power until one of the feeders is back in service.

The standby generator normally stays off and disconnected from the CP bus. When both feeders are off, the generator is started up immediately, brought up to speed, synchronized and connected to the CP bus. It should take 10-20 seconds for the generator to come on line, and pick up the load of both AA and AAA customers. It is reasonable to assume that CP Control will supervise this fully automated diesel driven or gas turbine generator of 5-10 MW size. When only one feeder is off, CP Control will alert all the customers and also the utility to confirm that the generator is available, has adequate fuel supply, and to ensure that the utility is extra careful in its system operation; the CP Control can in fact start up the standby generator and bring it online.

Under peak load conditions and/or when one circuit off, the CP Control may even bring the generator up and connected. It can become a co-generator, even if both incoming feeders are intact. Furthermore co-generation may be used as often as economic conditions are favorable for co-generation.

In order to ensure that the CP- AAA customers are not deprived of power during the period that the generator is brought up to speed and on line, and to supply them power without dips, distortion and imbalance, a combination of Active Filter, Dynamic Voltage Restorer, and hot standby storage is provided as shown on the right hand side of Figure 2.15.

In addition, connection to the AAA customers can also be made through solid state current limiting circuit breakers (SSCL). This can ensure that the fault

current resulting from faults in the CP-AAA customers own system does not exceed, say, 2 times their peak load for about 1 or 2 seconds before tripping. This will further ensure that other CP-AAA customers are not affected. SSCLs can provide coordination with the downstream protective relays of the CP-AAA customers. These SSCLs also limit over loading on the DVR. Another alternative would be to provide a separate series converter (DVR) for each customer or a CP super-AAA customer, etc. The active filter, can filter exactly the amount of harmonics it is ordered to filter. Thus with current measurement on its AAA customer side, it can ensure that the AAA customers' harmonics are filtered. CP Control will supervise such an operation, as well as monitor harmonics from other customers. On the other hand, it can also sum the measured current of selected customers, and filter the harmonics of these customers. The overriding considerations will be to ensure that the active filter is not overloaded, harmonic voltage on the CP bus is not excessive and that the total harmonics entering the feeders is reasonable. Because the harmonics from various customers may cancel each other to some extent, it may be best to order the active filter to minimize harmonic content in the common busbar connection between the two STSs and the CP bus. As mentioned earlier, practically all customer facilities generate harmonics and need active filter support.

Each customer's waveform is monitored by the CP Control, and all power quality events are captured, logged, and managed for periodic assessment of the service being provided. It is also necessary to evaluate specific events for continued improvement, and collect the information required to resolve disputes, performance-based payments/penalties, etc. (Hingorani, 1995)

3. MODELING OF THREE-WIRE SHUNT APF (ACTIVE POWER FILTER)

3.1. Introduction

Modern semiconductor switching devices are currently employed in a wide variety of domestic and industrial loads. These loads are often referred to as “power electronics loads”. They offer reliable and economical solutions to control of electric power, from a few watts to many megawatts. The nonlinear characteristic of semiconductor devices as well as the operational function of most power electronics circuits cause distorted current and voltage waveforms on the supply system. In contrast with the conventional linear loads, the power electronics loads are categorized as nonlinear loads. An example of a nonlinear load is a six pulse bridge rectifier with a smoothing reactor. These loads are commonly referred to as “power system polluters” or “distorting sources” in relevant literature. The presence of power electronics related distorting elements in virtually all major industrial loads is viewed by the power distribution authorities as the major cause of an alarming amount of harmonic distortion in electric power systems. The problems caused by these types of loads is a part of Electric Power Quality studies.

The concept of using active power filters to mitigate harmonic problems and to compensate reactive power was proposed more than two decades ago [Akagi et al., 1984]. Since then the theories and applications of active power filters have become more popular and have attracted great attention. Without the drawbacks of passive harmonic filters, the active power filter appears to be a viable solution for reactive power compensation as well as for eliminating harmonic currents.

Fuzzy logic and neural network techniques are now being increasingly applied to power electronics [Bose et al., 1997, Grabowski et al., 2000, Vazque et al., 2000, Jain et al., 2002, Madtharad et al., 2002, Abdelrahim et al.,2002]. The integration of fuzzy logic with neural networks and genetic algorithms is now making automated cognitive systems a reality in many disciplines. The power of fuzzy systems when integrated with learning capabilities of neural networks and

genetic algorithms is responsible for new commercial products and processes that are effective cognitive systems.

Adaptive Neuro-Fuzzy Inference System (ANFIS) which was put forward in [Shing et al., 1993] is a fuzzy inference system structure that combined fuzzy logic with neural networks. Adaptive neuro-fuzzy inference systems use linguistic variables to build databases in the form of fuzzy if-then rules. They are able to adapt their parameters in order to match the nonlinear performance of targeted systems. Such abilities make ANFIS a good candidate to develop controllers for nonlinear systems like power electronic converters since the converter is truly a nonlinear system. ANFIS based controllers for power electronic converters mostly used in motor drives are presented in [Ushakumari et al., 2001, Rubaai et al., 2004, Vasudevan et al., 2004, Miloudi et al., 2004, Ahn et al., 2001, Aware et al., 2000]. ANFIS is also suitable for fault diagnosis of electric machinery when trained using various healthy and faulty case studies as presented in [Awadallah 2004, Awadallah et al., 2004, Park et al., 2004]. ANFIS based controllers for some other nonlinear process control purposes are presented in [Engin et al., 2004, Canete et al., 2000]. However application of ANFIS based controllers and hierarchical neuro-fuzzy control is not reported for any custom power device like active power filters and any other power electronic device in the literature. It appears that the nonlinear control is more suitable than the linear type since the converter ‘the heart of active power filter system’ is truly a nonlinear system.

In this chapter, first a single fuzzy logic controller based active power filter is presented. The modeling approach adopted is graphical in nature, as opposed to mathematical models embedded in code using a high-level computer language. For improving the performance of the single fuzzy logic controller system increase in the number of inputs and membership functions appeared to be necessary. A neuro-fuzzy controller is connected hierarchically to the output of first fuzzy logic controller which we call hierarchical neuro-fuzzy control to improve the performance. Since, standard fuzzy logic controllers suffer from exponential increase in the number of rules with the number of input variables, we opt to employ hierarchical fuzzy systems that are known to reduce the computational burden. Fuzzy

logic controllers are computationally intensive, thus requiring a very powerful processor for real-time implementation. Nonetheless, hierarchical fuzzy logic controllers are much less computationally demanding than standard fuzzy logic controllers without compromising the controller performance [Abdelrahim et al.,2002]. The method of current controller development is very interesting here and may be applied to other power electronic converter applications.

3.2. System Description

The active power filter uses power electronic switching to generate harmonic currents that cancel the harmonic currents from a load. The active filter configuration investigated in this study is based on a voltage source inverter that interfaces to the system through an interface reactor. In this configuration, the filter is connected in parallel with the load being compensated. Therefore the configuration is often referred to as a shunt (parallel) active filter. The approach is based on the principle of injecting harmonic current into the AC system, of the same amplitude and reverse phase to that of the load current harmonics.

Figure 3.1 shows the main components of a typical active power filter system and their interconnections. Figure 3.2 shows the Matlab / Simulink model of designed system.

The main components of the above system are as follows.

- Mains supply
 - Nonlinear load
 - Active Power Filter
 - Voltage source inverter
 - Interface reactor
 - Reference current generator
 - Current Controller
- | | |
|---|-----------------|
| } | Power circuit |
| } | Control circuit |

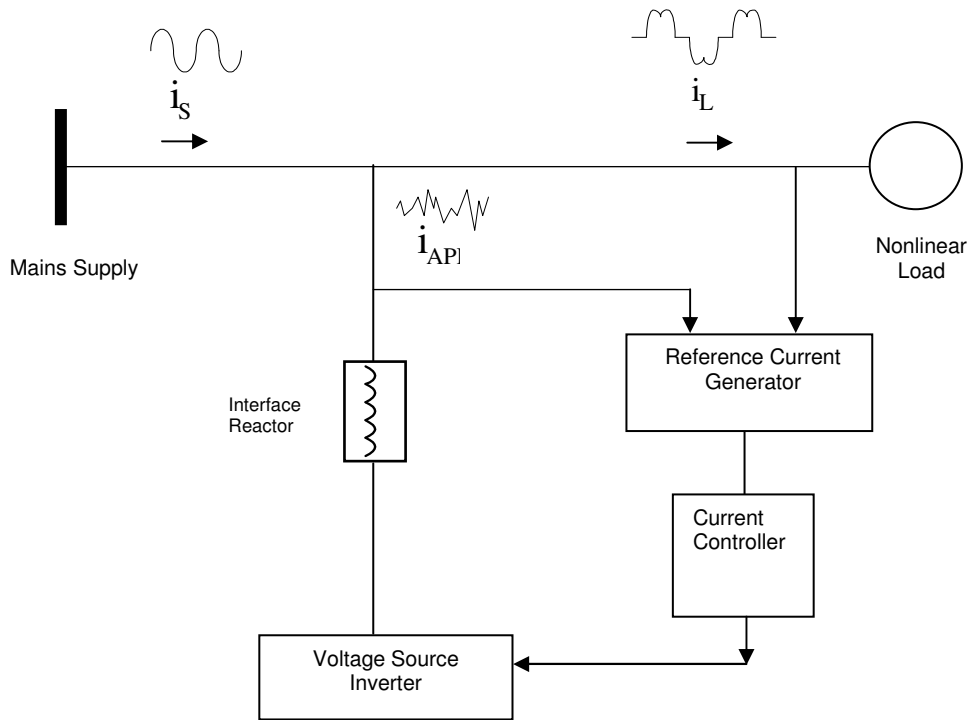


Figure 3.1 Diagram illustrating components of the shunt connected active power filter with waveforms showing cancellation of harmonics from a nonlinear load.

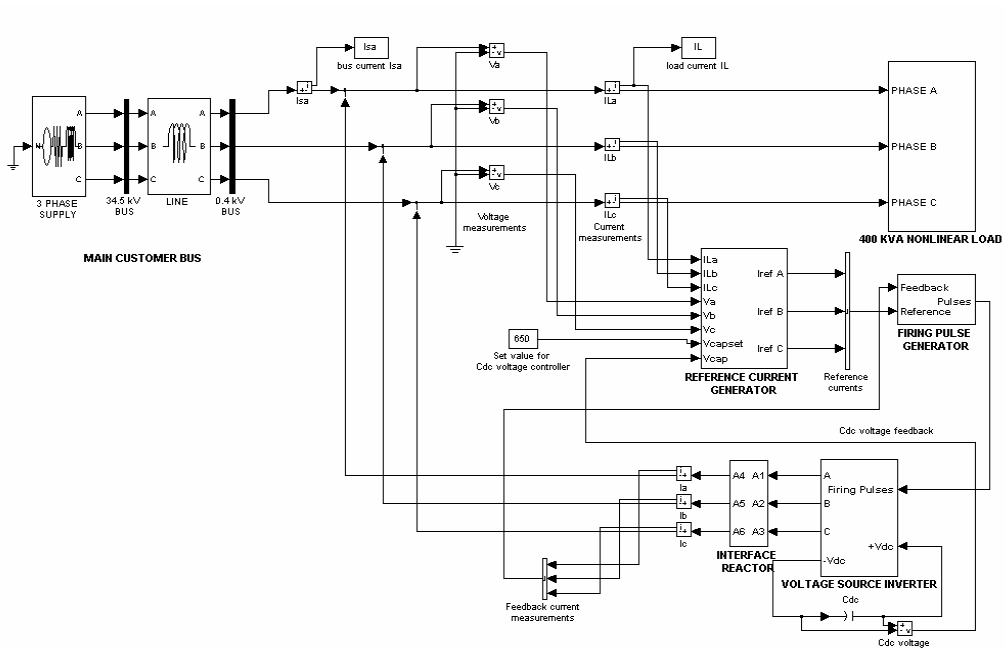


Figure 3.2 Matlab/Simulink model of designed system

3.2.1. Mains Supply

Mains supply is a three phase 380V 50 Hz wye connected power supply with a grounded neutral point equivalent of the actual system.

3.2.2. Nonlinear Load

The nonlinear load block is a three-phase fully controlled bridge rectifier feeding a DC motor. The DC motor is modeled with a resistance, inductance and a back emf. It is possible to control the firing angle of the controlled three-phase rectifier. According to German VDE standards minimum of 5% series reactor should be connected to the supply side of the rectifier. The Matlab / Simulink model of the nonlinear load block is shown in Figure 3.3.

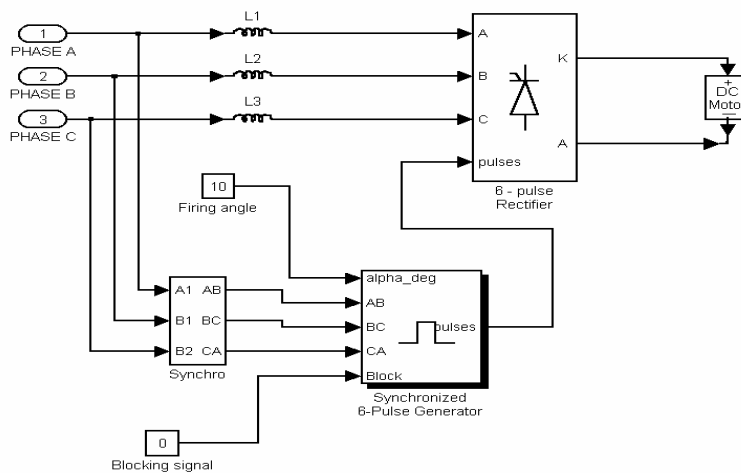


Figure 3.3 Matlab / Simulink model of the nonlinear load.

3.2.3. Voltage Source Inverter

The voltage source inverter used in the active power filter makes the harmonic control possible. This inverter uses a dc capacitor as the supply and can

switch at a high frequency to generate a signal which will cancel the harmonics from the nonlinear load.

The current waveform for canceling harmonics is achieved with the voltage source inverter and an interface reactor. The interface reactor converts the voltage signal created by the inverter to a current signal. The desired waveform is obtained by accurately controlling the switches in the inverter. Control of the current waveshape is limited by the switching frequency of the inverter and by the available driving voltage across the interface reactor. The driving voltage across the interface reactor determines the maximum di/dt that can be achieved by the filter. This is important because relatively high values of di/dt may be needed to cancel higher order harmonic components.

The voltage source inverter is the heart of the active power filter. Matlab / Simulink model of the voltage source inverter is shown in Figure 3.4.

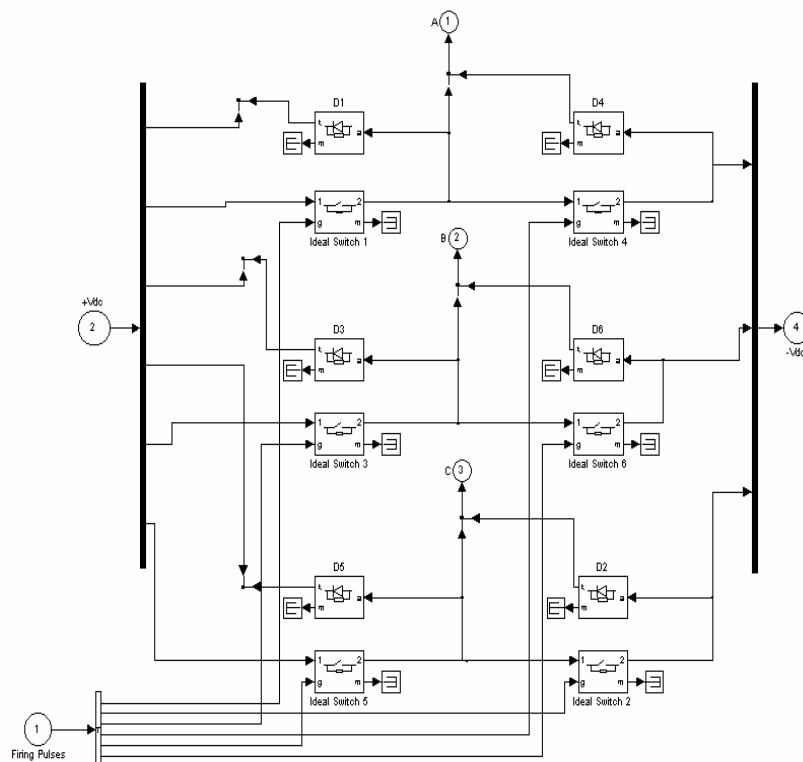


Figure 3.4 Matlab / Simulink model of voltage source inverter

This three phase, full-wave inversion bridge is built using three identical inverter legs each consisting of two ideal switches and two antiparallel diodes. The ideal switch is modeled as a resistor (R_{on}) and inductor (L_{on}) in series with a switch controlled by a logical signal in the Matlab/Simulink. It switches between on and off state instantaneously when triggered.

3.2.4. Interface Reactor

The interface reactor provides the isolation and filtering between the output of the voltage source inverter and the power system where the active power filter is connected. The Matlab / Simulink model of the interface reactor is shown in Figure 3.5.

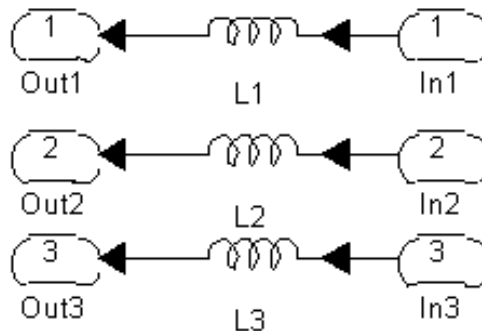


Figure 3.5 Matlab / Simulink model of interface reactor.

The inductance allows the output of the active power filter to look like a current source to the power system. The inductance makes it possible to charge the dc capacitor to a voltage greater than the ac line-to-line peak voltage. The inductance also functions like a commutation impedance. It limits the magnitude of a current spike during commutation and prevents the switching device from seeing an excessive rate of current change. Besides these, it is not possible to connect a sinusoidal voltage supply to the nonsinusoidal output of the voltage source inverter without a reactor. Sizing of the reactor value must take into account control of the

inverter switching frequencies and the characteristics of the nonlinear load to be compensated.

3.2.5. Reference Current Generator

In this shunt active power filter, control is accomplished by monitoring the three phase line currents to the nonlinear load and the three phase line-to-neutral voltages at the load bus, and then generating the three phase reference currents that should be supplied by the voltage source inverter. In this simulation study compensating current reference signal is derived from the measured quantities by the use of the Instantaneous Reactive Power Theory based method. The general definitions of active and reactive power have been presented in references [Akagi et al., 1984, Akagi et al., 1986]. In this formulation, active and reactive power are expressed as the dot and cross product of voltage and current vectors.

Once the compensating currents are detected, they are used as a reference signal in the inverter current control loop and thus compared with the real voltage source inverter current to generate the switches control signals.

To deal with instantaneous voltages and currents in three-phase circuits mathematically, it is adequate to express their quantities as the instantaneous space vectors. For simplicity the three phase voltages and currents excluding zero-phase sequence components will be considered.

In a, b, c coordinates, the a, b and c axes are fixed on the same plane, apart from each other by $2\pi/3$. The instantaneous space vectors e_a and i_a are set on the a axis and their amplitude and direction vary with the passage of time. These space vectors are easily transformed into α, β coordinates as follows:

$$\begin{bmatrix} e_\alpha \\ e_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (3.1)$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (3.2)$$

where the α and β axes are the orthogonal coordinates. Necessarily, e_α and i_α are on the α axis and e_β and i_β are on the β axis. Their amplitude and direction vary with the passage of time.

The conventional instantaneous power on the three-phase circuit can be defined as follows:

$$p = e_\alpha i_\alpha + e_\beta i_\beta = e_a i_a + e_b i_b + e_c i_c \quad (3.3)$$

In order to define instantaneous reactive power, the instantaneous imaginary power space vector is defined as follows:

$$q = e_\alpha \times i_\beta + e_\beta \times i_\alpha \quad (3.4)$$

This space vector is the imaginary axis vector and is perpendicular to the real plane on the α, β coordinates, to be in compliance with the right hand rule. Taking into consideration that e_α is parallel to i_α and e_β to i_β , the conventional instantaneous power p and the instantaneous imaginary power q , are expressed by

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} e_\alpha & e_\beta \\ -e_\beta & e_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (3.5)$$

By using the theory explained above, the transformation of the three-phase bus voltages v_a, v_b and v_c and the three-phase nonlinear load currents i_{La}, i_{Lb} and i_{Lc} into the $\alpha - \beta$ orthogonal coordinates gives the following expressions:

$$\begin{bmatrix} e_\alpha \\ e_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (3.6)$$

$$\begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad (3.7)$$

The instantaneous real power p_L and the instantaneous imaginary power q_L on the load side can be defined as

$$\begin{bmatrix} p_L \\ q_L \end{bmatrix} = \begin{bmatrix} e_\alpha & e_\beta \\ -e_\beta & e_\alpha \end{bmatrix} \begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} \quad (3.8)$$

Equation (3.8) is changed into

$$\begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} = \begin{bmatrix} e_\alpha & e_\beta \\ -e_\beta & e_\alpha \end{bmatrix}^{-1} \begin{bmatrix} p_L \\ q_L \end{bmatrix} \quad (3.9)$$

The determinant with respect to e_α and e_β in (3.9) is not zero.

\bar{p}_L and \tilde{p}_L are the dc and ac components of p_L . Likewise, \bar{q}_L and \tilde{q}_L are the dc and ac components of q_L , respectively. Then the following relation exists:

$$p_L = \bar{p}_L + \tilde{p}_L \quad q_L = \bar{q}_L + \tilde{q}_L \quad (3.10)$$

From equation (3.9), the α - phase load current $i_{L\alpha}$ is divided into the following components:

$$i_{L\alpha} = \frac{e_\alpha}{e_\alpha^2 + e_\beta^2} \bar{p}_L + \frac{-e_\beta}{e_\alpha^2 + e_\beta^2} \bar{q}_L + \frac{e_\alpha}{e_\alpha^2 + e_\beta^2} \tilde{p}_L + \frac{-e_\beta}{e_\alpha^2 + e_\beta^2} \tilde{q}_L \quad (3.11)$$

The first term of the right hand-side of (3.11) is the instantaneous value of the conventional fundamental active current. The second term is the instantaneous value of the conventional fundamental reactive current. The third term is the instantaneous value of the harmonic currents which represents the ac component of the instantaneous real power. The fourth term is the instantaneous value of the harmonic currents which represents the ac component of the instantaneous imaginary power. From (3.11) it is seen that the active power filter should compensate second, third and fourth terms to compensate for the harmonics and the reactive power. Figure 3.6 shows a basic compensation scheme of the instantaneous reactive power and harmonic currents. From the scheme it is seen that the active power filter supplies the reactive power and harmonic real power so that only real power at fundamental frequency is drawn from the mains.

In the calculation circuit of the compensating reference currents, the following expression results:

$$\begin{bmatrix} i_{refa} \\ i_{refb} \\ i_{refc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} e_\alpha & e_\beta \\ -e_\beta & e_\alpha \end{bmatrix}^{-1} \begin{bmatrix} p^* + p_{av} \\ q^* \end{bmatrix} \quad (3.12)$$

where p_{av} is the instantaneous real power corresponding to the loss of the active power filter, and p^* and q^* are given by

$$p^* = -\tilde{p}_L \quad q^* = -q_L \quad (3.13)$$

Figure 3.7 shows the calculation circuit of p^* . This basically consists of a high-pass filter configuration using a Butterworth low-pass filter. So, this circuit outputs \tilde{p}_L from p_L . The design of the low-pass filter is the most important in the

control circuit, because various compensation characteristics are obtained in accordance with the cutoff frequency and order of the low-pass filter.

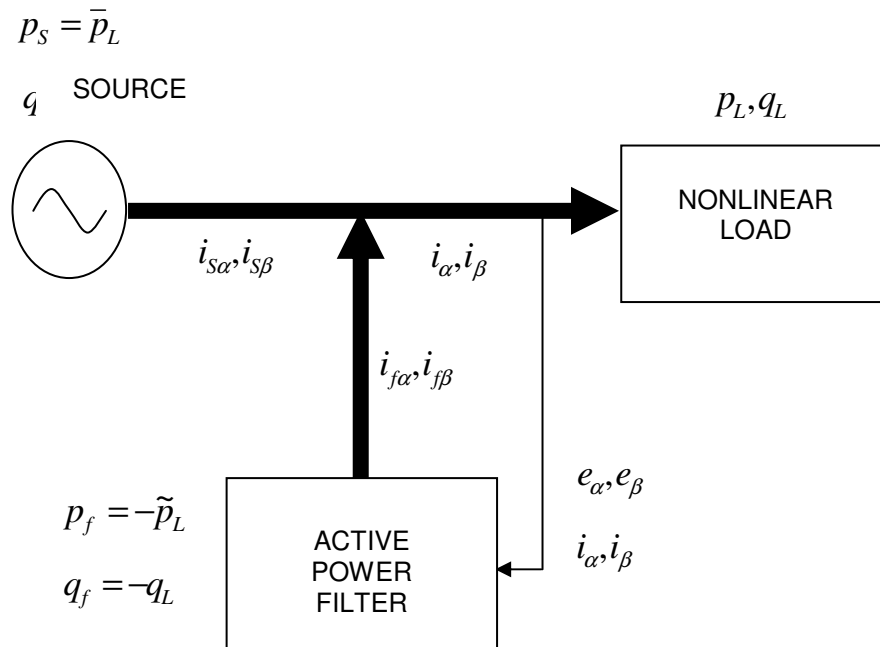


Figure 3.6 Compensation scheme

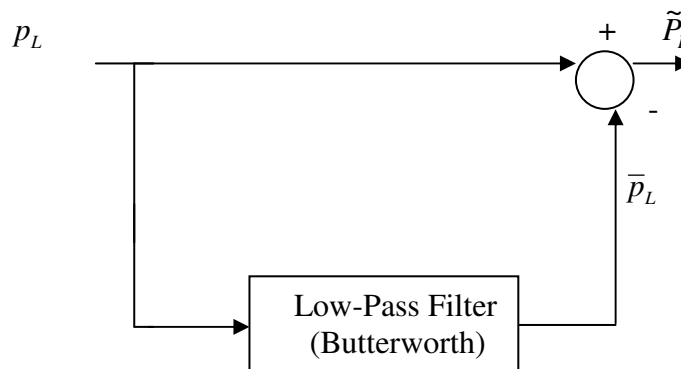


Figure 3.7 Calculation circuit of p^* .

The DC bus voltage V_{DC} of the voltage source inverter can not be kept constant, owing to the power loss of the inverter circuit as no suitable DC voltage control circuit is used. This problem can be solved by controlling the magnitude of mains current.

A PI controller is used to control the DC capacitor voltage. Its transfer function can be represented as

$$H(s) = K_p + \frac{K_I}{s} \quad (3.14)$$

where K_p is the proportion constant that determines the dynamic response of the DC bus voltage and K_I is the integration constant that determines its settling time.

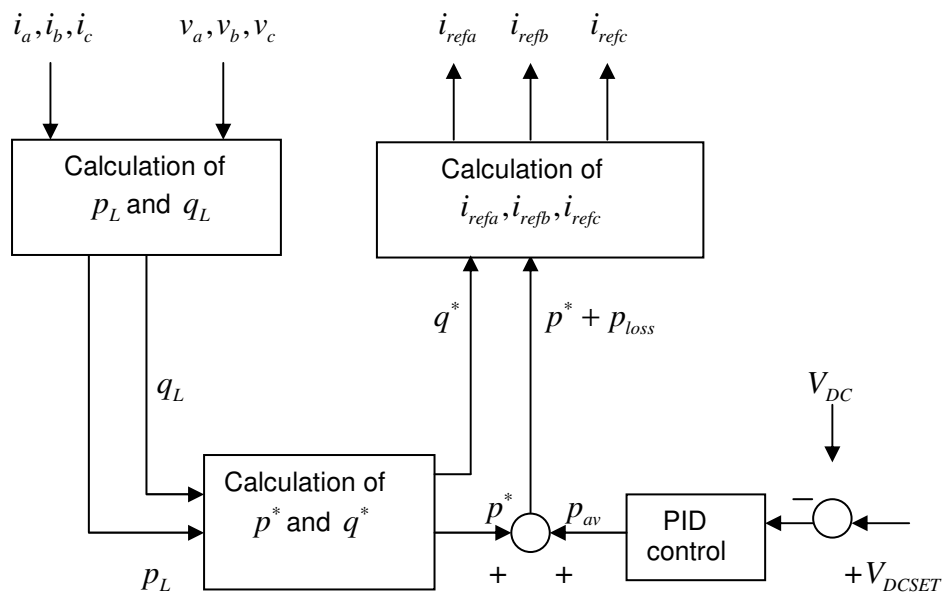


Figure 3.8 Block diagram of reference current generator.

The DC bus voltage is controlled by trimming the instantaneous real power p_{av} , which corresponds to the loss of the active power filter, while the instantaneous imaginary power does not have any effect on the DC capacitor voltage. The control circuit has the negative feedback loop to trim p_{av} automatically. The actual DC bus voltage value is fed back and compared with the desired DC bus voltage value. The difference is fed to a PID controller whose output is p_{av} . p_{av} is added to p^* and p_{av}

adds a positive or negative DC value to p^* which corresponds to an active current at fundamental frequency. So the active line current at fundamental frequency flows into or out of the DC capacitor to regulate the DC voltage. Fig.7 shows the block diagram of the reference current generator including the DC capacitor voltage control.

3.2.6. PWM Current Controller

Our main interest in this chapter is on PWM current controller development. Among the various current control techniques, hysteresis current control is the most extensively used technique. It is easy to realize with high accuracy and fast response. In the hysteresis control technique the error function is centered in a preset hysteresis band. When the error exceeds the upper or lower hysteresis limit the hysteretic controller makes an appropriate switching decision to control the error within the preset band. However, variable switching frequency and high ripple content are the main disadvantages of hysteresis current control. The proposed PWM current controller in the following sections provides fixed switching frequency and lower ripple content.

3.2.6.1. Single Fuzzy Logic Controller Based Active Power Filter and Problem Definition

In this study first a single fuzzy logic controller based PWM current controller is developed for an improved performance with respect to conventional hysteresis current control. Figure 3.9 shows the single fuzzy logic controller based PWM current controller.

Inverter current data and reference current data are the inputs to the PWM current controller. Reference current data is a vector of the desired compensation current reference signals and inverter current data is a vector of the measured actual voltage source inverter output currents.

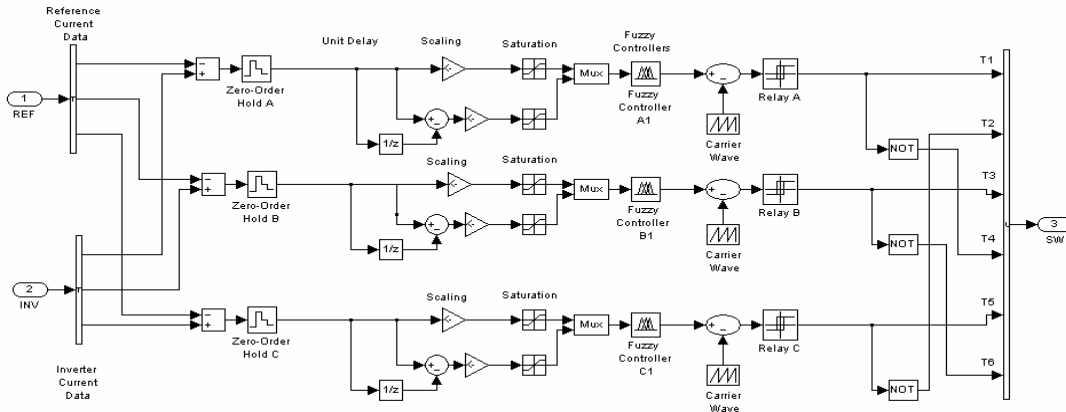


Figure 3.9 Single fuzzy logic controller based PWM current controller.

In the configuration shown in Figure 3.9 only one fuzzy logic controller is employed for each phase, totally three fuzzy logic controllers. They are named as Fuzzy Logic Controller A1, B1 and C1, connected to the phases A, B and C respectively. These controllers are used to generate firing pulses needed by the voltage source inverter. This configuration will be called single fuzzy control scheme from this point.

The fuzzy logic controller has two inputs, named error and error rate and one output named actuatinsig. Error is the difference between voltage source inverter current data and reference current data for each phase.

$$Error = I_{inv} - I_{ref} \quad (3.15)$$

Errors for each phase are discretized by the zero order hold blocks. The error rate is the derivative of the error and it is obtained by the use of unit delay block. By means of the scaling elements connected to error and error rate, the error and error rate quantities are resized to small values and entered to the saturation block. The saturation block imposes upper and lower bounds on a signal. When the input signal is within the range specified by the lower limit and upper limit parameters, the input signal passes through unchanged. When the input signal is outside these bounds, the signal is clipped to the upper or lower bound. The output of the saturation blocks are

inputs to the fuzzy logic controllers. The outputs of these fuzzy logic controllers is used in generation of PWM switching signals of the voltage source inverter. The switching signals are generated by means of comparing a carrier signal with the output of the fuzzy logic controllers.

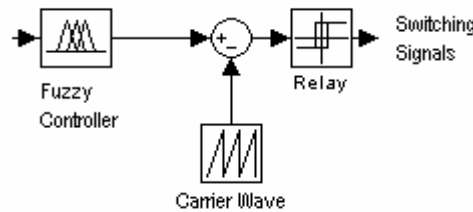


Figure 3.10 Generation of switching signals.

Figure 3.10 is used to explain the generation process of switching signals in the model. The output of the fuzzy logic controller is compared with a carrier signal. The relay element is set to give output when the input of itself is greater than 0. The output of the fuzzy logic controller is set to take values between -0.622 to 0.622 . The carrier signal is set to take values between -0.55 to 0.55 with a frequency of 10 kHz.

The outputs of the relay blocks are directly fed as the firing pulse of upper bridge device of each leg of the voltage source inverter and NOT of that signal is fed as the firing pulse of lower bridge device of each leg. This is necessary for operation and avoiding the conduction of same leg switches simultaneously. Fuzzy logic controllers for the single fuzzy control scheme have input and output membership functions given in Figure 3.11.

Fuzzy logic controllers for the single fuzzy controller scheme are characterized as follows:

- three fuzzy sets for each of the two inputs
- three fuzzy sets for the output
- triangular and trapezoidal membership functions
- implication using the "*min*" operator

- Mamdani fuzzy inference mechanism based on fuzzy implication
- Defuzzification using the "centroid" method

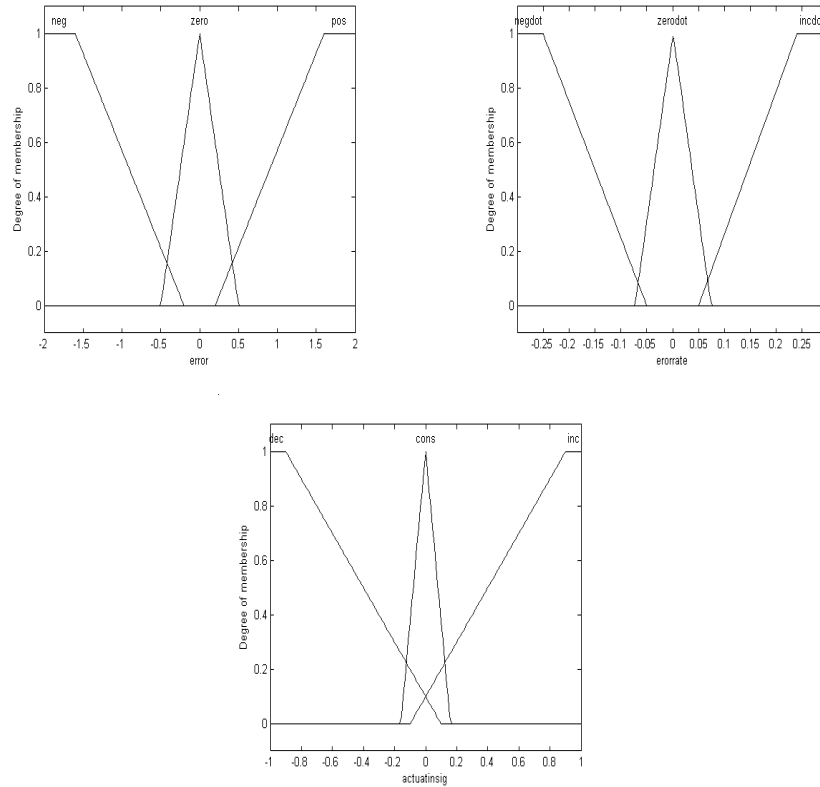


Figure 3.11. Input and output membership functions.

Fuzzy control rule design involves defining rules that relate the input variables to the output model properties. The linguistic rules about the system will result the necessary action for the output current by interpreting all the rules and contributions of each and aggregating all the implied results and then determining the optimum decision for the current. The change in the active power filter output current will be different according to the error and error rate i.e. having slower increase when the error and error rate are small and faster increase when the error and error rate are large, so as to minimize the error between the reference current and active power filter output current faster. In defining the linguistic rules conventional hysteresis current controller principle is taken as the basis and the rules are optimized by designer experience and simulations. Developed rules provide improved performance

and better compensation characteristics with respect to conventional hysteresis current control as presented in Figure 3.12 and Table 3.1. The linguistic rules for the fuzzy logic controller are as follows:

- I. If error is big and error rate is high then actuatsig is dec
- II. If error is zero and error rate is high then actuatsig is dec
- III. If error is small and error rate is high then actuatsig is inc
- IV. If error is big and error rate is zero then actuatsig is dec
- V. If error is zero and error rate is zero then actuatsig is constant
- VI. If error is small and error rate is zero then actuatsig is inc
- VII. If error is big and error rate is low then actuatsig is dec
- VIII. If error is zero and error rate is low then actuatsig is inc
- IX. If error is small and error rate is low then actuatsig is inc

Load current and compensated source current waveforms are obtained for the hysteresis control scheme and single fuzzy controller scheme. These waveforms are presented in Figure 3.12 and the table of magnitudes of harmonics in % of fundamental component of these current waveforms are presented in Table 3.1. Load current THD is 25.10%, while the source current THD is 0.69% for hysteresis control scheme and 0.66% for single fuzzy controller scheme. The 5th, 7th, 11th, 13th, 17th, 19th, 23rd and 25th harmonics are the harmonics that are effecting the system.

It can be easily seen from the table, the harmonic content of the load current is successfully filtered from the source current for both schemes and single fuzzy logic controller performance is slightly better than the conventional hysteresis control scheme in terms of harmonic filtering. It must be noted that the firing angle of the three-phase fully controlled six-pulse bridge rectifier used as the nonlinear load is 10°.

However, it appears that the performance of the single fuzzy control scheme can be improved. An investigation of control signals for the single fuzzy logic controller have showed that there are some uncontrollable error points in control signal generation. To understand these error points, consider the Table 3.2 given below.

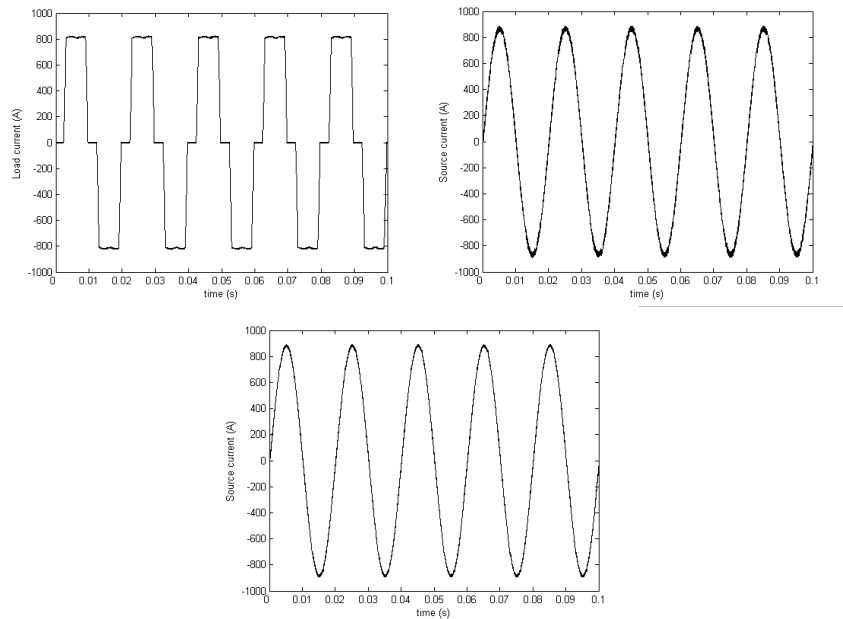


Figure 3.12 Load current and compensated source currents for the hysteresis control scheme and single fuzzy logic controller scheme respectively.

Table 3.1 Magnitudes of harmonics in % of fundamental component in the currents for the hysteresis control scheme and the single fuzzy controller scheme for the case firing angle is 10° .

Harmonic Number	Load current harmonic magnitudes in % of fundamental	Source current harmonic magnitudes in % of fundamental for hysteresis control scheme	Source current harmonic magnitudes in % of fundamental for single fuzzy controller scheme
1 st	100	100	100
5 th	19.27	0.32	0.28
7 th	12.67	0.14	0.19
11 th	6.99	0.21	0.25
13 th	5.28	0.23	0.17
17 th	2.99	0.18	0.22
19 th	2.23	0.20	0.08
23 rd	1.09	0.17	0.13
25 th	0.75	0.07	0.10

In the table, see the lines where the actuating signal, the column named “Actsigs” is 0. As described in previous paragraphs about switching signal generation, the relay will give output 1 when the difference between actuating signal and carrier signal is positive and it will give output 0 when the difference between actuating signal and carrier signal is negative. The carrier signal, the column named “Carrier” in the table, is taking values between -0.55 to 0.55 . From Table 2 while the carrier

signal has taken values from -0.55 to -0.13 and actuating signal is 0 and relay output is 1. But as seen from the table, while the reference current (column named “Ref”) is taking the values approximately 1.8 A, the inverter current (column named “Inv”) goes up to 13A. This problem occurs at the positive and negative peak points of the source current and this is why the ripple content is higher at the peak points of source current as also seen in Fig. 5. This was the error point of the single fuzzy control scheme. This showed that there are some uncontrollable regions in PWM current control and current tracking capability deteriorates in these regions. Problem is that the carrier signal may take any value at a time interval for an error and error rate input. In other words, lets us assume that the carrier signal given in the table is taking values between 0.13 to 0.33. Then the relay output will take the value 0 and the system will work properly. But without controlling the carrier signal, you cannot know which values it will take.

Table 3.2 Simulation details table for the single fuzzy controller scheme.

Error	Erate	Actsig	Carrier	Switch	Source	Inv	Ref
0.000000	0.000000	0.000000	-0.550000	1.000000	0.024580	-0.004097	0
0.000000	0.000000	0.000000	-0.506000	1.000000	0.025934	-0.005577	0.020356
0.000000	0.000000	0.000000	-0.462000	1.000000	0.029978	-0.009893	0.020085
0.000000	0.000000	0.000000	-0.418000	1.000000	0.036720	-0.016951	0.019768
0.000000	0.000000	0.000000	-0.374000	1.000000	0.046258	-0.026798	0.019459
-0.002227	-0.000167	0.000000	-0.330000	1.000000	0.058421	-0.039238	0.019182
-0.002227	-0.000167	0.000000	-0.286000	1.000000	-2.040276	3.303284	1.262922
-0.002227	-0.000167	0.000000	-0.242000	1.000000	-4.562605	6.349692	1.786908
-0.002227	-0.000167	0.000000	-0.198000	1.000000	-7.328792	9.223032	1.893955
-0.002227	-0.000167	0.000000	-0.154000	1.000000	-10.230062	11.998133	1.767674
-0.002227	-0.000167	0.000000	-0.132000	1.000000	-11.706657	13.365862	1.658751
0.483468	0.036260	-0.497250	-0.110000	0.000000	-13.191665	14.726505	1.534331
0.483468	0.036260	-0.497250	-0.066000	0.000000	-11.945035	10.721684	-1.223740
0.483468	0.036260	-0.497250	-0.022000	0.000000	-9.794603	7.333499	-2.461381
0.483468	0.036260	-0.497250	0.022000	0.000000	-7.166234	4.270843	-2.895562
0.483468	0.036260	-0.497250	0.066000	0.000000	-4.259626	1.396168	-2.863529
0.483468	0.036260	-0.497250	0.088000	0.000000	-2.742780	0.001188	-2.741616

Table 3.2 has been generated automatically by an interface program that is designed to show the simulation details. This program takes values from Matlab by means of a comma separated text file and writes into a database to ease the management of the data. The interface of the program is given Figure 3.13 below. This program is written in Visual Basic and uses report tools to report the values seen in Table 3.2.

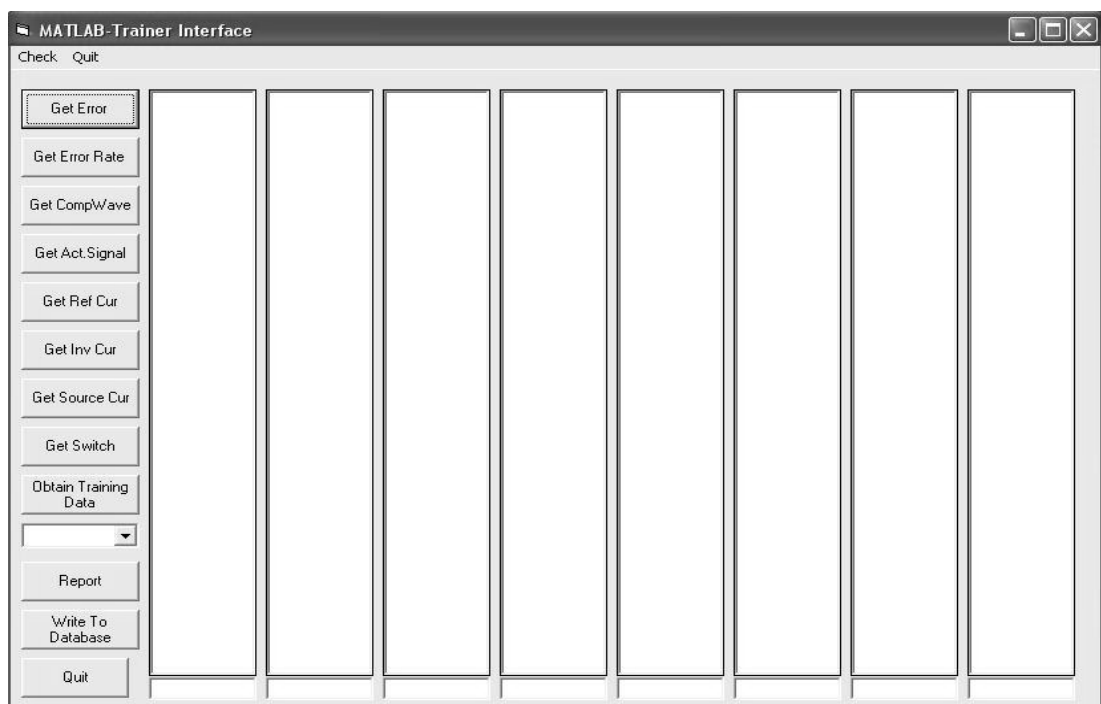


Figure 3.13 Interface of the program written for generating the data in Table 2.

3.2.6.2. Proposed Hierarchical Neuro Fuzzy Controller for Shunt Active Power Filter

As described in the previous part, the single fuzzy control scheme has some uncontrollable regions that is found by analyzing the inputs, output and switching signals of the model. This problem could be solved by taking the carrier signal into the fuzzy logic control scheme as an input. Since standard fuzzy logic controllers suffer from exponential increase in the number of rules with the number of input

variables, we opt to employ hierarchical fuzzy systems that are known to reduce the computational burden. If a carrier signal is included as an input to the single fuzzy control scheme a full rule base would have N^3 rules where N is the number of membership functions assigned to each input. Alternatively when employing a hierarchical fuzzy control, the rule base could be split to two rule bases[Abdelrahim et al., 2002].

At this point, it is the time to introduce the second group fuzzy logic controllers. The second group fuzzy logic controllers have actuating signal and carrier signal as inputs and they are connected hierarchically to the first group of fuzzy logic controllers. In Figure 3.14, the error and error rate values, the feedback signals coming from the system, are connected to the first group fuzzy logic controllers introduced before having the membership functions given in Fig. 4. The outputs of these controllers then become inputs for second group fuzzy logic controllers. Hierarchical model comes into play here; an output of a fuzzy logic controller is connected to another fuzzy logic controller's input. The other input of the second group controllers is the carrier signal. The outputs of these fuzzy logic controllers are used in generation of PWM switching signals of the voltage source inverter. The switching signals are generated by means of comparing the carrier signal with the output of the second group fuzzy logic controllers.

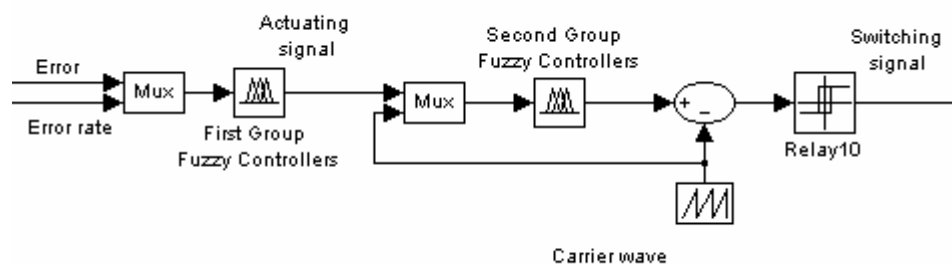


Figure 3.14 Hierarchical system employed in the model.

The important point here is that the second group fuzzy logic controllers employed in the model are Adaptive Neuro Fuzzy Inference Systems. They are

developed by using the ANFIS tool of the Matlab Fuzzy Logic Toolbox. They are employed to correct error points of the first group controllers. As explained before, without controlling the carrier signal, it may not be known, what the switching signals are, if the error or error rate is not high enough to make the output value high enough to pass the carrier signal. To correct this, a training data has been developed that includes the input/output data pairs of the neuro-fuzzy controllers in the second group. There are two types of training used in neural networks, with different types of networks using different types of training. These are supervised and unsupervised training, of which supervised is the most common. In the proposed controller supervised training is used. In supervised training the designer assembles a set of training data. The training data contains examples of inputs together with the corresponding outputs and the network learns to infer the relationship between the two. The training data for this study is based on the input-output characteristics of the first group fuzzy logic controllers with designer made corrections. In this training data, at the error points, by using the reference signal input, the correct output values are trained to neuro-fuzzy controllers. No testing data is used, because the controller is directly tested and satisfactory results are obtained in the simulated system.

The basic idea behind using neuro-adaptive learning techniques is very simple. This technique allows implementation of multi-input – single-output first order Sugeno-type FIS with weighted average defuzzification. This approach provides off-line learning capability to the control system. Here, learning is understood as the process of tuning the input membership functions, building the fuzzy inference rules of the knowledge base and identifying the consequent parameters of the FIS necessary to reproduce the input-output behaviour of system. The learning process is of training type. It could take place prior to the operation of the control system or upon demand during operation. The learning process develops through the following stages. First a set of input-output data, to be used as training data needs to be generated or obtained from the process. Another optional data set can be used as test data after training, which is not applied in this study. Second the initial FIS structures need to be created. For each input, the range of operation, number of membership functions, as well as their shape must be defined. Finally, the

learning process is carried out using the training data to adjust the membership functions, to create the inference rules and to determine the consequent parameters [Ramirez et al., 2000]. These techniques provide a method for the fuzzy modeling procedure to learn information about a data set, in order to compute the membership function parameters that best allow the associated fuzzy inference system to track the given input/output data. This learning method works similarly to that of neural networks.

Using a given input-output data set, ANFIS constructs a fuzzy inference system whose membership function parameters are tuned (adjusted) using either a back propagation algorithm alone, or in combination with a least squares type of method. This allows your fuzzy systems to learn from the data they are modeling.

A network-type structure similar to that of a neural network, which maps inputs through input membership functions and associated parameters, and then through output membership functions and associated parameters to outputs can be used to interpret the input-output map.

The parameters associated with the membership functions will change through the learning process. The computation of these parameters (or their adjustment) is facilitated by a gradient vector, which provides a measure of how well the fuzzy inference system is modeling the input-output data for a given set of parameters. Once the gradient vector is obtained, any of several optimization routines could be applied in order to adjust the parameters so as to reduce some error measure (usually defined by the sum of the squared difference between actual and desired outputs). ANFIS uses a combination of least squares estimation and back propagation for membership function parameter estimation.

The model of the hierarchical neuro-fuzzy current controller developed for the shunt active power filter is shown in Figure 3.15. Similar to the first group controllers, second group has three controllers for each phase. Fuzzy logic controller A2 is used for Phase A, fuzzy logic controller B2 is used for Phase B and fuzzy logic controller C2 is used for Phase C. The membership functions for the ANFIS based second group fuzzy logic controllers are given below in Figure 3.16.

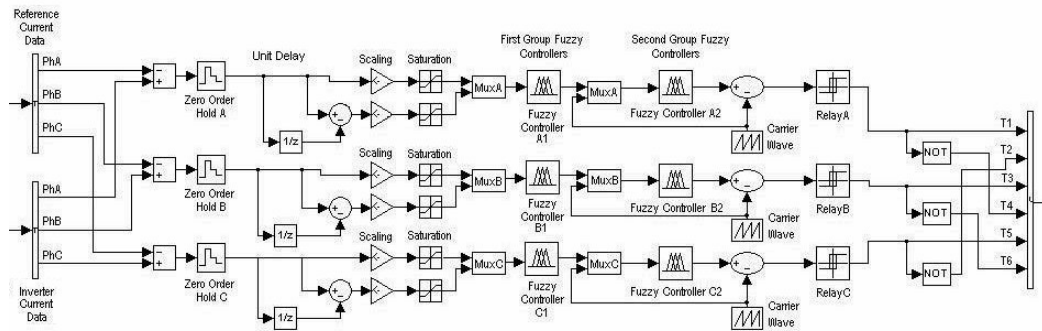


Figure 3.15 Hierarchical neuro-fuzzy PWM current controller.

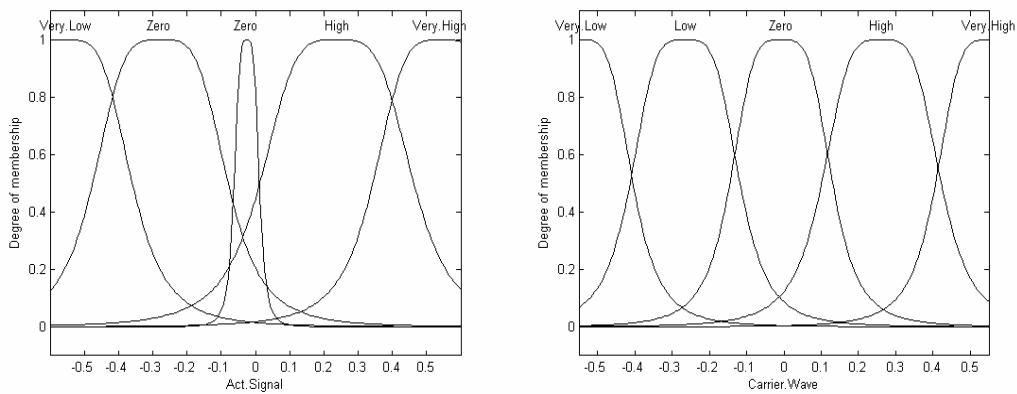


Figure 3.16 Input membership functions for the second group fuzzy logic controllers.

An adaptive neuro-fuzzy inference system (ANFIS) has been proposed for the first time in [Shing et al., 1993]. Figure 3.17 shows the architecture of ANFIS used in second group fuzzy logic controllers . The generic fuzzy rules of ANFIS are:

$$R^1: \text{IF } x \text{ is } A_1 \text{ and } y \text{ is } B_1 \text{ THEN } f_1 = p_1x + q_1 + r_1 \quad (3.16)$$

$$R^2: \text{IF } x \text{ is } A_2 \text{ and } y \text{ is } B_2 \text{ THEN } f_2 = p_2x + q_2 + r_2 \quad (3.17)$$

where x, y are inputs, A_i, B_i are membership functions and p_i, q_i and r_i are consequent parameters and i is the node number [Shing et al., 1993]. The system has

a total of five layers and the function of each layer is as follows:

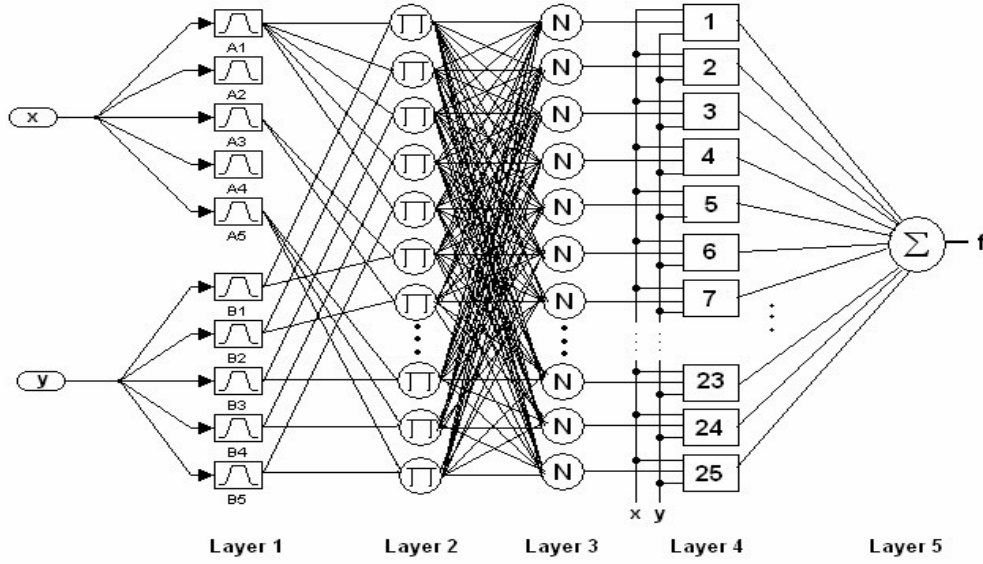


Figure 3.17 Structure of ANFIS.

Layer 1. This layer is composed of a number of computing nodes whose activation functions are fuzzy logic membership functions. In the study, bell-shaped membership functions are employed.

$$\mu_{A_i}(x) = \frac{1}{1 + \left| \frac{x - c_i}{a_i} \right|^{2b_i}} \quad (3.18)$$

where parameters a and b vary the width of the curve and parameter c locates the center of the curve. The output of this layer is given by,

$$O_i^1 = \mu_{A_i}(x) \quad (3.19)$$

$$O_j^1 = \mu_{B_j}(y)$$

Layer 2.

Each node in this layer calculates the firing strength of a rule via multiplication.

$$O_i^2 = \omega_i = \mu_{A_i}(x) \times \mu_{B_i}(y) \quad (3.20)$$

Layer 3.

Node i in this layer computes the ratio of the firing strength of i^{th} rule to the total of all firing strengths.

$$O_i^3 = \bar{\omega}_i = \frac{\omega_i}{\sum_j \omega_j} \quad (3.21)$$

Layer 4.

Node i in this layer compute the contribution of i^{th} rule toward the overall output, with the following node function.

$$O_i^4 = \bar{\omega}_i f_i = \bar{\omega}_i (p_i x + q_i y + r_i) \quad (3.22)$$

Layer 5.

The single node in this layer computes the overall output as the summation of contribution from each rule. The result of this node creates control signal.

$$O_i^5 = \sum_i \bar{\omega}_i f_i = \frac{\sum_i \omega_i f_i}{\sum_i \omega_i} \quad (3.23)$$

3.3. Simulation Results

In this part simulation results for the single fuzzy control scheme and

hierarchical neuro-fuzzy control scheme are presented and compared for different cases. Harmonic generating nonlinear load is a fully-controlled six-pulse rectifier driving a dc motor which is a very common load type in the industry. The line-line voltage, the value of interface reactor, dc bus voltage set value and dc bus capacitance for the active power filter are 380 V, 90 μH , 650 V and 10 mF respectively. Three different load conditions are considered to evaluate the performance of proposed method. Nonlinear load current and compensated source currents are presented to show the filtering performance of active power filter. Reference compensating currents and actual active power filter output currents are also presented to show the current tracking ability of proposed controllers. In Figure 3.18 load current, compensated source currents for the single fuzzy controller scheme and hierarchical neuro fuzzy control scheme are given. Firing angle of the three-phase six-pulse fully controlled rectifier is 10° for this case.

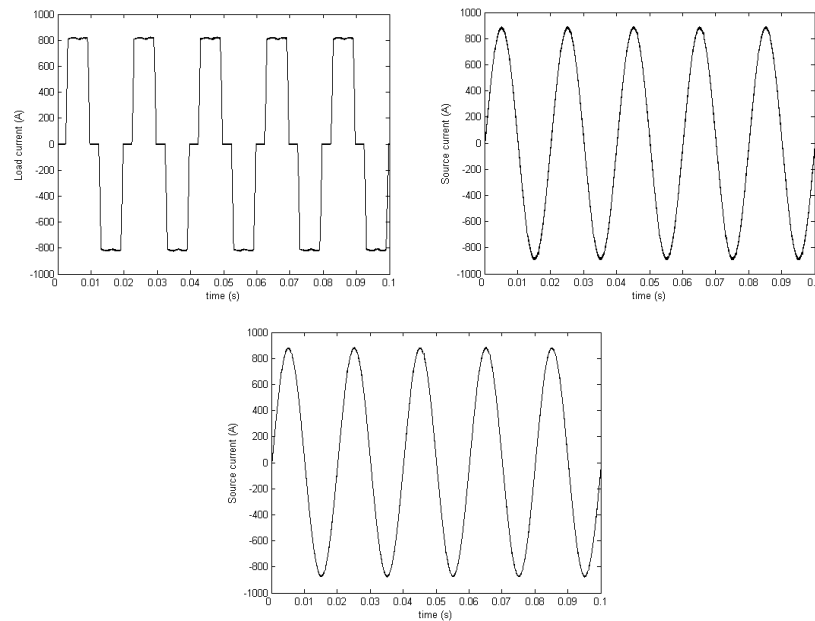


Figure 3.18 Load current and compensated source currents for the single fuzzy controller scheme and hierarchical neuro-fuzzy control scheme for the case firing angle is 10° .

Table 3.3 Magnitudes of harmonics in % of fundamental component in the currents for the single fuzzy controller scheme and hierarchical neuro-fuzzy controller scheme for the case firing angle is 10° .

Harmonic Number	Load current harmonic magnitudes in % of fundamental	Source current harmonic magnitudes in % of fundamental for single fuzzy controller scheme	Source current harmonic magnitudes in % of fundamental for hierarchical neuro-fuzzy controller scheme
1 st	100	100	100
5 th	19.27	0.28	0.11
7 th	12.67	0.19	0.18
11 th	6.99	0.25	0.09
13 th	5.28	0.17	0.11
17 th	2.99	0.22	0.11
19 th	2.23	0.08	0.12
23 rd	1.09	0.13	0.10
25 th	0.75	0.10	0.06

Above in the Table 3.3 a comparison between single fuzzy controller scheme and hierarchical neuro-fuzzy controller scheme is given. It is seen that the hierarchical neuro-fuzzy controller scheme provided better results. Harmonics are effectively compensated and THD of source current is lowered to 0.46 with the hierarchical neuro-fuzzy controller scheme where it is 0.66 for the single fuzzy controller scheme. To demonstrate the effectiveness of proposed hierarchical-neuro fuzzy controller in current tracking, reference compensating current and active power filter output currents for both schemes are given in Figure 3.19. Figure 3.19 shows the effectiveness of proposed method where the current ripple magnitudes are considerably reduced in the active power filter output current which contributes to improved filtering performance.

As a second load condition to demonstrate the performance of proposed controller firing angle of the three-phase six-pulse fully controlled rectifier is increased to 30° . Nonlinear load current, compensated source currents for the single fuzzy controller scheme and hierarchical-neuro fuzzy controller scheme are obtained and presented in Figure 3.20. Table of magnitude of harmonics in % of fundamental component is given in Table 3.4. THD of the nonlinear load current is 27.72% for this case. THD of the source current for the single fuzzy controller scheme is 5,35% and THD of the source current for the hierarchical neuro-fuzzy controller scheme is

4.01%. The improved performance in current filtering is also verified for this case. Reference compensating current and active power filter output currents for both schemes are given in Figure 3.21. Current ripple magnitudes are again considerably reduced in the active power filter current for this load case.

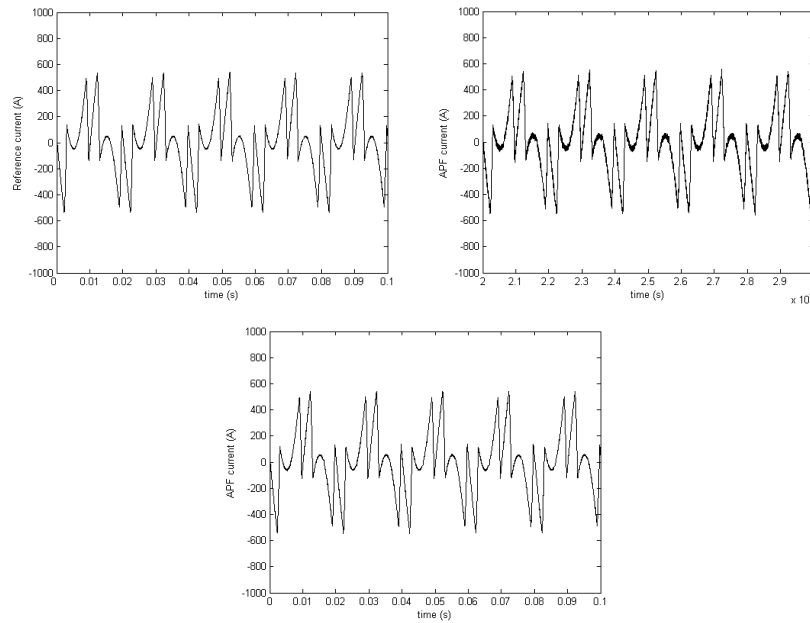


Figure 3.19 Reference compensating currents and active power filter output currents for the single fuzzy controller scheme and hierarchical neuro-fuzzy control scheme for the case firing angle is 10° .

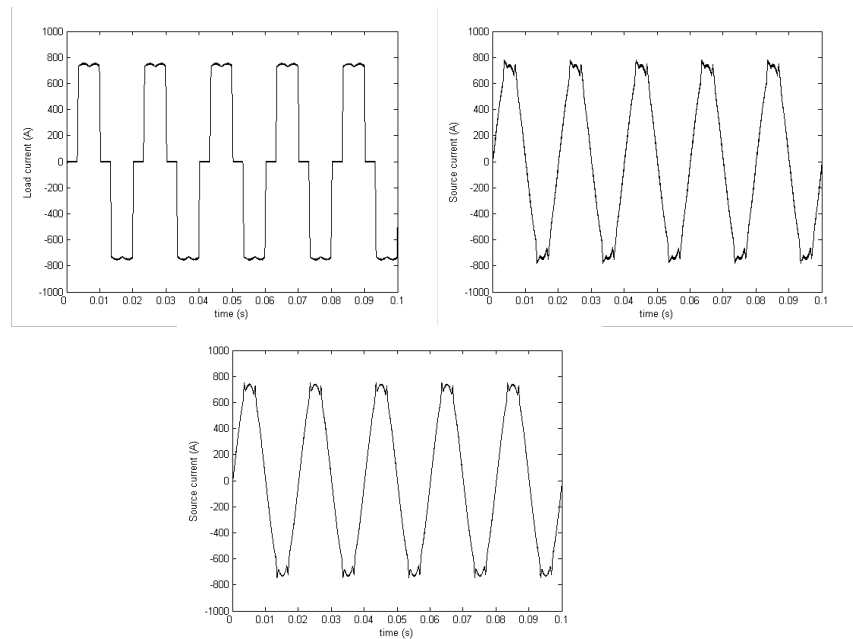


Figure 3.20 Load current and compensated source currents for the single fuzzy controller scheme and hierarchical neuro-fuzzy control scheme for the case firing angle is 30° .

Table 3.4 Magnitudes of harmonics in % of fundamental component in the source currents for the single fuzzy controller scheme and hierarchical neuro-fuzzy controller scheme for the case firing angle is 30° .

Harmonic Number	Load current harmonic magnitudes in % of fundamental	Source current harmonic magnitudes in % of fundamental for single fuzzy controller scheme	Source current harmonic magnitudes in % of fundamental for hierarchical neuro-fuzzy controller scheme
1 st	100	100	100
5 th	20.30	3.15	1.78
7 th	13.12	2.55	1.44
11 th	8.45	2.39	1.59
13 th	6.68	1.67	1.51
17 th	4.87	1.27	1.34
19 th	4.07	0.77	1.18
23 rd	3.05	0.66	0.99
25 th	2.60	0.56	0.79

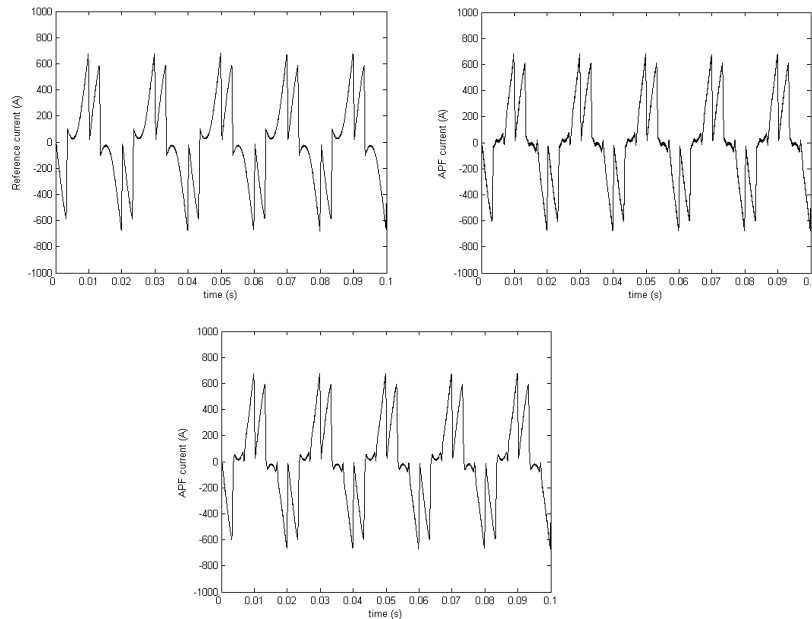


Figure 3.21 Reference compensating currents and active power filter output currents for single fuzzy controller scheme and hierarchical neuro-fuzzy control scheme for the case firing angle is 30° .

Results for the compensated source currents for the single fuzzy controller scheme and hierarchical neuro fuzzy control scheme are also obtained for the cases where the firing angle of the three-phase six-pulse fully controlled rectifier is 45° and 60° . Current waveforms are not presented here but the magnitude of harmonics in % of fundamental component are listed as a table for these two cases together with the previous ones in Table 3.5.

From the table, it can easily be seen that the simulation results of the hierarchical neuro-fuzzy control scheme provides superior compensation for all cases than the single fuzzy controller scheme.

As a last case to test the dynamic performance of the proposed hierarchical neuro-fuzzy control scheme, source current waveforms are obtained for the case where the firing angle of the three-phase six-pulse fully controlled rectifier is changed from 10° to 40° during operation. Obtained source current waveforms are given in Figure 3.22. THD of the source current for the single fuzzy controller scheme is 6,37% and THD of the source current for the hierarchical neuro-fuzzy controller scheme is 5.17% while the THD of load current is 28.52% for the case

where firing angle of the six-pulse fully controlled rectifier is 40° . Table of magnitude of harmonics in % of fundamental component is given in Table 3.6. The quick dynamic response and improved performance in current filtering is also verified for this case.

Table 3.5 Comparison of magnitudes of harmonics in % of fundamental component of compensated source currents for the single fuzzy controller scheme and hierarchical neuro-fuzzy control scheme for the cases where firing angle is 10° , 30° , 45° and 60° .

Harmonic Number	Single Fuzzy Control Scheme				Hierarchical Neuro-Fuzzy Control Scheme				
	Firing Angle	10°	30°	45°	60°	10°	30°	45°	60°
1 th		100	100	100	100	100	100	100	100
5 th		0,28	3,15	2,69	2,46	0,11	1,78	1,98	2,35
7 th		0,19	2,55	2,08	2,71	0,18	1,44	1,48	2,82
11 th		0,25	2,39	2,73	3,09	0,09	1,59	2,14	2,86
13 th		0,17	1,67	1,84	2,94	0,11	1,51	1,69	2,96
17 th		0,22	1,27	2,39	2,86	0,11	1,34	1,90	2,76
19 th		0,08	0,77	1,28	2,76	0,12	1,18	1,40	2,78
23 rd		0,13	0,66	1,82	2,61	0,10	0,99	1,72	2,52
25 th		0,10	0,56	0,74	2,48	0,06	0,79	1,01	2,48
THD		0,66	5,35	6,10	8,78	0,46	4,01	5,22	8,72

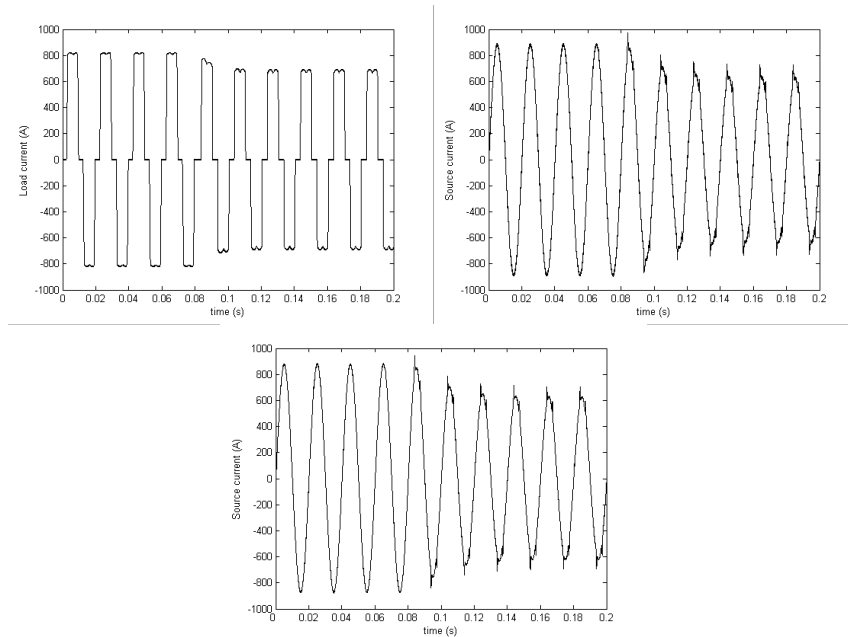


Figure 3.22 Load current and compensated source currents for the single fuzzy controller scheme and hierarchical neuro-fuzzy control scheme for the case firing angle changed from 10° to 40° .

Table 3.6 Magnitudes of harmonics in % of fundamental component in the source currents for the single fuzzy controller scheme and hierarchical neuro-fuzzy controller scheme for the case firing angle changed from 10° to 40° .

Harmonic Number	Load current harmonic magnitudes in % of fundamental	Source current harmonic magnitudes in % of fundamental for single fuzzy controller scheme	Source current harmonic magnitudes in % of fundamental for hierarchical neuro-fuzzy controller scheme
1 st	100	100	100
5 th	20.60	3.10	2.16
7 th	13.20	2.63	1.82
11 th	8.71	2.56	1.93
13 th	6.93	1.75	1.67
17 th	5.25	1.64	1.60
19 th	4.48	0.90	1.13
23 rd	3.54	0.99	1.09
25 th	3.12	0.45	0.90

4. MODELING OF FOUR-WIRE SHUNT APF (ACTIVE POWER FILTER)

4.1. Introduction

This chapter presents the design of a fuzzy logic current controller for a three-phase four wire shunt active power filter with “three-leg split capacitor” inverter topology. The proposed fuzzy logic controller employs the voltage difference on the voltage source inverter interface reactor together with error and error rate for active filter current as inputs for control. The proposed method provides high dc link voltage utilization and fixed switching frequency. Results for the proposed method are also compared with the conventional hysteresis control. In this chapter analytical study for the design of proposed method and simulation results are presented.

In many commercial and industrial installations power is distributed through a three-phase four wire system. This type of system has unique problems. If nonlinear single-phase loads are present, or the three-phase load is unbalanced, the line currents are unbalanced and neutral currents flow. These neutral currents contain both fundamental and harmonic components. In extreme cases, the neutral currents are potentially damaging to both the neutral conductor and the transformer to which it is connected. Three-phase three-wire active power filters can not adequately reduce or eliminate line harmonics in this situation [Haddad et al., 1996].

In recent years, three-phase four-wire shunt active power filters have appeared as an effective method to solve the problem of harmonics, unbalanced load currents together with reactive power compensation. In three phase four wire active filters two topologies for current controlled voltage source inverters are commonly used, the “three-leg split capacitor” inverter topology and the “four-leg” inverter topology. The controllability of the “four-leg” inverter topology is better than the three-leg “split-capacitor” inverter topology. However the “three-leg split-capacitor” inverter topology is preferred because of its lower number of power semiconductor devices.

DC link voltage control for “three-leg split-capacitor” topology and current control for all active power filter topologies are important in active power filter

control. Since load harmonics to be compensated may be very complex and changing rapidly and randomly, active power filter has to respond quickly and work with high control accuracy in current tracking. Moreover in order to keep high safety and efficiency in filter operation the required voltage source inverter switching frequency and dc source voltage, which are highly relevant to the current tracking method used should be as low as possible. It is clear that active power filter current control technique is the key issue of its performance [Zeng et al, 2003].

Besides the advantage of employing lower number of semiconductors the “three-leg split-capacitor” inverter suffers from dc link voltage problem. The problems and solutions related to the dc link voltage control in “ three-leg split-capacitor” inverter topology is reported in [Mishra et al, 2003] and [Aredes et al, 1997].

For active filter applications, the hysteresis-band current control shows a superiority with respect to other techniques due to its quick response, good accuracy, simple implementation and inherent peak current limiting capability. However this technique presents variable switching frequency, which makes difficult the inverter input passive filter design and can provoke undesirable resonance situations [Rodriguez et al, 2002]. For this reason the emphasis is on developing fixed frequency current controllers for active power filters. In [Zeng et al, 2003] a hysteresis current control based on optimal voltage space vector is presented for a three-phase three-wire active filter. In [Vazquez et al, 2003] and [Madtharad et al, 2002] hysteresis based neural network current controllers are presented and in [Elmitwally et al, 2000] a triangular carrier modulation technique based neural network current controller is presented for three-phase four-wire shunt active power filters and satisfactory results compared to hysteresis control is obtained.

In all above mentioned articles the focus on current controller design is either improving DC link voltage control or providing a fixed frequency operation for the current controller, but not both.

In this chapter a three input one output fuzzy logic current controller is presented for a three-phase four-wire active power filter with “three-leg split-capacitor” inverter topology providing fixed frequency operation and maximum dc

link voltage utilization. Fuzzy logic controllers for active power filters are reported in [Dixon et al, 1999], [Jain et al,2002] and [Aquila et al, 2002]. Their common point is that all fuzzy logic controllers have two inputs, the error and its incremental variation. In [Dixon et al, 1999] and [Jain et al, 2002] the main control variable is the DC link voltage and in [Aquila et al, 2002] the active filter current and these fuzzy logic controllers are developed for three-phase three-wire systems. The proposed current controller employs both active filter currents and DC link voltage as the control variable and has three inputs and one output for optimum control. The performance of the current control achieved with fuzzy logic is also compared to conventional hysteresis current control. Employed reference current generation method provides harmonics, zero sequence and reactive power compensation even under distorted and unbalanced voltages. The proposed control philosophy may be extended to dc link control in multilevel active power filters.

4.2. Proposed Three-Phase Four-Wire Active Power Filter Configuration

The shunt three-phase four-wire active power filter proposed in this chapter is presented in Figure 4.1. The components of the active power filter are reference current generator, dc voltage controller, fuzzy logic current controller and voltage source inverter with interface reactor. The information regarding the harmonic current generated by group of nonlinear loads, load voltages and active power filter loss (\bar{p}_{loss}) are supplied to the reference current generator to generate compensating reference currents. The reference currents together with dc link capacitor voltages, load voltages and active filter output currents are processed in the fuzzy logic current controller to produce switching pulses for the voltage source inverter. For DC link voltage regulation a PI controller in the inner loop to compensate active power filter losses and a fuzzy logic controller in the outer loop to regulate imbalances due to zero sequence currents is utilized. The use of interface reactor voltage, which is the difference between load and DC link voltage, as an input of fuzzy logic current controller provides fixed frequency operation and high dc link voltage utilization.

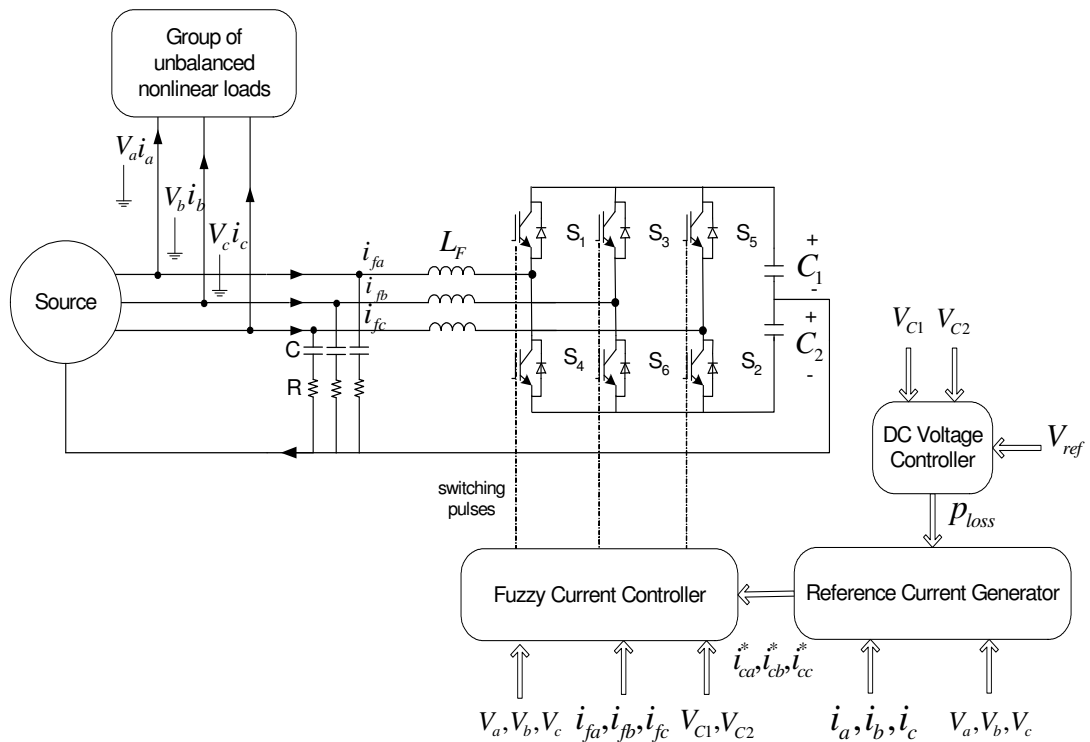


Figure 4.1 Block diagram of the proposed three-phase four-wire shunt active power filter

In this chapter the reference current generation method presented in [Aredes et al, 1997] namely Sinusoidal Source Current Strategy is employed. This strategy is an extended version of Instantaneous Reactive Power Theory and provides sinusoidal currents to the source, even under distorted and unbalanced voltages and whole zero sequence power of the load can be compensated.

The shunt active filter ability to deliver the desired current lies not only on a good current control, but also on a high utilization of dc link voltage feeding the filter which means low sensitivity to voltage imbalance or no voltage imbalance and low dc voltage distortion. Performing these tasks results very hard owing to system complexity, but the use of fuzzy logic approach may be helpful in solving this problem [Aquila et al, 2002]. In this chapter the proposed fuzzy logic current controller has three inputs and one output performing these tasks. The current error, error rate and the value of voltage difference on the interface reactor which is equal to the voltage difference between dc link voltage and ac supply voltage are used to generate the firing pulses to the voltage source inverter. Because the interface reactor

voltage difference is included in the control this provides a self regulating effect for dc voltage imbalance or less sensitivity to imbalance and fixed frequency operation.

4.3. Reference Current Generation

In the proposed active power filter, compensating current reference signal is derived from the measured quantities by the use Sinusoidal Source Current Strategy. The sinusoidal source current control strategy provides a compensation that makes the active filter to compensate the current of a non-linear load, even under an unbalanced and/or distorted system voltage, such that a balanced sinusoidal current is drawn from the source [Aredes et al, 1997].

The α - β -0 transformation is an algebraic transformation of three-phase voltages and currents into a stationary reference frame, also called the Clarke Transformation. The expressions for obtaining α - β -0 transformed three-phase voltages (V_α, V_β, V_0) , currents (i_α, i_β, i_0) , real power p , the imaginary power q , and the zero sequence power p_0 are given in [Aredes et al, 1997].

The block diagram of the reference current generator is shown in Figure 4.2. It includes positive sequence voltage dedector, dc voltage regulator, and transformation and filter blocks. The active filter can compensate load currents under unbalanced system voltages to provide sinusoidal, balanced currents to the source. The phase angle and frequency of the fundamental positive sequence voltage must be accurately determined by the positive sequence dedector. The active filter handles the load as connected to a sinusoidal balanced voltage source. Thus, \tilde{p} , \tilde{q} , \bar{q} and i_0 are compensated by the active filter, the source currents must be now sinusoidal and contain only the active portion of fundamental positive sequence component that is in phase with voltage positive sequence. The positive voltage detector as shown in Figure 4.3 satisfies the above constraints.

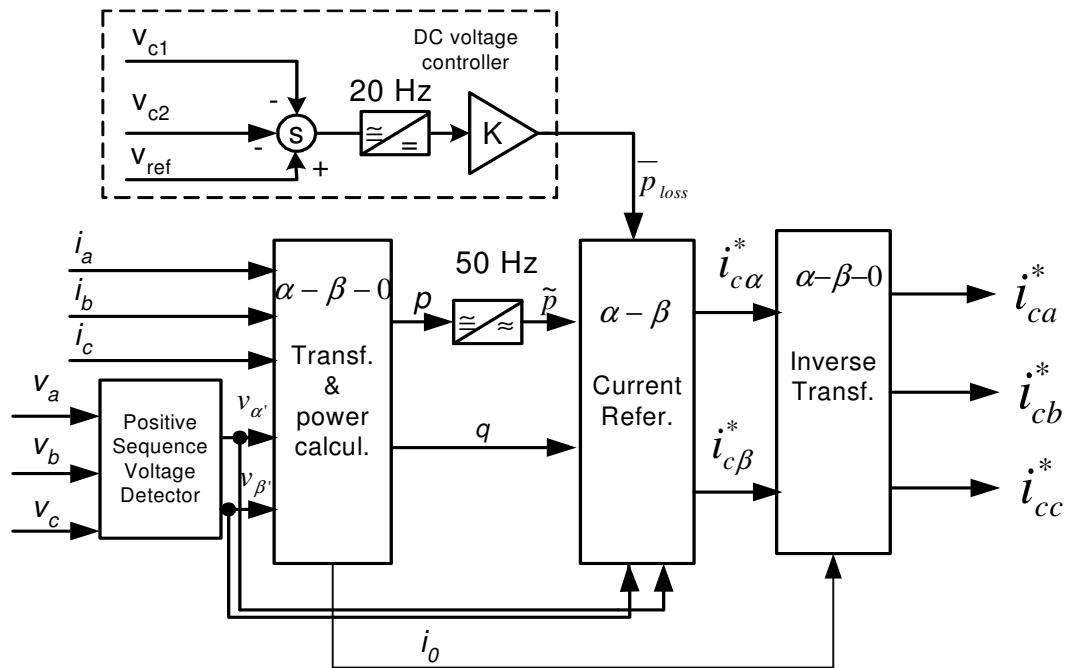


Figure 4.2 Control block diagram of the Sinusoidal Current Control Strategy

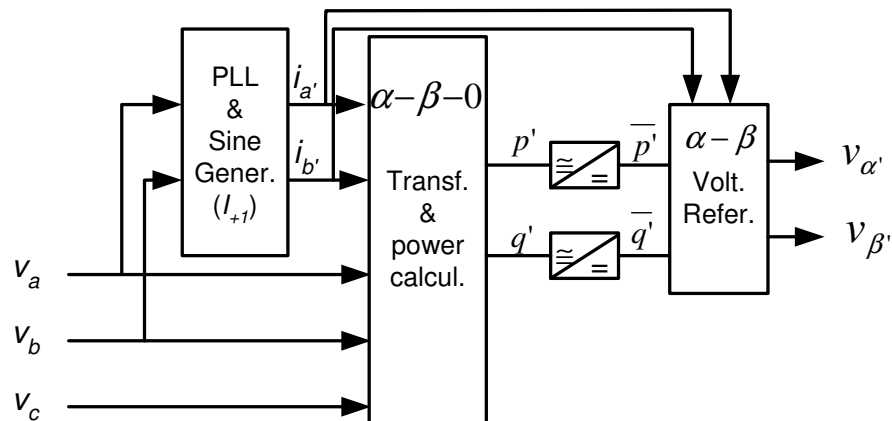


Figure 4.3. Fundamental positive sequence voltage detector

As seen in Figure 4.3 the distorted and unbalanced supply voltages are fed to the positive sequence voltage detector circuit. The voltages V_a, V_b, V_c are transformed into α, β axis to give V_α to V_β . The positive sequence detector also uses a PLL circuit locked to the fundamental frequency of system voltage generating

$i'_\alpha = \sin(\omega_1 t)$ and $i'_\beta = -\cos(\omega_1 t)$. V_α and V_β together with i'_α and i'_β for calculating auxiliary powers p' and q' . Since i'_α and i'_β depend only on an auxiliary positive sequence current it is possible to see that the average values of p' and q' are composed only from fundamental positive sequence voltage. The influence of the fundamental negative sequence and the harmonics will appear only in the high frequency components of p' and q' . Two 5th order Butterworth low pass filters are used for obtaining the average values of the real ($= \bar{p}'$) and imaginary ($= \bar{q}'$) power. Finally the α - β voltage reference block calculates the voltages V'_α and V'_β which correspond to the fundamental positive sequence component of the system voltage transformed into α - β axis as follows:

$$\begin{bmatrix} V'_\alpha \\ V'_\beta \end{bmatrix} = \frac{1}{i'^2_\alpha + i'^2_\beta} \begin{bmatrix} i'_\alpha & i'_\beta \\ i'_\beta & -i'_\alpha \end{bmatrix} \begin{bmatrix} \bar{p}' \\ \bar{q}' \end{bmatrix} \quad (4.1)$$

The outputs of the positive sequence voltage dedector V'_α and V'_β together with unbalanced nonlinear load currents i_a, i_b, i_c are used to calculate i_α, i_β and i_0 and then p and q .

A high pass filter with 50 Hz cut off frequency separates the power \tilde{p} from p . The powers \tilde{p}, p_0 of the load together with q should be compensated to perform the function of harmonic filtering, zero sequence current and reactive power compensation. Thus the α - β current references are found to be :

$$\begin{bmatrix} i^*_{c\alpha} \\ i^*_{c\beta} \end{bmatrix} = \frac{1}{v^2_\alpha + v^2_\beta} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} -\tilde{p} + \bar{p}_{loss} \\ -q \end{bmatrix} \quad (4.2)$$

In (4.2) \bar{p}_{loss} is the voltage source inverter losses.

Finally the α - β -0 inverse transformation box of Figure 4.2 calculates the instantaneous current references for the current control of the VSI:

$$\begin{bmatrix} i_{ca}^* \\ i_{cb}^* \\ i_{cc}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1 & 0 \\ 1/\sqrt{2} & -1/2 & \sqrt{3}/2 \\ 1/\sqrt{2} & -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} -i_0 \\ i_{c\alpha}^* \\ i_{c\beta}^* \end{bmatrix} \quad (4.3)$$

With this approach the active filter supplies the whole i_0 to the load. The signal \bar{p}_{loss} is used in the active filter controller as an average real power. It is included in the current reference calculation to force the voltage source inverter to absorb (deliver) energy from (to) the ac network. If the sum of split capacitor voltages V_{C1} and V_{C2} is smaller than a predefined DC bus voltage reference V_{ref} then voltage source inverter is absorbing energy from the ac network to charge the capacitors. The inverse occurs if $V_{C1} + V_{C2} > V_{ref}$. The PI controller can be tuned to provide a desired ac current amplitude to neutralize the dc bus voltage variation. Low pass filters with a cut-off frequency at 20 Hz are inserted in the voltage regulator to render it insensitive to the fundamental frequency variations which appear when the active filter compensates the fundamental zero sequence current of the load. Further, this slower feedback loop is also useful to correct variations due to compensation errors that occur during transient response of the shunt active filter.

4.4. Voltage Source Inverter Current Control

4.4.1. DC Link Voltage Imbalance Problem

The capacitors in three-leg split capacitor topology are associated with the problem of voltage imbalance. The reasons for this may be listed as follows [Mishra et al, 2003], [Aredes et al, 1997] and [Rodriguez et al, 2002]:

- Unequal capacitance leakage currents

- Asymmetrical circuit configuration (due to measurement and signal conditioning circuit)
- Asymmetrical charging of capacitors during transients
- Injection of zero-sequence compensating currents through dc capacitors with unequal switching times
- Loads containing dc components

The first two items are practical problems related with characteristic of components used in the circuit. Others are related with the operation of the active filter. The solution of fifth item needs using extra power semiconductors as in [Mishra et al, 2003] . The method proposed in this chapter provides a solution for the first four items.

Figure 4.4 shows the injected current by leg a using hysteresis current control and the approach presented in [Rodriguez et al, 2002] will be used to analyze the voltage imbalance in three-leg split capacitor topology when hysteresis current control is employed. One switching period of S1 is shown in Figure 4.4. The dash lines are upper hysteresis band limit, lower hysteresis band limit and current reference in the middle. $T_a = t_{1a} + t_{2a}$ is the switching period for S1. During t_{1a} S1 is ON and t_{2a} S1 is OFF. The duty cycle evolution for each leg d_i depends on the technique utilized for injected current control, where d_i represents the duty cycle of leg i where $i = \{a, b, c\}$. Voltage source inverter interface reactors L_f have been considered identical for the three legs and $C_1 = C_2 = C$.

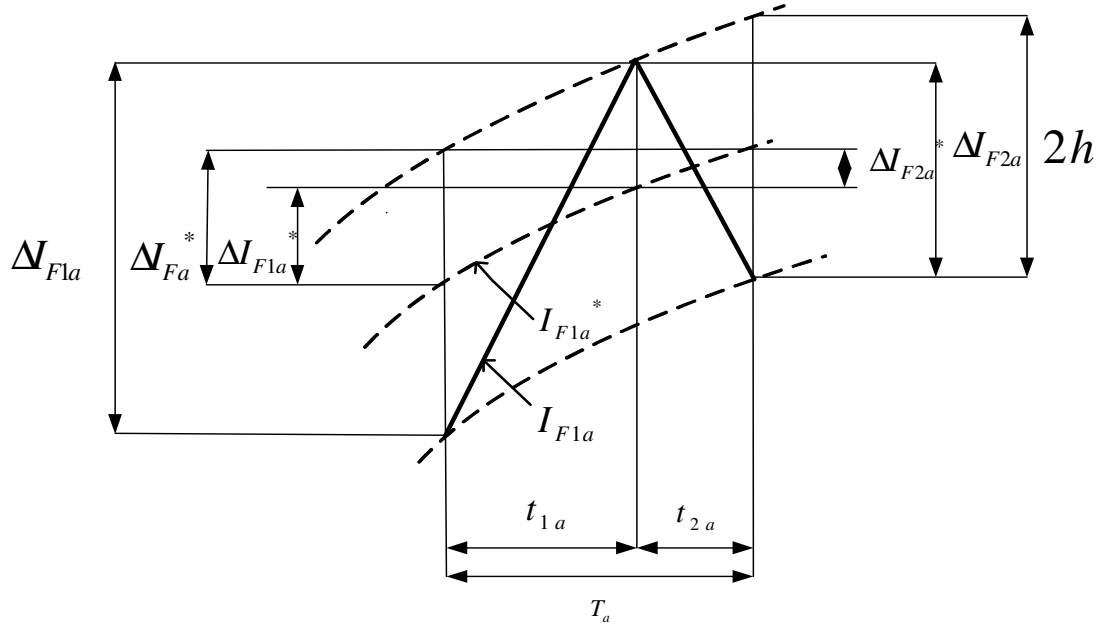


Figure 4.4 Injected current by leg a in hysteresis current control

Expressing the injected current as $I_{Fa} = \delta_a + I_{Fa}^*$ where δ_a represents the instantaneous error in the reference current tracking and considering the time origin at the beginning of a switching period, then the following equations can be written for the switching intervals t_{1a} and t_{2a} .

$$V_{C1} - V_a = L_F \left(\frac{d\delta_a}{dt} + \frac{dI_{Fa}^*}{dt} \right) \quad t \in [0, t_{1a}] \quad (4.4)$$

$$-V_{C2} - V_a = L_F \left(\frac{d\delta_a}{dt} + \frac{dI_{Fa}^*}{dt} \right) \quad t \in [t_{1a}, T_a] \quad (4.5)$$

Presuming sufficiently high switching frequency it is possible to assume that V_{C1} , V_{C2} , V_a , $\frac{d\delta_a}{dt}$ and $\frac{dI_{Fa}^*}{dt}$ are constant during switching intervals t_{1a} and t_{2a} .

Then (4.4) and (4.5) can be written as

$$\frac{1}{L_F}(V_{C1} - V_a).t_{1a} = 2h + \Delta I_{F1a}^* \quad (4.6)$$

$$-\frac{1}{L_F}(V_{C2} + V_a).t_{2a} = -2h + \Delta I_{F2a}^* \quad (4.7)$$

Adding (4.7) and (4.8) and dividing by T_a , we have

$$\frac{1}{L_F}[(V_{C1} + V_{C2}).d_a + (-V_{C2} - V_a)] = \frac{\Delta I_{Fa}^*}{T_a} \quad (4.8)$$

where $\Delta I_{Fa}^* = \Delta I_{F1a}^* + \Delta I_{F2a}^*$ represents the reference current variation for leg a over a switching period. Therefore the duty cycle d_a is given by

$$d_a = \frac{1}{V_{C1} + V_{C2}} \left(V_a + V_{C2} + L_F \frac{dI_{Fa}^*}{dt} \right) \quad (4.9)$$

The current in the conductor connected to the dc bus midpoint is the neutral line current and equal to the sum of active filter output currents for legs a,b and c. Referring to average values over a switching period, the contribution of leg a for the current in capacitors C_1 and C_2 is given by

$$\bar{I}_{C1a} = d_a \bar{I}_{Fa} \text{ and } \bar{I}_{C2a} = (1 - d_a) \bar{I}_{Fa} \quad (4.10)$$

Substituting the duty cycle d_a expression (4.9) in (4.10)

$$\bar{I}_{C1a} = -\frac{V_{C2}}{V_{C1} + V_{C2}} \bar{I}_{Fa} - \frac{1}{V_{C1} + V_{C2}} \cdot \bar{P}_{Fa} - \frac{L_F}{V_{C1} + V_{C2}} \cdot \frac{dI_{Fa}^*}{dt} \cdot \bar{I}_{Fa} \quad (4.11)$$

$$\bar{I}_{C2a} = -\frac{V_{C1}}{V_{C1} + V_{C2}} \cdot \bar{I}_{Fa} + \frac{1}{V_{C1} + V_{C2}} \cdot \bar{p}_{Fa} + \frac{L_F}{V_{C1} + V_{C2}} \cdot \frac{dI_{Fa}^*}{dt} \cdot \bar{I}_{Fa} \quad (4.12)$$

where $\bar{p}_{Fa} = V_a \bar{I}_{Fa}$ represents the instantaneous power developed by the voltage source inverter. The contributions of legs b and c are similar to a. The sum of contributions of leg a,b and c give \bar{I}_{C1} .

I_{C1} and I_{C2} are directly involved through the change of V_{C1} and V_{C2} because

$$V_{C1} = \frac{1}{C_1} \int I_{C1} dt, V_{C2} = \frac{1}{C_2} \int I_{C2} dt \quad (4.13)$$

Each expression in (4.11) and (4.12) consist of three terms. The first term is the the compensated zero sequence current returning through the ac neutral wire and causes imbalance in the voltage sharing between the two capacitors ($\Delta \bar{V}_C = \bar{V}_{C1} - \bar{V}_{C2}$). The second term is due to active power filter losses and is the absorbed and delivered energy from/to the supply line and give rise to a variation in the absolute dc bus voltage ($\bar{V}_{DC} = \bar{V}_{C1} + \bar{V}_{C2}$). In other words it brings about a change in the energy stored in the dc bus capacitors and is related with \bar{p}_{loss} in (4.2). The third term is the consequence of a variation in the energy stored in the voltage source inverter interface reactances resulting from a reference currents modification, which in turn also changes the dc absolute value.

While the coefficients of second and third terms are similar, the coefficients of first term are different which is the term related with compensation of the load current zero-sequence components and imply an imbalance in the dc-bus voltage sharing. This imbalance problem should be solved either in the reference current generation or current control. As seen in (4.11) and (4.12) the term related with imbalance includes V_{C1} and V_{C2} which necessitates including V_{C1} and V_{C2} in control. The proposed fuzzy logic current controller below provides a solution for this imbalance problem together with fixed frequency operation and stable dc voltage

control. The dc voltage control about active power filter losses (\bar{p}_{loss}) is realized by a PI controller in the reference current generator and imbalance control due to zero sequence currents is done in the fuzzy logic current controller including VC1 and VC2 in the controller. The third term in (4.11) and (4.12) causes high frequency ripples on the DC link voltage and can be minimized by choosing correct DC link capacitor value.

4.4.2. Fuzzy Logic Current Controller

Recently, fuzzy logic controllers have generated a good deal of interest in certain applications. The advantages of fuzzy logic controllers over conventional controllers are that they do not need an accurate mathematical model, they can work with imprecise inputs, can handle non-linearity and they are more robust than conventional nonlinear controllers. Fuzzy logic control of inverter switching allows the independence of electrical parameters, and it can be easily managed during its development. Fuzzy logic control may be designed in order to have different direct actions in each critical point of reference waveform.

In this chapter a fuzzy logic controller with three inputs one output is presented for a three-phase four-wire active power filter with split-capacitor inverter topology focusing on fixed frequency operation and maximum dc link voltage utilization. The block diagram of the fuzzy logic current controller is shown in Figure 4.5.

In order to implement the control algorithm of fuzzy logic current controller for each phase the nonlinear load current of that phase (i_{fa} for phase a) is measured and compared with the reference value (i_{ca}^* for phase a) obtained from the reference current generator. The obtained error ($e = i_{fa} - i_{ca}^*$) and change of error signal ($ce(n) = e(n) - e(n-1)$) at the nth sampling instant are the two of the three inputs for fuzzy processing. The third input is the voltage difference on the voltage source interface reactor for phase a. However the expression to calculate the value of the

voltage difference on the interface reactor changes according to active power filter operation modes.

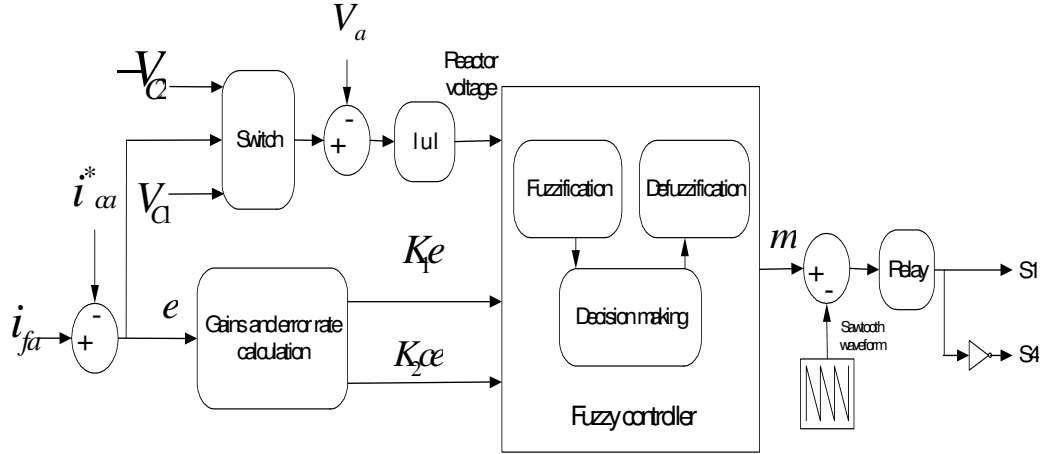


Figure 4.5 Block diagram of the proposed fuzzy logic current controller

If the current references include also zero sequence components the line currents will return through the ac neutral wire. This forces in the leg “split-capacitor” inverter topology, the current of each phase to flow either through C_1 or through C_2 and to return through the ac neutral wire. The currents can flow in both directions through the switches and capacitors. This causes the total dc voltage $V_{C1} + V_{C2}$ and the voltage difference $V_{C1} - V_{C2}$ to oscillate both at the switching frequency and corresponding frequency of zero sequence currents that is being generated by the voltage source inverter.

If the modes of operation during the flow of zero sequence current for leg a are investigated:

MODE 1: S1 ON, S4 OFF

If we apply KVL in Figure 4.6.

$$-V_a - V_L + V_{C1} = 0 \quad (4.14)$$

$$V_L = V_{C1} - V_a \quad (4.15)$$

The active filter output current is flowing in the shown direction and increasing and V_{C1} is decreasing.

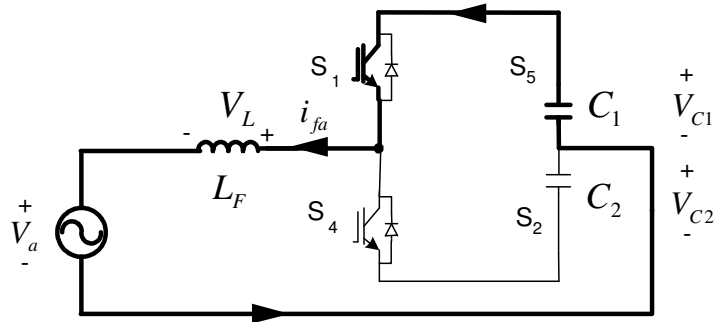


Figure 4.6 MODE 1 operation

MODE 2: S1 OFF, S4 OFF

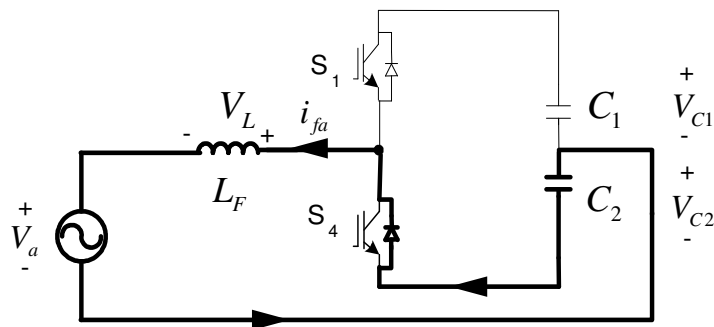


Figure 4.7 MODE 2 operation

If we apply KVL in Figure 4.7.

$$-V_a - V_L - V_{C2} = 0 \quad (4.16)$$

$$V_L = -V_{C2} - V_a \quad (4.17)$$

The active filter output current is flowing in the shown direction and decreasing and V_{C2} is increasing.

MODE 3: S1 OFF, S4 ON

If we apply KVL in Fig.8.

$$-V_a - V_L - V_{C2} = 0 \quad (4.18)$$

$$V_L = -V_{C2} - V_a \quad (4.19)$$

The active filter output current is flowing in the shown direction and increasing and V_{C2} is decreasing.

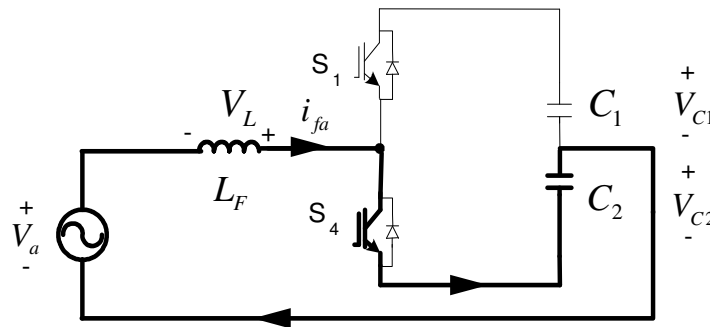


Figure 4.8 MODE 3 operation

MODE 4: S1 OFF, S4 OFF

If we apply KVL in Figure 4.9.

$$-V_a - V_L + V_{C1} = 0 \quad (4.20)$$

$$V_L = V_{C1} - V_a \quad (4.21)$$

The active filter output current is flowing in the shown direction and decreasing and V_{C1} is increasing.

The voltage difference on interface reactor is calculated by two expressions in different modes of operation given below

$$V_L = V_{C1} - V_a \quad \text{and} \quad V_L = -V_{C2} - V_a \quad (4.22)$$

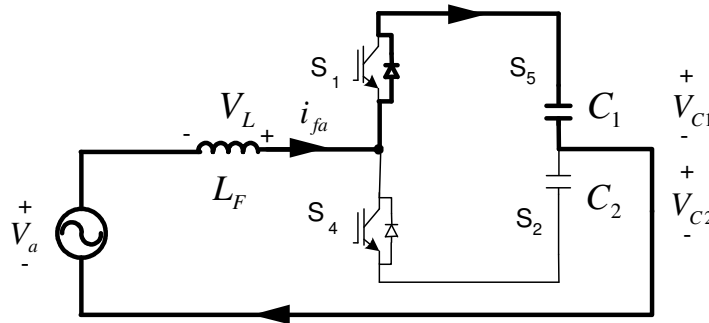


Figure 4.9 MODE 4 operation

The sign of error signal determines which expression will be used. Referring back to hysteresis current control figure Figure 4.4, when S1 becomes ON the currents starts increasing, the error is negative and (4.15) applies for this mode of operation. When S1 becomes OFF the current starts decreasing, the error is positive and (4.17) applies for this mode of operation. As a consequence, the third input for the fuzzy processing is

$$|V_{C1} - V_a| \quad \text{when } e > 0 \quad (4.23)$$

$$|-V_{C2} - V_a| \quad \text{when } e < 0 \quad (4.24)$$

The selection of inputs is done by switching two inputs according to sign of error. By including the voltage difference on the interface reactor in the control loop the value of V_{C1} and V_{C2} are included in the control. This provides adjusting switching times according to V_{C1} and V_{C2} instantaneous values resulting in a satisfactory operation when there is a voltage imbalance between V_{C1} and V_{C2} , self regulating the imbalance and fixed frequency operation.

The fuzzy logic control rule design involves defining rules that relate the input variables to the output model properties. As fuzzy logic controller is independent of system model, the design is mainly based on system operation principle.

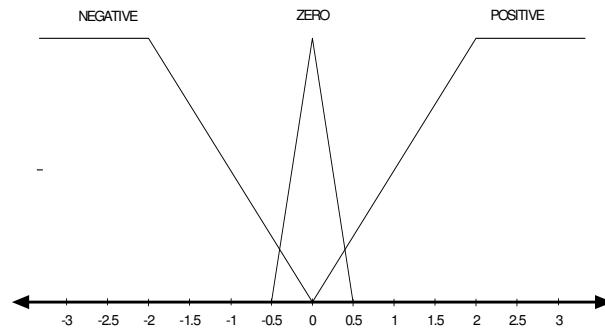
The input variables for the fuzzy logic controller are error (e), change of error signal (ce) and voltage difference on interface reactor (V_L). The output is the modulating signal for PWM switching. In the fuzzy logic controller mainly error rate and voltage difference on interface reactor are used in determining the switch conduction times and error is used in determining the switching action for increasing or decreasing the active filter output current. Based on these basic assumptions the elements of the below rule table (Table 4.1) are obtained and membership functions are developed by an understanding of system behaviour and simulation performance.

The decision making by the use of the input is done by the inference about corresponding rules to make the actual active power filter current to track the reference signal. Triangular and trapezoidal membership functions are used in fuzzification and defuzzification of inputs and outputs respectively. The membership functions for error (e), change of error signal (ce), voltage difference on interface reactor (V_L) and modulating signal m are shown in Figure 4.10. The fuzzy subspaces NEGATIVE, ZERO, POSITIVE for e and ce may be partitioned to smaller subspaces. However this will increase the number of rules so increasing the computational time and slowing down the response. The performance of the fuzzy logic controller is more than satisfactory as will be shown in results.

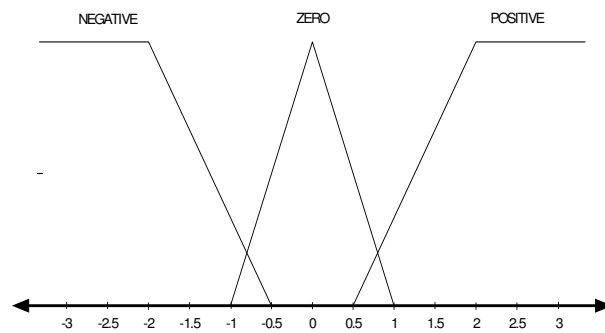
The Matlab / Simulink model of the fuzzy logic current controller is shown in Figure 4.11.

Table 4.1 Rule table of proposed fuzzy logic controller

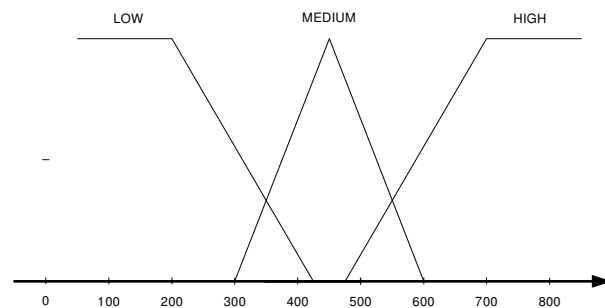
RULES	e	ce	V_L	m
Rule 1	POSITIVE	POSITIVE	LOW	DECREASE MORE
Rule 2	POSITIVE	POSITIVE	MEDIUM	DECREASE
Rule 3	POSITIVE	POSITIVE	HIGH	DECREASE LESS
Rule 4	NEGATIVE	POSITIVE	LOW	INCREASE MORE
Rule 5	NEGATIVE	POSITIVE	MEDIUM	INCREASE
Rule 6	NEGATIVE	POSITIVE	HIGH	INCREASE LESS
Rule 7	POSITIVE	ZERO	LOW	DECREASE MORE
Rule 8	POSITIVE	ZERO	MEDIUM	DECREASE
Rule 9	POSITIVE	ZERO	HIGH	DECREASE LESS
Rule 10	ZERO	POSITIVE	-	DECREASE LESS
Rule 11	ZERO	ZERO	-	CONSTANT
Rule 12	ZERO	NEGATIVE	-	INCREASE LESS
Rule 13	NEGATIVE	ZERO	LOW	INCREASE MORE
Rule 14	NEGATIVE	ZERO	MEDIUM	INCREASE
Rule 15	NEGATIVE	ZERO	HIGH	INCREASE LESS
Rule 16	POSITIVE	NEGATIVE	LOW	DECREASE MORE
Rule 17	POSITIVE	NEGATIVE	MEDIUM	DECREASE
Rule 18	POSITIVE	NEGATIVE	HIGH	DECREASE LESS
Rule 19	NEGATIVE	NEGATIVE	LOW	INCREASE MORE
Rule 20	NEGATIVE	NEGATIVE	MEDIUM	INCREASE
Rule 21	NEGATIVE	NEGATIVE	HIGH	INCREASE LESS



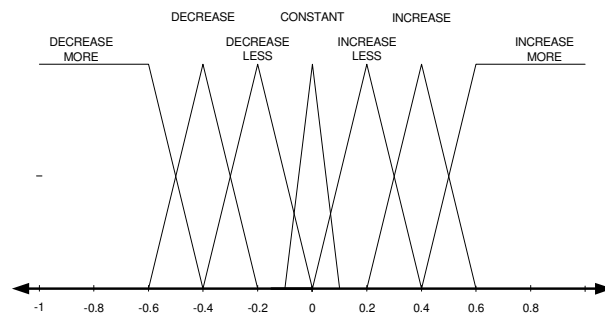
Membership function for error



Membership function for error rate



Membership function for interface reactor voltage difference



Membership function for PWM modulating signal

Figure 4.10 Membership functions used in fuzzification

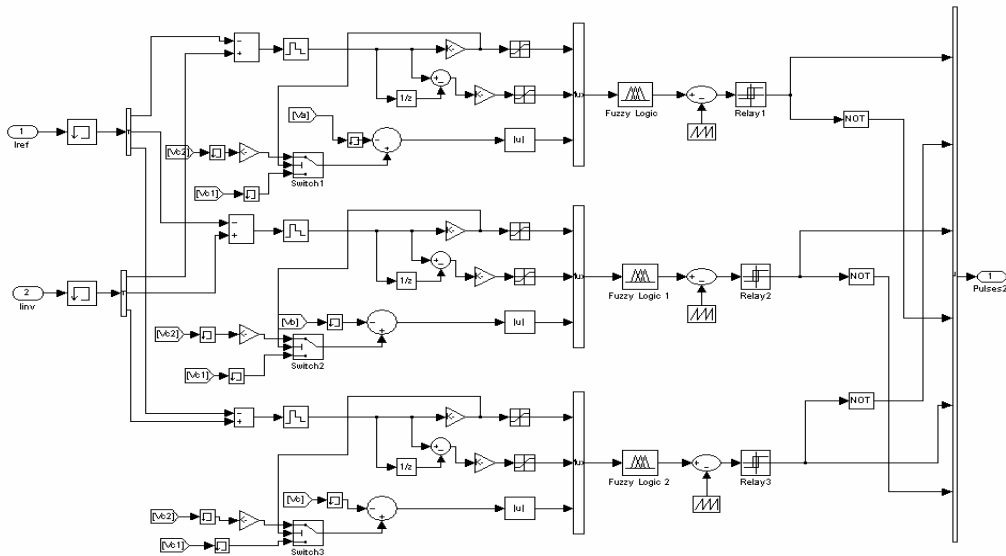


Figure 4.11 Matlab / Simulink model of fuzzy logic based current controller

4.5. Simulation Results

The proposed three-phase four-wire shunt active power is designed and modeled in Matlab. To demonstrate the good performance of the proposed control, the conditioning of the load current generated by a group of nonlinear loads is carried out. This load group is composed of a three-phase full-bridge fully controlled rectifier, single phase uncontrolled bridge rectifier with resistive-capacitive loading connected to phase B and and a R-L load connected to phase C. Three different loads are selected to demonstrate compensation performance of proposed filter for different nonlinear loads. A list of the system parameters considered in the simulation is given in Table 4.2.

Figure 4.12 a-d shows the unbalanced nonlinear load currents for the phases A, B and C and the uncompensated neutral current flowing in the neutral conductor of distribution system.

For comparison purposes the same active filter is operated to compensate same group of nonlinear loads with hysteresis current control and proposed fuzzy logic current control approach. Figure 4.13 show the three phase compensated source currents for the hysteresis current controlled active filter. Figure 4.14 show

the three phase compensated source currents and the neutral current for the fuzzy logic current controlled active filter. The hysteresis band is 3 A for the hysteresis current control.

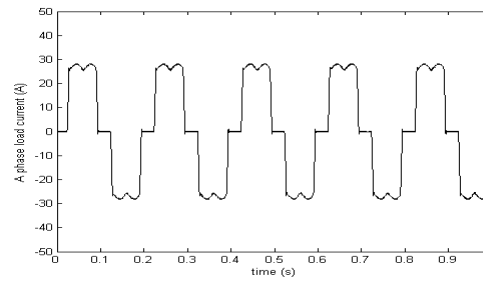
Table 4.2 System parameters

Utility Source	Phase voltage= 220 V(RMS)
	Frequency = 50 Hz
	Source resistance = 0.1 Ω
	Source inductance= 0.5 mH
Active Power Filter	$C_1 = C_2 = 8800 \mu\text{F}$
	$L_F = 3 \text{ mH}$
	$V_{DC} = 850 \text{ V}$
	P=1, I=10 for PI controller
RC filter	R=3.5 Ω , C=120 μF
Fully controlled bridge rectifier	$I_{dc} = 25 \text{ A}$, $\alpha = 10^\circ$, $L_C = 2 \text{ mH}$
Single-phase uncontrolled bridge rectifier	$L_C = 5 \text{ mH}$, $C = 250 \mu\text{F}$, R=60 Ω
Single phase R-L load	P=1500W, Q =200W

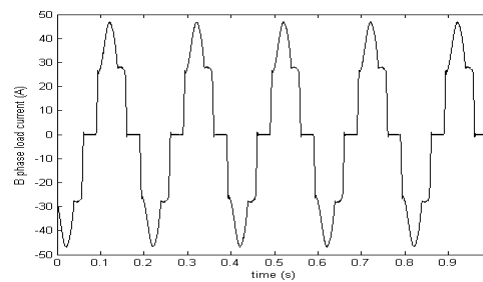
Table 4.3 summarizes the THD values for load currents, source currents with hysteresis control and fuzzy logic control. THD values for fuzzy logic control is superior with respect to hysteresis control. Fixed frequency operation enabling better inverter input passive filter filtering and more stable dc link voltage observed in Figures 4.15 and 4.16 with lower voltage variation are the main factors of improved performance. Less ripple content in compensated source currents with fuzzy logic control is also clearly observed comparing Figure 4.13 and 4.14. High and variable frequency content for the hysteresis control is clear also looking at the neutral current in Figure 4.13.

Table 4.3: THD values for load currents, active filter currents with hysteresis control and fuzzy logic control.

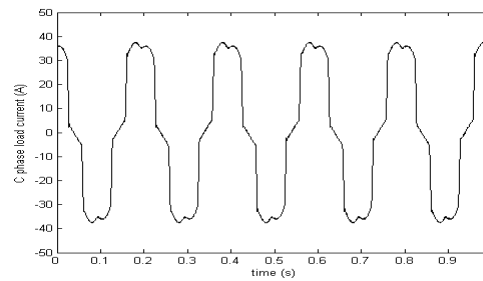
Phases	THD for load currents	THD for source currents compensated by hysteresis control	THD for source currents compensated by fuzzy logic control
Phase A	%25.63	%1.60	%1.17
Phase B	%25.35	%1.49	%1.29
Phase C	%19.22	%1.23	%1.06



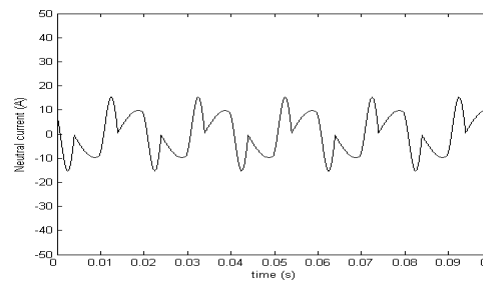
a) A phase load current for nonlinear load



b) B phase load current for nonlinear load

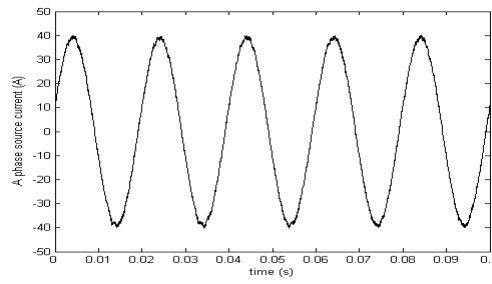


c) C phase load current for nonlinear load

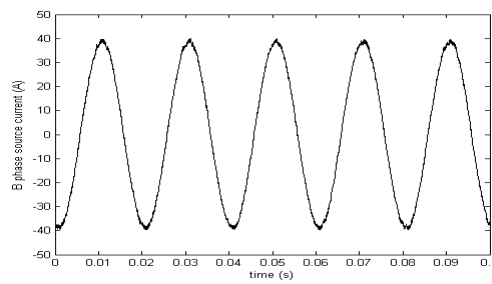


c) Neutral current

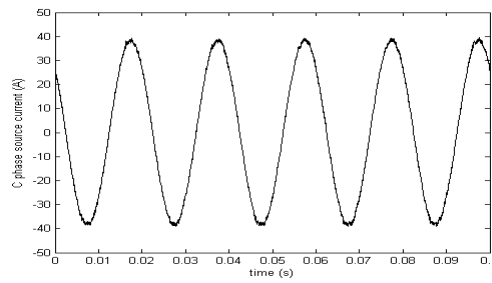
Figure 4.12 A, B and C phases nonlinear load currents and neutral current.



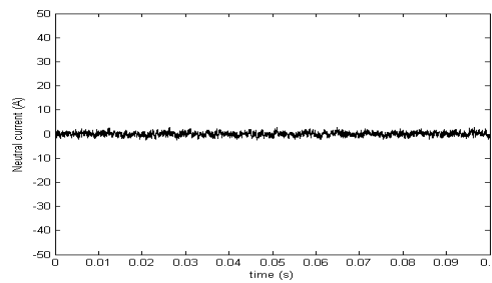
a) A phase source current



b) B phase source current

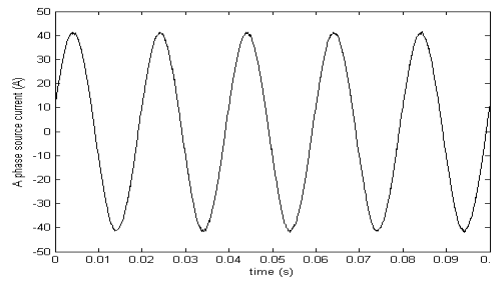


c) C phase source current

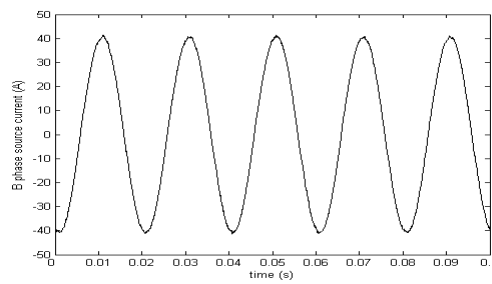


d) Neutral current

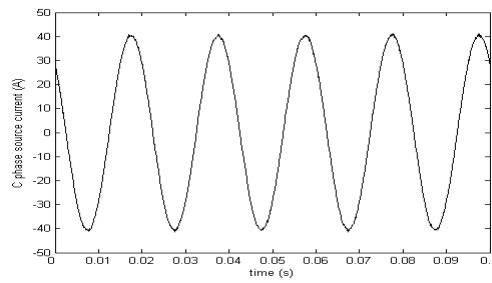
Figure 4.13 Source currents and neutral current with hysteresis control



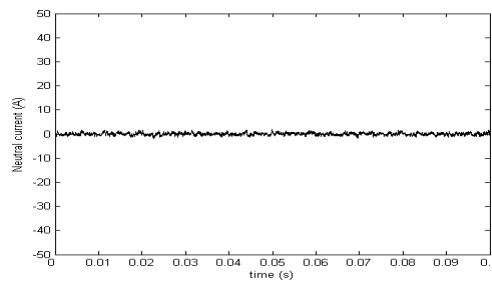
a) A phase source current



b) B phase source current



c) C phase source current

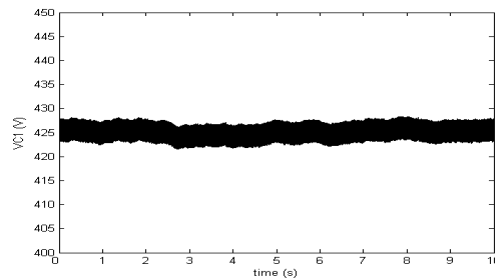


d) Neutral current

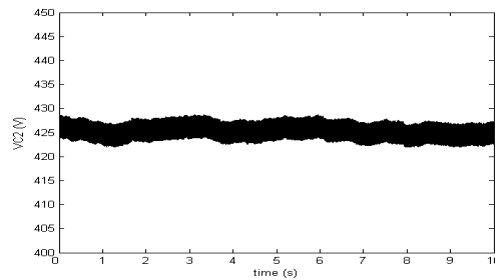
Figure 4.14 Source currents and neutral current with fuzzy logic control.

Figures 4.15 and 4.16 show the dc link voltages of active power filters for hysteresis current controlled active filter and fuzzy logic current controlled active filter.

Figures 4.17 and 4.18 show the dynamic responses in dc link voltage control for the hysteresis control and proposed fuzzy logic control. The three-phase full-bridge fully controlled rectifier is disconnected at second 2 to observe a transient event. The response of hysteresis control is slower with respect to proposed method. Improved transient performance on DC link voltage control also effects source currents.

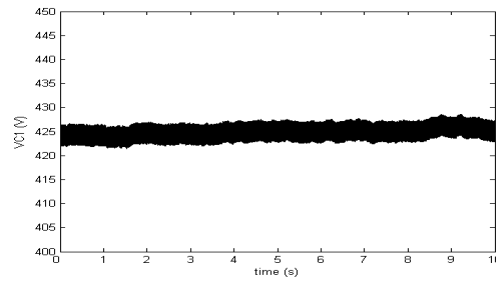


a) VC1

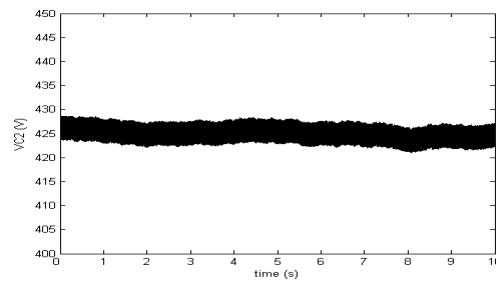


b) VC2

Figure 4.15 VC1 and VC2 with hysteresis control



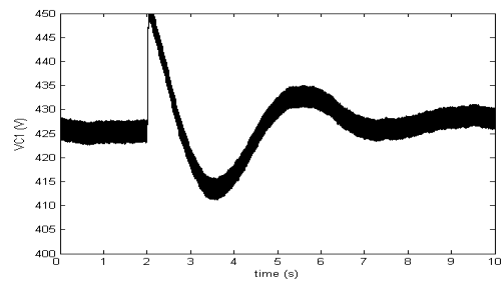
a) VC1



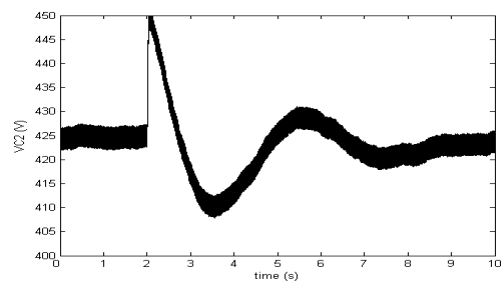
b) VC2

Figure 4.16 VC1 and VC2 with fuzzy logic control

It is clear from the results that both the steady state and transient performance of the proposed fuzzy logic controller is better than conventional hysteresis current controller. The dc voltage control about active power filter losses (\bar{p}_{loss}) is realized by a PI controller in the reference current generator and imbalance control due to zero sequence currents is done in the fuzzy logic current controller including VC1 and VC2 in the controller. This provides a perfect control performance for the dc link voltage which is important for the active filter performance. This stable control performance in the dc link enables choosing a smaller dc link voltage which means smaller ratings for dc link capacitors. The performance of this control is far better than hysteresis current control with more stable DC link voltage, imbalance regulation and fixed frequency in steady state operation.

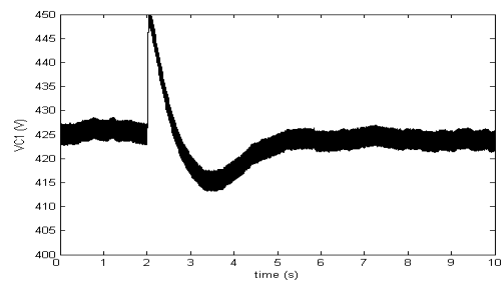


a) VC1

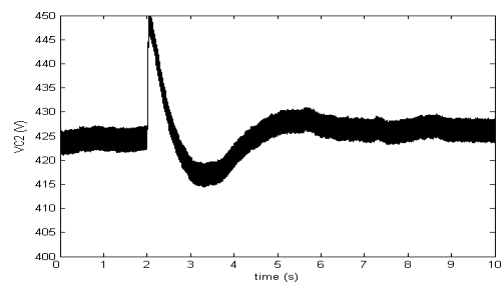


b) VC2

Figure 4.17 Dynamic response of active power filter for hysteresis current control.



a) VC1



b) VC2

Figure 4.18 Dynamic response of active power filter for fuzzy logic control.

5. MODELING OF STATIC TRANSFER SWITCH (STS)

5.1. Introduction

The increasing sensitivity of consumer equipment has given rise to growing interest concerning the "quality" of the electric power. Voltage sags of even low magnitude and short duration can cause financial losses to industrial customers due to process down-time, lost production, idle work forces, and other factors. There is a growing need, therefore, for power conditioning devices that will act very fast resulting in mild voltage sags of minimum duration experienced by the load. Many devices based on power electronics technology have been proposed and applied in many cases where mitigation of voltage sags is needed. The static transfer switch (STS), the dynamic voltage restorer (DVR), the distribution static compensator (DSTATCOM), the static var compensator (SVC), and the solid state tap changer (SSTC) are the most used devices.

One of the most effective solutions from the aforementioned is the STS. If an alternate feeder exists or can be provided to the critical load at reasonable cost, STS can transfer quickly enough the voltage supply to an alternate source and sensitive load experiences only a shallow sag of short duration. Obviously, STS is not effective in the event of a utility complete outage and cannot provide power conditioning, if both feeders sag in voltage simultaneously, as might be the case for a fault near the point where the two feeders join.

The voltage sag magnitude and duration at the load terminals depend directly on the STS control scheme. Hence, voltage detection and transfer need to be as fast as possible. Furthermore, transfer and gating logic must assure that in no case paralleling of the sources will occur, which would cause severe damage to thyristor switches [Moschakis et al., 2003].

In this chapter, a fast thyristor based STS system which employs fast voltage-detection and thyristor-gating strategies is presented. The STS performance is simulated for different faults scenarios using the Matlab/Simulink.

5.2. Static Transfer Switch Circuit Topologies, Operation and Controls

The design and application of a STS takes into account numerous considerations including[Rauch et al., 1999]:

1. Correct measurement of applied voltages and currents,
2. Thyristor firing control under the condition of non-sinusoidal load current operation,
3. Transfer operation with up-stream/down-stream fault discrimination,
4. Protection functions to avoid producing power quality problems for connected loads and to afford protection for the STS from additional failure,

The STS is a relatively complex device from a control and monitoring point-of-view. Notwithstanding complexity and the large number of components that make up a STS, the fact remains that there are many years of experience with thyristor applications where reliability issues were previously addressed in order to deliver viable products.

The principal contribution to thyristor application technology in the STS are the algorithms that make firing control possible without delays at current zero crossings, and the near instantaneous detection of fault direction to inhibit transfer of downstream faults[Rauch et al., 1999].

5.2.1. STS Circuit Topologies

A variety of medium voltage STS circuit topologies are applied in practice. Each arrangement is optimized for its specific application, taking into account the number of sources (generally two) and number of customer load busses. Using simplified single line diagrams, two common STS arrangements are the preferred/alternate source with single load bus, and the split bus design with two load busses.

Single Load Bus: A preferred/alternate source with single load bus configuration is illustrated in Figure 5.1. In this sketch, the combination series and parallel thyristor elements are simplified into anti-parallel components, with a functional indication of series and by-pass mechanical switching elements. Under

normal operating conditions, the load bus is served by a preferred source, such as that labeled as "Source 1" in Figure 5.1. The STS bypass devices are normally open, and remain that way unless the STS is taken out of service. The left-hand side thyristor components are operating in full conduction, whereas the right-hand thyristor bank is not gated. Any undesired voltage disturbance that occurs upstream in Source 1 is detected by the STS controller, whereupon the right-hand thyristor stack is gated into conduction forcing the left-hand stack off. This sequence of events can take place within about four milliseconds, or one quarter of a cycle [Rauch et al., 1999].

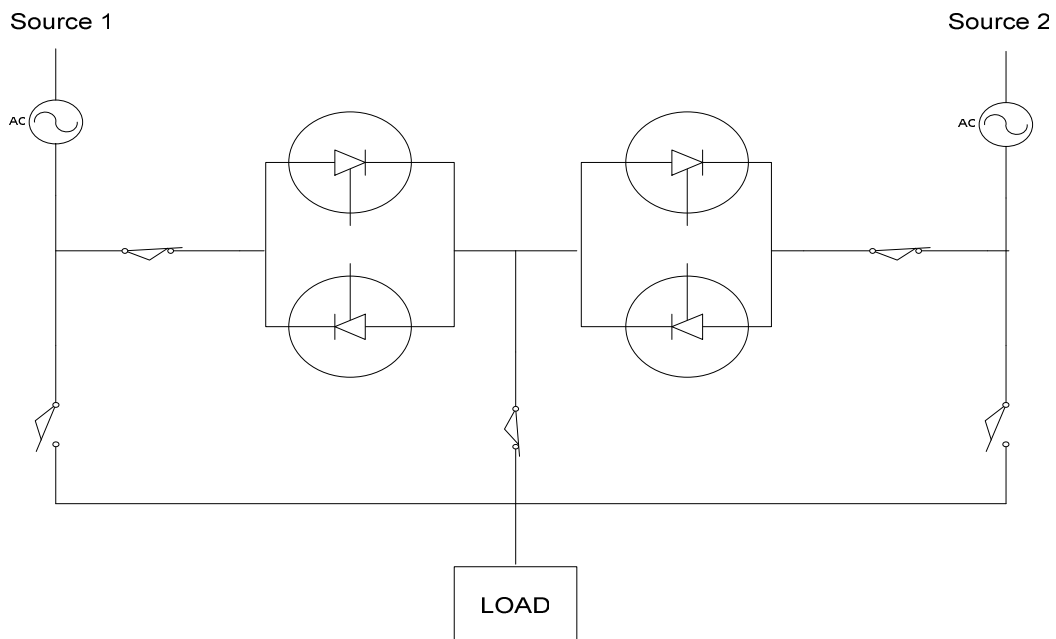


Figure 5.1 Single line diagram single load bus configuration.

The high speed switching of load from Source 1 to a nominal Source 2 helps maintain continuity of sensitive loads connected to the customer's load bus.

Split Bus Configuration: A split bus source with two load busses is illustrated in Figure 5.2. In this drawing, an additional stack of thyristors is applied to provide for split bus transfer of load. Hence, two thyristor stacks are normally gated on, thus providing the two load busses with service from either source [Rauch et al., 1999].

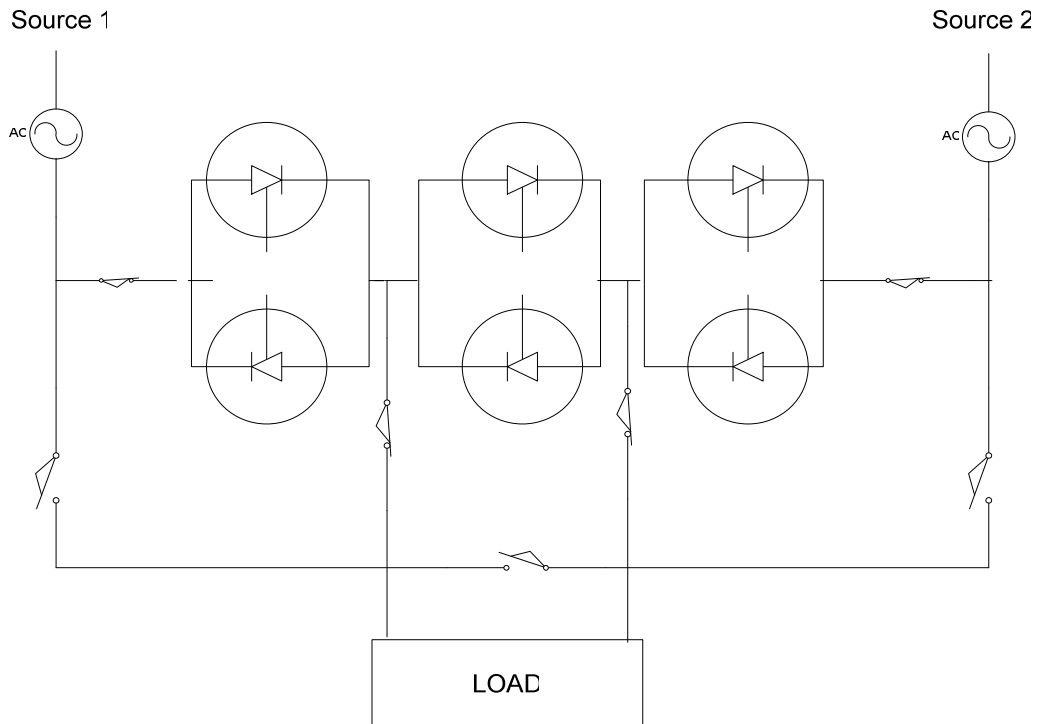


Figure 5.2 Single line diagram of split bus configuration.

5.2.2. STS Operation

The basic ON-state and OFF-state properties of a thyristor are used to form an intelligent switch which can choose between two upstream power sources and provide the best available power to the electrical load downstream. The basic configuration is that of back-to-back thyristors on the preferred and alternate sides of the switch as shown in Figure 5.3. In this chapter only the single-phase, two-source version is considered in order to preserve simplicity and clarity. The three-phase and/or three-source STS is merely an extension of the same fundamental concepts.

The application of the STS is optimized when the preferred and alternate sources of power provided to the STS are independent. Two sources are independent if the probability of simultaneous failure of the two sources is minimal. In practice, sources from separate utility sub-stations; or from separate UPS systems; or from a utility line and a UPS; or a UPS and a generator; are typical examples of independent sources [Bhanoo, 1998].

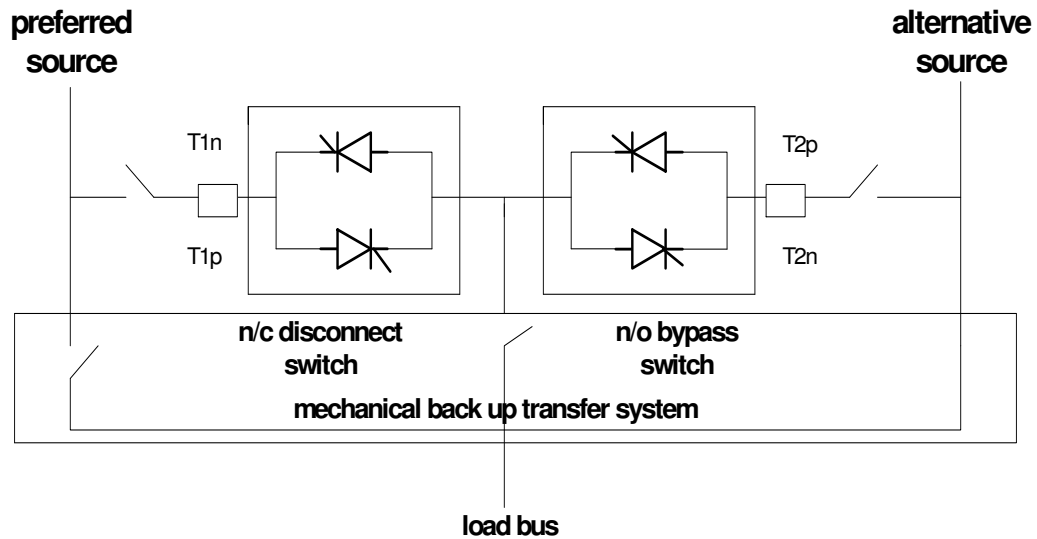


Figure 5.3 Static Transfer Switch System

5.2.3. STS Controls

STS control system is composed of voltage detection logic and a gating strategy. The detection logic is based on transforming ac voltages into a synchronously rotating frame. The gating system generates suitable gating patterns for the thyristor switches before, during and after a load transfer based on the direction of line current. Two different transfer schemes can be employed; zero-current strategy and commutation strategy [Mokhtari, 2002].

5.2.3.1. Zero-Current Gating Strategy

In this method of gating, load transfer to the backup feeder is not performed until T_1 switches are turned off. Figure 5.4 shows a block diagram of a control system based on zero current. When a disturbance is detected in the main feeder, the gating signals are removed from T_1 switches. The gating logic will then wait for T_1 thyristors to be turned off which occurs after a current zero crossing is reached. In practice, since real zero current cannot be measured, a zero-current threshold limit, e.g. 2% of the rated current, is used as a reference for the zero current. To

compensate for the resulting error, a turn-off delay is considered before gating the other set of thyristors which connect the load to the back up source.

By applying zero-current gating scheme, a “break-before-make” (BBM) transfer can be achieved. However, the disadvantage of this system is the long transfer time. In the worst case condition, a transfer time can take as long as half a cycle [Mokhthari,2002].

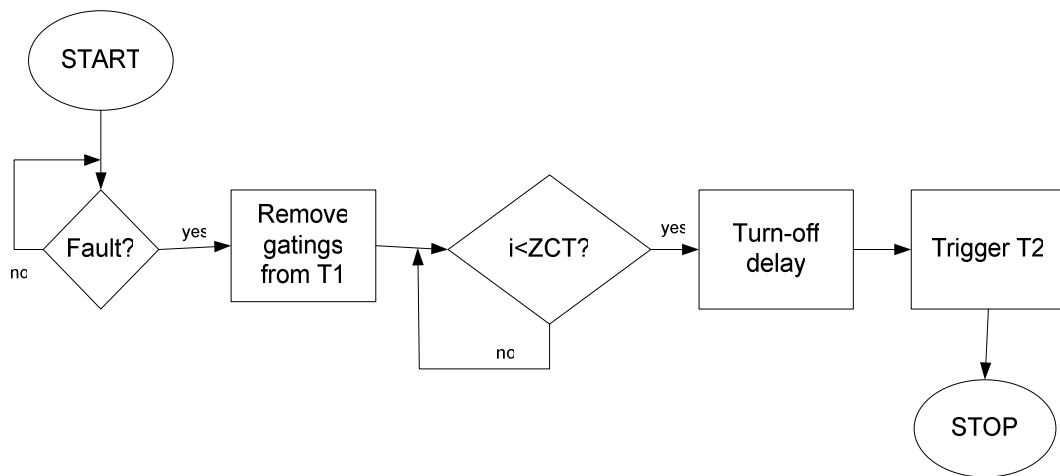


Figure 5.4 Block diagram of zero-current transfer logic

5.2.3.2. Commutation Gating Strategy

To achieve a faster load transfer, commutation gating strategy can be employed. In this method of gating, the control system does not wait for the current zero-crossings and starts the transfer as soon as the disturbance is detected. However, to avoid source paralleling and cross current, the transfer process is proceeded according to the direction of line currents (selective gating) Figure 5.5 shows a block diagram of the commutation gating logic.

In this method of gating, after a fault is detected, line current is compared against the zero-current threshold limit ZCT. Depending on the direction of the line current, one of the T_2 switches is gated. If commutation occurs and is completed, the other leg of T_2 is also gated and the load transfer process is over. Otherwise, the transfer will be postponed until commutation conditions are met. This happens if

either voltage polarity or line current direction changes. This type of transfer is normally referred to as "make-before-break" transfer (MBB) [Mokhtari,2002].

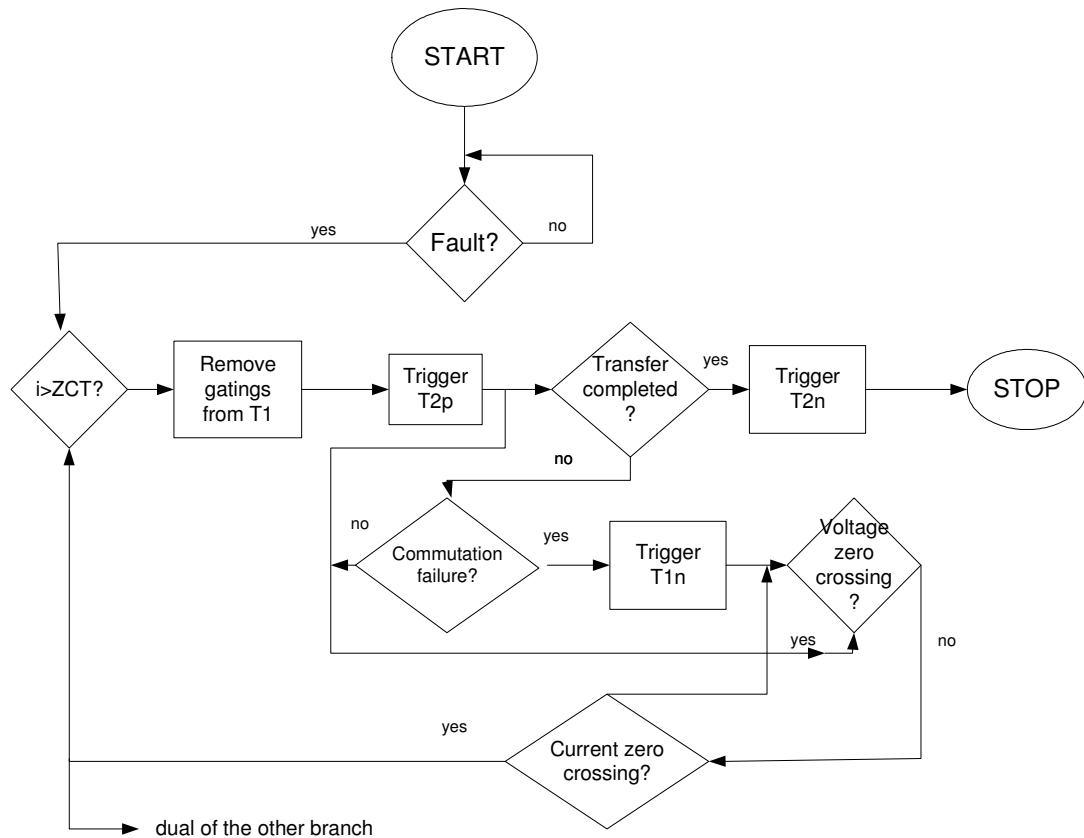


Figure 5.5 Block diagram of commutation gating strategy

The time required for completing the actual transfer of the load is thus dependent on the conditions of the circuit when the event occurs. This "switching time" (the time to reverse bias the switches) adds to the detection time, as fault detection and firing of the thyristors are sequential, thus giving the total transfer time [Mokhtari et al., 2000], [Sannino, 2001].

5.3. Proposed STS Controls

The control circuit of the proposed STS, as shown in Figure 5.6 is composed of two sections; voltage-detection and transfer-and-gating sections. Commutation

gating strategy (Make-before-break “MBB”) is used in the proposed control method. The control circuit is responsible for monitoring the quality of the source voltages and performing a load-transfer when needed. Line voltages and line currents from each source are the required input signals to the control circuit. The outputs of the control circuit are the gating patterns for the preferred source and alternate source thyristor switches. Figure 5.7 shows the Matlab/Simulink model of Static Transfer Switch.

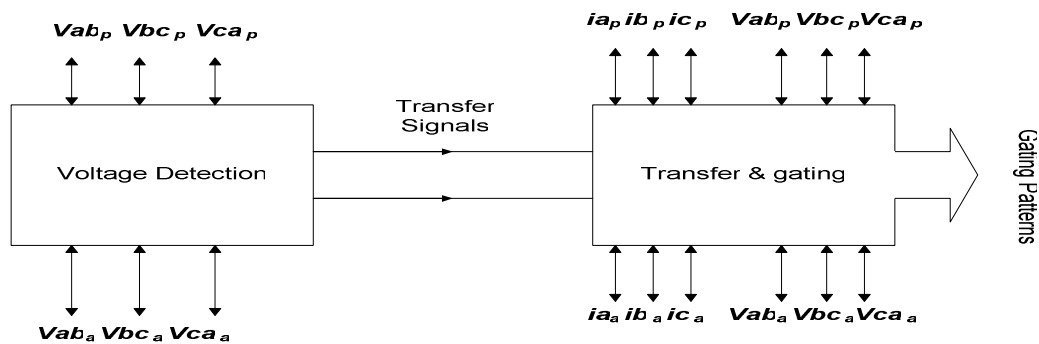


Figure 5.6 Block diagram of the control circuit of a STS.

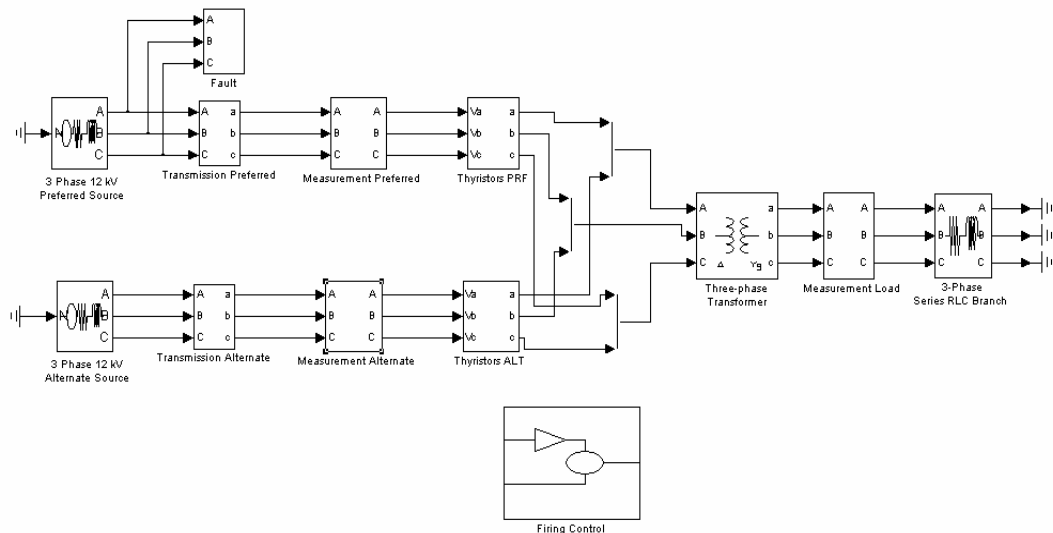


Figure 5.7 Matlab/Simulink Model of Static Transfer Switch.

5.3.1. Sag Detection Logic

Figure 5.8 shows a simplified block-diagram of the voltage-detection logic. Based on *abc-to-dq0* transformation, system line voltages are transformed into a synchronously rotating frame. This change of variables is through Park's transformation matrix:

$$V_{dq0_p} = K_s V_{abc_p} \quad (5.1)$$

where:

$$(V_{dq0_p})^T = [V_{d_p} \quad V_{q_p} \quad V_{0_p}] \quad (5.2)$$

$$(V_{abc_p})^T = [V_{ab_p} \quad V_{bc_p} \quad V_{ca_p}] \quad (5.3)$$

$$K_s = \frac{2}{3} \begin{pmatrix} \cos(\theta) & \cos(\theta-120) & \cos(\theta+120) \\ \sin(\theta) & \sin(\theta-120) & \sin(\theta+120) \\ 1/2 & 1/2 & 1/2 \end{pmatrix} \quad (5.4)$$

$$\theta(t) = \int_0^t \omega(\xi) d\xi + \theta(0) \quad (5.5)$$

where

V_{ab_p} , V_{bc_p} , V_{ca_p} ; are the preferred source line voltages,

V_{d_p} , V_{q_p} , V_{0_p} ; are the dq0 components of the preferred source voltage in the

rotating frame,

w is the rotating frame angular frequency

$\theta(0)$ is the initial value of θ .

The *rms* value of V_{d_p} and V_{q_p} will then be calculated as:

$$V_p = \sqrt{V_{d_p}^2 + V_{q_p}^2} \quad (5.6)$$

The output of the *abc-to-dq0* transformation block, i.e., V_p is compared to a dc reference, i.e. V_{ref} . The error e_r is passed through a low-pass filter which attenuates impacts of voltage transients. The filter introduces a certain amount of delay to the error signal which is determined by the filter cut-off frequency (f_c). The filter output is then compared to a tolerance limit E_{tot} . Output of the comparator is the transfer-signal which initiates a transfer process if the preferred source fails. Two identical logics have been used for both sources [Mokhtari et al.,2000].

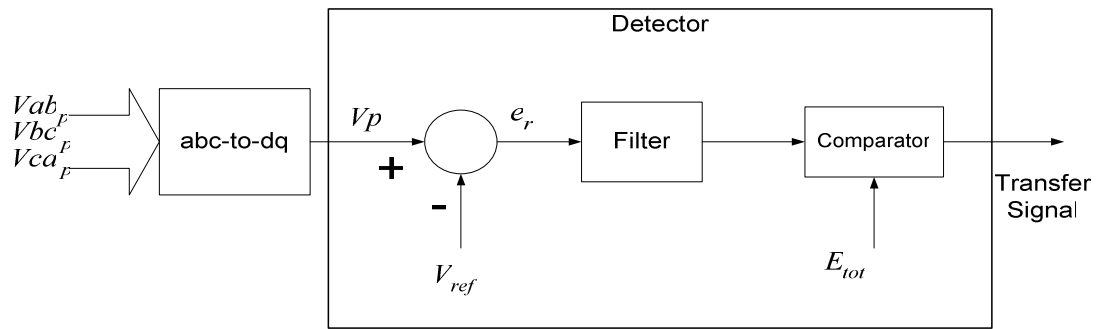


Figure 5. 8 Block-diagram of the voltage-detection circuit.

If the utility system operates in normal condition, or if any symmetrical fault occurs, then V_{d_p} and V_{q_p} are DC quantities. If any unsymmetrical fault occurs, the resulting voltage sag is unbalanced and contains both positive sequence and negative sequence component. The synchronous frame voltages V_{d_p} and V_{q_p} then have DC components and ripples. Voltage sags will certainly lead to the reduction of the positive sequence voltage component, which is used by the proposed STS controller to identify voltage sags [Cheng et al., 2004].

The detection time is shorter for a more severe fault. The response of the voltage detection logic is mainly determined by the filter cut-off frequency f_c . The higher the f_c the faster the detection circuit and the shorter the detection time.

However, increasing f_c makes the logic more sensitive to voltage transients, e.g., capacitor switchings. Therefore, a trade-off needs to be made between the speed of the detection logic and its sensitivity to voltage transients.

The transfer time is determined by gating strategy, load type, fault type, fault instant and system configuration. Each phase has its own transfer time, and the maximum transfer time occurs in the phase for which the commutation process fails. Commutation fails when the voltage drop across the incoming thyristor is negative. The worst case scenarios occur for a regenerative load when the load feeds the fault through T_1 thyristors and the transfer cannot be completed until the polarity of voltage drop across the incoming T_2 thyristor changes.

Since the selective gating strategy is based on detecting line current direction, the structure of the direction detection logic plays an important role in the performance of STS. The more accurate the current direction detection circuit, the better the performance of STS. Erroneous current direction detection may result in a cross current between the two sources [IEEE PES TF,2001].

5.3.2. Transfer and Gating Strategy

The proposed transfer strategy is based on a selective gating scheme during the transfer. The scheme is to transfer the load within the shortest possible time and prevent the sources from being paralleled during the transfer process. The selective gating strategy relies on the polarities of the line currents. The following steps summarize the principles of operation of the gating logic during the load-transfer process:

1. When a disturbance/fault in the preferred source is detected, the gating signals are removed from both T1p and T1n, switches.
2. Then, the logic checks the line current, and depending on the polarity of the line current, triggers one of the T2 switches. Assume the line current polarity is positive and T1p is in ON state. Then T2p (incoming switch) is gated as soon as the disturbance is detected.

3. If commutation is successful and the preferred source current drops below a certain limit (zero-current threshold limit), the other T2 switch (T2n in this case) is also gated and the transfer process is completed [Mokhtari et al., 2000].

4. When the fault conditions are passed, after 10 cycles delay, load is transferred back to preferred source as using the same transfer process.

Table 5.1 shows the truth table of the transfer and gating process. The following abbreviations represent:

Prf: is the output of the counter logic of preferred source side (Figure 5.9(a)). '0' represents fault, '1' represents safe condition for transfer. In the counter logic, a memory element is connected for obtaining a past value. If the both past value and the present values are '1', output of Prf is 1. If the present value is '0' output is '0' too. Any transition of present value from 0 to 1 makes a delay for 10 cycles, in order to prevent misfiring between sources.

Alt: is the output of the counter logic of alternate source side. Same detection method and counter logic is used separately for alternate source.

***Alt:** Past value of the alternative side thyristors' gating pulse.

Zct: In practice, since real zero current cannot be measured, a zero-current threshold limit, e.g. 2% of the rated current, is used as a reference for the zero current. If the line current is in the range of $\pm i_{ZCT}$ output is '1' otherwise '0'.

Drct: Each line current is passed through a low-pass filter in order to prevent multiple zero-crossing detection. The comparator compares the filtered line current with a zero current threshold limit. This limit is determined by the precision of current measurement devices and control system. If the current direction is positive Drct is '1', and '0' for negative direction. Figure 5.9 (b) shows the Matlab model of detection of zero current and direction.

Prf+: The gating pulse for the positive direction of preferred source thyristors.

Prf-: The gating pulse for the negative direction of preferred source thyristors. Figure 5.10 shows the thyristor switches.

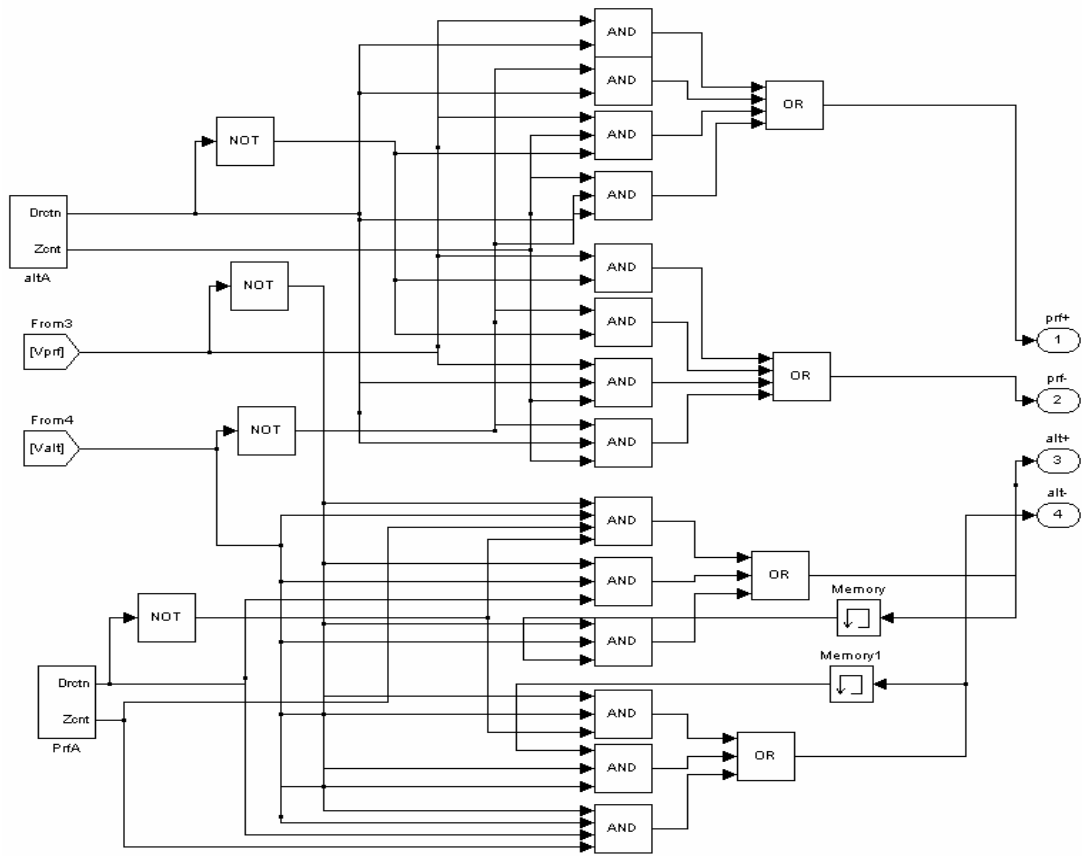
Alt+: The gating pulse for the positive direction of alternate source thyristors.

Alt-: The gating pulse for the negative direction of alternate source thyristors.

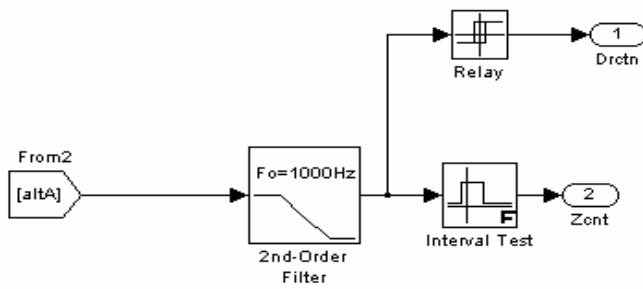
In each phase has its own transfer process and transfer time so for each phase this truth table is implemented. Figure 5.9(a) shows the transfer logic for phase A.

Table 5.1 Truth table of transfer and gating process

Min NO	Prf	Alt	Drct	*Alt	Zct	Prf+	Prf-	Alt+	Alt-
0	0	0	0	0	0	0	1	0	0
1	0	0	0	0	1	1	1	0	0
2	0	0	0	1	0	0	1	0	0
3	0	0	0	1	1	1	1	0	0
4	0	0	1	0	0	1	0	0	0
5	0	0	1	0	1	1	1	0	0
6	0	0	1	1	0	1	0	0	0
7	0	0	1	1	1	1	1	0	0
8	0	1	0	0	0	0	0	0	1
9	0	1	0	0	1	0	0	1	1
10	0	1	0	1	0	0	0	1	1
11	0	1	0	1	1	0	0	1	1
12	0	1	1	0	0	0	0	1	0
13	0	1	1	0	1	0	0	1	1
14	0	1	1	1	0	0	0	1	1
15	0	1	1	1	1	0	0	1	1
16	1	0	0	0	0	0	1	0	0
17	1	0	0	0	1	1	1	0	0
18	1	0	0	1	0	0	1	0	0
19	1	0	0	1	1	1	1	0	0
20	1	0	1	0	0	1	0	0	0
21	1	0	1	0	1	1	1	0	0
22	1	0	1	1	0	1	0	0	0
23	1	0	1	1	1	1	1	0	0
24	1	1	0	0	0	0	1	0	0
25	1	1	0	0	1	1	1	0	0
26	1	1	0	1	0	0	1	0	0
27	1	1	0	1	1	1	1	0	0
28	1	1	1	0	0	1	0	0	0
29	1	1	1	0	1	1	1	0	0
30	1	1	1	1	0	1	0	0	0
31	1	1	1	1	1	1	1	0	0



(a)



(b)

Figure 5.9 (a) Transfer logic for phase A, (b) direction and zero current detection for preferred source phase A.

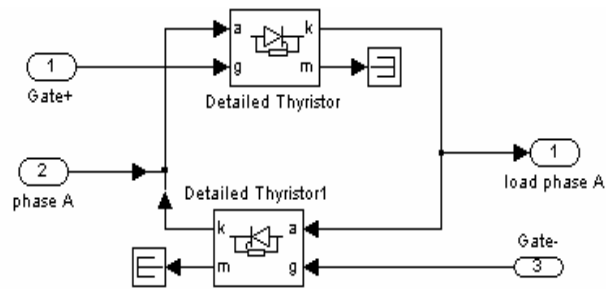


Figure 5.10 Preferred source Phase A Thyristor switches.

If any unsymmetrical fault occurs, the resulting voltage sag is unbalanced and contains both positive sequence and negative sequence component. The synchronous frame voltages V_{d_p} and V_{q_p} then have DC components and ripples. If the ripples have oscillations at the reference level, it causes switchings between preferred source and alternate source. For preventing these oscillations, hysteresis comparator (Relay) is used. (Figure 5.11) The relay block allows its output to switch between two specified values. When the error signal is bigger than the first tolerance value ($10\% V_{ref}$) the output of relay is '0'. If the error signal is less than the second tolerance value ($0.02\% V_{ref}$) the output of the relay is '1'.

When the voltage on the preferred source returns to acceptable values, load is transferred back to the preferred source after a time delay (10 cycles) to ensure that preferred source phase voltages are perfectly restored. A logic circuit is designed for this purpose. Table 2 shows truth table of counter logic. Figure 5.11 shows the counter logic. The counter is only enabled when the relay output is changed from '0' to '1'. If the enable signal of the counter is set ('1'), counter starts counting 10 cycles of 50 Hz pulses in order to get 200 ms time delay. If enable signal is removed ('0'), either counter is counting or not, counter resets.

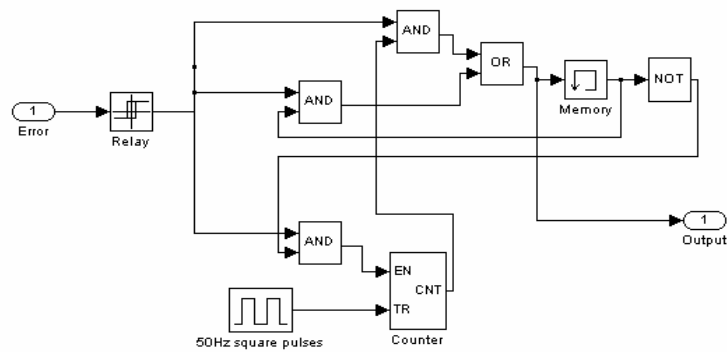


Figure 5.11 Counter logic

Table 5.2 Truth table of counter logic.

Min NO	Present value of Error	Past value of Error	Output of counter	Enable of counter	Output
0	0	0	0	0	0
1	0	0	1	0	0
2	0	1	0	0	0
3	0	1	1	0	0
4	1	0	0	1	0
5	1	0	1	1	1
6	1	1	0	0	1
7	1	1	1	0	1

5.4. Simulation Results

Figures 5.12-5.40 show simulated performance of STS system. The simulations are performed using MATLAB/Simulink. Voltage sags are created by reducing the amplitude of the preferred source voltage. Faults are created at the preferred source terminals. Definitions of detection, transfer and total load-transfer times are as follows:

Detection time: The difference between the time at which a disturbance occurs and the time it is detected.

Transfer time: The difference between the time at which a disturbance is detected and the time at which the last faulty phase is transferred.

Total load-transfer time: The sum of detection time and transfer time [Sannino,2001].

The parameters of the STS simulation are as follows:

Preferred and alternate source systems:

12 kV, 50 Hz

$$R_p = R_a = 0.015 \Omega, X_p = X_a = 3.6 \Omega$$

Transmission line :

12 kV/115kV, 250MVA, 50 Hz Δ/Y step up transformer

Line impedances $0.05 \Omega + j0.4806 H$

115 kV/12kV, 250MVA, 50 Hz Y/Δ step down transformer

Three-phase Δ/Y load transformer

12 kV/380 V, 1 MVA, 50 Hz

Each pair of thyristor valves has a snubber circuit composed of $R = 1 M \Omega$ and $C = 0.001 \mu F$

Load system is composed of a three-phase RL load .The series RL load has the following parameters:

$$R_l = 0.402 \Omega, X_l = 0.225 \Omega$$

Control circuit parameters:

$$V_{ref} = 16.97 \text{ kV}$$

Voltage-change tolerance limit $E_{tot} = 10\% V_{ref}$

Filter cut-off frequency $f_c = 50 \text{ Hz}$

Line current smoothing filter cut-off frequency = 1 kHz

Zero-current threshold limit $i_{zth} = 0.4 \text{ A}$

Thyristor turn-off time = 1 ms [6].

5.4.1. Three Phase Balanced Fault

Figure 5.12 shows the 30% three phase balanced preferred source voltage sag. The fault occurs at $t_1 = 0.107 \text{ s}$ and detected at $t_2 = 0.109 \text{ s}$. Figure 5.13 shows the alternative source voltage and Figure 5.14 shows the load voltage. The simulation has duration of 0.5s. The transitions can be observed on the figure. Figure 5.15 shows the transition of preferred source to alternate source.

The fault has a detection time 2ms. For phase A, phase B, phase C, transfer time is 1 ms, so total transfer time is 3 ms. The maximum transfer time is also 3ms.

Figure 5.16 shows the transition back to preferred source from alternate source. The fault is cleared at 0.2 s and the system delays 10 cycles in order to transfer back to preferred source. There is no need to consider the detection time. For phase A, the transfer time is 2 ms, for phase B and C the transfer time is 5 ms. The maximum transfer time is 5 ms.

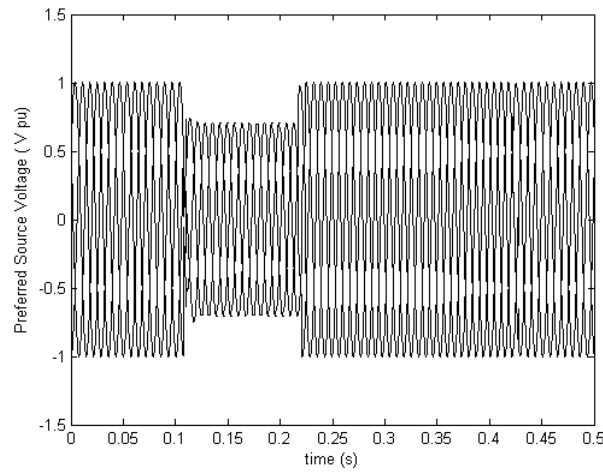


Figure 5.12 Preferred source voltage

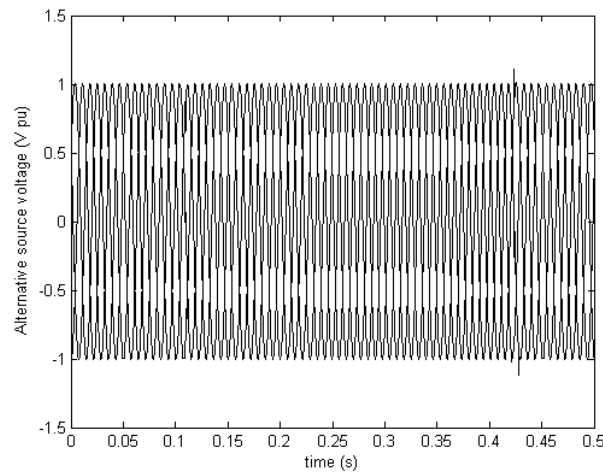


Figure 5.13 Alternative source voltage

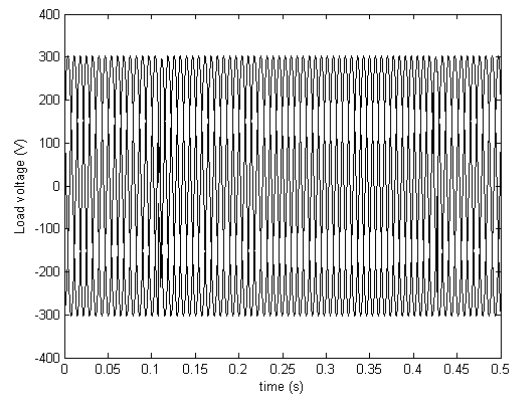


Figure 5.14 Load voltage

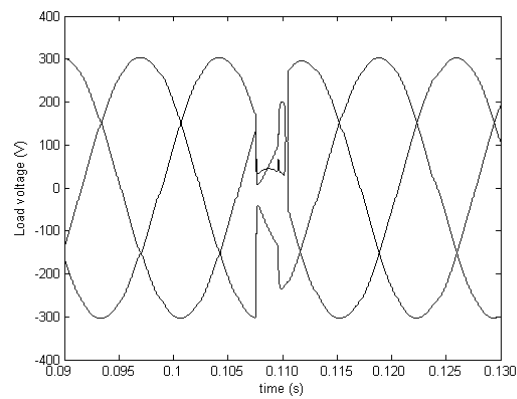


Figure 5.15 Preferred to alternative source transition for voltage during fault

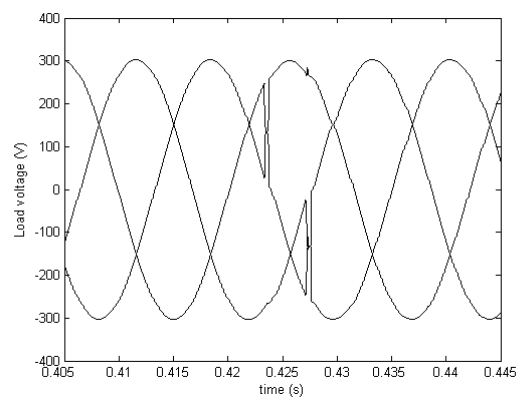


Figure 5.16 Alternative source to preferred source transition for voltage 10 cycles after the fault is cleared

Figures 5.17, 5.18 and 5.19 show preferred source currents, alternative source currents and load currents respectively. Load current is measured from low voltage side. It is seen that load is feed from only one of the sources, there isn't any source paralleling and there isn't any cross currents. Figure 5.20 shows preferred to alternative source transition for current during fault and Figure 5.21 shows alternate source to preferred source transition for current 10 cycles after the fault is cleared. It is seen that the load current is transferred effectively.

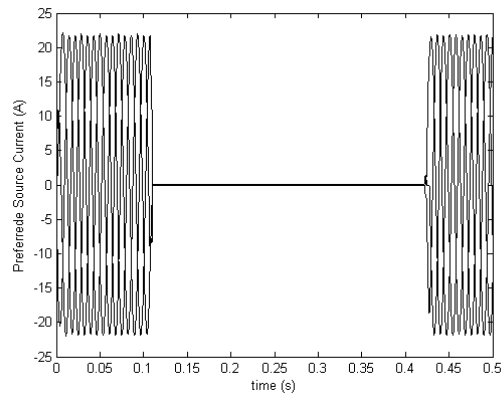


Figure 5.17 Preferred Source Current

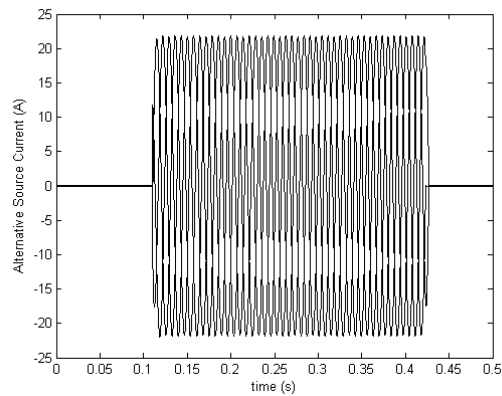


Figure 5.18 Alternative Source Current

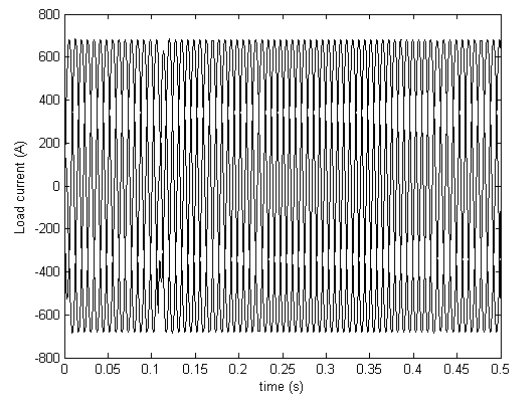


Figure 5.19 Load Current

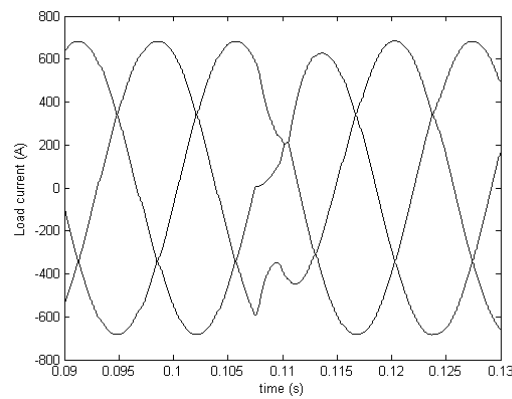


Figure 5.20 Preferred to Alternative source transition for current during fault

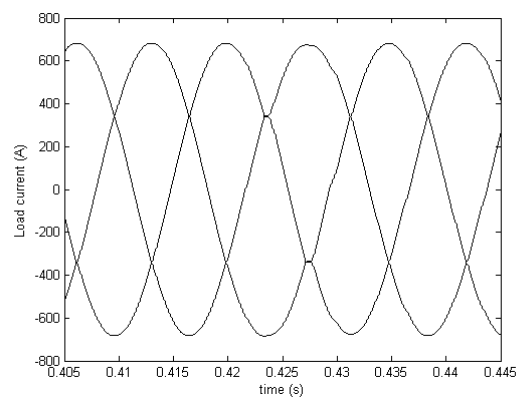


Figure 5.21 Alternative source to preferred source transition for current 10 cycles after the fault is cleared

5.4.2. Three Phase Unbalanced Fault

Figure 5.22 shows the unbalanced voltage sag at preferred source voltage. Figures 5.23 and 5.24 show the alternative source voltage and load voltage respectively. The simulation has duration of 0.5 s. Figure 5. 25 shows the transition of preferred source to alternate source. The fault has a detection time 2 ms. For phase A, phase B, phase C transfer time is 1ms, so total transfer time is 3ms. The maximum transfer time is also 3ms. Figure 5.26 shows the transition of back to preferred source from alternate source 10 cycles after the fault is cleared.

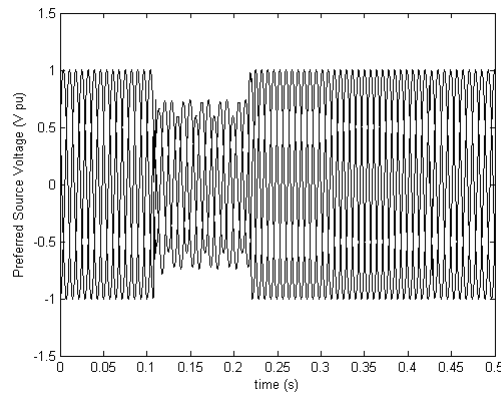


Figure 5.22 Preferred source voltage

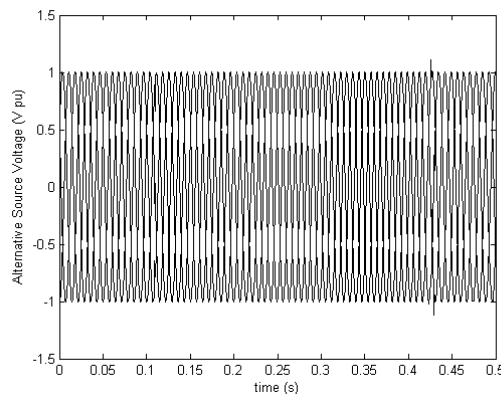


Figure 5.23 Alternative source voltage

The fault is cleared at 0.2 s and the system delays 10 cycles in order to transfer back to preferred source. For phase A, the transfer time is 2ms, for phase B and phase C the transfer time is 5 ms. The maximum time is considered as the transfer time so the maximum transfer time is 5ms.

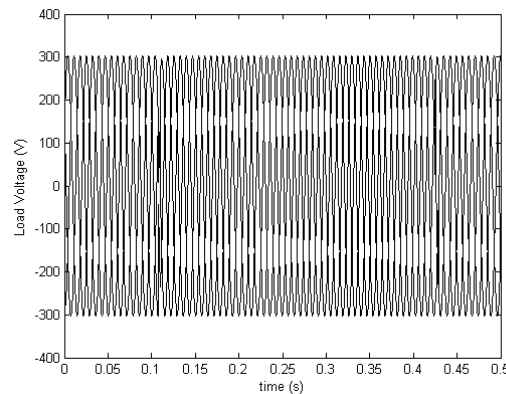


Figure 5.24 Load Voltage

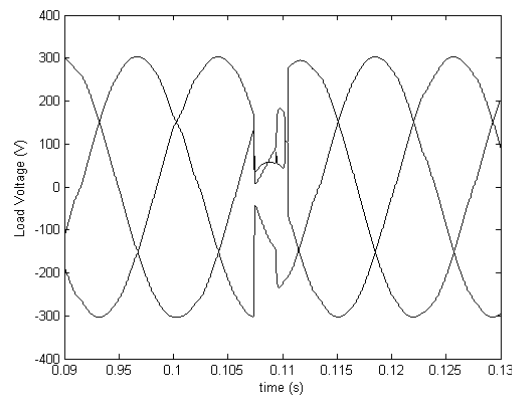


Figure 5.25 Preferred to alternative source transition for voltage during fault

Figures 5.27, 5.28 and 5.29 show preferred source currents, alternative source currents and load currents respectively. Load current is measured from low voltage side. It is seen that load is feed from only one of the sources, there isn't any source paralleling and there isn't any cross currents. Figure 5.30 shows preferred to alternative source transition for current during fault and Figure 5.31 shows alternate

source to preferred source transition for current 10 cycles after the fault is cleared. It is seen that the load current is transferred effectively.

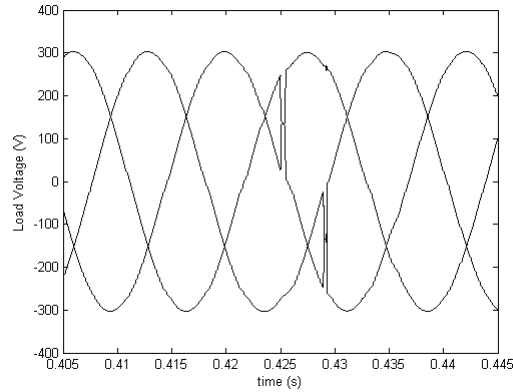


Figure 5.26 Alternative source to preferred source transition for voltage 10 cycles after the fault is cleared

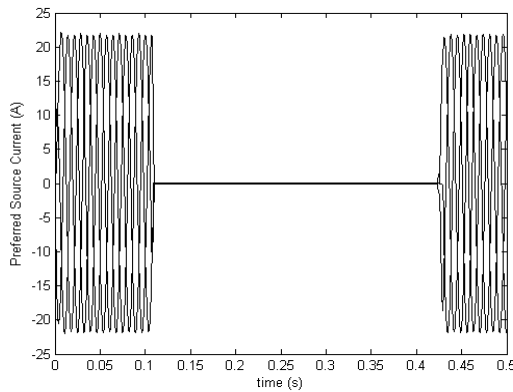


Figure 5.27 Preferred Source Current

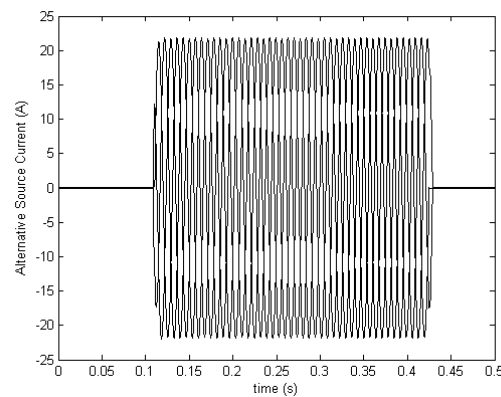


Figure 5.28 Alternative Source Current

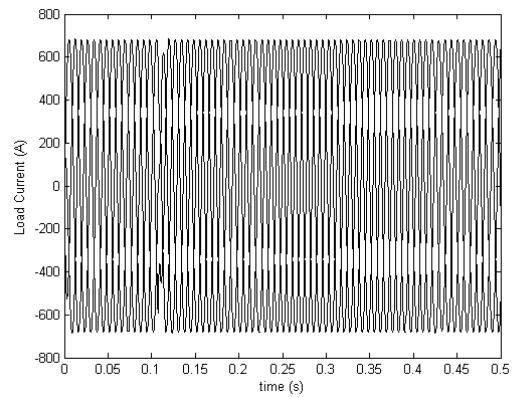


Figure 5.29 Load Current

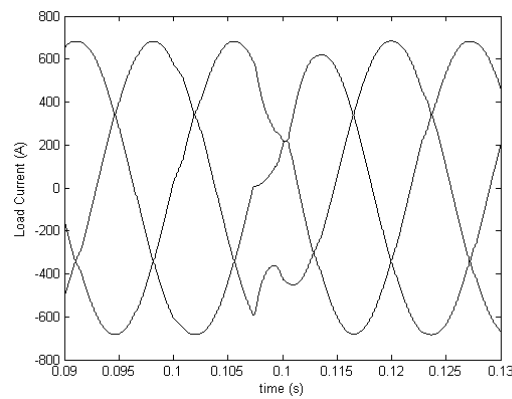


Figure 5.30 Preferred to alternative source transition for current during fault

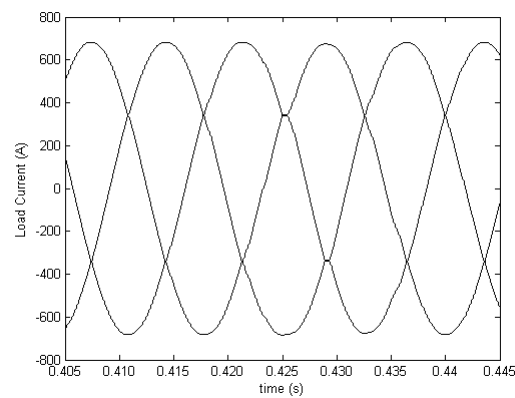


Figure 5.31 Alternative source to preferred source transition for current 10 cycles after the fault is cleared

5.4.3. Single Phase to Ground Fault

In this case only phase A is switched at the fault. Figure 5.32 shows the preferred source voltage (sag). Figure 5.33 and 5.34 show the alternative source voltage and load voltage respectively. The simulation has a duration of 0.5s. Figure 5.35 shows the transition of preferred source to alternate source. The fault has a detection time of 6ms. For phase A, phase B, phase C transfer time is 1ms, so total transfer time is 7ms. The maximum transfer time is also 7 ms. Figure 5.36 shows the transition of back to preferred source from alternate source.

The fault is cleared at 0.2 s and the system delays 10 cycles in order to transfer back to preferred source. For phase A, the transfer time is 2 ms, for phase B and phase C the transfer time is 6 ms. The maximum time is considered as the transfer time so the maximum transfer time is 6 ms.

Figures 5.37, 5.38 and 5.39 show preferred source currents, alternative source currents and load currents respectively. Load current is measured from low voltage side. It is seen that load is feed from only one of the sources, there isn't any source paralleling and there isn't any cross currents. Figure 5.40 shows preferred to alternative source transition for current during fault and Figure 5.41 shows alternate source to preferred source transition for current 10 cycles after the fault is cleared. It is seen that the load current is transferred effectively.

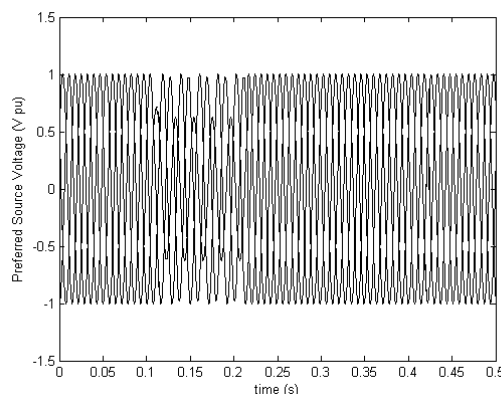


Figure 5.32 Preferred source voltage

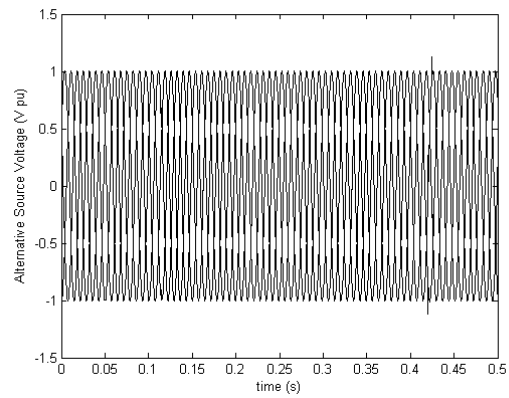


Figure 5.33 Alternative source voltage

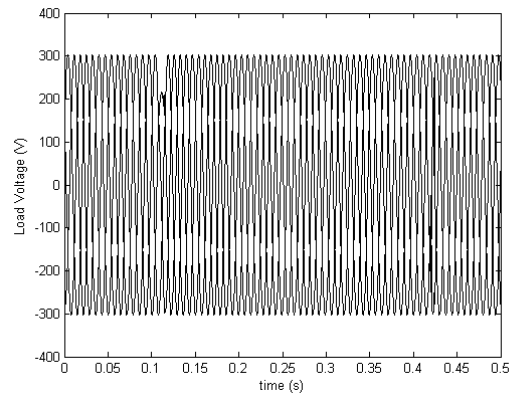


Figure 5.34 Load Voltage

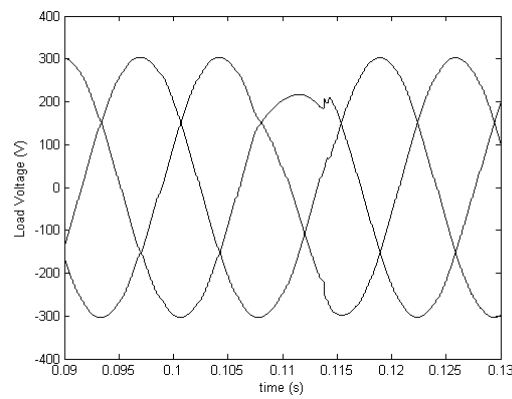


Figure 5.35 Preferred to alternative source transition for voltage during fault

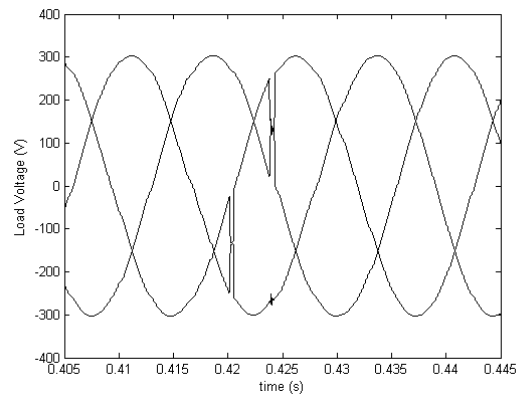


Figure 5.36 Alternative source to preferred source transition for voltage 10 cycles after the fault is cleared

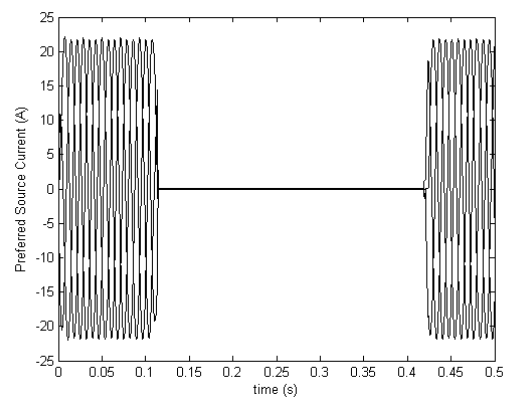


Figure 5.37 Preferred Source Current

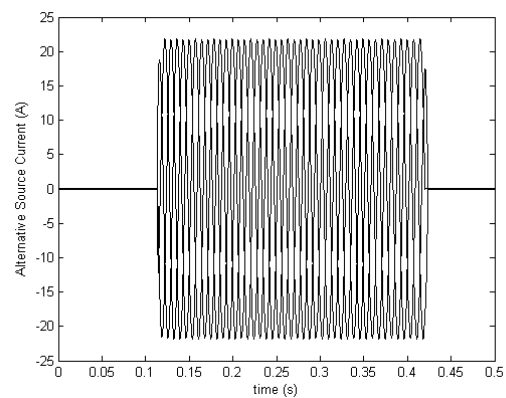


Figure 5.38 Alternative source Current

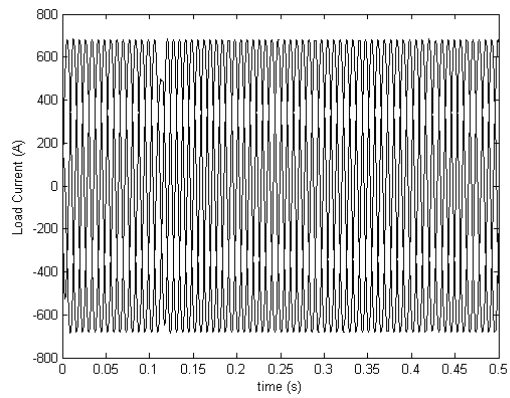


Figure 5.39 Load Current

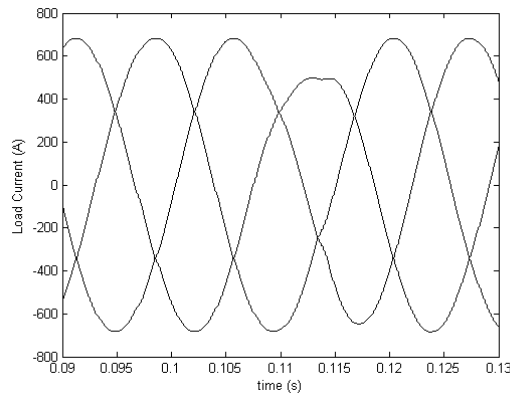


Figure 5.40 Preferred to alternative source transition for current during fault

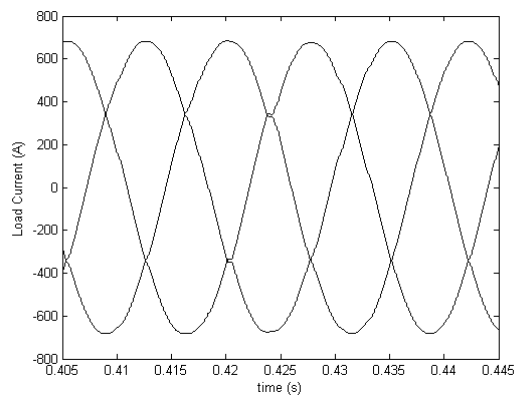


Figure 5.41 Alternative source to preferred source transition for current 10 cycles after the fault is cleared.

6. MODELING OF DYNAMIC VOLTAGE RESTORER

6.1. Introduction

'Reliability' is a key word for utilities and their customers in general, and it is crucial to companies operating in a highly competitive business environment, because it affects profitability, which definitely is a driving force in the industry. Although electrical transmission and distribution systems have reached a very high level of reliability, disturbances can not be totally avoided. Any disturbances to voltage waveform can cause problems related with the operation of electrical and electronic devices. Users need constant sine wave shape, constant frequency and symmetrical voltage with a constant rms value to continue the production. This increasing interest to improve efficiency and eliminate variations in the industry has resulted more complex instruments sensitive to voltage disturbances such as voltage sag, voltage swell, interruption, phase shift and harmonic. Voltage sag is considered the most severe since the sensitive loads are very susceptible to temporary changes in the voltage. In some cases, these disturbances can lead to a complete shutdown of an entire production line, in particular at high-tech industries like semiconductor plants, with severe economic consequences to the affected enterprise[Nguyen et al., 2004], [Daehler et al., 2000].

The DVR is a power quality device, which can protect these industries against the bulk of these disturbances, i.e. voltage sags and swells related to remote system faults. A DVR compensates for these voltage excursions, provided that the supply grid does not get disconnected entirely through breaker trips[Daehler et al., 2000].

Modern pulse-width modulated (PWM) inverters capable of generating accurate high quality voltage waveforms form the power electronic heart of the new Custom Power devices like DVR. Because the performance of the overall control system largely depends on the quality of the applied control strategy, a high-performance controller with fast transient response and good steady state characteristics is required.

The main considerations for the control system of a DVR include: sag detection, voltage reference generation and transient and steady-state control of the injected voltage.

Monitoring of $\sqrt{V_d^2 + V_q^2}$ or V_d in a vector controller is the simplest type of sag detection, which will return the state of supply at any instant in time and hence, detect whether or not a sag has occurred [Fitzer et al., 2004]. To separate the positive and negative sequence components, LPF (Low Pass Filter)s are used after the d-q transformation. For effective removal, the cut off frequency of the filter must be reduced, but has the side effect of reducing controller response. The sag detection method in this chapter passes the positive and negative sequence components through a differentiator. The resulting values are then crisscrossed with the original positive and negative signals and calculated to extract the real positive and negative sequence component signals. This improves the response time of sag detection with respect to classical LPF method [Jung et al., 2002].

On determining the reference compensation voltages, whole situation of three-phase voltages has to be considered. Typically d-q-0 transformation has been widely used in determining the reference compensation voltages [Jung et al., 2002], [Etxeberria et al., 2002], [Jurado, 2004], [Jurado et al., 2002], [Jurado et al., 2003], [Nielsen et al., 2001]. This technique does not respond fast or does not give accurate results to the instantaneous unbalanced voltage sags because the inaccuracy which is associated with the passive filters used in this technique [Elnady et al., 2005].

To control DVR systems a cascaded scheme of voltage and current feedback controller has been proposed in [Vilathgamuva et al., 2002]. However the cascaded controller has quite low control dynamics since the bandwidth of voltage control is limited by the inner current loop bandwidth. To overcome this limitation a modified control method has been tried to feedback both current and voltage signal in parallel, but its performance was not satisfactory [Lee et al., 2004].

The application of NN and FL is recently growing in power electronic systems. Recently new Fuzzy Logic methods have been applied to Custom Power Devices, especially active power filters [Vazquez et al., 2003], [Madtharad et al.,

2002], [Elmitwally et al, 2000], [Dixon et al., 1999],[Jain et al., 2002], [Aquila et al., 2002]. The operation of DVR is similar to that of active power filters in that both compensators must respond very fast on the request from abruptly changing reference signals.

The advantages of fuzzy logic controllers over conventional controllers are that they do not need an accurate mathematical model, they can work with imprecise inputs and can handle non-linearity. In basic applications, the fuzzy logic controller is used as a substitute for the conventional PI compensator. The voltage error and its derivative are the FL controller input crisp values. The reference voltages for the PWM generator are the FL controller crisp output commands. When a fuzzy controller is used, the tracking error and the transient overshoots of PWM can be considerably reduced. This is because in contrast to the conventional PI compensator, the control surface of the FL controller can be shaped to define appropriate sensitivity for each operating point [Jurado et al., 2003]. The FL controller can easily be implemented as an off-line precalculated three-dimensional look-up table consisting of the control surface [Dzianiakowski et al., 1995].

Fuzzy logic control of DVR is reported only in [Jurado et al., 2003] in literature. In [Jurado et al., 2003] the fuzzy logic controller is used as a substitute for the conventional PI controller. The three-phase source voltages are transformed into d and q coordinates. The reference values for V_d and V_q are compared with these transformed values and voltage errors are obtained. These errors are processed by two FL controllers evaluating 81 linguistic rules. Resulting outputs are re-transformed into three-phase domain and compared with a carrier signal to generate Pulse Width Modulated (PWM) inverter signals. In this method there is no sag detection which means DVR is always in operation and generates compensating voltage also for small voltage drops within 10% which causes high losses and results only for balanced sags are presented.

The proposed novel control method for DVR does not include any transformations. Three-phase source voltages are directly processed by a FL controller to improve the response time of DVR. The number of rules is decreased to 49 to achieve better performance. Sag detection is also included in the model. The

proposed DVR has the capability of both balanced and unbalanced voltage sag compensation and can track changes in supply phase. In the proposed method PLL is applied to each supply phase independently. It can easily be implemented in real time and there are no current publications in this method as reported in [Fitzer et al., 2004].

In this chapter, the unbalanced voltage sags are mitigated using three single-phase DVRs. The proposed mitigating device and control algorithm presented in this chapter differ from the previously discussed approaches in the following ways:

1. The proposed mitigating device is a multifunction device since it can mitigate all types of voltage sags, voltage unbalance and can track supply phase changes.
2. There is no transformation in voltage compensation control and each phase is controlled independently.
3. The tracking and extraction of disturbances are fast and accurate. Passive filters are avoided in sag detection and fuzzy logic adds flexibility to the voltage compensation controls.

This chapter presents a novel approach of adding functionalities to the DVR to increase its usability in the normal operation of the system as well as in the transient time to mitigate the voltage disturbances. These proposed functionalities will make the proposed DVR superior and more beneficial with respect to previously designed ones.

6.2. DVR Power Circuit and Operation Principles

The power circuit of the DVR can be divided into four parts shown in Figure 6.1: A- Series converter; B- filter circuit; C- three single-phase injection transformers; and D-energy storage and power converter.

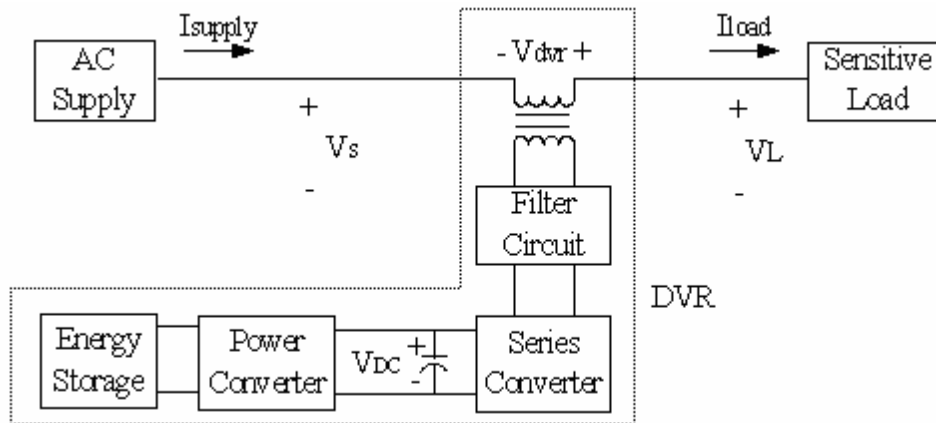


Figure 6.1 Main configuration of DVR

6.2.1. VSI

Three single phase H-bridge PWM inverters are used in the series converter circuit as shown in Figure 6.2. VSI inverter rating is relatively low in voltage and high in current due to the use of step-up injection transformers.

6.2.2. Filter Circuit

The filtering scheme in a DVR can be placed either on the high-voltage side or the inverter side of the series injection transformer. The advantage of the inverter-side filter is that it is on the low-voltage side of the series transformer and is close to the harmonic source. The filtering scheme considered in this chapter pertains to that appearing on the inverter-side. Using this scheme, the high order harmonic currents are prevented from penetrating into the series transformer, thus reducing the voltage stress on the transformer.

6.2.3. Injection Transformers

Generally distribution systems use a three-phase three-wire topology or a three-phase four-wire topology. In the U.K a common arrangement is where a Δ -Y transformer winding connection is used to step down the voltage level. This winding

arrangement prevents zero sequence components from propagating to the secondary side of the transformer when an unbalanced fault occurs on the primary side network. However, in some countries, such as China, Korea and Turkey there are extensive three-phase four wire systems, which use a Y-Y winding with the neutrals grounded. This transformer connection allows propagation of zero sequence components to the loads when an unbalanced fault takes place. Therefore a control algorithm and circuit configuration is required to control the positive, negative and zero sequence voltages injected during the unbalanced fault period [Zhan et al., 2003].

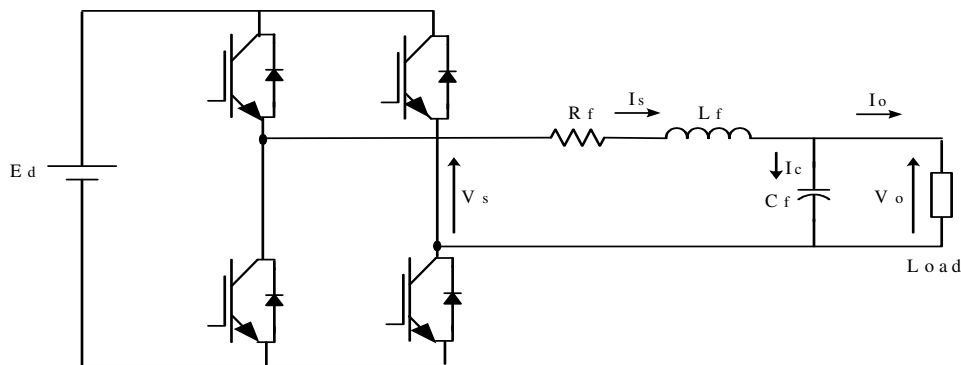


Figure 6.2 VSI and filter circuit

The three single-phase injection transformers are connected to the output of filter unit. H-bridge single-phase inverters and single phase injection transformers allows the injection of positive, negative and zero-sequence voltages.

For a 0.5 pu single-phase sag compensation, the DVR connection transformers turns ratio is set to 110:68 when the average dc voltage of battery units is around 100 V. The leakage inductance in each single transformer was designed to be 0.01 pu in order to reduce the voltage drop it produces. Moreover to avoid saturation under all conditions, the injection transformer must be sized to handle at least twice the normal steady-state flux requirement at maximum rms injection voltage without saturation.

6.2.4. Energy Storage and DC Converter

A regulated constant DC supply is employed as energy storage and DC converter unit and details are not emphasized in this report.

The Matlab / Simulink model of proposed DVR is shown in Figure 6.3. Three single-phase full bridge PWM inverters consisting of IGBT switches are used to produce compensating voltages. The inverter side filters eliminate PWM inverter harmonics. The three phase adjacent parallel loads create balanced or unbalanced fault at desired time and size. Maximum single-phase injection capability is %50 of nominal value.

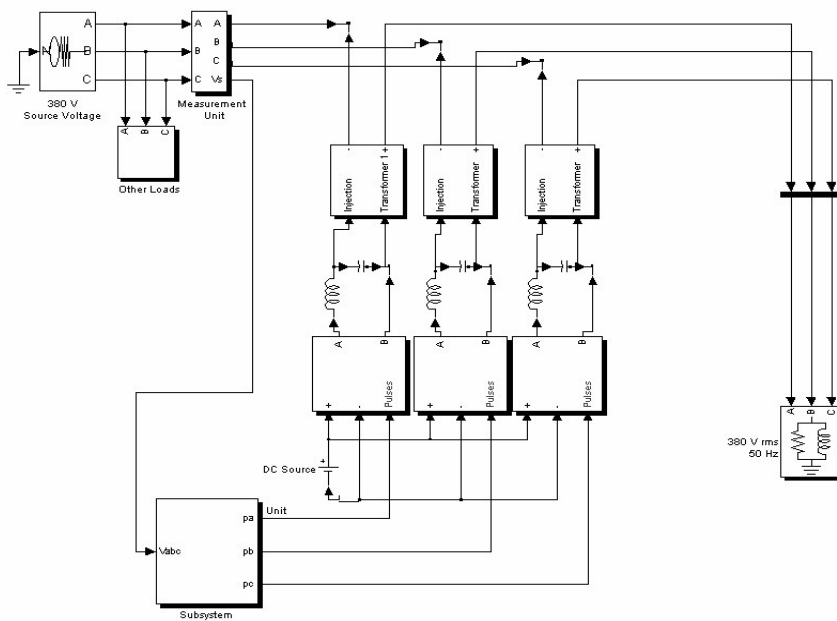


Figure 6.3 Matlab / Simulink model of proposed DVR.

6.3. Proposed DVR Controls

The control scheme of a DVR is composed of two main blocks: the sag detection block and the compensation strategy block. It is not enough to detect the disturbance, it is also necessary to identify the disturbance in order to correct it by injecting the exact amount of energy required. Once the disturbance has been

identified, there may exist many different compensation possibilities depending on the characteristics of the load and the identification method that has been used. In some cases it may only be necessary to restore the amplitude of the voltage and in other cases the phase must also be restored. The choice of compensation strategy has an important influence on the injected voltage and energy, and consequently on the energy storage capacity and the inverter rating of DVR [Etxeberria et al., 2002].

6.3.1. Sag Detection

An essential part of the control of DVR is the sag detection circuit. A voltage sag must be detected fast and corrected with a minimum of false operations.

Quick sag detection is important. A pre-fault phase-locked-loop (PLL) output can be used to regulate the load voltage. In the case of fault, the PLL output is frozen to the pre-fault value and feeds to the controller. In this application, a fast response of freezing the PLL output against the fault is very important. But the freezing process is usually delayed by a fault detection circuit and the delay affects the control dynamics worse. Another important consideration in this application is the resynchronization of the PLL output to the grid when the fault is cleared [Lee et al., 2004]. In the proposed DVR sag detection block provides the resynchronization to the supply after the sag is cleared, by unfreezing the PLL.

When there is a disturbance within the distribution system, the three phase voltage generally becomes unbalanced, resulting in both positive and negative sequence components existing in the distribution system. To remove the steady state phase lag, the positive and negative sequence components need to be detected as a DC component and controlled. To separate the positive and negative sequence components, low pass filters are used after the d-q transformation. To separate only the negative sequence components the large positive sequence components with 120 Hz that exist in the d-q transformed negative sequence components must be removed. For effective removal, the cut-off frequency of the filter must be reduced, but has the side effect of reducing the controller response time. This chapter presents a method that ensures the stability and precision of control by passing the positive and negative

sequence components. The resulting values are then crisscrossed with the original positive and negative signals and calculated to extract the real positive and negative sequence component signals [Jung et al., 2002].

In the proposed sag detection method the source side terminal voltages V_a, V_b, V_c are transformed into d-q values of positive sequence SRF (Synchronous Reference Frame) as shown in (6.1), (6.2) and (6.3).

$$C = \begin{pmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{pmatrix} \text{ and } R(\omega t) = \begin{pmatrix} \cos(\omega t) & -\sin(\omega t) \\ \sin(\omega t) & \cos(\omega t) \end{pmatrix} \quad (6.1)$$

$$\begin{pmatrix} V_{d(p)} \\ V_{q(p)} \end{pmatrix} = 2/3 * R(\omega t) * C * \begin{pmatrix} V_a \\ V_b \\ V_c \end{pmatrix} \quad (6.2)$$

$$V_0 = 1/3(V_a + V_b + V_c) \quad (6.3)$$

$R(\omega t)$ is a matrix that rotates by phase angle ωt . The subscript (p) represents that this is the value in positive sequence SRF. The subscript d and q represent d-axis and q-axis values in SRF respectively. The subscript p and n shows that this is the value of positive and negative sequence components at $t=0$. Thus this vector is a constant value. Since the positive sequence rotates counterclockwise and the negative sequence rotates clockwise direction in the stationary reference frame, when they are shown in positive sequence SRF the positive sequence becomes a DC component and the negative sequence a 120 Hz component as expressed in (6.4) For the symmetrical balanced faults, there is no need to extract the positive and negative sequence SRF. Using only d component is sufficient for control of DVR. The d component is a DC value for symmetrical balanced faults. Unbalanced voltage sag causes negative sequence components to appear in the source voltage. For effective control without phase shift in steady state, the positive and negative sequence components that have DC values should be separated. In order to achieve this the

differential controller method is used. Fig. 4 shows the Matlab / Simulink model for sag detection block.

Equation (6.2) is composed of both of positive and negative sequence components. This is expressed as equation (6.4).

$$\begin{pmatrix} V_{d(p)} \\ V_{q(p)} \end{pmatrix} = \begin{pmatrix} V_{dp} \\ V_{qp} \end{pmatrix} + R(-2\omega t) \begin{pmatrix} V_{dn} \\ V_{qn} \end{pmatrix} \quad (6.4)$$

(6.5) shows equation (6.4) differentiated in time domain

$$\begin{pmatrix} \dot{V}_{d(p)} \\ \dot{V}_{q(p)} \end{pmatrix} = -2\omega R\left(\frac{\pi}{2}\right) R(-2\omega t) \begin{pmatrix} V_{dn} \\ V_{qn} \end{pmatrix} \quad (6.5)$$

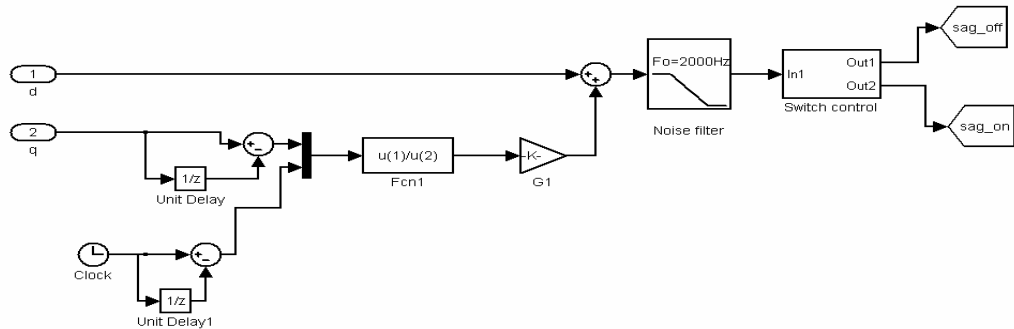


Figure 6.4 Matlab/Simulink Model for sag detection

The differential of $R(-2\omega t)$ becomes $-2\omega R(\pi/2)R(-2\omega t)$ and the differential of the positive sequence is zero since it is constant. (6.5) is rotated by 90° and divided by -2ω , as follows

$$-\frac{1}{2\omega} R\left(\frac{\pi}{2}\right) \begin{pmatrix} \dot{V}_{d(p)} \\ \dot{V}_{q(p)} \end{pmatrix} = R(\pi) R(-2\omega t) \begin{pmatrix} V_{dn} \\ V_{qn} \end{pmatrix} \quad (6.6)$$

Since the sum of a vector and the same vector phase shifted by 180° becomes zero, the sum of (6.2) and (6.6) leaves an only positive sequence component that is a DC component and all negative sequence components are removed.

$$\begin{pmatrix} V_{d(p)} \\ V_{q(p)} \end{pmatrix} - \frac{1}{2w} R\left(\frac{\pi}{2}\right) \begin{pmatrix} \dot{V}_{d(p)} \\ \dot{V}_{q(p)} \end{pmatrix} = \begin{pmatrix} V_{dp} \\ V_{qp} \end{pmatrix} \quad (6.7)$$

(6.7) shows that positive sequence components can be detected without using LPFs, so the stability and accuracy of control can be obtained. With the same method, the DC negative sequence components can be calculated with the following equation.

$$\begin{pmatrix} V_{d(n)} \\ V_{q(n)} \end{pmatrix} - \frac{1}{2w} R\left(\frac{\pi}{2}\right) \begin{pmatrix} \dot{V}_{d(n)} \\ \dot{V}_{q(n)} \end{pmatrix} = \begin{pmatrix} V_{dn} \\ V_{qn} \end{pmatrix} \quad (6.8)$$

In conclusion, we can separate the positive and negative sequence components. High quality voltages only includes positive sequence d component. For an efficient sag compensation, following reference d, q components are chosen. These values are represented as V_{dpref} , V_{qpref} .

$$V_{dpref} = 1 , V_{qpref} = 0 \quad (6.9)$$

The resulting V_{dp} , V_{qp} are added and passed through a noise filter. This noise filter barely has any influence on the control system since the noise filter has a large cut-off frequency. The output of noise filter is compared with the addition of $V_{dpref} = 1$ and $V_{qpref} = 0$ which equals unity that represents an ideal signal to generate the sag detection signal. Necessary hysteresis bandwidth is introduced to let sags occur without compensation for a defined limit.

When the sag is detected, the PLL output is frozen to the pre-fault value and feeds to the controller. The sag detection block provides the resynchronization to the supply after the sag is cleared by unfreezing the PLL.

When the supply voltage is between 0.9 pu and 1.1 pu of nominal voltage in accordance with EN 50160 the power system is considered to be in an acceptable operating mode, i.e. experiencing neither a sag nor swell. These are phase voltages, since the response of single phase loads need to be considered. Loads are assumed to be able to operate indefinitely if the supply voltage remains within this envelope, and so the DVR is set to 'stand-by' mode in this region. During stand-by mode operation, the bottom switch of each inverter leg is switched on to provide a short-circuit path for the current at the inverter side of the injection transformer. The injection transformer is always in the energized state carrying current. A very fast response to voltage injection can thus be achieved during a sag, since there is no waiting time associated with building current in the transformer leakage inductance [Ramachandaramurthy et al., 2004].

6.3.2. Reference Voltage Compensation

The block diagram of reference voltage compensation block of proposed DVR controller is shown in Figure 6.5. In the proposed method PLL is applied to each supply phase independently. The PLL for each phase tracks the phase of network voltage phasor and generates a reference signal with magnitude of unity locked to supply frequency for each phase. The supply voltage for each phase is converted to per unit and error is obtained from the difference of reference PLL generated signal and actual supply voltage converted to per unit. Error and error rate are the inputs for the fuzzy logic controller. Output of the fuzzy logic controller is fed to the PWM generator to produce switching pulses for the voltage source inverter. This method can easily be implemented in real time and there are no current publications in this method as mentioned in [Fitzer et al., 2004].

A software PLL is used to create sinusoidal load voltage references. The desired response from DVR PLL system is quite different from other applications.

This is because the phase of the supply voltage prior to the sag is generally preferred, and if the PLL reacts too quickly to changes in the phase during a sag, the post-sag phase may be used. Therefore, the DVR would not be able to compensate for the phase jump. Conventionally, once a sag is detected, the target phase of the voltage reference is fixed to the pre-sag phase to ensure that if the reference is faithfully tracked, then the load voltage phase will remain unaffected [Nielsen et al., 2004]. This method is known as a pre-fault method because it permits to restore the load voltage to the voltage and phase conditions (both) previous to the disturbance (even in the case of positive network phase voltage is modified by a sag with a phase jump.)

The characteristic of the protected load determine the identification method and the compensation strategy chosen for the DVR. The main parameter for this choice is the sensitivity of load to phase jumps. The most sensitive loads from the point of view of phase jumps are the systems that use the supply voltage phase for their operation, such as thyristor based systems. A phase angle jump can provoke erroneous firing of the thyristor and therefore a mismatch between the desired output voltage and the real output voltage. If phase jumps can provoke the erroneous operation of the load, the DVR will have to be able to keep the pre-fault phase of the load voltage at any case. Therefore, a pre-fault identification method must be used [Etxeberria et al., 2002].

The proposed DVR can compensate positive sequence, negative sequence and zero sequence components and this is verified with different case studies.

Direct feed-forward-type control model is preferred in the proposed controller. To maximize dynamic performance direct feed-forward-type control architecture should be applied in the control concept of DVR. With this concept a fast response time (approximately 1 ms) can be achieved to compensate voltage sags [Daehler et a., 2000].

The core of this controller is the phase-locked-loop (PLL). The difference between the supply and the reference vector for each phase produces an injected voltage vector that can be used by the final part of the DVR controller to produce the pulse patterns that are used to control the inverter. This type of control is commonly

known as space-vector pulse width modulation (SVPWM)[Zhan et al., 2003],[Zhan et al., 2001].

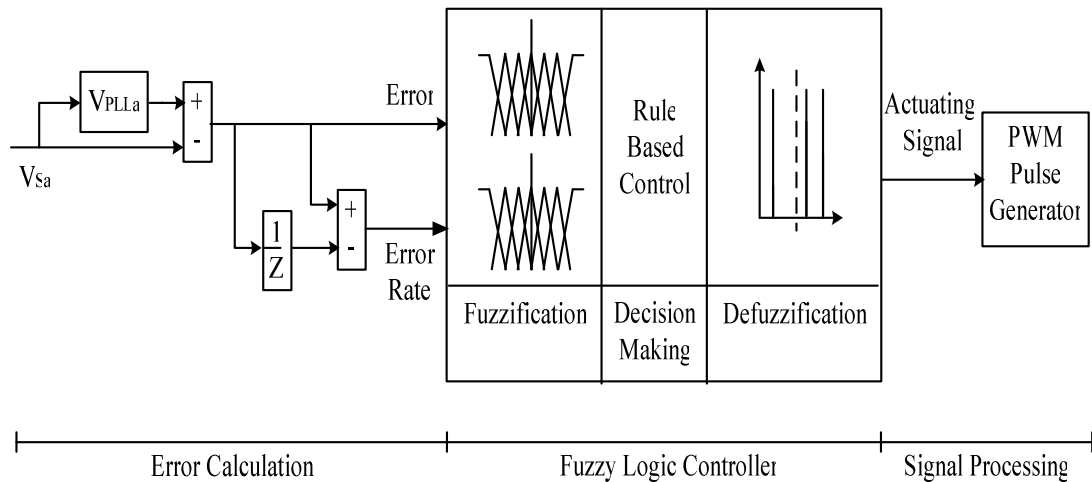


Figure.6.5 The block diagram of reference voltage compensation block of proposed DVR controller

A DVR utilizing vector control can also protect downstream loads from any phase shift that may occur, which results in a DVR system that can protect downstream loads from all types of sags, provided the sag depth is not beyond the capacity of the DVR. The PLL is applied to each supply phase independently and is tuned to respond to phase jumps in the supply quickly.

Here a continuous tracking strategy using SPLL is used. Through a suitable choice of the time constant of the SPLL block, the DVR restores the instantaneous voltage waveform in the sensitive load side to the same phase and magnitude as the initial presag voltage.

With the supply voltage in its normal level the DVR is held in a null state to keep the losses to a minimum. Once a voltage sag is detected the DVR converts into active mode to react as fast as possible and inject the required ac voltage to the grid.

6.3.3. Fuzzy Logic Controller and PWM Generator

In fuzzy logic modeling, the operator's experience, defining the input and output variables of the system and understanding how these variables are processed

by control mechanism has more influence than mathematical modeling of the system.

The following advantages make FL superior to other conventional methods:

- Reliable and fast response
- High voltage accuracy and low distortion of output
- Robustness for nonlinear load conditions, sudden load changes and system parameter variations
- Less rule and data storage than traditional controllers
- Excellent control of nonlinear systems that would be difficult or impossible to model mathematically.

The fuzzy logic controller for the proposed DVR has two real time inputs measured at every sampling time, named error and error rate and one output named actuating-signal for each of the phases. The input signals are fuzzified and represented in fuzzy set notations by membership functions. The defined ‘if ... then ...’ rules produce the linguistic variables and these variables are defuzzified into control signals for comparison with a carrier signal to generate PWM inverter gating pulses.

The measured source voltages V_a , V_b , and V_c are converted into per unit values. The error is calculated from the difference between source voltage data and the Phase Locked Loop (PLL) data for each phase as shown in Figure 6.5. The error rate is the rate of change of error. For phase A, the error and error rate are defined as,

$$err_A = V_{PLL_A} - V_{S_A} \quad (6.10)$$

$$\Delta err_A = err_A(n) - err_A(n-1) \quad (6.11)$$

Fuzzy logic control involves three steps: fuzzification, decision-making and defuzzification. Fuzzification transforms the non-fuzzy (numeric) input variable measurements into the fuzzy set (linguistic) variable that is a clearly defined boundary. In the proposed controller, the error and error rate are defined by linguistic variables such as large negative (LN), medium negative (MN), small negative (SN),

small (S), small positive (SP), medium positive (MP) and large positive (LP) characterized by memberships. The memberships are curves that define how each point in the input space is mapped to a membership value between 0 and 1. The membership functions belonging to the other phases are identical. Membership functions for the inputs are shown in Figure 6.6.

The if-then rules define a Fuzzy Inference System (FIS) by connecting the input to the output. Fuzzy inference process is realized by one of the Mamdani or Sugeno methods. Fuzzification of inputs and applying the fuzzy operator are completely the same in both methods. The main difference is that the output membership functions of the used Sugeno-type are linear or constant. It provides higher performance, accuracy to nonlinear dynamic systems under various operating conditions. The output is defined by linguistic variables such as negative big (NB), negative medium (NM), negative small (NS), zero (Z), positive small (PS), positive medium (PM) and positive big (PB) characterized by memberships. The membership function of output variable is shown in Figure 6.7. The solution of defuzzification process results from equation (6.12)

$$U = \frac{\sum_i y_i \mu(y_i)}{\sum_i \mu(y_i)} \quad (6.12)$$

where U denotes the crisp value of the output, y_i represents the normalized controller output for the i th interval and $\mu(y_i)$ is the associated membership grade.

There are 49 rules to carry out optimum control action and each rule expresses an operating condition in the system as shown in Table 6.1. The person's experience and knowledge about the system behavior help to define the rules. The correct combinations of these rules improve the system performance. All rules are evaluated in parallel and the order of the rules is not important. The decision table for fuzzy logic control rules is shown in Table 6.1.

Table 6.1 Fuzzy decision table

		Error Rate						
		LP	MP	SP	S	SN	MN	LN
Error	LP	PB	PB	PB	PM	PM	PS	Z
	MP	PB	PB	PM	PM	PS	Z	NS
	SP	PB	PM	PM	PS	Z	NS	NM
	S	PM	PM	PS	Z	NS	NM	NM
	SN	PM	PS	Z	NS	NM	NM	NB
	MN	PS	Z	NS	NM	NM	NB	NB
	LN	Z	NS	NM	NM	NB	NB	NB

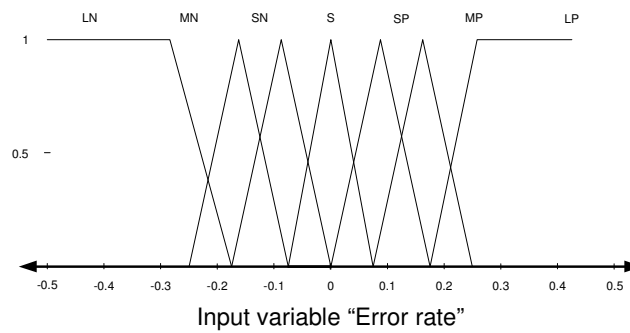
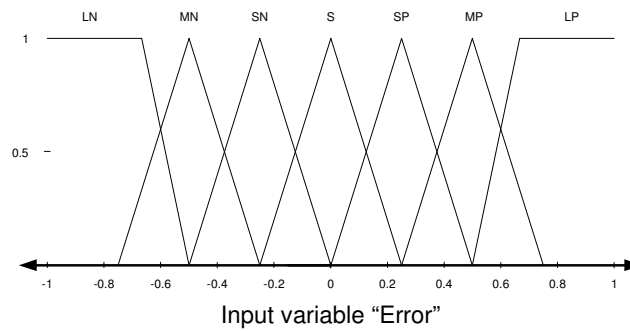


Figure 6.6 Membership functions for inputs

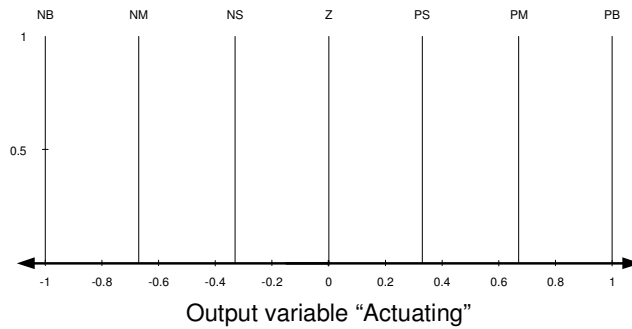


Figure 6.7 Membership function for output

The outputs of FLC process are the control signals that are used in generation of PWM inverter switching signals by comparing a carrier signal. The generation of switching signals for single phase of the system is shown in Figure 6.8 where the configuration will be the same for other phases.

The relay element gives output when the input of itself is greater than 0. The upper relay element is set to give output when the input of itself is greater than 0. The output of lower relay is the complement of upper one. The output of the fuzzy controller is set to take values between -1 to 1. The carrier signal is set to take values between -0,9 to 0,9 with a frequency of 2 KHz.

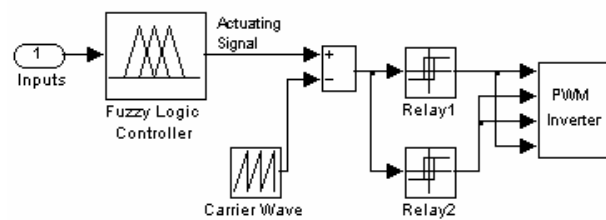


Figure 6.8 Generation of PWM switching signals

6.4. Simulation Results

The performance of the designed DVR is evaluated under Matlab / Simulink. The system runs at 50 Hz frequency and sample time is chosen to be 100 μ s. The

total period of simulation for each case is 0.3s and the simulation parameters are given in Table 6.2.

Under normal conditions, three-phase voltages are sinusoidal and in balance. Voltage sags are detected by sensing the voltages at PCC during the fault period. Different types of faults are applied to the system. The method presented in section 6.4.1 can detect most of the common types of voltage sags (balanced and unbalanced sags.)

Table 6.2 Simulation Parameters

Power Supply	380Vph-ph rms, 50 Hz Supply resistance, $R = 0.06 \Omega$
Sensitive Load	380 Vrms, 3 kVA
Injection Transformer	68/110 Vrms, 1 kVA
DC Link	100 V
LC Filter	$L=7\text{mH}$, $C=28.4\mu\text{F}$

The results demonstrate the effectiveness of the proposed control algorithm, and the capabilities of the DVR to ultimately compensate different types of voltage sags, compensate voltage unbalance and adaptively minimize the voltage harmonics.

6.4.1. Single-phase to Ground Fault

Most of the faults are single-phase line to ground faults. The single-phase line to ground fault occurs on phase A resulting in 50% decrease from nominal value between the period 0.05s and 0.2s. Figure 6.9 shows the supply voltage, injected voltage and load voltage. Phase A voltage of sensitive load and average load power are maintained at almost 1 p.u.

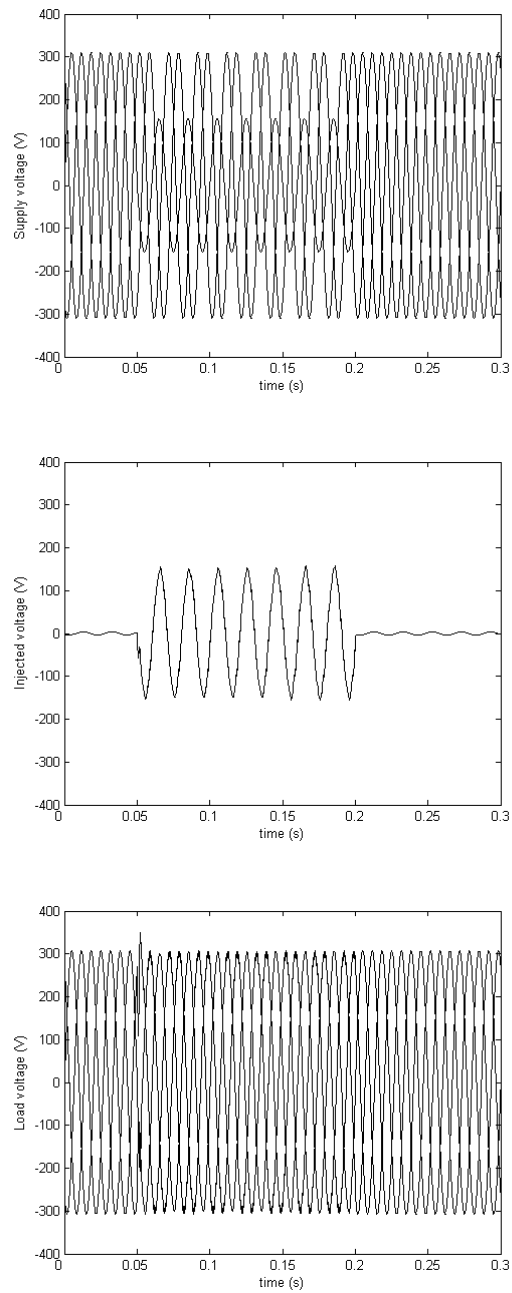


Figure 6.9. Case 1: The supply, injected and load voltages

6.4.2. Three-phase Balanced Fault

In Case 2, the three-phase balanced fault occurs. 50% voltage sag takes place between the period 0.05s and 0.2s. Figure 6.10 shows the supply voltage, injected

voltage and load voltage under balanced three-phase sag. During Case2 period, all the phase voltages of sensitive load are maintained at [0.99-1.02] p.u. and average load power is 0.99 p.u.

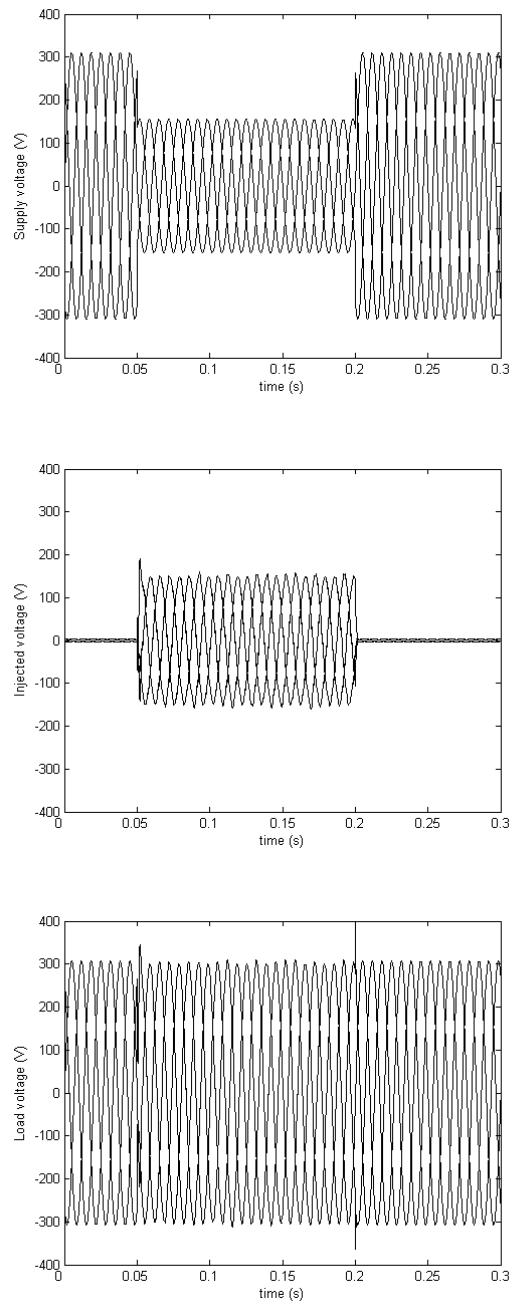


Figure 6.10 Case 2: The supply, injected and load voltages

6.4.3. Three-phase Unbalanced Fault

In this case, A phase, B phase and C phase voltages are decreased to 50%, 70% and 80% from their nominal values between the period 0.05s and 0.2s. Figure 6.11 shows the supply voltage, injected voltage and load voltage at three-phase unbalanced sag. During unbalanced sag period, the values of A phase, B phase and C phase voltages are maintained at [0.99-1.02] p.u. The average load power is 0.99 p.u.

6.4.4. Voltage Sag Associated with Phase Angle Jump

The phase angle jump is the character which may be associated with the unbalanced voltage sags. In general, the phase angle jump appears with the voltage sags for two reasons; the first reason is the difference of X_F / R_F ratio before and during the fault period. The second reason is the unbalance components that might come up with unbalance faults. In Case 4, A phase is decreased to 50% from the nominal value between the period 0.05s and 0.2s with a phase shift of 36° . Figure 6.12 shows the voltage sag with 36° phase angle jump, the injected voltage and the load voltage. It is apparent that the injected voltage is not in phase with the sagged voltage. The phase angle jump has been reduced to 4° as shown in Figure 6.12. The phase angle jump is measured based on the time between the consecutive peaks.

The PWM control scheme controls the magnitude and the phase of the injected voltages, restoring the voltage very effectively. The sag mitigation is performed, with a smooth, stable, rapid DVR response; no transient overshoots are observed when the DVR comes in and out of operation. The fidelity of the DVR output voltage depends on the accuracy and dynamic behaviour of the PWM voltage synthesis scheme and the control system adapted.

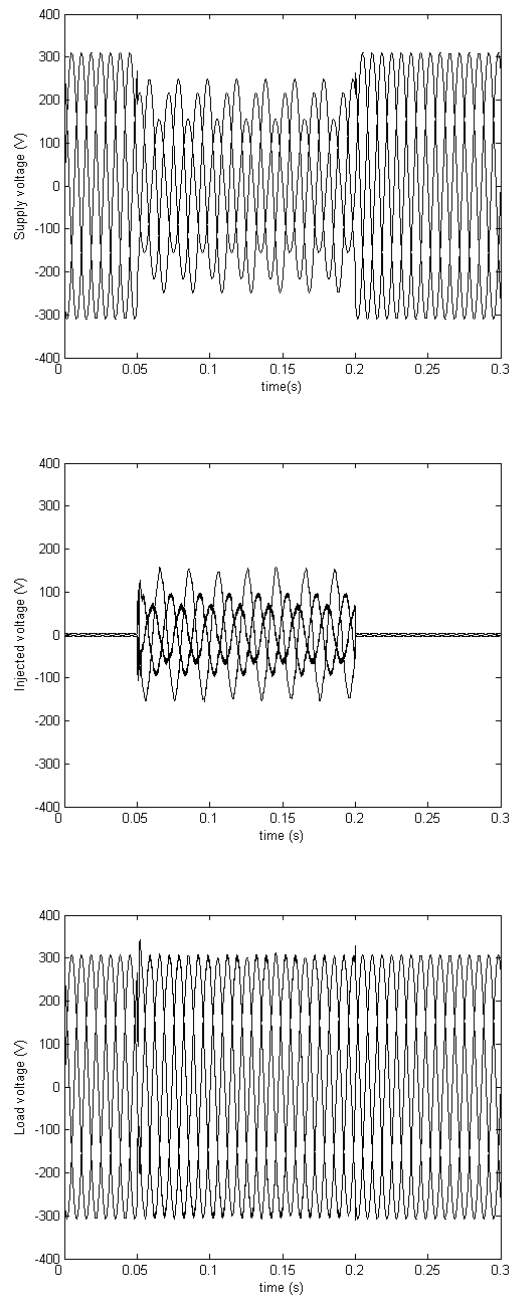


Figure 6.11 Case3: The supply, injected and load voltages

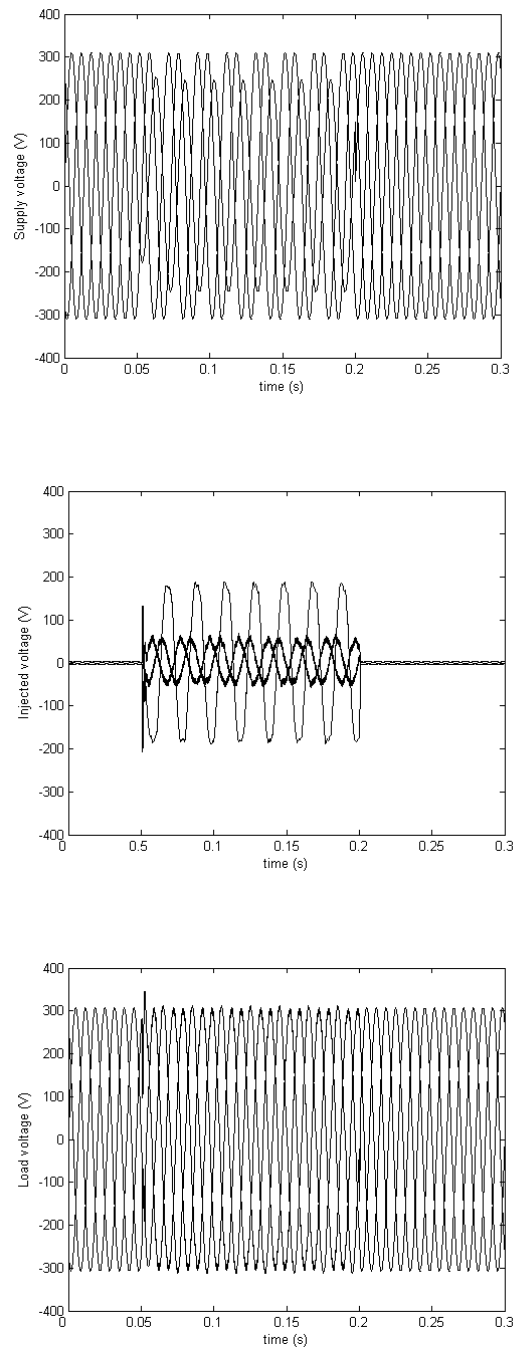


Figure 6.12 Case 4: The supply, injected and load voltages

7. MODELING OF UNIFIED POWER QUALITY CONDITIONER (UPQC)

7.1. Introduction

The recent growth in the use of the non-linear loads has caused many power quality problems such as voltage flicker, current and voltage disturbance and current unbalance. The current harmonics may propagate to upstream networks and produce voltage drops on the transmission lines or feeders impedances, which lead to voltage disturbance at the load terminals. Also the voltage sags may cause equipment tripping, malfunction, or shut down for the domestic and industrial equipment, and misoperation to the drive systems. These effects could be expensive for both customers and utilities.[Eldany et al.,2001]

To soften the drawbacks produced by the nonlinear loads, unified power quality conditioners (UPQC) were presented during 1998. The main purpose of a UPQC is to compensate the supply voltage and load current imperfections, such as sags, swells, interruptions, imbalance, flicker, harmonics, reactive currents, and current unbalance. In other words, the UPQC has the capability of improving power quality at the point of installation on power distribution systems or industrial power systems. The UPQC is a combination of series active filter and shunt active filter. The series active filter is responsible for cancellation of voltage imbalance, flicker, sags and swells, and provides a stable balanced and sinusoidal voltage to the load. The parallel active filter is used to compensate the imbalance, reactive power, neutral current and harmonics of the source current.[Ng et al., 2004]

d-q theory is used in many of the proposed UPQC's because of the ease of implementation such as in [Graovac et al, 2000], [Eldany et al., 2001], [Sepulveda et al., 2004] and [Vilathgamuva et al., 1998]. The application of NN and FL is recently growing in power electronic systems. Only [Singh et al., 1998] employs FLC for the control of UPQC. The proposed UPQC with FLC in this thesis differ from [Singh et al., 1998] in many ways. In [Singh et al., 1998] FLC is used only in the control of shunt part , series part is operated in current control mode and the proposed UPQC can mitigate only current and voltage harmonics. The proposed UPQC can mitigate

current harmonics and also voltage sags which are the most critical power quality problems for industry. With these functions, the proposed UPQC is suitable for connecting at the PCC of industrial drives which are most sensitive to sags and are the main cause of harmonics. The three-level voltage source converter used for maintaining DC link voltage is another distinguishing property of the proposed UPQC. The series part operate in voltage control mode for sag mitigation and the shunt part operate in current control mode. FLC is used both in series part and shunt part. The series active filter in the proposed UPQC operates as a DVR.

7.2. UPQC Configurations

UPQC consists of a series active filter and a shunt active filter. Figure 7.1 shows basic system configurations of a general unified power quality conditioner consisting of the combination of a series active filter and a shunt active filter. There are two types of configurations: right-shunt structure and left-shunt structure.

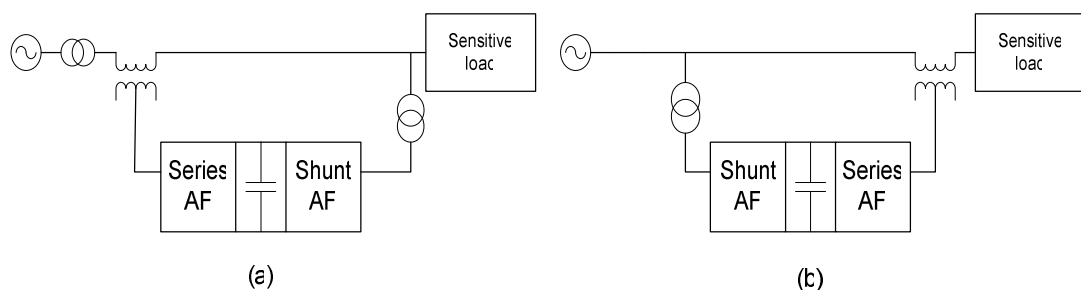


Figure 7.1 (a) Right-Shunt UPQC and (b) Left-Shunt UPQC

In this study right-shunt UPQC is used because of the following advantages:

- The right-shunt UPQC operates in a zero power injection/absorption mode, while left-shunt UPQC can not operate in this mode.
- The right-shunt UPQC can make power factor unity at the load terminal, the power factor at the load terminal depends on the load for the left-shunt UPQC.
- The shunt compensator in the right-shunt UPQC can supply the entire requirement of the reactive power by the load whereas the shunt compensator in the

left -shunt UPQC can only supply the mean of the reactive power.[Ghosh et al., 2002[1]].

7.3.Proposed UPQC Model

Matlab/Simulink model of the proposed UPQC is shown in Figure 7.2. The model can be divided into three main parts:

- DC link regulator
- Series connected DVR
- Shunt connected active filter

7.3.1. DC Link Regulator

A three phase three level PWM voltage source converter is used for the regulation of DC link voltage. Three level three phase ideal switches are controlled by a PWM modulator. The DC regulator uses two PI regulators to control the DC voltage while maintaining a unity input power factor for the AC supply. DC link consists of 2 capacitors with a rating 75.000 μ F. DC link voltage is regulated at 750 V. The regulation of DC link voltage is very critical both for shunt active filter and series connected DVR. If the DC link voltage collapses during a sag DVR is unable to compensate the sag which is the case mentioned in [Ghosh et al., 2004] The employed three phase three level PWM voltage source converter in the proposed UPQC guarantees the propoer functioning both for series connected DVR and shunt active filter.

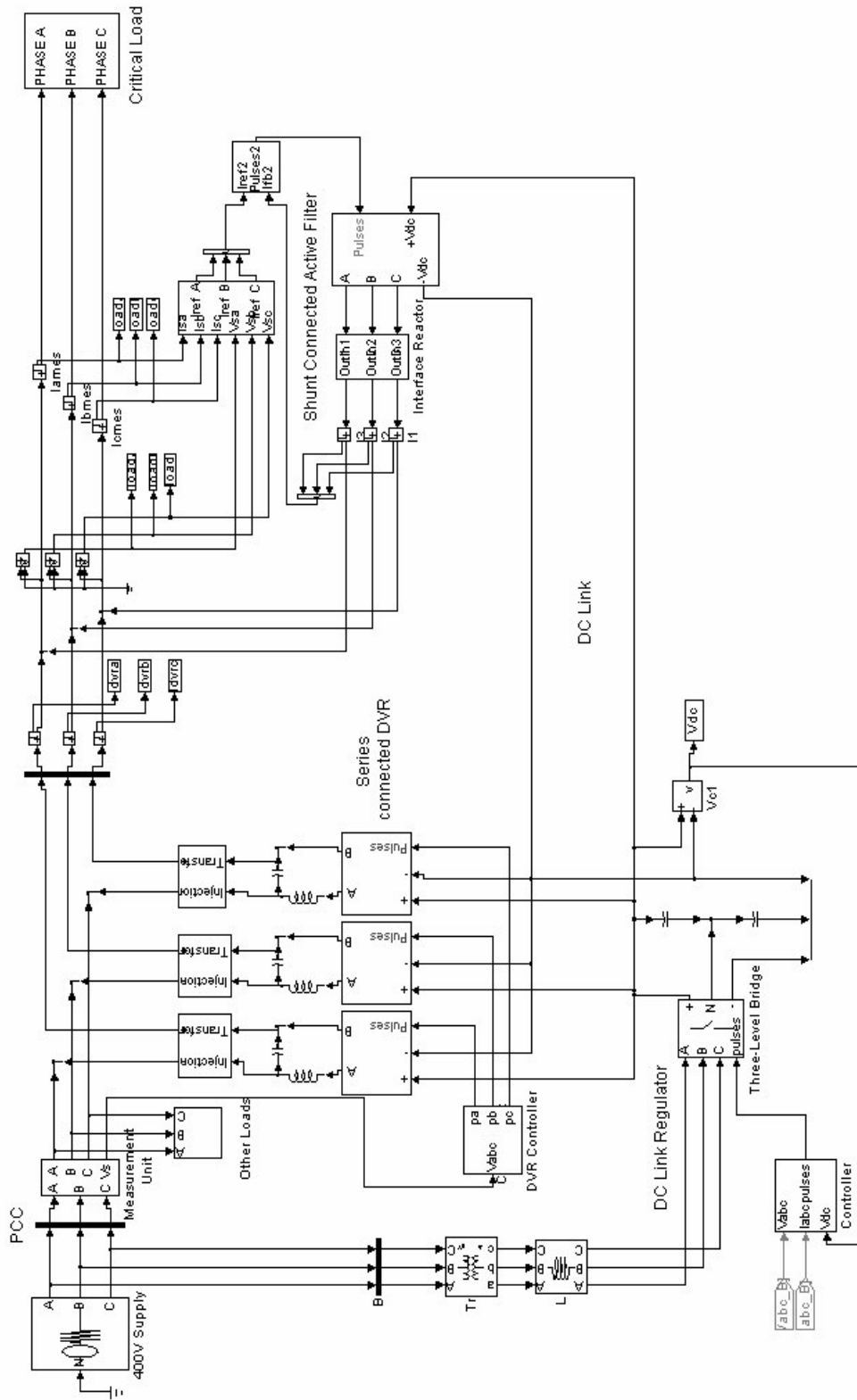


Figure7.2 Matlab / Simulink model of UPQC

7.3.2. Series Connected DVR

Series connected DVR has the same control principle as proposed in Chapter 6. Sag detection is performed with the method as proposed in 6.3.1. Reference voltage compensation method is as proposed in 6.3.2. However the parameters of power circuit is different than the DVR proposed in Chapter 6, because in UPQC, series connected DVR and shunt active filter utilize the same DC link. It is known that DC link voltage should be greater than the peak value of the line-to-line mains supply voltage for a successful operation of shunt active filter, so shunt active filter operation is the main determining factor in DC link voltage selection. Parameters of the power circuit for series connected DVR is as follows:

Table 7.1. Power Circuit Parameters

Power Supply	400V ph-ph rms, 50 Hz Supply resistance, $R = 0.06 \Omega$
Sensitive Load	400 Vrms, 400 kVA
Injection Transformer	450/120 Vrms, 66 kVA
DC Link	750 V, $C=75.000 \text{ mF}$
LC Filter	$L=0.9\text{mH}$, $C=1340.4\mu\text{F}$

7.3.3. Shunt Connected Active Filter

The active filter configuration employed in the proposed UPQC is based on the proposed active filter configuration of Chapter 3. Harmonic producing nonlinear load and the voltage source converter is the same as presented in 3.2.2 and 3.2.3. The compensating current reference signal is derived from the measured quantities by the use of the Instantaneous Reactive Power Theory as in 3.2.5. The difference from the theory of 3.2.5 is that the shunt active filter of proposed UPQC does not have the function of regulating DC link voltage. DC link voltage is regulated by the three

phase three level PWM voltage source converter. The resulting formula for calculating reference currents is obtained by neglecting p_{av} in (3.12) as given below.

$$\begin{bmatrix} i_{refa} \\ i_{refb} \\ i_{refc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} e_\alpha & e_\beta \\ -e_\beta & e_\alpha \end{bmatrix}^{-1} \begin{bmatrix} p^* \\ q^* \end{bmatrix} \quad (7.1)$$

The block diagram of reference current generation is given in Figure 7.3.

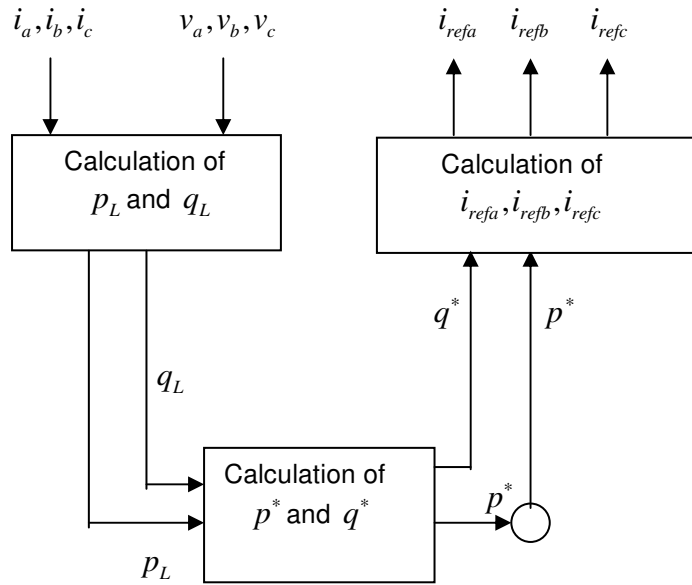


Figure 7.3 Block diagram of reference current generator.

The current controller employed in the proposed UPQC is the single fuzzy logic controller based PWM current controller presented in section 3.2.6.1.

7.4. Simulation Results

The performance of the proposed UPQC is evaluated under Matlab / Simulink with two case studies. The total period of simulation for each case is 0.2s.

Under normal conditions, three-phase voltages and currents are sinusoidal and in balance. The critical load is a three phase six pulse fully controlled rectifier.

Besides producing harmonics it is very sensitive to voltage sags. UPQC is expected to compensate the harmonics produced by nonlinear load, eliminate voltage sags and provide reactive power compensation at PCC. Voltage sags are detected by sensing the voltages at PCC during the fault period. Different types of faults are applied to the system. The results demonstrate the effectiveness of the proposed UPQC.

7.4.1. Case 1

Most of the faults are single-phase line to ground faults. Figure 7.4 shows the three phase supply voltages where the single-phase line to ground fault occurs on phase A resulting in 40% decrease from nominal value between the period 0.04s and 0.12s. Figure 7.6 shows the three phase load voltages where all three-phase voltages are within allowable limits. Swell happens to occur in phase A at the beginning of sag which is due to ripples on DC link voltage. Figure 7.8 shows the DC link voltage. It is seen that the magnitude of the ripples are increased during the sag, because the DC link provides the power necessary for the compensation of sag. The DC link voltage is successfully regulated by three level PWM voltage source converter. Figure 7.7 shows the harmonic containing load currents and Figure 7.5 shows the compensated sinusoidal source currents at PCC.

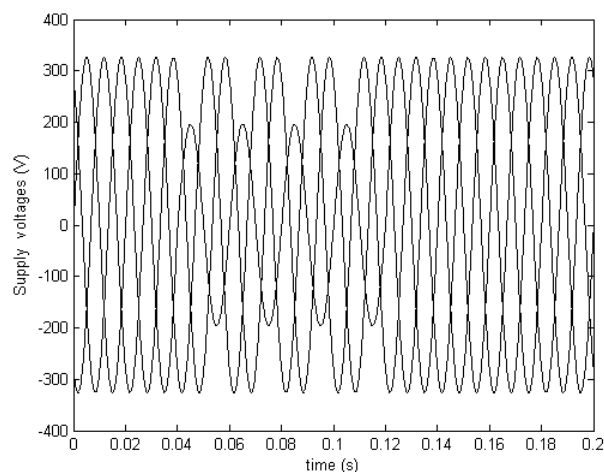


Figure 7.4. Case 1: The supply voltages

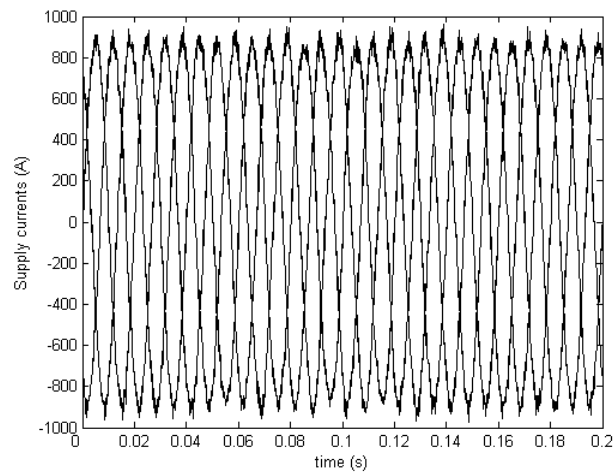


Figure 7.5. Case 1: The supply currents

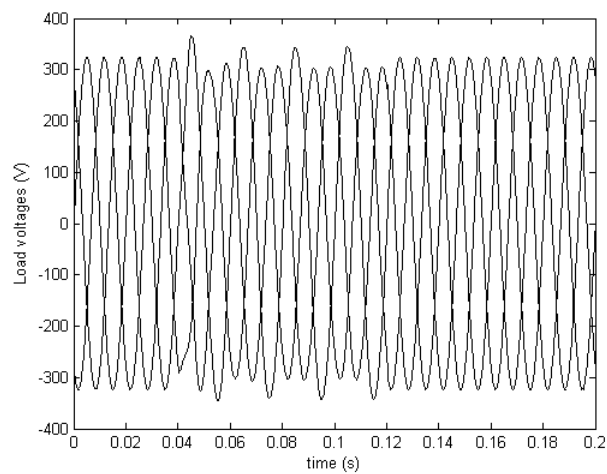


Figure 7.6. Case 1: The load voltages

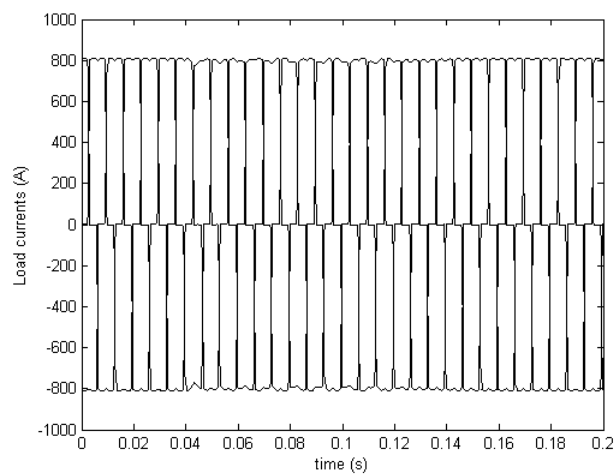


Figure 7.7. Case 1: The load currents

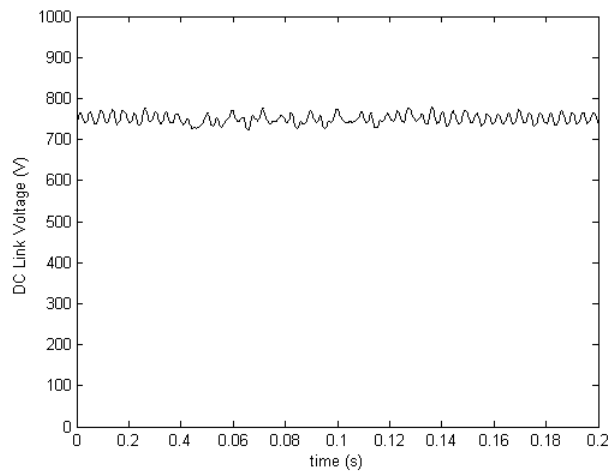


Figure 7.8. Case 1: DC link voltage

6.4.2. Case 2

In Case 2, a three-phase balanced fault case is tested. Figure 7.9 shows the three phase supply voltages where the three-phase balanced fault occurs resulting in 30% decrease from nominal value between the period 0.04s and 0.12s in all phases. Figure 7.11 shows the three phase load voltages where all three phase voltages are within allowable limits. Figure 7.13 shows the DC link voltage. It is seen that the DC link voltage tends to decrease during the starting period of sag and then the DC link voltage is successfully regulated by three level PWM voltage source converter. DC link voltage decreases more with respect to case 1 because the power necessary for the compensation of sag is more for a three-phase sag. . Figure 7.10 shows the harmonic containing load currents and Figure 7.12 shows the compensated sinusoidal source currents at PCC.

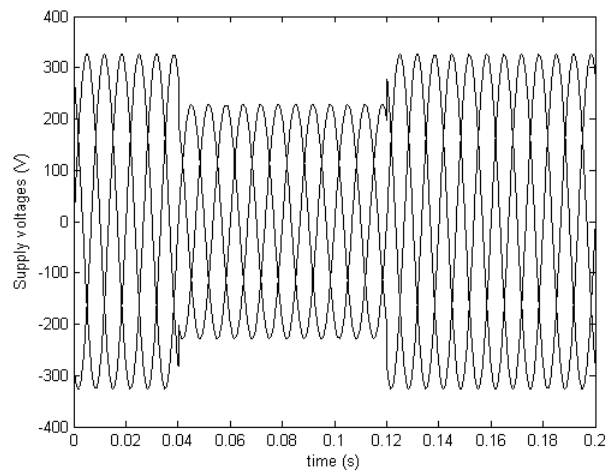


Figure 7.9. Case 2: The supply voltages

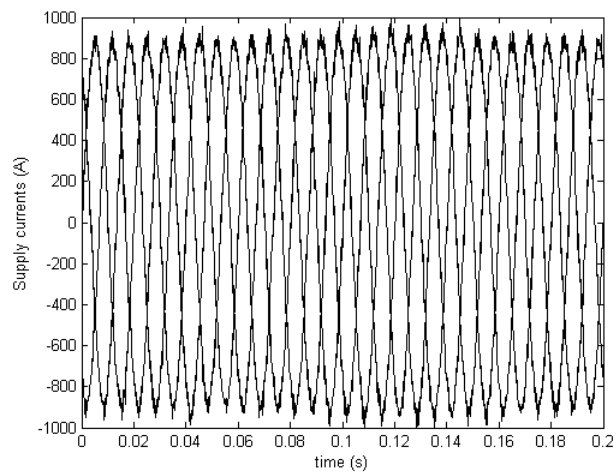


Figure 7.10. Case 2: The supply currents

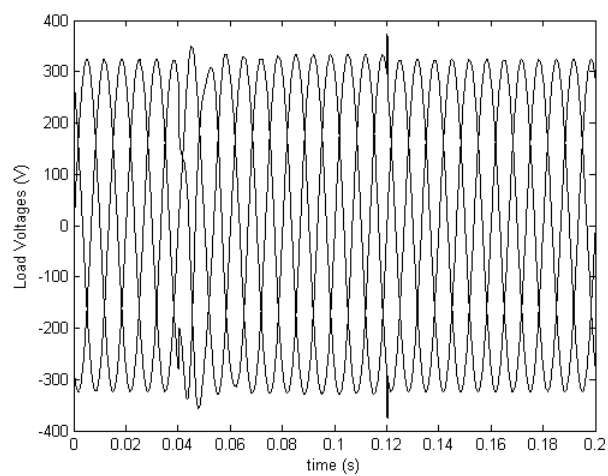


Figure 7.11. Case 2: The load voltages

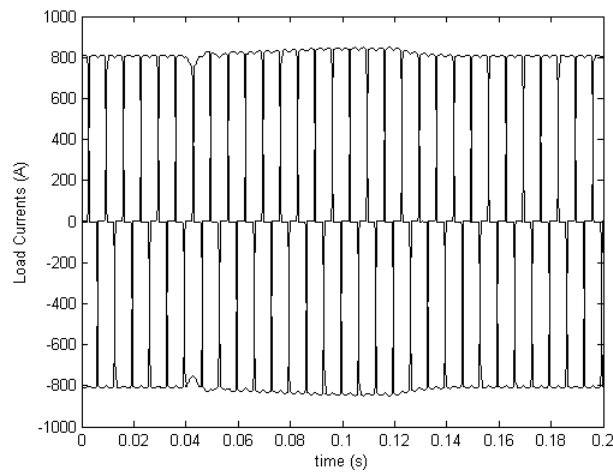


Figure 7.12 Case 2: The load currents

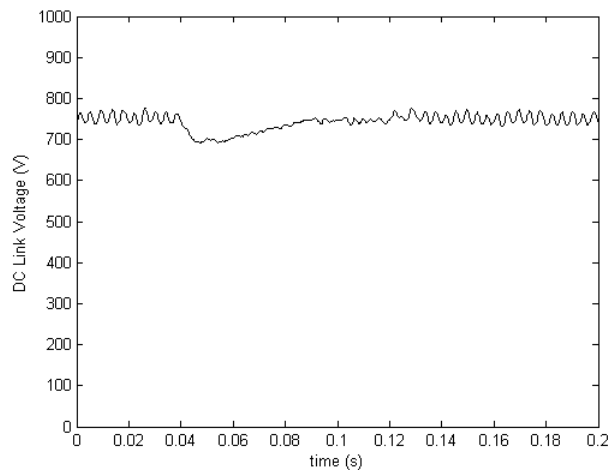


Figure 7.13 Case 2: DC link voltage

In both cases it is observed that load voltage quality and source current quality are maintained. Load is protected from sag which would cause tripping and source current is sinusoidal with unity pf at load terminals and undesired harmonics compensated. With these functions, the proposed UPQC is suitable for connecting at the PCC of industrial drives which are most sensitive to sags and are the main cause of harmonics. DC link capacitor value is critical for performance. A selection between cost and performance should be done. In this study DC link capacitor is

selected as $75.000\mu\text{F}$. A larger capacitance with higher cost may be selected. The increased capacitance of DC link reduces the ripples on DC link voltage and provides a smoother DVR and shunt active filter control.

8. CONCLUSIONS AND FUTURE WORK

Power quality is an issue that is becoming increasingly important to electricity consumers at all levels of usage. Sensitive equipment and non-linear loads are commonplace in both the industrial and the domestic environment, because of this a heightened awareness of power quality is developing. Occurrences on the supply network that were once considered 'normal' by electricity companies and users are now considered a problem to the users of more sensitive equipment.

Custom power offers the customer: no interruptions; tight voltage regulation; low harmonic voltages; and acceptance of fluctuating and non-linear loads without effect on terminal voltage.

Custom Power provides utilities with a means for enhancing their electric service. In an industry undergoing transition into a competitive marketplace, this type of value-added service can open up additional business opportunities, enhance business relations with customers, and position utilities and their customers for the competitive markets foreseen for the 21st century. Combined with the impact of power electronics through the flexible ac transmission system, Custom Power along with the competitive forces of wheeling and distributed generation, points the way to the transmission and distribution system of the 21st century.

It has been shown that custom power devices provide in many cases higher performance compared with traditional mitigation methods. However, the choice of the most suitable solution depends ultimately on the characteristic of the supply at the point of connection, the requirements of the load and economics, i.e the customer value added by the installation of a power-electronics based device.

Ongoing development and commercial availability of high power semiconductors will further increase opportunity and cost effectiveness of advanced technologies like Custom Power Devices.

In this thesis Custom Power Device models are presented. The highly developed graphic facilities available in Matlab / Simulink were used to conduct all aspects of model implementation and to carry out extensive simulation studies.

In all models, control loops of the systems are modeled in detail, but simplified switch models are employed. Consequently this model is very useful for conceptual analysis and for obtaining steady state waveforms. During simulation, the sampling resolution of the simulated system should not be very different from the real system sampling resolution. Otherwise, significant errors can be introduced.

The study on shunt active power filter focused on applying hierarchical neuro-fuzzy current control scheme. This type of controller for active power filters is new in literature and can be applied to other power electronic converter applications for superior performance. Problems faced on performance improvement of the single fuzzy control scheme are overcome by developing an ANFIS based neuro-fuzzy controller connected hierarchically to the first fuzzy logic controller. The second group fuzzy logic controllers in the model are neuro-fuzzy controllers trained by the data based on the input-output characteristics of the first group fuzzy logic controllers with designer made corrections. An interface program developed to collect necessary data from Matlab helped in analyzing the data. Simulation results show that proposed method provides superior current tracking capability and improved filtering performance.

Application of a three-input, one output fuzzy logic controller for a three-phase four-wire shunt active power filter is also presented in this thesis. The results with the same parameters have shown that conventional hysteresis method and proposed method both provide harmonic, unbalance and reactive power compensation. The proposed method provides a more stable dc link voltage with less ripple and fixed switching frequency. Better utilization of dc link enables selecting lower voltages for dc link capacitors and fixed switching frequency enables better elimination of high frequency ripples in the active filter current by the passive filter. The proposed method may be extended for use in multilevel converter applications where capacitor voltage imbalance is a problem.

Static Transfer Switch (STS) transfers the load from a preferred feeder to an alternate feeder. In this thesis, a fast thyristor based STS system that employs fast voltage-detection and thyristor-gating strategies is presented. The STS performance is simulated for different faults/disturbance scenarios using the Matlab/Simulink. The voltage-detection logic is able to detect faults/disturbances in the power system within a short time and can be used for any three-phase system.

The proposed controller uses the magnitude of the positive sequence component of the line voltages to detect if any voltages sag occurs. The positive sequence voltages are transformed into DC quantities under the synchronous reference frame. Then the magnitude of the positive sequence voltage is calculated. If the magnitude reduces below a certain threshold level (typically 80% to 90% of the normal value), then the controller recognizes the occurrence of a voltage sag event and issues the transfer command to the STS. The proposed control method can identify voltage sags very rapidly, typically within 5ms. The use of a low-pass filter makes the detection logic insensitive to capacitor-switching voltage transients. Also, the designed selective thyristor-gating scheme performs a fast load-transfer and prevents paralleling the two sources.

DVR is especially used for compensating the sags and swells. It is connected in series with a distribution feeder and is capable of generating or absorbing real and reactive power at its ac terminals. By adapting advanced FL control technique in generation of reference signals for PWM, a high level of efficiency and dynamic performance of DVR are both achieved. The simulation results show that the DVR compensates the sags quickly and provides excellent voltage regulation under various operating conditions. The proposed method does not involve any transformation resulting in quicker response compared to the conventional control methods.

Fuzzy logic control of DVR is new in literature and the proposed control method can easily be applied for superior performance and as an alternative control method for conventional or complex system configurations.

Used differential controller sag detection and fuzzy logic controller compensated the fault of source voltage with fast response characteristics and

improved the performance compared to a DVR system with only the conventional LPF.

A UPQC is a new device which has a shunt inverter and series inverter, both connected together through a dc storage capacitor. The dc capacitor facilitates power exchange between the two inverters. The UPQC can independently or jointly perform the tasks of both the series and shunt compensators. UPQC presented in this thesis is the marriage of shunt active filter and DVR previously presented. A three-level voltage source converter is used for maintaining DC link voltage at the common DC link. The proposed UPQC can mitigate current harmonics and also voltage sags which are the most critical power quality problems for industry. With these functions, the proposed UPQC is suitable for connecting at the PCC of industrial drives which are most sensitive to sags and are the main cause of harmonics. The series part operate in voltage control mode for sag mitigation and the shunt part operate in current control mode. FLC is used both in series part and shunt part.

It should be realized that the use of Custom Power is still in its infancy. There is lot future work to do on this topic. The existence of Custom Power Devices make possible the implementation of a Custom Power Park that would provide a guaranteed improvement in the quality of electrical service to the tenants of the park. This thesis focused on performance evaluation of devices operating individually. As a future work a Custom Power Park model should be implemented and performance of the Park and device interactions and coordinations should be studied during different fault scenarios.

The state of art equipment allows the development of FRIENDS and Custom Power Park concepts. FRIENDS (Flexible, Reliable and Intelligent Electrical Energy Delivery Systems) and Custom Power Park are the advanced technologies that provide the means by which the electric utility may add value incrementally via additions to its infrastructure.

Number of installations of Custom Power Devices is increasing in the world. Increasing competitiveness and new utility regulations force the industrial consumers towards installation of Custom Power Devices. Mostly shunt active power filter

installations are reported in Turkey and the market and research on Custom Power Devices is expected to grow in the near future.

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Areas of Interest:

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Custom Power and FACTS Devices

Control in Power Electronics

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EEE 465 Power Electronics 1

EEE 464 Power Electronics 2

Some Industrial Projects:

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İsdemir BOF 154 kV Switchyard and 60 MVAR Static Var Compensation System

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İsdemir Power Plant 2*250 ton/h Steam Boilers

Publications:

a) Journals (SCI)

BAYINDIR K. Ç., CUMA M.U., TÜMAY M., 2006. Hierarchical neuro-fuzzy current controls for a shunt active power filter. Neural Computing and Applications.

BAYINDIR K. Ç., ERMİŞ M., TÜMAY M., 2006. Understanding the modelling and analysis of a shunt active power filter. International Journal of Electrical Engineering and Education(IJEEE) Accepted to be published in July issue 43, no:3.

b) International Conferences

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