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MSc THESIS

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MODELING OF DYNAMIC VOLTAGE RESTORER

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

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FEN BİLİMLERİ ENSTİTÜSÜ

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YÜKSEK LİSANS TEZİ

ELEKTRİK ELEKTRONİK MÜHENDİSLİĞİ ANABİLİM DALI

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ÖZ

YÜKSEK LİSANS TEZİ

DİNAMİK GERİLİM İYİLEŞTİRİCİNİN MODELLENMESİ

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Danışman: **Doç. Dr. Mehmet TÜMAY**
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Yrd. Doç. Dr. Mutlu AVCI

Güç elektroniği teknolojisindeki hızlı gelişmeler, güç sistemlerindeki gerilim bozukluklarının hafifletilmesini mümkün hale getirmiştir. Endüstriyi uğraştıran gerilim bozuklukları arasında, gerilim düşümleri duyarlı yüklere karşı en önemli sorun olarak düşünülür. Dinamik Gerilim İyileştiricisi (DGİ) sistemdeki gerilim düşümlerini hafifletebilen ve duyarlı yük gerilimini hata öncesindeki değerine getirebilen seri bağlantılı güç elektroniği tabanlı bir cihazdır. DGİ bu probleme karşı en iyi çözüm olarak kabul edilir. DGİ'nin temel avantajı kullanıcıları hat üzerinde her zaman yüksek kaliteli sabit gerilimde tutarak üretimin devamlılığını sağlamasıdır.

Bu tezde, DGİ için referans gerilimi üreten yeni bir kontrol metodu sunulmuştur. Önerilen metot herhangi bir dönüştürme işlemi içermediğinden varolan metotlara göre üstün bir performans sağlar. Kontrol planı oldukça kolay, esnek maliyetli ve mükemmel bir gerilim düzeltme yeteneğine sahiptir.

Tezin temel amacı, 50-kVA'lık bir duyarlı yükü koruyan DGİ'nin analizini, modellemesini ve simülasyonunu yapmaktır. Önerilen metodun performansı ve verimliliği Matlab/Simulink programında farklı simülasyon çalışmalarıyla incelenmektedir.

Anahtar Kelimeler: Dinamik Gerilim İyileştirici, Gerilim Düşümü ve Güç Kalitesi

ABSTRACT

MSc THESIS

MODELING OF DYNAMIC VOLTAGE RESTORER

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DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING
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The fast developments in power electronic technology have made it possible to mitigate voltage disturbances in power systems. Among the voltage disturbances challenging the industry, the voltage sags are considered the most important problem to the sensitive loads. Dynamic Voltage Restorer (DVR) is a series connected power electronic based device that can quickly mitigate the voltage sags in the system and restore the load voltage to the pre-fault value. DVR is recognized to be the best effective solution to overcome this problem. The primary advantage of the DVR is keeping the users always on-line with high quality constant voltage maintaining the continuity of production.

A new method for the generation of reference voltage for a DVR is presented in this thesis. The proposed method provides superior performance compared to conventional control methods because of not involving any transformation process. The control scheme is rather simple, flexible in cost and has an excellent voltage regulation capability.

The basic purpose of this thesis is analyzing, modeling and simulating the DVR, which protects a 50-kVA sensitive load. The performance and efficiency of the proposed method are investigated with different simulation studies by MATLAB/ Simulink program.

Keywords: Dynamic Voltage Restorer, Voltage Sag and Power Quality

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Ahmet TEKE

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LIST OF SYMBOLS

C_{DC}	DC link capacitor
C_f	Filter capacitance
D	Maximum single-phase voltage sag to be compensated
D_r	Switch duty ratio
err_A	Error signal
$E_{Storage}$	Energy stored in the capacitor
f_n	Nominal frequency
f_s	Switching frequency
I_{fault}	Short circuit current
I_{load}	Load current
I_{shunt}	Shunt converter current
L_{base}	Base inductance used for each winding
L_f	Filter inductance
$L^{(l)}$	Fuzzy If-Then rule base
L_{sc}	Short circuit inductance of the transformer
P	Pre-fault voltage value
P_{load}	Three-phase power handled by the load
P_{series}	Three-phase power handled by the series converter
P_{shunt}	Three-phase powers handled by shunt converter
R_{base}	Base resistance used for each winding
R_c	Core losses (hysteresis and eddy current losses)
R_f	Fault resistance
R_{ps}	Resistance of primary side coils
R_s	Source resistance
R_{sc}	Short circuit resistance of the transformer
R_{ss}	Resistance of secondary side coils

T_{max}	Allowable time during input voltage stays below V_{min}
V_{DC}	DC link voltage
V_h	Actual output voltage of DVR
V_h'	Inverter terminal voltage
V_{inj}	Injection voltage
V_L	Load voltage
$V_{Lprefault}$	Pre-fault load voltage
V_{min}	Threshold voltage to operate correctly
V_{pcc}	Remaining voltage at PCC during sag
V_{PLLa}	A phase PLL voltage
V_r	Rated rms voltage of the primary feeder
V_{rs}	Rated supply voltage
V_s	Source voltage
V_{Sa}	A phase source voltage
w^l	Overall truth value of the premise of the rule $L^{(l)}$
X_f	Fault reactance
X_m	Reactance related with the magnetization of the core
X_{ps}	Leakage reactance in the primary side
X_s	Source reactance
X_{ss}	Leakage reactance in the secondary side
z	Impedance of the feeder per-unit length
Z_{DVR}'	Internal impedance of the DVR
Z_f	Fault impedance
Z_{line}	Line impedance
Z_s	Source impedance
Δerr_A	Error-rate signal
$\Delta\phi$	Phase angle jump

LIST OF ABBREVIATIONS

ASD	Adjustable Speed Drive
CBEMA	Computer Business Equipment Manufacturer Association
CSI	Current Source Inverter
D-STATCOM	Distribution Static Compensator
DVR	Dynamic Voltage Restorer
FACTS	Flexible AC Transmission System
FIS	Fuzzy Inference System
FLC	Fuzzy Logic Control
GTO	Gate Turn-Off Thyristor
IEEE	Institute of Electrical and Electronics Engineers
et al.	And Others
IGBT	Insulated Gate Bipolar Thyristor
ITIC	Information Technology Industry Council
MOSFET	Metal-Oxide-Semiconductor Field Effect Transistor
PCC	Point of Common Coupling
PI	Proportional-Integral
PLC	Programmable Logic Controllers
PLL	Phase Locked Loop
PQ	Power Quality
pu	Per-Unit
PWM	Pulse Width Modulation
rms	Root Mean Square
SLGF	Single-Line to Ground Fault
SSTS	Solid State Transfer Switch
STATCOM	Static Synchronous Compensator
THD	Total Harmonic Distortion
UPFC	Unified Power Flow Controller
UPS	Uninterruptible Power Supply
VSI	Voltage Source Inverter

1. INTRODUCTION

The high quality sinusoidal waveform is produced at power stations. The widespread applications of power electronic based non-linear devices and faults cause deviation from pure sinusoidal waveform. These situations facing electricity customers and suppliers have increased the popularity and development of power quality studies. Power quality is becoming an increasingly important topic in the performance of many industrial applications such as information technology, significant influence on high technology devices related to communication, advanced control, automation, precise manufacturing technique and on-line service.

Users need constant sine wave shape, constant frequency and symmetrical voltage with a constant root mean square (rms) value to continue the production. To satisfy these demands, the disturbances must be eliminated from the system. The typical power quality disturbances are voltage sags, voltage swells, interruptions, phase shifts, harmonics and transients (Stump *et al.*, 1998).

Among the disturbances voltage sag is considered the most severe since the sensitive loads are very susceptible to temporary changes in the voltage. Voltage sag is a short-duration reduction in voltage magnitude. The voltage temporarily drops to a lower value and comes back again after approximately 150 millisecond (ms). Despite their short duration, such events can cause serious problems for a wide range of equipment (Bollen, 2001). The characterization of voltage sags is related with:

- The magnitude of remaining voltage during sag
- Duration of sag

In practice the magnitude of the remaining voltage has more influence than the duration of sags on the system. Voltage sags are generally within 40% of the nominal voltage in industry. Voltage sags can cost millions of dollars in damaged product, lost production, restarting expenses and danger of breakdown.

Short circuit faults, motor starting and transformer energizing will cause short duration increase in current and this will cause voltage sags on the line (Bollen, 2001). For certain end users of sensitive equipment the voltage correction device may be the only cost-effective option available (Fitzer *et al.*, 2004).

Different approaches exist to limit the costs caused by voltage dips and one interesting approach considered here is to use voltage source converters connected in series between the supply system and the sensitive load, this type of devices are often termed a Dynamic Voltage Restorer (DVR). Unlike uninterruptible power supply (UPS), the DVR is specifically designed for large loads ranging from a few MVA up to 50 MVA or higher (Barnes *et al.*, 2004). The DVR is fast, flexible and efficient solution to voltage sag problems. It can restore the load voltage within a few milliseconds and hence avoiding any power disruption to that load. The main idea of the DVR is detecting the voltage sag and injecting the missing voltage in series to the bus by using an injection transformer as shown in Figure 1.1.

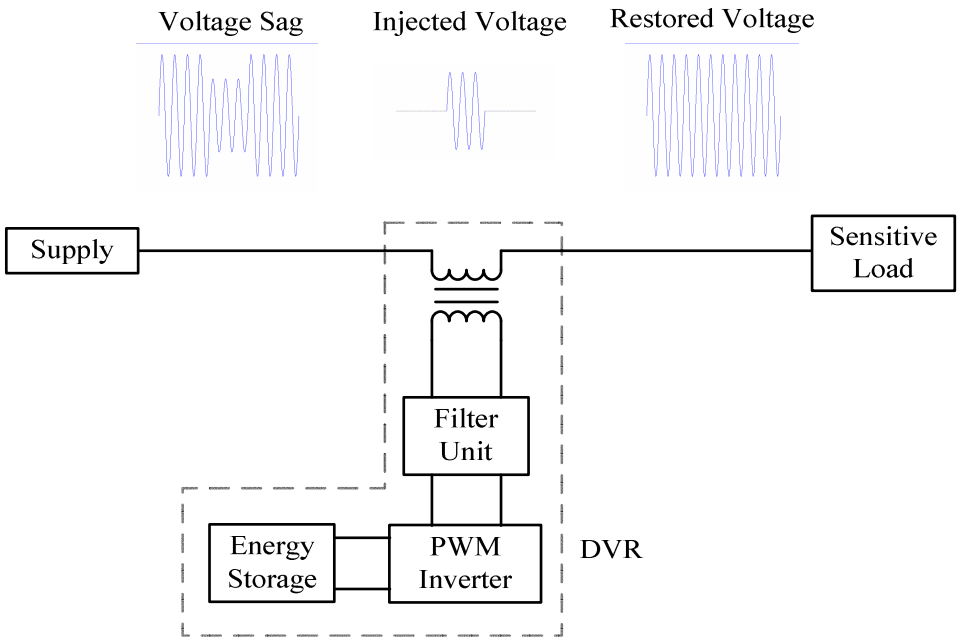


Figure 1.1 Typical application of DVR in distribution system

The DVR can be divided into four component blocks, namely:

- Voltage source PWM inverter
- Injection transformer
- Energy storage device
- Filter unit

During the standby mode (non-faulted times) DVR will do nothing and it should be ensured that the load is not disturbed by the DVR. If the voltage drop caused by the injection transformer exceeds the limit, DVR may inject small voltage to compensate fault. In standby mode, DVR only produces conduction losses because no voltage source PWM inverter switching takes place.

In the event of a fault on the load side of the DVR, a fast rising current surge through the low voltage side of the injection transformer and the voltage source PWM inverter occurs. The protection system guarantees that power semiconductor switching can take place when current levels exceed the switching capability of the power semiconductor. In the event that a critical current level is detected the DVR is bypassed (Wunderlin *et al.*, 1998). The bypass system protects DVR components from abnormally high downstream load or fault currents. The DVR should have clever bypass schemes so as not to create additional disturbances onto the system, which will affect the load (Middlekauff *et al.*, 1998).

When voltage sag depth to be corrected is between the ratings of DVR, DVR starts to generate the equivalent missing voltage and inject it to the line. DVR will continue the injection process until the bus voltage reaches its pre-fault value. DVR will inject three single-phase ac voltages with controllable amplitude and phase. The voltage sags resulting from faults can be corrected either in the transmission or distribution system. DVR can compensate small disturbances by injecting reactive power and compensate larger disturbances by injecting real power to the system.

To obtain missing voltage DVR compares the distorted source voltage with its pre-fault value and then generate the control signal for PWM. The control unit gives information on required voltage to be inserted and its duration during sag. Sinusoidal pulse width modulation technique is used to control DVR. Solid-state power electronic switching devices are used in PWM (Chang *et al.*, 2000).

The output of PWM may contain harmonics and they can be filtered on the inverter side or the line side to smooth the voltage waveform. The filtering scheme should keep the total harmonic distortion (THD) of the remaining voltage at the supply side and the injected voltage within limits determined by standards (Choi *et al.,* 2002; Li *et al.,* 2001).

Voltage restoration of DVR needs to inject energy from DVR to distribution system. The required energy for injection during sag may be supplied from the grid or energy storage devices such as batteries or super conducting magnetic energy storage systems. However, the capability of energy storage that usually consists of capacitors in DVR is limited. Therefore, it must be considered how the injection energy can be minimized during deep voltage sags and the load voltage can be made close to pre-fault voltage. This strategy is known as dynamic voltage restorer with minimum energy injection (Choi *et al.,* 2000).

The DVR is a series connected device onto the system and it acts as an additional energy source. Carefully design considerations must be taken to integrate the device into the system. Figure 1.2 can mainly summarize the main operation principle of DVR.

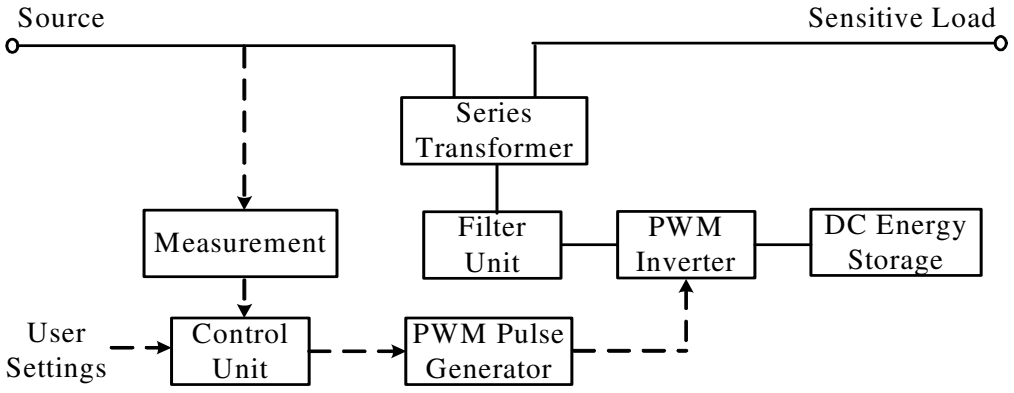


Figure 1.2 Simplified DVR blocks

The DVR control system compares the input voltage to an adaptive reference signal and injects voltage so that the output voltage remains within specifications, e.g. 1 per-unit (Stump *et al.*, 1998). The dynamic performance ability of DVR leads an improving supply quality for future and allows us more complex devices to use. The quick delivery time, portability and simple operation of DVR satisfy the power quality demands of customers. The investment cost, outage cost and remaining voltage on the system will determine the optimum technology method and rating of a DVR.

As a result, the aim of the thesis is characterizing voltage sags and inserting the missing voltage by DVR. The simulations are performed by using MATLAB/ Simulink program.

The content of the thesis is arranged as follows:

After this introductory chapter, Chapter 2 defines the custom power concept and some terms related to the power quality issue used along the thesis. The causes and characteristics properties of the voltage sags are analyzed and the mitigation techniques of voltage sags are discussed.

In Chapter 3, the hardware components of DVR are explained in detail. The circuit configuration, operation and basic functions are presented. The required equations for modeling of DVR are included.

In Chapter 4, main operation modes of DVR are explained, emphasizing the location and requirements of solid-state breakers in the system. Overviews of different applications of voltage injection strategies are presented.

In Chapter 5, a new control method for DVR is presented by combining a Fuzzy Logic Controller with a PWM inverter. The superior properties compared to traditional methods are discussed and the proposed control algorithm is deeply analyzed.

In Chapter 6, the power system equivalents of DVR components are designed in Simulink program for simulation cases. The equations derived in previous chapters are adopted for the design of DVR components.

In Chapter 7, the challenges in computer simulation of power electronic system are discussed. A number of case studies are performed to validate the performance of proposed control strategy and to verify the behavior of modeled DVR under dynamic conditions.

In Chapter 8, the important conclusions of the study are explained and the future work topics on DVR are given.

2. POWER QUALITY AND VOLTAGE SAG

2.1. Power Quality and Custom Power Devices

Power quality can be defined as having a bus voltage that closely resembles a sinusoidal waveform of required magnitude. Increasing number of sensitive devices to variations, the requirement for reducing losses and the behaviors of interconnected networks are some reasons which increase the importance of power quality concept. In the industry, power quality polluting loads are increasing day by day. The main reasons for concern with power quality (PQ) are as following (Dong *et al.*, 2004):

- End user devices become more sensitive to PQ due to many microprocessor based controls.
- Complexity of industrial processes: the re-startup is very costly.
- Large computer systems in many businesses facilities
- Power electronics equipment used for enhancing system stability, operation and efficiency. They are major source of bad PQ and are vulnerable to bad PQ as well.
- Deregulation of the power industry
- Complex interconnection of systems, which results in more severe consequences if any one component fails.
- Continuous development of high performance equipment: Such equipment is more susceptible to power disturbances.

The users demand higher power quality to use more sensitive loads to automate processes and improve quality. Some basic criterions for power quality are constant rms value, constant frequency, symmetrical three-phases, pure sinusoidal wave shape and limited THD. These values should be kept between limits determined by standards if the power quality level is considered to be high. Power quality covers several types of problems of electrical supply and power system disturbances. The cost of power interruptions and disturbances can be quite high as a result of the important processes controlled and maintained by the sensitive devices. Power quality disturbances can be summarized as follows (Dong *et al.*, 2004):

- Transients
  - Impulsive transients: Sudden, non-power frequency change in the steady state condition of the voltage, current or both
  - Oscillatory transients: Voltage or current whose instantaneous value changes polarity rapidly.
- Short duration voltage variations
  - Sag: 0.1 ~ 0.9 pu; 0.5 cycles to one minute; caused by system faults, energisation of heavy loads and starting of large motors
  - Swell: 1.1 ~ 1.8 pu; 0.5 cycles to one minute; caused by system fault conditions
  - Interruption: Less than 0.1 pu; not exceeding one minute; caused by power system faults, equipment failures and control malfunctions
- Long duration voltage variations
  - RMS deviation longer than one minute; voltage, current, frequency
  - Types: overvoltage, undervoltage
- Voltage imbalances
  - Percentage maximum deviation from the average of three-phase voltages or currents
- Waveform distortions: DC offset, harmonics, notching, noise
- Power frequency variations
  - Deviations of the power system fundamental frequency from its specified nominal value
  - Depends on: load characteristics, response of generation control system to load
- Voltage fluctuations
  - Systematic variations of the voltage envelop or series of random voltage changes
  - Not normally exceed 0.9 to 1.13 pu

Power electronic based devices provide protection for industry and commercial customers from power quality problems basically sags, swells, harmonics, interruption and unbalance voltages that are shown in Figure 2.1.

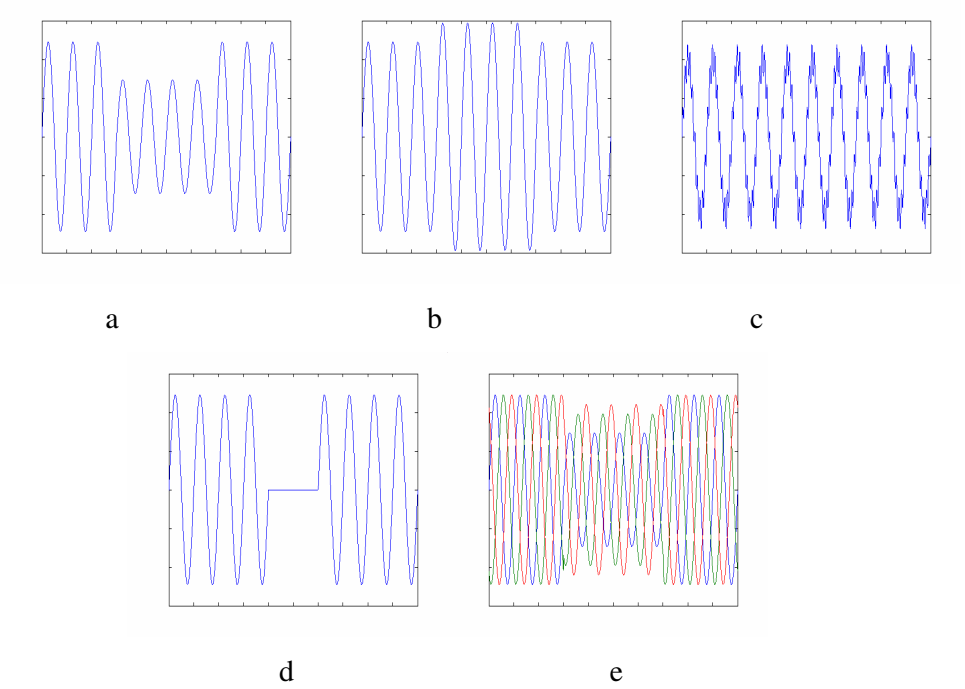


Figure 2.1 Waveforms of (a) voltage sag, (b) swell, (c) harmonic, (d) outage and (e) unbalance

These devices are known as custom power devices and they can increase the availability of sensitive loads in the system and supply reliable power. Custom power devices are typically building on the distribution system to provide higher power quality and most economic solution. High power solid-state switches insulated gate bipolar transistor (IGBT) and gate turn-off thyristor (GTO) with controlled turn- off capability are used to achieve high power quality. They perform rapid response and provide continuous and dynamic control in real time processes.

Custom power devices are mainly used in voltage sag mitigation, protection and control of sensitive loads, reactive power and voltage regulation and harmonic elimination applications. There are three principle elements to the custom power concept; these are (Taylor, 1995):

- The Dynamic Voltage Restorer (DVR), it provides series compensation by voltage injection for power system sag and swell. It can supply or absorb both real and reactive power to compensate the disturbances. DVR is primarily for use at the distribution level.

- The Distribution Static Compensator (D-STATCOM), it provides continuously variable shunt compensation by current injection for eliminating voltage fluctuations and obtaining correct power factor in three-phase systems. An ideal application of it is to prevent disturbing loads from polluting the rest of the distribution system.
- Solid State Transfer Switch (SSTS), it protects circuits from electrical disturbances by transferring load from a faulted line (main source) to a healthy line (back up source). SSTS does not operate in the same way as a conventional circuit breaker. It interrupts fault currents by monitoring both steady current and rate of change of current and only interrupts when the onset of a fault is detected.

The proper selection of necessary custom power strategies in addition to accurate system modeling and appropriate protection devices will increase the power quality. The applications of custom power devices are summarized in Table 2.1.

Table 2.1 Custom power devices and their applications

Custom Power Devices	**Power System Disturbances**
Dynamic Voltage Restorer	Voltage sags, voltage swells, harmonic blocking, voltage balancing
Distribution Static Compensator	Voltage regulation, harmonic elimination, correct power factor,
Solid State Transfer Switch	Interruptions, current limiting

Custom power devices applied to distribution systems provide high power quality to the critical loads. Flexible AC Transmission System (FACTS) devices, namely the Static Synchronous Compensator (STATCOM) and the Unified Power Flow Controller (UPFC), compensate the transmission system problems. The subject of FACTS devices is out of the scope of the thesis.

Any device that depends on a volatile memory chip for information storage is potentially at risk from power quality events. Many processes in industry depend on

automated microprocessor control systems. Solutions to the power quality problems encountered with this type of devices that are known as sensitive equipment (Stones *et al.,* 2001). These devices are usually installed in the low voltage system (< 1 kV) and three types are listed below:

- Programmable Logic Controllers (PLC)
- Electromechanical Relays and Motor Contactors
- Adjustable Speed Drives (ASD)

They often consist of protection for the control system alone, the actual process not being sensitive to the more common disturbances.

2.2. Introduction to Voltage Sag

Among the power quality problems voltage sags are the most important and common of the system. According to IEEE standard 1100-1992, sag (or dip) is an rms reduction in the ac voltage at the power frequency for durations from a half a cycle to a few seconds (IEEE Std. 1100, 1992).

It is important to note that interruptions are the disappearance of supply voltage and they have longer durations than typical sags. It is assumed that the rms values between 90% and 110% of nominal voltage cannot disturb the circuit operation. Voltage sag event occurs when the rms value of nominal voltage drops below the threshold voltage (typical value is 90%). Magnitude and duration are two essential and important sag characteristics that determine the equipment behavior (Radhakrishna *et al.*, 2001):

- Sag Magnitude: It is the net rms voltage reduction during the fault, in percent or in pu system nominal (rated) voltage. Field surveys have shown that the sag magnitude is relatively constant during the fault.
- Sag duration: Sag duration is the time the voltage is low, usually less than 1 second. The sag duration is dependent on the overcurrent protection equipment and how long the fault current is allowed to flow.

In Figure 2.2, the voltage sag has a magnitude of 50% and duration of 4 cycles.

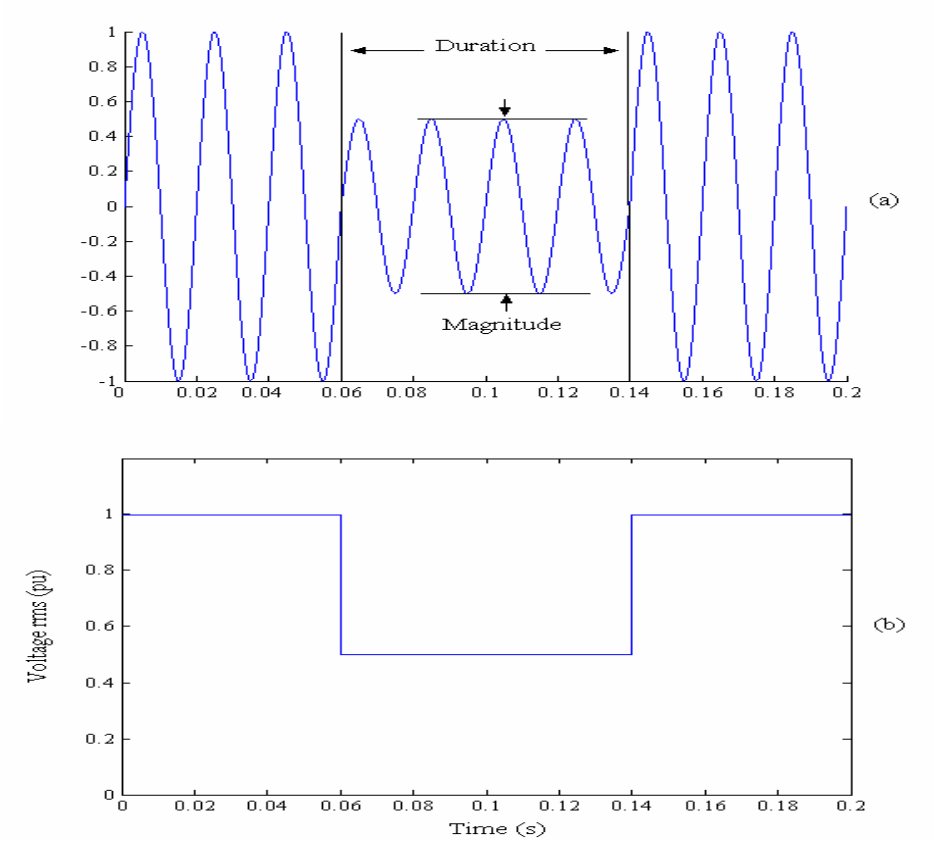


Figure 2.2 (a) Voltage sag to 50% at normal voltage and (b) rms voltage

Voltage sags can cause tripping of contactors, motor starters, relays, restarting expense of computers and shutdown of an entire production line. The sources of voltage sags are basically faults on adjacent feeders, lighting, short circuit event, start up of heavy loads, transformer energizing and motor starting (Bollen, 2001).

Most of these faults are self-clearing within a few milliseconds. If the fault is not cleared by itself, the protective devices operate rapidly to interrupt current within 3 to 30 cycles, depending on fault current magnitude and the type of overcurrent protection. Deeper voltage sags generally cause higher current peaks. The peak current after voltage sag depends on both the voltage sag magnitude and the voltage magnitude before the voltage sag. The peak current change is almost proportional to the step change in voltage (Carlsson, 2005).

2.2.1. Voltage Sag Types

The different types of faults increase the severity of balanced and unbalanced voltage sags. If the phase voltages during the sag have unequal magnitudes or phase relationship other than 120, the sag is considered to be unbalanced (Radhakrishna *et al.*, 2001). The fault type, transformer connection and equipment influence the characteristics of voltage sag in each phase of a three-phase system. The voltage sags experienced by three- phase loads can be classified into seven types denoted as A, B, C, D, E, F and G.

Type A is balanced sag and the other types are unsymmetrical sags. Figure 2.3 shows the phasor diagrams of voltage sag types (Elnady *et al.*, 2005; Guasch *et al.*, 2004).

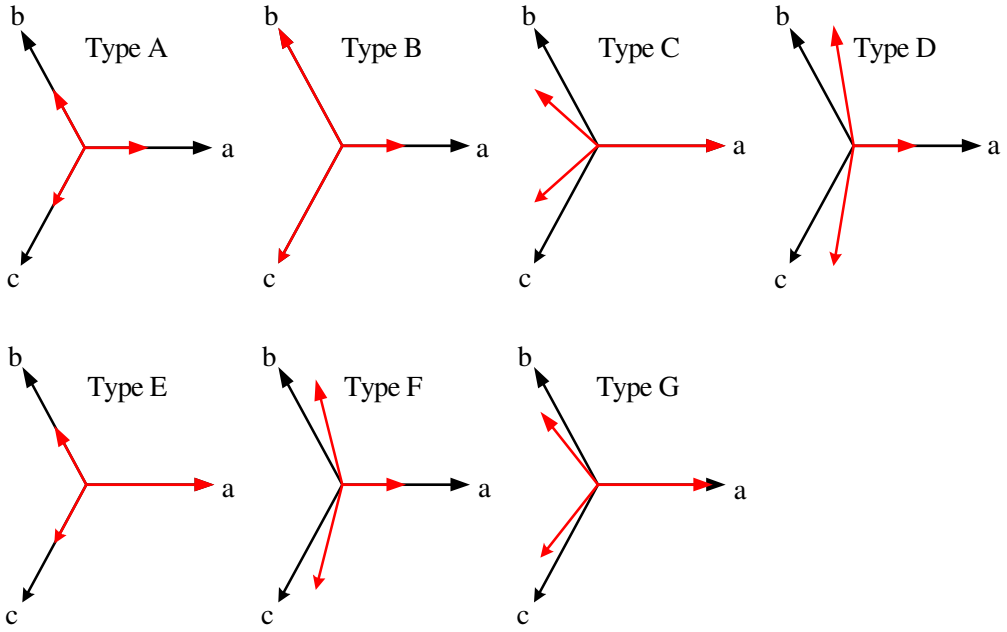


Figure 2.3 The phasor diagrams of voltage sag types

Type A sag generally occurs on the end user devices. It is rarely occurred in the distribution systems. The power requirement is the same for each of the three-phase devices.

Type B and D are the sags of single-line faults and they are the most common types in the distribution systems, it has an occurrence percent of 70% among all sags. In Type B sag, the system is solidly grounded so the non-faulted phases are kept healthy. In Type D sag, the system is grounded through the impedance. The non-faulted phases experience voltage change because the zero sequence differs from positive and negative impedance of the system.

Type C and E are the sags of double-line faults. These voltage sags have an occurrence of percentage of 20% among all types of sags that happen in distribution systems. Type C and E sags have common properties except for the angle between the sagged phases.

Type F and G are the sags of double-line ground faults. The worst case scenario for this type of sag is that the system is grounded through impedance. In that condition, the zero sequence voltage drop is increased drastically, so it is expected to have voltage change in non-faulted phases. The voltage changes in non-faulted phases occur because the zero sequence voltage drop increases effectively.

2.2.2. Characterization of Voltage Sags

The duration of sag and remaining voltage at point of common coupling (PCC) determine the characterization of the voltage sags. The PCC is the point from which both the fault and load are fed (Chung *et al.*, 2003).

The magnitude of the remaining voltage has more affect on the system operation than the duration of voltage sag. According the sample data taken from distribution feeders, remaining voltages at PCC range from 75% to 80% of nominal voltage and the duration of the sag is shorter than 200 ms (Stump *et al.*, 1998):

The below criterions determine the remaining voltage on the PCC:

- The capacity of the system
- The conductor type, size and length
- The value of fault and source impedances
- Characteristics properties of protective devices
- Node connection

The duration of voltage sag on the system is related with following criterions:

- The protection scheme of the system
- The settings of protection relays
- Time delay of the breakers

The total fault clearing time is sum of these criterions and determines the duration of voltage sag in the systems. The voltage sags always occur between two conductors such as sag between phase A and phase B or sag between phase A and neutral. The single-phase to ground faults are more common than three-phase faults.

When a fault occurs on *Load*1, its voltage goes to zero. *Load*2 voltage experiences sag and the sensitive load voltage is almost kept constant as shown in Figure 2.4.

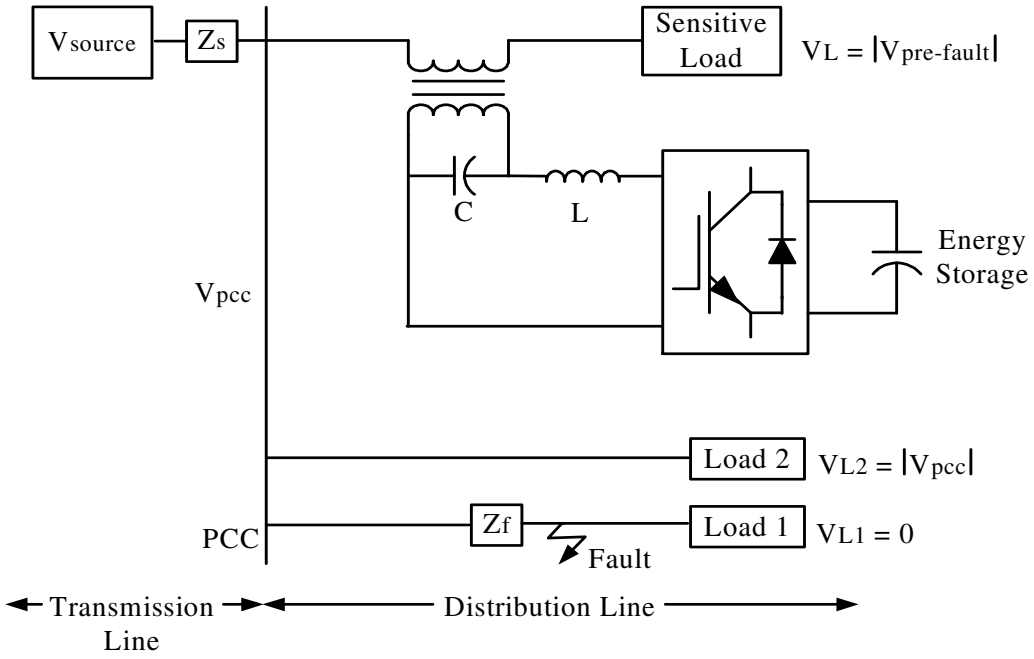


Figure 2.4 Power circuit of the DVR

The remaining voltage at PCC is calculated by Equation (2.1). The pre-fault voltage value P is normally equal to 1 pu.

$$V_{pcc} = P\frac{Zf}{Zf + Zs} \tag{2.1}$$

$$Z_s = R_s + jX_s \tag{2.2}$$

$$Z_f = R_f + jX_f \tag{2.3}$$

V_{pcc} is the remaining voltage at PCC; Z_s is the source impedance at the PCC; R_s is the source resistance; X_s is the source reactance; Z_f is the impedance between the PCC and the fault; R_f is the fault resistance; X_f is the fault reactance.

Voltage sag is mostly accompanied by phase angle jump ($\Delta\phi$) (Chung *et al.*, 2003), which can be obtained by Equation (2.4):

$$\Delta\phi = arg(V_{pcc}) = arctan(\frac{X_f}{R_f}) - arctan(\frac{X_s + X_f}{R_s + R_f}) \tag{2.4}$$

A common cause of voltage sags on the electrical distribution system is single-line to ground faults (SLGF). Table 2.2 shows what the transformer secondary voltages would be with SLGF and the tradeoffs on the impact to the phase voltages that occur, based on the wiring configuration of the transformer (Lasseter *et al.*, 1997).

Table 2.2 Transformer secondary voltages (pu) with SLGF

Transformer Connection (Primary - Secondary)	**Phase to Phase**			**Phase to Neutral**		
	Va	**Vb**	**Vc**	**Van**	**Vbn**	**Vcn**
Grounded wye - grounded wye	0.58	1.00	0.58	0.0	1.00	1.00
Grounded wye - ungrounded wye	0.58	1.00	0.58	0.0	1.00	1.00
Ungrounded wye - ungrounded wye	0.58	1.00	0.58	0.33	0.88	0.88
Ungrounded wye - grounded wye	0.58	1.00	0.58	0.33	0.88	0.88
Delta - delta	0.58	1.00	0.58	---	---	---
Ungrounded wye - delta	0.33	0.88	0.88	---	---	---
Grounded wye - delta	1.00	0.5	0.5	---	---	---
Delta - grounded wye	0.88	0.88	0.33	0.58	1.00	0.58
Delta - ungrounded wye	0.88	0.88	0.33	0.58	1.00	0.58

For example, where there are wye-wye or delta-delta connections, two phase to phase voltages will drop to 58% of nominal, while the other phase to phase is unaffected. However, for delta-wye and wye-delta connections, one phase to phase voltage will be as low as 33% of nominal, while the other two voltages will be 88% of nominal. It is the circulating fault current in the delta secondary.

2.2.3. General Solutions to Sag Mitigation

Voltage magnitude, waveform and frequency determine the quality of power supply. Several measures may be taken by the utility, end user and equipment manufacturer to reduce the number and severity of voltage sags caused by faults. The realization of a good system design and using correct protective devices can be insufficient to reduce the existence of voltage sags. The methods to mitigate the voltage sags by end user can be summarized by as follows:

- Modifying the overall system to decrease the number of voltage sags
- Using Ferro-resonant transformers, UPS on sensitive loads separately, motor generator sets or magnetic synthesizers
- Re-designing the loads firmly to voltage sags
- Choosing proper connection type of the transformer
- Using power electronic based custom devices if the voltage sag is major problem for a number of sensitive loads, using a DVR is more economic and effective solution because it will succeed the voltage sag mitigation lower energy ratings than the D-STATCOM or UPS.

The methods to mitigate the voltage sags by the utility can be summarized as follows (Dong *et al.*, 2004):

- Fault prevention activities include tree trimming, adding line arresters, insulator washing.
- Insulation on utility lines cannot be expected to withstand all lightning strokes.
- Any line that shows a high susceptibility of lightning, induced faults should be investigated.

- On transmission lines shielding effectiveness and tower footing resistance should be considered carefully.
- Fault clearing practices may include adding line reclosers, eliminating fast tripping, adding loop schemes and modifying feeder designs.

2.2.4. Power Quality Standards

The specific characteristics of supply voltage have been defined in standards, which are used to determine the level of quality with reference to: frequency, voltage level, wave shape and symmetry of the three-phase voltage (Mofty *et al.*, 2001). The IEEE 519-1992 and IEEE 1159-1995 describe the compatibility level required by equipment connected to the network, as well as the limits of emissions from the devices (IEEE Std. 519, 1992; IEEE Std. 1159, 1995). Table 2.3 summarizes the characteristic properties of disturbances.

Table 2.3 Typical characteristics of voltage disturbances

Disturbance Type	Typical Voltage Magnitude	Typical Duration
Sag	0.1-0.9 pu	0.5-30 cycle
Swell	1.1-1.8 pu	0.5-30 cycle
Flicker	0-1 %	Steady state
Interruption	< 0.1 pu	0.5 cycle-3 s
Imbalance	0.5-3 %	Steady state
Harmonics	5 %	Steady state

Most of the power system events are classified according to appropriate standards. A wide range of analytical techniques has been applied to the general topic of voltage sags. The customers' load can also be modeled, but load diversity and time dependent operation make this approach impracticable. Instead, equipment sensitivity to voltage sag can be considered and presented in the form of power acceptability curves. One of these curves is Computer Business Equipment Manufacturer Association (CBEMA) curve as shown in Figure 2.5.

The design goals of the CBEMA curve is to give a typical envelope of tolerance that devices such as the computer have to operate within. If the voltage exceeds the upper limit or lies under the lower limit, the device may fail to operate and/or possibly be damaged.

In the CBEMA curve shown in Figure 2.5, the vertical scale shows percent change in the bus voltage and the horizontal scale shows the duration of a disturbance event as seen at the load point.

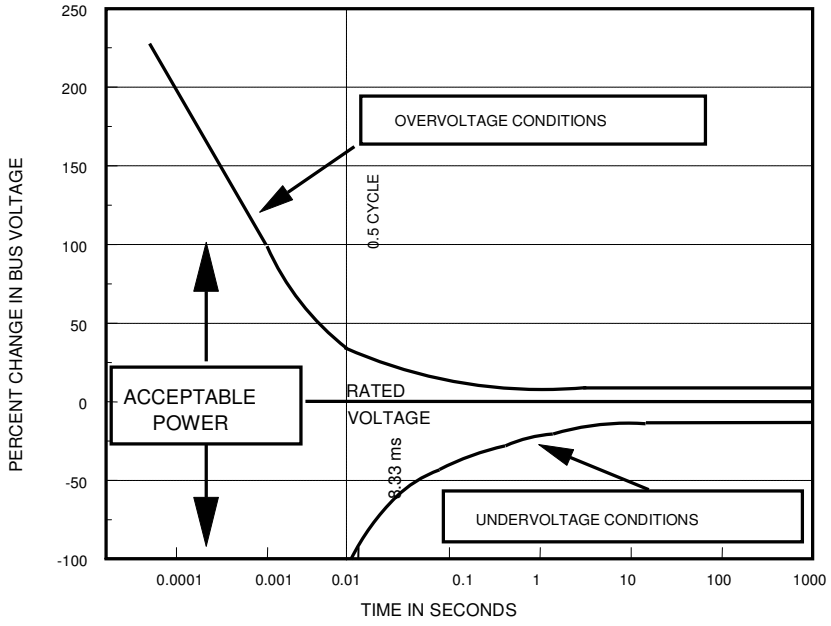


Figure 2.5 The CBEMA Curve

The “acceptable power” operating range is shown as the region included between the upper (overvoltage) limb and the lower (undervoltage) limb. Although the overvoltage region of power acceptability curves is important, the high visibility of the effects of momentary low voltage events gives particular interest to voltage sags. The area between the upper and lower limit is safe for the operation and outside of this region is dangerous for the operation of equipment. This curves aid the manufacturers for designing the power supply protection circuits.

The CBEMA curve is probably the best known of the power acceptability curves. The curve imposes power quality limits for typical computer systems. Most recently, CBEMA has changed its name to the Information Technology Industry Council (ITIC) and the existing curve has been changed. The more recent ITIC curve is shown in Figure 2.6.

Instrumentation to check compliance with the ITIC curve is more easily designed. It is claimed that the ITIC curve was developed to better reflect real world performance of electronic equipment.

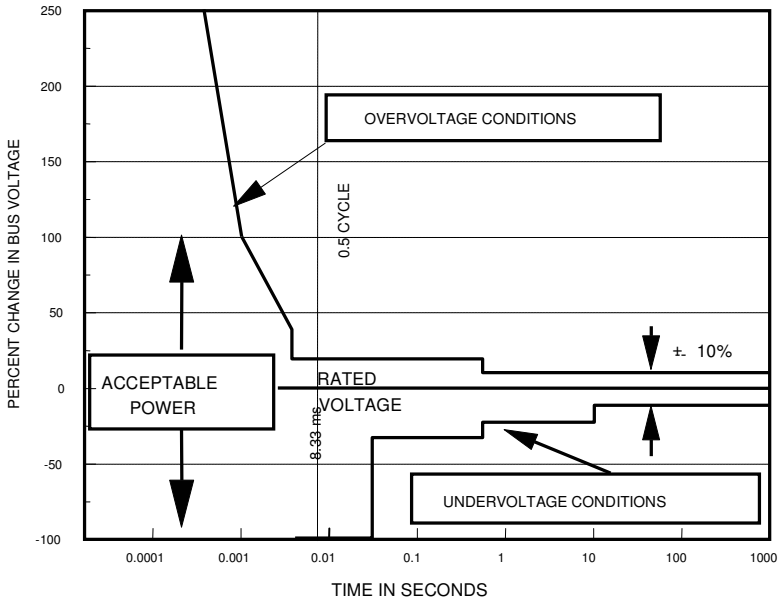


Figure 2.6 The ITIC Curve

The both of curves are an empirical set of curves that represents the intensity and duration of bus voltage disturbances. These curves are discussed with regard to the energy delivered to the load and alternatives for the assessment and measurement of bus voltage sags. Special attention is given to the three-phase case.

The voltage tolerance characteristics of some other devices are shown in Table 2.4 (Chung *et al.*, 2003; Won *et al.*, 2003).

Table 2.4 The voltage tolerance values of some devices

Equipment	**Vmin**	**Tmax**
PLC	60%	260 ms
AC control relay	65%	20 ms
5hp ac drive	75%	50 ms
Motor starter	50%	50 ms
Personal computer	60%	50 ms

V_{min} is the threshold voltage to operate correctly; T_{max} is the allowable time during input voltage stays below V_{min}.

The sensitivity of various devices to the voltage sags is determined by the standards. As shown in Table 2.4, the voltage tolerance characteristics are various for each equipment. Accordingly, the effects on each equipment caused by the same sag are also different. For example, AC Control Relay has 65% V_{min} and 20 ms T_{max}. It means that any sag longer than 20 ms and deeper than 35% (voltage drop) will cause to tripping of the equipment.

3. THE COMPONENTS OF DVR

3.1. General

The main components of DVR are energy storage unit, inverter circuit, filter unit and series injection transformer. The components are described with more details on the following.

3.2. Energy Storage Unit

The energy storage unit supplies required power for compensation of load voltage during voltage sag. The reactive power exchanged between the DVR and the distribution system is internally generated by the DVR without any ac passive reactive components, e.g. reactors or capacitors. Real power exchanged at the DVR ac terminals must be provided at the DVR dc terminal by an auxiliary energy storage system or grid itself (Woodley *et al.*, 1999). For most DVR applications, the energy source can be an electrolytic capacitor bank. The selection of the optimum topology and DVR ratings is related with the distribution of the remaining voltage, the outage cost and investment cost (Nielsen *et al.*, 2001).

3.2.1. Storage Systems with Auxiliary Supply

This topology is applied to increase the performance when the grid of DVR is weak. In this type, variable DC link voltage or constant DC link voltage topologies are applied.

3.2.1.1. Variable DC Link Voltage

The topology of this type is simple solution for short time voltage sags. The application of this topology is shown in Figure 3.1. The performance of this type decreases significantly when long duration voltage sags occur because DC link

capacitor decays exponentially during sag and the rating of DC link is small. Equation (3.1) calculates the energy stored in the capacitor.

$$E_{Storage} = \frac{1}{2} C_{DC} V_{DC}^2 \tag{3.1}$$

$$P_{series} = (1 - V_{pcc} / V_{rs})\, P_{load} \tag{3.2}$$

V_{DC} is the DC link voltage; C_{DC} is the DC link capacitor; V_{rs} is the rated supply voltage; V_{pcc} is the phase voltage during sag (remaining voltage); P_{series} is the three-phase power handled by the series converter; P_{load} is the three-phase power handled by the load.

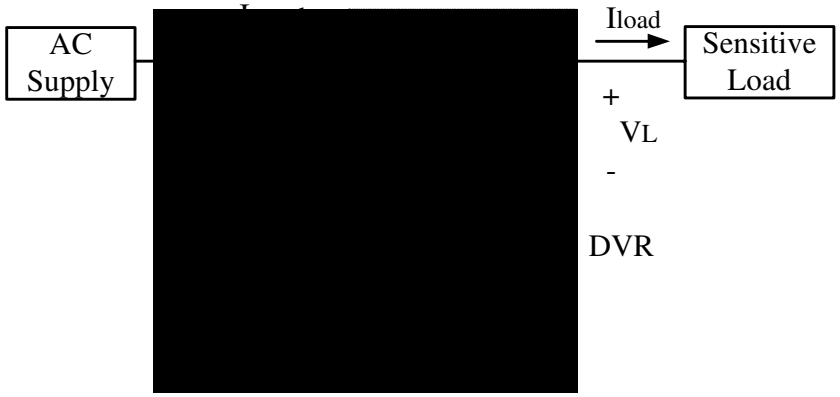


Figure 3.1 DVR with energy storage and variable DC link voltage

The charging of the DC link may be supplied either from a low rated auxiliary charging converter or from the series converter. This method proposes a relatively simple power topology (Acar, 2002).

3.2.1.2. Constant DC Link Voltage

The increased performance and continuity of constant voltage are obtained in this topology because the necessary energy is supplied from a large storage to a small rated DC link.

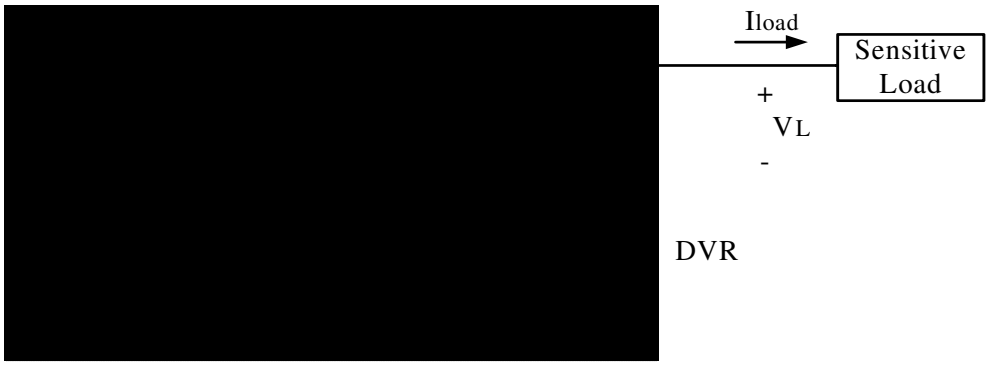


Figure 3.2 DVR with constant DC link voltage

$$P_{PowerConverter} = P_{series} \cong (1 - V_{pcc} / V_{rs})\, P_{load} \quad (3.3)$$

The application of this topology is shown in Figure 3.2. The DC link voltage is almost kept constant with this topology but complexity of the power circuit increases.

3.2.2. Storage Systems with Grid Itself

The remaining voltage on supply side or load side is used to supply necessary power to the system if the DVR is connected to the strong grid.

3.2.2.1. Supply Side Connected Converter

In this topology, uncontrollable DC link voltage and shunt converter charge the DC link capacitor as shown in Figure 3.3. During voltage sag, the DC link voltage will drop with respect to the remaining sag voltage according to:

$$V_{DC} = \sqrt{6}\, V_s = \sqrt{6}\, V_{pcc} \quad (3.4)$$

$$P_{shunt} = P_{series} \cong 3\,(1 - V_{pcc} / V_{rs})\, P_{load} \quad (3.5)$$

$$I_{shunt} \cong \frac{(1 - V_{pcc} / V_{rs})}{V_{pcc} / V_{rs}} I_{load} \quad (3.6)$$

Figure 3.3 DVR with no energy storage and supply side connected converter

V_s is the supply voltage (rms); P_{shunt} is the three-phase powers handled by shunt converter.

In this topology, the power handled by the shunt converter is proportional to the missing voltage. In case of severe sags, the current drawn by the converter rises significantly (Acar, 2002).

3.2.2.2. Load Side Connected Converter

The DC link is fed from load side as shown in Figure 3.4. The DC link voltage is almost constant because it is fed from corrected constant load voltage.

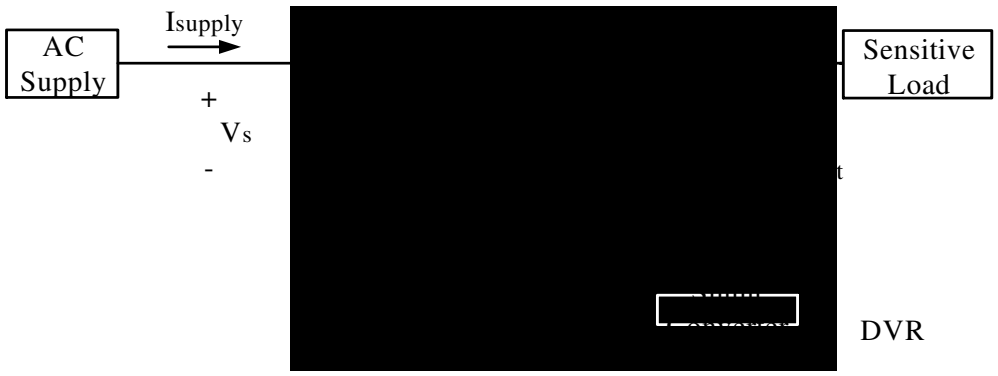


Figure 3.4 DVR with no energy storage and load side connected converter

$$V_{DC} = \sqrt{6}\, V_L \tag{3.7}$$

$$P_{shunt} = P_{series} = \frac{(1 - V_{pcc} / V_{rs})}{V_{pcc} / V_{rs}} P_{load} \tag{3.8}$$

The main drawback of this topology is the distorted current drawn by the shunt converter that will significantly degrade the quality of the load voltage.

3.3. Inverter Circuit

The inverters circuits convert DC power to AC power. The types of inverter are voltage source (fed) inverter and current source (fed) inverter (Dixon *et al.*, 1997; Nielsen *et al.*, 2003). Solid-state semiconductor devices with turn-off capability are used in the inverter circuits.

3.3.1. Current Source Inverter (CSI)

Current source inverters are like DC current source of high impedance at the input. Variable current source can be obtained by using large inductance in series to variable voltage source as shown in Figure 3.5. The load with a stiff current source does not disturb the output current waves.

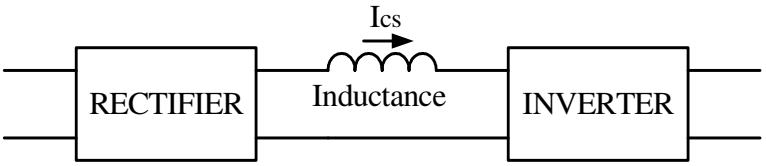


Figure 3.5 Main circuit configuration of CSI

The inductance value is relatively large to satisfy almost constant I_{cs}. Inverter circuit can adjust the magnitude of the current. In the current source inverter, it is easy to limit overcurrent conditions but the value of output voltage varies widely with changes in load. In this thesis, the primary concern is supplying the constant load voltage at different fault condition by controlling the injected voltage. Current source inverter does not achieve the variable output voltage of the inverter.

3.3.2. Voltage Source Inverter (VSI)

A voltage source inverter is energized by a stiff DC voltage supply of low impedance at the input as shown in Figure 3.6. The output voltage is independent of load current. Voltage source inverters are widely used in low and high power applications such as motor drives, traction, UPS and bi-directional AC-DC converters.

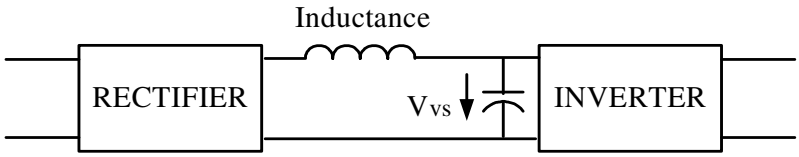
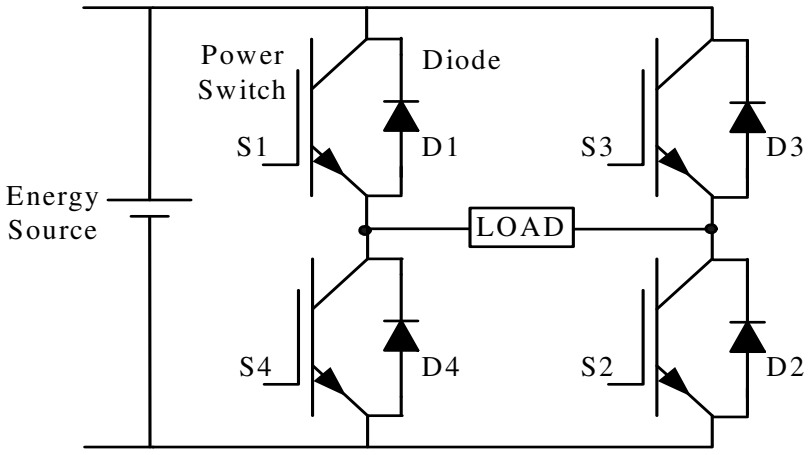
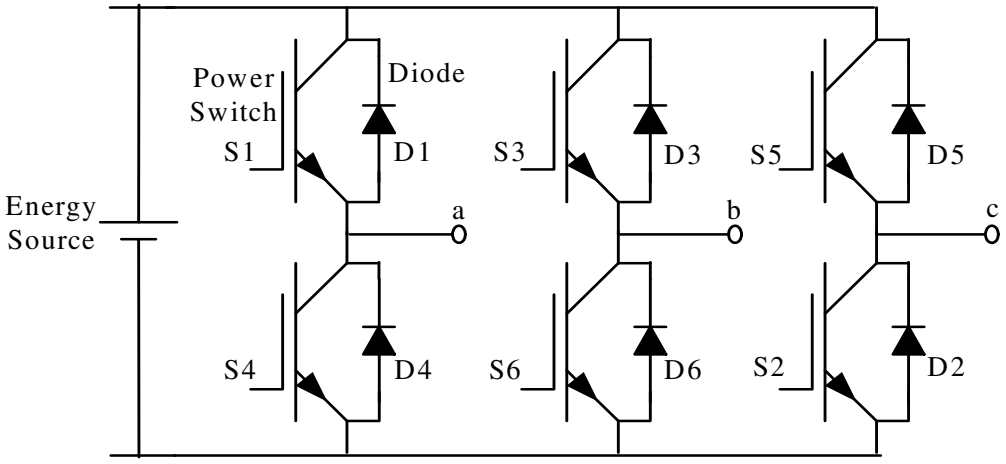


Figure 3.6 Main circuit configuration of VSI

In the voltage source inverter, the values of output voltage variations are relatively low due to capacitor but it is difficult to limit current because of capacitor. The inverters are then connected in series to the distribution line through a set of three single-phase injection transformers. The most common voltage source inverter types are single-phase and three-phase bridge inverters as shown in Figure 3.7.



(a) Basic single phase inverter



(b) Basic three-phase inverter

Figure 3.7 (a) Basic single-phase and (b) three-phase inverter

The three single-phase Pulse Width Modulation (PWM) voltage source inverters will be used in this thesis. PWM switched inverters provide better performance to control unsymmetries and especially overcurrents during unbalanced faults. The voltage control is achieved by modulating the output voltage waveform within the inverter. The rating of PWM voltage source inverter is low in voltage and high in current because of using the step up injection transformer.

The main advantage of PWM inverter is including fast switching speed of the power switches. PWM technique offers simplicity and good response. Besides, high switching frequencies can be used to improve on the efficiency of the converter, without incurring significant switching losses (Lara *et al.*, 2002).

The basic idea of PWM is varying the on or off periods at a constant frequency so that the on periods are longest at the peak of the wave. The control of switch duty ratio adjusts the output voltage. The switch duty ratio (D_r) can be expressed as:

$$D_r = \frac{t_{on}}{T} \tag{3.9}$$

t_{on} is the on interval; T is the switching period; D_r is varied from zero to one depending on the level of the reference signal.

The PWM modifies the width of the pulses in a pulse train by using control signal. When the value of control voltage increases, it results wider pulses. The waveform of control voltage for a PWM circuit will determine the waveform of the produced voltage.

In Figure 3.8, sinusoidal control wave is compared with carrier wave, which has a higher frequency. Between the crossover points, where the value of the triangle wave is lower than the value of the sinusoidal waveform, $S3$ and $S4$ are triggered, at other times $S1$ and $S2$ are triggered. In this type of PWM, the pulse width is varied throughout the half cycle in a sinusoidal manner and low order harmonics are eliminated.

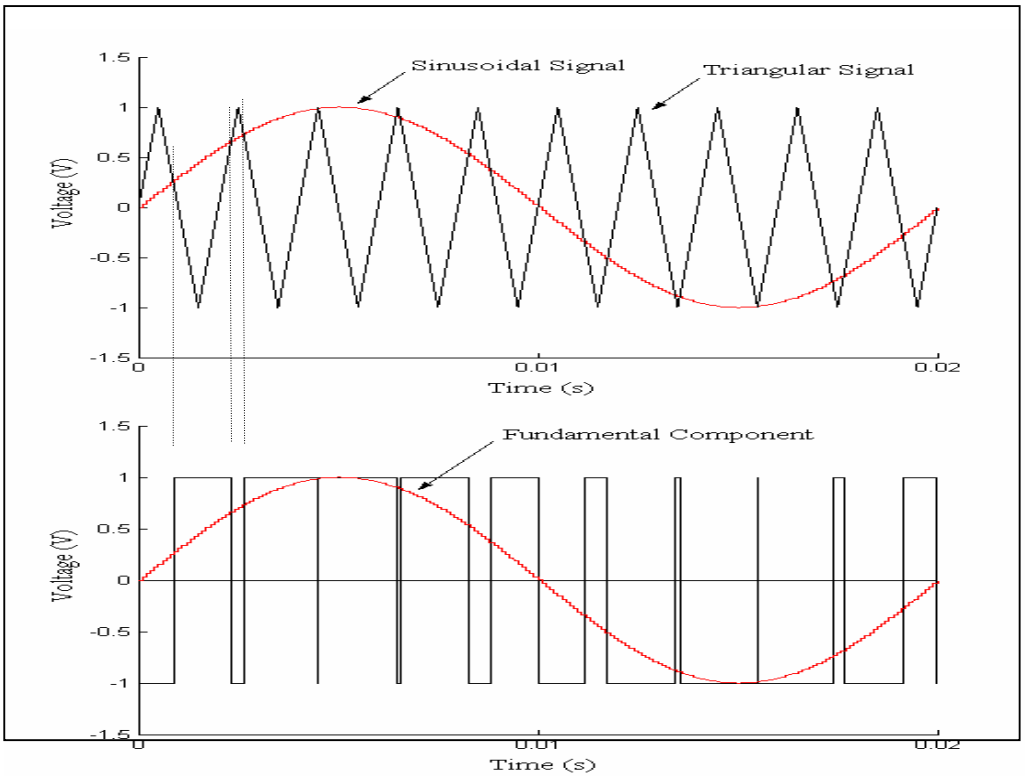


Figure 3.8 Switching strategy for PWM inverter

This comparison produces the output waveform at the same fundamental frequency with the control voltage. The sinusoidal input voltage allows the inverter switches to be turn-off or on at or very near input voltage zero crossing. This switching technique virtually eliminates switching losses.

Due to the produced output voltage is not pure sinusoidal waveform, it will have voltage values at other frequencies. The harmonics can cause the increase of the rms value and the peak value of the distorted waveform. The connection type of transformer and filtering unit eliminate the basic harmonics. The inverter requires an inductance to eliminate the current ripples. If large inductance is used, it will increase the impedance of DVR so increased voltage drop on DVR system.

Depending on the connection respective to the AC network, the VSI can have a configuration based on shunt or series connected. Table 3.1 shows the functions of series and shunt inverters (Taylor, 1995).

Table 3.1 The multifunction tasks of VSI types

VSI Type	Main Tasks
Series	Mitigation of sags and unbalance on the supply voltage, harmonic blocking, power flow control
Shunt	Harmonic elimination, flicker mitigation, load balancing, reactive power and voltage control

To approach ideal inverter characteristics, the voltage drop on it should be decreased. Choosing a more complicated inverter topology can help achieve low DVR impedance, low current ripple and low switching frequency, but the penalty is higher complexity of the system and cost (Praveen *et al.*, 2004).

3.4. Series Injection Transformers

The ac electrical energy is converted from one ac voltage level to another ac voltage level at the same frequency by transformers. The sketch of an ideal single-phase transformer is shown in Figure 3.9.

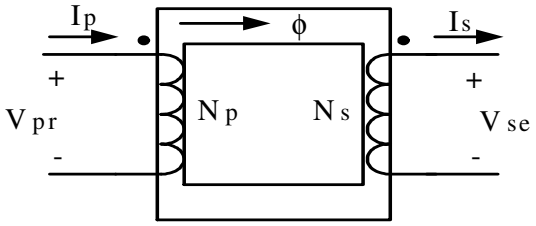


Figure 3.9 Sketch of an ideal transformer

The magnetic flux presents a connection between the primary and secondary coils. The basic relationship between the parameters is shown in below:

$$\frac{V_{pr}}{V_{se}} = \frac{I_s}{I_p} = \frac{N_p}{N_s} = m \tag{3.10}$$

V_{pr} is the voltage produced on the primary side; V_{se} is the voltage produced on the secondary side; N_p is the turn of wire on its primary; N_s is the turn of wire on its secondary respectively; m is the turn-ratio of the transformer.

The equivalent circuit of a real transformer is shown in Figure 3.10.

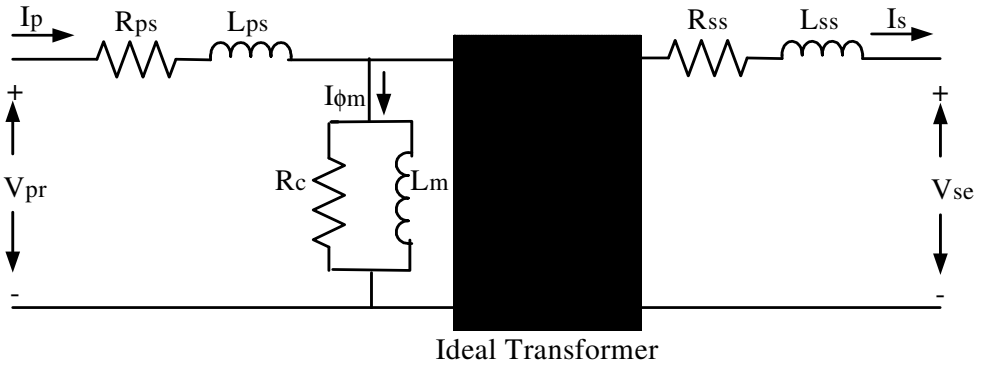


Figure 3.10 The equivalent circuit of a real transformer

In practice, $I_{\phi m}$ is considerably smaller than I_p current. By ignoring this current that results absence of R_c and L_m, the circuit can be simplified as shown in Figure 3.11.

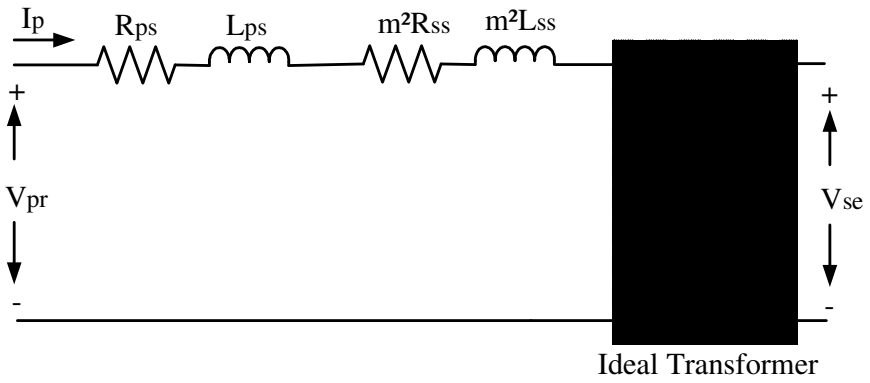


Figure 3.11 The simplified circuit of a real transformer

R_{ps} is the resistance of primary side coils; R_{ss} is the resistance of secondary side coils; L_{ps} is the leakage inductance in the primary side; L_{ss} is the leakage inductance in secondary side; R_c is the core loss (hysteresis and eddy current losses); X_m is the reactance related with the magnetization of the core.

The transformers not only reduce the voltage requirement of the inverters, but also provide isolation between the inverters. This prevents the dc storage capacitor from being shorted through switches in different inverters (Ghosh *et al.*, 2002).

The electrical parameters of series injection transformer should be selected correctly to ensure the maximum reliability and effectiveness. IGBT switches are commonly used in series connected circuits. In normal bypass mode, full load currents pass through these semiconductor switches. In addition to this, the flowing current will increase during sags because of injected power for compensation so the switches should handle the total current.

It has been recognized that in order to guarantee the maximum reliability and effectiveness of this restoration scheme, judicious selection of the injection transformer is a prerequisite. To integrate the injection transformer correctly into the DVR the MVA rating, the short circuit impedance, the primary winding voltage and current ratings, the turn-ratio and winding parameters of the injection transformer should be carefully calculated (Li *et al.*, 2000).

3.4.1. MVA Rating

The MVA rating is determined by using power calculation equation by considering safety margin denoted as K_s. V_{pr} is the primary voltage of the injection transformer and I_{pr} is the current rating of injection transformer.

$$P = K_s V_{pr} \mathrm{I}_{pr} \tag{3.11}$$

The correct value of safety margin will include the instantaneous voltage and current values during switching period in system design. The injection transformer should be designed to keep at least the twice the normal steady state flux to avoid from the saturation.

3.4.2. The Primary Winding Voltage and Current Ratings

The primary (high voltage) side voltage rating of series injection transformer is related with the maximum voltage sag depth, energy storage scheme, filtering unit and voltage sag characteristics. The rating of the injection transformer can be calculated by using Equation (3.12).

$$V_{inj} = DV_r \tag{3.12}$$

$$V_s = (1 - D)\, V_r \tag{3.13}$$

V_r is the rated rms voltage of the primary feeder; D is the maximum single-phase voltage sag to be compensated ($D<1$); V_{inj} is the injection voltage.

The sources of voltage sags are typically lighting strikes or short circuit faults. The faults can cause the phase and amplitude shift of the supply voltage. The voltage injection strategies are described in the next chapter. These strategies will restore the voltage and determine the magnitude of the voltage rating on the primary side.

The cost of energy storage unit is related with its size of capacity. The magnitude of the injected voltage is determined by the injection strategy. The request of minimizing the injected power can change the primary voltage rating. For example, in-phase method increases the magnitude of injected voltage to minimize the injected active energy.

The filtering system of DVR is another parameter that determines the voltage ratings. The filtering system can be placed either on the line side (high voltage side) or inverter side (low voltage side). The inverter side filtering system will eliminate the high order harmonics from the inverter and thus transformer current rating can be neglected. In line side filtering system the high order harmonic currents will penetrate through injection transformer and they will carry harmonic voltages.

The primary side current rating is primarily determined by the rated capacity of the sensitive load because the inverter side filtering system will not allow the high order harmonics to penetrate through the injection transformer. The more calculations are required for line side filtering scheme because the high order harmonics generated by the inverter will change the current carrying capability of the inverter. The place of energy storage unit affects the current rating of the transformer. The additional current sourced by auxiliary supply or grid itself is different.

3.4.3. Turn-Ratio

The turn-ratio determines the secondary (low voltage) voltage and current ratings. By taking into account the available switching devices (proper current carrying capability, blocking voltage and cost) and DC link capacitor, the optimum secondary parameters are determined. In practice, the turn-ratio is adjusted until finding available switching devices with minimum cost of storage device.

3.4.4. Short Circuit Impedance

The system generally operates in steady state conditions but the characteristic of the system in the short circuit or abnormal conditions must be known. The fault

current, design of filtering system and the voltage drop on transformer are related with short circuit impedance value. The shorter the electrical distance between the DVR and the fault, the closer is the characteristics of the voltage sensed at the DVR to that at the fault location.

The simplified equivalent circuit of DVR when inverter side filtering is applied is shown in Figure 3.12.

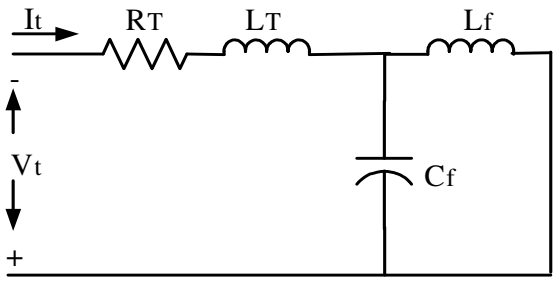


Figure 3.12 Equivalent circuit of DVR with inverter side filter

V_t is the specified voltage drop value across the injection transformer during the normal operating conditions of the system; R_T is the short circuit resistance value; X_T is the short circuit reactance value; C_f is the filter capacitance value; X_f is the filter reactance value.

$$R_T = R_{ps} + m^2 R_{ss} \tag{3.14}$$

$$L_T = L_{ps} + m^2 L_{ss} \tag{3.15}$$

The voltage drop across the injection transformer during standby mode must be less than specified value. To satisfy this condition, the short circuit impedance should be as below equation:

$$\sqrt{R_T{}^2 + w^2 (L_T + L_f \,//(1 - w^2 L_f C_f))^2} \;\langle\; (V_T / I_T) \tag{3.16}$$

The simplified equivalent circuit with line side filtering is shown in Figure 3.13.

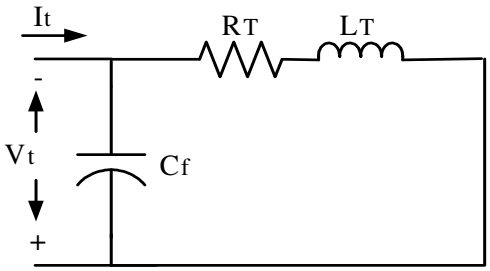


Figure 3.13 Equivalent circuit of DVR with line side fitler

Under normal conditions the short circuit impedance of injection transformer determines the voltage drop across the DVR. This impedance must be low and must have an impact on the fault current through the voltage source PWM inverter on secondary side caused by a short circuit at load side.

3.4.5. Winding Parameters

As shown in Figure 3.10, the transformer block consists of the winding resistances (R_{ps}, R_{ss}), the leakage inductances (L_{ps}, L_{ss}) and the magnetizing characteristic of the core (R_c, L_m). In order to comply with industry, the resistance and inductance of the windings should be specified in per-unit (pu) system. The values are based on the transformer rated power P_n (VA), nominal frequency f_n (Hz) and nominal voltage V_n (rms) of the corresponding winding (Simpowersystems for use with MATLAB, 2002). For each winding, the per-unit resistance and inductance are defined as:

$$R_{(pu)} = \frac{R(\Omega)}{R_{base}} \tag{3.17}$$

$$L_{(pu)} = \frac{L(H)}{L_{base}} \tag{3.18}$$

The base resistance and base inductance used for each winding are:

$$R_{base} = \frac{(V_n)^2}{P_n} \tag{3.19}$$

$$L_{base} = \frac{R_{base}}{2\Pi f_n} \tag{3.20}$$

To specify a magnetizing current of 0.5% (resistive and inductive) based on nominal current, the per-unit values of 1/0.005 = 200 pu for the resistance and the inductance of the magnetizing branch should be entered.

3.5. Filter Unit

The semiconductor switching devices are used in wide variety of industrial loads. The non-linear characteristics of semiconductor devices cause distorted waveforms associated with harmonics. To overcome this problem and providing clean electrical supply filter unit is used. The filter unit eliminates the dominant harmonics produced by inverter circuit. The inverter side filtering and line side filtering are basic types of filtering scheme (Choi *et al.,* 2002; Li *et al.,* 2001).

The inverter side filtering scheme has the advantage of being closer to the harmonic source thus high order harmonic currents are prevented to penetrate into the series injection transformer but this scheme has the disadvantages of causing voltage drop and phase angle shift in the fundamental component of the inverter output. In the line side filtering system harmonic currents penetrate into the series injection transformer but the voltage drops and phase shift problems do not disturb the system (Acar, 2002).

As the unique values of the parameters of the LC filter cannot be specified based on the total harmonic of the capacitor voltage alone an additional criterion based on the minimum reactive power of the LC filter is used to specify these parameters (Dahono *et al.*, 1995). In this thesis, the inverter side filtering is preferred for harmonic elimination, so it will be analyzed deeply.

3.5.1. Inverter Side Filter

The inverter side filter is closer to the harmonic source and low voltage side thus it prevents the harmonic currents to penetrate into the series injection transformers (Choi *et al.,* 2002). This can cause voltage drop and phase shift in the fundamental component of the inverter output.

At present, the LC filter is usually designed based on the Fourier series of the inverter output voltage waveform. Accurate results, therefore, cannot be obtained without taking into account a large number of harmonics with the associated complex additions and multiplications (Dahono *et al.*, 1995). The equivalent circuit of single-phase PWM inverter is shown in Figure 3.14.

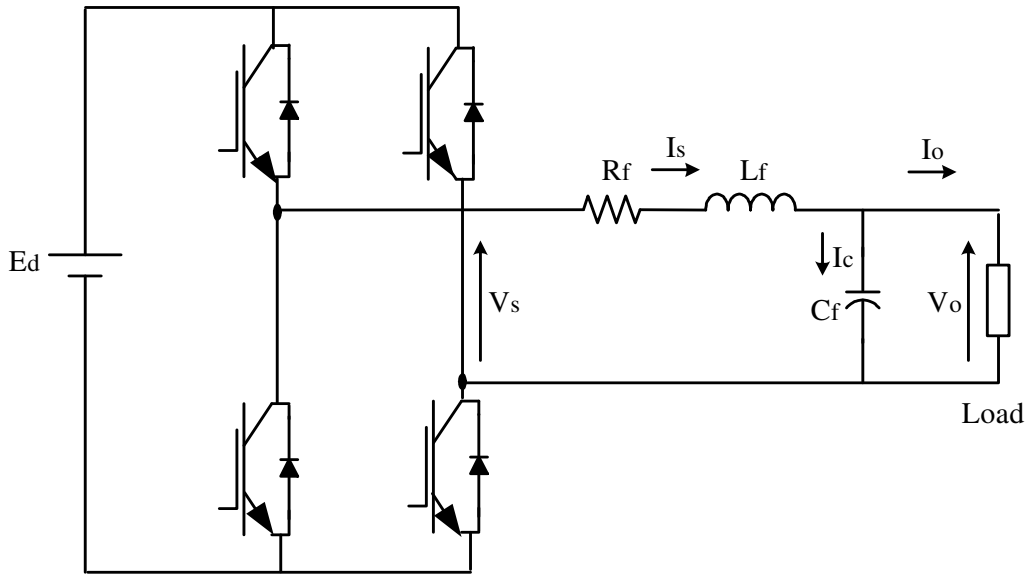


Figure 3.14 Equivalent circuit for inverter side filter

E_d is the nominal dc source voltage; V_s is the output voltage of the PWM inverter; R_f is the filter resistance; I_s is the source current; L_f is the filter inductance; I_c is the capacitor current; C_f is the filter capacitance; I_o is the load current; V_o is the load voltage.

In this analysis, the followings are assumed:

- The dc source voltage E_d is ripple free and constant.
- The inverter switching devices are assumed as ideal switches.
- The equivalent series resistance of the filter capacitor is neglected.
- The load is a linear load.

Based on the Figure 3.14, the output voltage equation of the inverter can be written as:

$$V_s = V_o + R_f I_s + L_f \frac{dI_s}{di_t} \tag{3.21}$$

According to reference (Dahono *et al.*, 1995), although a criterion based on the minimum cost, size and losses can be used as an additional criterion, a criterion based on the minimum reactive power is used in the paper. Minimization of the reactive power also indirectly minimizes the size, losses and cost of the filter.

The design procedure of the LC filter can be divided into three steps by considering the assumptions. The following equations are obtained through comprehensive analysis of derived formulas. The deeper analysis about the derivation of formulas can be obtained from the paper.

- Calculation of modulation index: Based on the dc source voltage E_d and nominal load voltage V_o, the modulation index is calculated.

$$k = \sqrt{2} \frac{V_o}{E_d} \tag{3.22}$$

Because the voltage drop across the filter inductor cannot be determined before the parameters of the filters are specified, this voltage drop can be assumed to be negligible. The rms value of the output voltage of the inverter can be assumed the equal to the rms value of the load voltage ($V_s \cong V_o$). The result is used to calculate the factor K by using Equation (3.23).

$$K = \left[\frac{k^2 - \frac{15}{4}k^4 + \frac{64}{5\Pi}k^5 - \frac{5}{4}k^6}{1440} \right]^{1/2} \tag{3.23}$$

- Calculation of the inductance of the filter: Equation (3.24) calculates the optimum value of the filter inductance.

$$L_f = \frac{V_o}{I_o f_s} \left\{ K \frac{E_d}{V_{o,av}} \left[1 + 4\Pi^2 \left(\frac{f_r}{f_s} \right)^2 K \frac{E_d}{V_{o,av}} \right] \right\}^{1/2} \tag{3.24}$$

f_s is the switching frequency; $V_{o,av}$ is the total harmonic of the load voltage; f_r is the fundamental output frequency.

- Calculation of the capacitance of the filter: Equation (3.25) calculates the filter capacitance

$$C_f = K \frac{E_d}{L_f f_s^2 V_{o,av}} \tag{3.25}$$

The LC filter attenuates the harmonics by providing a shunt path for the harmonic current and series impedance for the harmonic voltages.

3.5.2. Line Side Filter

The line side filter is closer to high voltage side so higher rating on transformer is needed (Li *et al.,* 2001). The filter voltage drop and phase shift problems do not disturb this system. A common problem facing these two filtering schemes is that the filter capacitor will cause an increase in the inverter rating (Zhan *et al.*, 2001). The equivalent circuit of line side filter is shown in Figure 3.15.

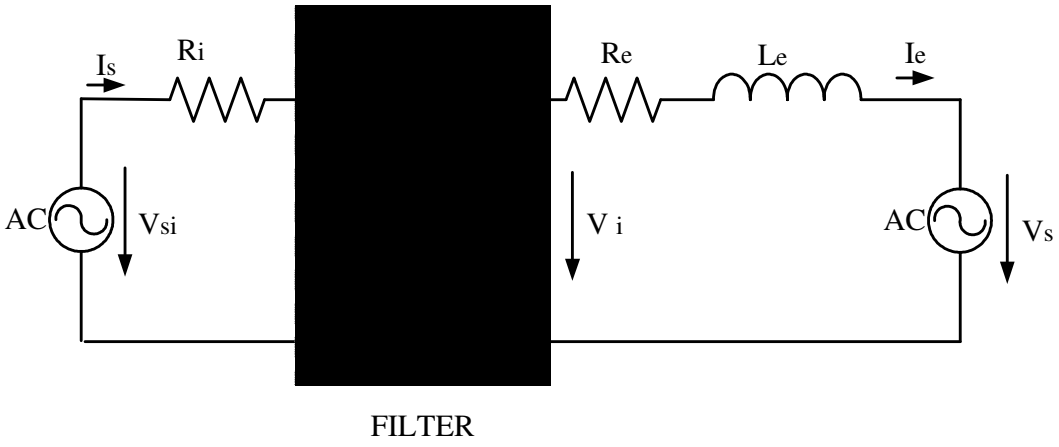


Figure 3.15 Equivalent circuit for line side filter

V_{si} is the voltage on the inverter side of the filter; R_i is the resistance of the series injection transformer; L_i is the leakage inductance of the series injection transformer; C is the filter capacitor; $Z_{e(m)} = R_e + jw_o L_e$ is the equivalent impedance of the system external to the DVR; V_s is the equivalent source of the power system; w_o is the fundamental angular frequency.

The filter capacitor provides a shunt path for harmonic currents. The formula for capacitor to attenuate the high order harmonics to a permissible level on V_i is:

$$\left|Z_{e(m)}\right| = K_f \left|Z_{c(m)}\right|, \; K_f \gg 1 \tag{3.26}$$

Here, $Z_e = R_e + jmw_o L_e$ and $Z_{c(m)} = -j/mw_o C$

Let $V_{si(n)}$ represents the nth order harmonic voltages (rms) on the inverter side of the series transformer, while $V_{i(n)}$ represents the nth order harmonic voltages (rms) across C, $n = m, m+1, m+2, ...M$ where M is the highest order of the harmonic voltages to be attenuated. By taking Equation (3.26) into consideration, the following relationship can be obtained.

$$\frac{V_{i(n)}}{V_{si(n)}} = \frac{1/(jnw_{oC})}{R_i + jnw_oL_i + 1/(jnw_oC)} \tag{3.27}$$

The absolute value of Equation (3.27) is:

$$\left|\frac{V_{i(n)}}{V_{si(n)}}\right| = \frac{1}{\sqrt{\left\{1-(nw_o)^2 L_iC\right\}^2 + (R_i nw_oC)^2}} \tag{3.28}$$

The permissible THD across the capacitor, denoted as V_T, is measured by using Equation (3.29).

$$V_T = K_{THD}V_p \tag{3.29}$$

K_{THD} is the permissible THD level at the source voltage level; V_p is the rated voltage of the primary feeder per-phase.

To satisfy the voltage THD requirement for the primary feeder from Equation (3.28), the following condition must be met:

$$\sqrt{\sum_{n=1}^{M} V_{i(n)}^2} = \sqrt{\sum_{n=m}^{M} \frac{V_{si(n)}^2}{\left\{1-(nw_o)^2 L_iC\right\}^2 + (R_i nw_oC)^2}} \langle V_T \tag{3.30}$$

The final equation obtained by the simplification of Equation (3.30) results in:

$$C \geq \frac{\left(1+\sqrt{\sum_{n=m}^{M}\left\{(\frac{m}{n})^2 V_{Si(n)}\right\}^2}\Big/(K_{THD}V_p)\right)}{(m\varpi_o)^2 L_i} \tag{3.31}$$

In order to determine the filter capacitor value, the THD requirement at the load side of the DVR and the harmonic spectrum of the inverter output for specific injection transformer parameters should be specified (Acar, 2002). The rate of the inverter is related with the capacitor value thus proper capacitor value should be chosen to get optimum solution. The line side filtering is deeply analyzed in references (Li *et al.,* 2001; Zhan *et al.*, 2000).

High order algebraic equations and derivations of formulas can be obtained from the references. Generally, small L and C values imply a high filter's cut frequency, demanding larger switching frequencies, which is not feasible for high power converters (Ahn *et al.*, 2004).

3.6. Harmonic Problems in Power Systems

The electrical and electronics devices in power systems are designed to operate at fundamental frequency. However, certain types of loads produce currents and voltages with frequencies that are integer multiples of the fundamental frequency. The most common sources of harmonics are power electronic loads and switch mode power supplies. Due to the tremendous advantages in efficiency and controllability, power electronic loads are proliferating and can be found at all power levels (Grady *et al.*, 2001).

It is interesting to note that some devices that are sensitive to power quality disturbances are often equipment that generates harmonics. For example, devices such as adjustable speed drives, computer power supplies, UPS equipment and other power electronics create harmonic currents. Harmonic currents generate harmonic voltages as they pass through the system impedance. These harmonic components can cause input voltage distortions, additional heating, overvoltages in distribution and transmission systems, errors in metering and the malfunction of protective relays (Dougherty *et al.*, 1997; Mohan *et al.*, 1995).

DVR uses diodes, power transistors and other electronic devices for correcting load voltage, controlling power flow, converting DC voltage to AC voltage and protecting itself from faults. During operation, the PWM inverter

produces harmonics. These harmonics must be reduced to an acceptable limit causing negligible impact to the load and utility supply. This is done by using a sophisticated modulation scheme that effectively attenuates low order harmonics (Wunderlin *et al.*, 1998).

The non-sinusoidal current interacts with system and produces voltage distortion. The most common measure of distortion is total harmonic distortion (THD). It is used in low-voltage, medium-voltage and high-voltage systems. It is expressed as a percent of the fundamental and is defined as:

$$THD = \frac{\sqrt{\sum_{2}^{\infty} C_k^2}}{C_1} \cdot 100\% \tag{3.32}$$

C_1 is the magnitude of the fundamental component; C_k is the magnitude of the harmonic components (k = 2, 3, 4...).

The voltage THD value should be below than 5% for sensitive loads. In this study, the following solutions are employed to improve the voltage restoration performance:

- Adoption of the new control scheme for PWM inverter
- Adding LC filter that is designed based on THD and minimum reactive power criterions
- Selection of proper transformer connection type to reduce the harmonics

The passive LC filters can be used for harmonic compensation if the produced harmonics have constant frequency but the passive filters can create low frequency resonances with the power system. The active filters can compensate the harmonics of different frequencies even if the harmonics are not constant. However, high switching frequency is necessary for the active filters. The hybrid active/passive filters can be applied for harmonic compensation and voltage regulation to reduce the costs and improve efficiency. Based on the characteristics of the designed system and the nature of the problems encountered, the suitable filter configuration can be employed for harmonic compensation.

3.7. Market Requirements of the DVR

The demand for new equipment (e.g. DVR) that protects the customer from loosing his plant will increase in the future due to the deregulation of the energy market. To insure the proper operation of the DVR the customer puts several requirements on the equipment. Following key points are of concern (Daehler *et al.*, 2000):

- Sag compensation capability
- Reliability and availability
- Losses
- Control and protection
- Harmonics
- Monitoring

4. OPERATION OF DYNAMIC VOLTAGE RESTORER

4.1. General

Among the voltage transients (sags, swells, harmonics…), the voltage sags are the most severe disturbance. The users may improve end-use devices or use protection devices to reduce the number of voltage sags. But overall solution to mitigate the voltage sags and recovering the load voltage to the pre-fault value is using a Dynamic Voltage Restorer (DVR). It is a solid state DC to AC switching power electronic converter that injects three single-phase AC voltages in series between the feeder and sensitive load. Furthermore DVR can be designed to reduce phase unbalance and compensate voltage harmonics (Ahn *et al.*, 2004). Using a DVR is more reliable and quick solution to maintain with a clean supply of electricity for customers. But standby losses, equipment costs and required large investigation for design are the main drawbacks of DVR. The DVR is connected in the utility primary distribution feeder as shown in Figure 4.1. This location of DVR will mitigate the certain group of customer by faults on the adjacent feeder (Fitzer *et al.*, 2004).

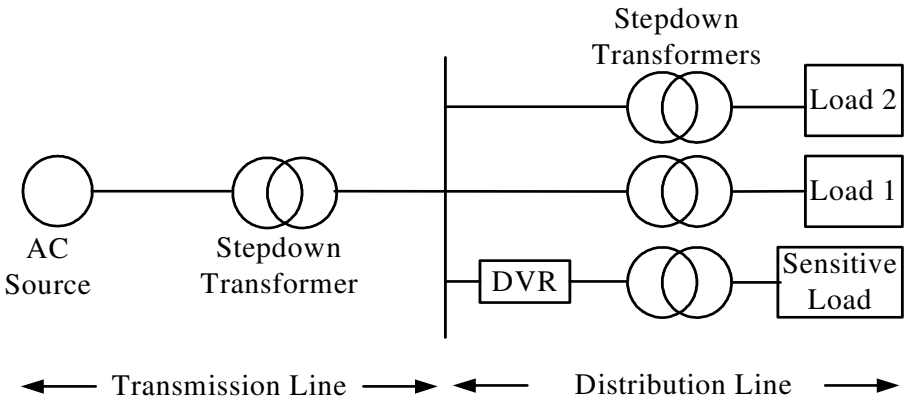


Figure 4.1 The location of DVR

The energy storage unit is common voltage source for PWM inverter and it is composed of DC capacitor bank. The PWM inverter unit produces required missing voltage by evaluating the control unit signals and this compensating voltage is inserted to the system by injection transformers.

4.2. DVR Operation Modes

The basic operation principle of DVR is measuring the missing voltage by using control unit and injecting the dynamically controlled missing voltage in series to the line and providing the load voltage unchanged during sag (Won *et al.*, 2003; Daehler *et al.*, 2000).

The phase angle and amplitude of the injected voltage are variable during sag. This will allow the control of active and reactive power exchange between the DVR and the distribution system. Generally, the operation of the DVR can be categorized into three operation mode: protection mode, standby mode (during steady state) and injection mode (during sag).

4.2.1. Protection Mode

The DVR will be isolated from the system if the system parameters exceed the predetermined limits primarily current on load side. The main reason for isolation is protecting the DVR from the overcurrent in the load side due to short circuit on the load or large inrush currents. The control system detects faults or abnormal conditions and manages bypass (transfer) switches to remove the DVR from system thus preventing it from damages as shown in Figure 4.2.

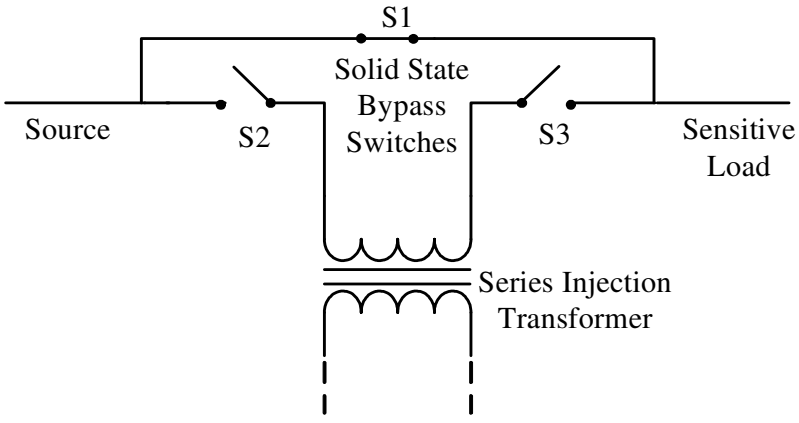


Figure 4.2 Scheme of the protection mode

During the overcurrent period, $S1$ will be closed, $S2$ and $S3$ will be opened so there will be another path for current to flow. By removing the DVR from system at fault condition, the effects of additional disturbances that can be caused by the DVR are prevented onto the system.

4.2.2. Standby Mode

In standby mode (normal steady state conditions), the DVR may either go into short circuit operation or inject small voltage to compensate the voltage drop on transformer reactance or losses. Short circuit operation of DVR is generally preferred solution in steady state because the small voltage drops do not disturb the load requirements. The solid-state bypass switches are used to perform short circuit operation and they are placed between the inverter and secondary (low side) of series injection transformer as shown in Figure 4.3.

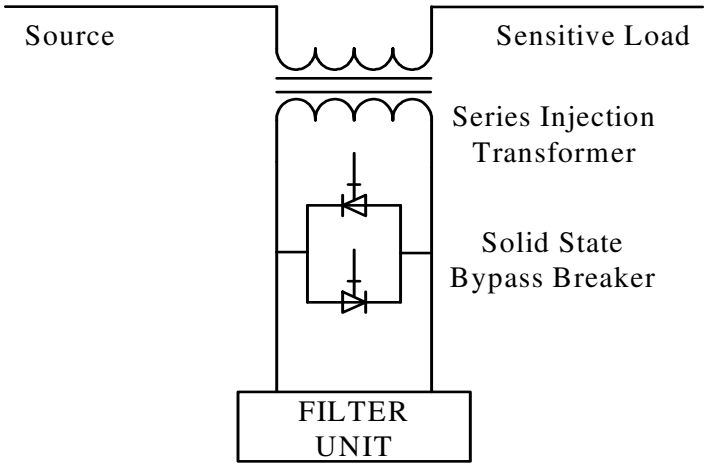


Figure 4.3 Scheme of the standby mode

If the distribution circuit is weak there is need to inject small compensation voltage to operate correctly. During short circuit operation, the injected voltages and magnetic fluxes are virtually zero thereby full load current pass through the primary. The DVR will be most of the time in normal mode operation. During standby mode normal operation), the short circuit impedance of the injection transformer determines the voltage drop across the DVR.

4.2.3. Injection Mode

The primary function of Dynamic Voltage Restorer is compensating voltage disturbances on distribution system. To achieve compensation, three single-phase ac voltages are injected in series with required magnitude, phase and wave shape.

The types of voltage sags, load conditions and power rating of DVR will determine the possibility of compensating voltage sag.

4.3. Available Voltage Injection Strategies

The DVR should ensure the unchanged load voltage with minimum energy dissipation for injection. The characteristic of load determines the required control strategy to inject compensation voltage. The methods for injection of missing voltage can be divided into four groups (Chung *et al.*, 2003; Won *et al.*, 2003):

- Pre-sag compensation method
- In-phase voltage injection method
- Phase advance method
- Voltage tolerance method with minimum energy injection

4.3.1. Pre-sag Compensation Method

This method injects the difference voltage between remaining voltage at PCC and pre-fault voltage to the system during sag as shown in Figure 4.4. The rms values of load voltage on the arc have the same magnitude (1 pu voltage) with different phase angles. The corrected voltage is the same with pre-sag voltage and this strategy can be used with balanced and unbalanced voltage sag.

$$V_{dvr} = V_{Lprefault} - V_{pcc} \tag{4.1}$$

$V_{Lprefault}$ is the pre-fault load voltage vector; V_L is the load voltage vector; V_{dvr} is the DVR voltage vector (injected).

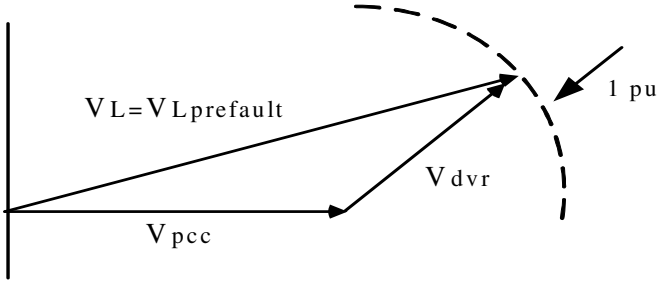


Figure 4.4 Vector diagram of pre-sag method

Some non-linear loads are very sensitive to phase angle jumps. It is the best solution to restore the sensitive load voltage to the same phase angle and magnitude as the nominal pre-sag voltage. As seen from single-phase vector diagram, the ideal restoration is achieved. However, there is no control on injected active power so high capacity energy storage is required.

4.3.2. In-Phase Voltage Injection Method

In second method injected voltage is in-phase with supply voltage. The magnitude of the injected voltage is minimized but it can cause phase shift between the remaining voltage vector at PCC and the pre-sag voltage as shown in Figure 4.5.

$$V_{dvr} = DV_p = V_L - V_{pcc} \tag{4.2}$$

V_p is the rated per-phase rms value of the primary feeder; D is the maximum voltage sag.

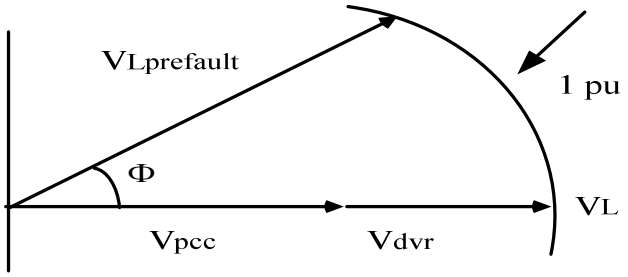


Figure 4.5 Vector diagram of in-phase method

The phase angles of the pre-sag and load voltage are different but the most important criteria for power quality, which is the constant magnitude of load voltage, is satisfied. For a given load current and voltage sag, the apparent power of DVR is minimized.

$$|V_L| = |V_{Lprefault}| \tag{4.3}$$

4.3.3. Phase Advance Method

In third method, decreasing the power angle between the remaining voltage and the load current minimizes real power spent by DVR. Pre-sag compensation and in-phase compensation inject active power to the critical load during sag. Active power is limited by stored energy in DC link and this part is one of the most expensive parts of DVR. The minimum energy injection is realized by making active power zero by having the remaining voltage phasor perpendicular to load current as shown in Figure 4.6. The values of load current and voltage are fixed in the system so injection power of DVR (P_{DVR}) depends on only the advance angle φ when V_{pcc} and θ have been given by the fault condition in the fixed xy plane.

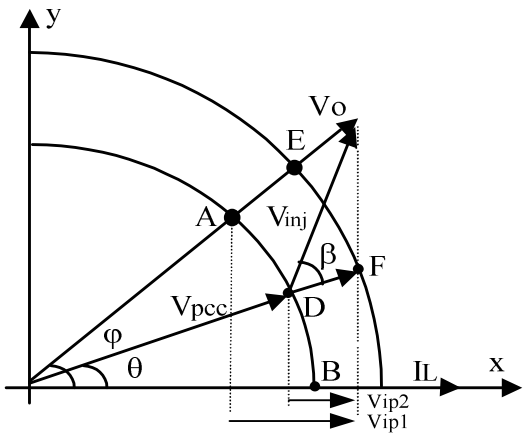


Figure 4.6 Vector diagram of phase advance method

$$P_{DVR} = P_{out} - P_{in} \tag{4.4}$$

P_{in} is the input power from the supply; P_{out} is the load power; $V_{ip1} * \mathrm{I}$ is the injected active power in-phase injection mode; $V_{ip2} * \mathrm{I}$ is the injected active power in phase advance mode.

The energy saving and compensation are achieved by using reactive power instead of active power. The main drawbacks of this method are increased magnitude of injected voltage, phase shift, waveform discontinuity and complexity of the control system.

In the phase advance method, the magnitude of restored load voltage should be equal to magnitude of pre-fault voltage. The source voltage and voltage injection limit of DVR will determine the minimum energy injection operation point. In Figure 4.6, operating point is denoted by D. Injected active power decreases when β increases and θ decreases.

In this method the magnitude of source voltage V_{pcc} is not changed. By decreasing the power angle of V_{pcc} at the same magnitude, the injected energy is minimized and it can be understood by using main power formula. It shows smaller the power angle smaller the power value. This method requires delay time to move phase angle from pre-sag angle to advance angle by decreasing the angle between source voltage and load current at the same source voltage magnitude.

If $V_{pcc} \langle V_o \cos\varphi$ and there is no limit for injection the operating point can lie on the arc AB. If $\theta = 0$, the injected power value ($V_{ip2} * \mathrm{I}$) approaches the minimum. When the voltage $V_{pcc} \rangle V_o \cos\varphi$ and again no limit is laced on the magnitude of injection voltage of DVR, the operating point can be anywhere on the arc EF. Zero power injection is at point F before θ approaches zero. However decreased θ causes the magnitude of injection voltage increases.

The magnitude of the injected voltage is the most important factor for economic consideration. Equation (4.5) calculates required magnitude of the voltage.

$$V_i = \sqrt{V_o^2 + V_{pcc}^2 - 2V_o V_{pcc} \cos\varphi} \tag{4.5}$$

In this method, the power consumption of DVR during sag is only related with advance angle. The best operating point is obtained when the DVR injects zero active power neither positive nor negative.

By minimizing the magnitude of the injected voltage, the capacity of energy storage device can be reduced. The phase advance method injects minimum energy compared to pre-sag and in-phase method. But it has not good performance when deep voltage sags or large phase angle shifts occur.

4.3.4. Voltage Tolerance Method with Minimum Energy Injection

In fourth method, the phase angle and magnitude of corrected load voltage within the area of load voltage tolerance are changed as shown in Figure 4.7. The small voltage drop and phase angle jump on load can be tolerated by load itself. The sensitivity of loads to phase angle jump and voltage magnitude is different.

Generally the voltage magnitude between 90%-110% of nominal voltage and phase angle variation between 5%-10% of normal state do not disturb the operation characteristics of loads. The magnitude and phase are control parameters of this method to achieve the minimum energy injection. The phase advance method uses only phase difference but this method uses both control parameters.

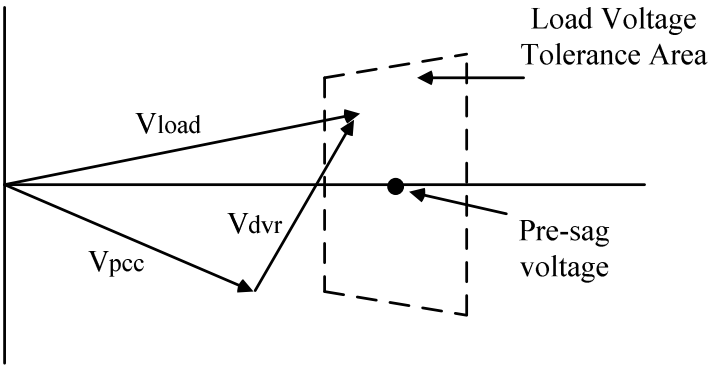


Figure 4.7 Vector diagram of voltage tolerance method

As stated before the voltage tolerance area is dependent on load. Some loads are sensitive to phase angle shift and other loads are sensitive to voltage magnitude variations. The operating point is determined by considering the load characteristic.

The voltage tolerance method can maintain load voltage in the tolerance area with small change of voltage magnitude by injecting smaller active power than other methods. According to below formula active power at the load side and source side can be calculated. I_L is the current in both source and load side because the system is series connected. Figure 4.8 shows the source, load and injected voltages and load current. The optimum performance is satisfied from this method even if deep voltage sags occur.

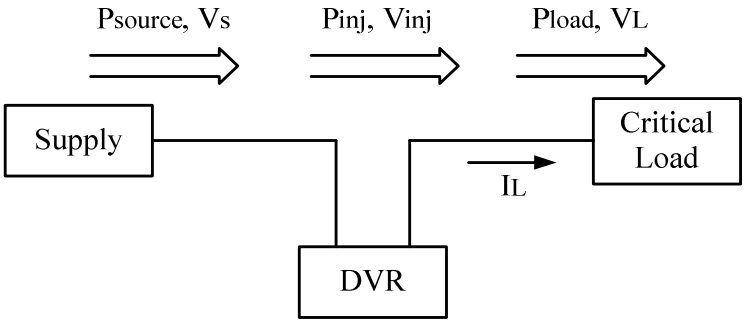


Figure 4.8 The circuit parameters of the system

$$P_{load} = V_L I_L \cos\alpha \tag{4.6}$$

$$P_{source} = V_s I_L \cos\beta \tag{4.7}$$

$$P_{inj} = P_{source} - P_{load} = I_L (V_s \cos\beta - V_L \cos\alpha) \tag{4.8}$$

I_L is the load current; α is the angle between V_L and I_L; β is the angle between V_s and I_L.

It is observed that the injected power decreases from method 1 to method 4 but the complexity and expenses increase. It is important to note that the overall researching about the characteristics of load will determine the required compensation strategy with minimum cost. The phase shift, magnitude and waveshape are some of the important considerations for compensation strategy. For

example, three-phase AC motor drives with front-end rectifiers are very sensitive to voltage magnitude and phase unbalance. Thyristor based power supplies (such as DC drives) need accurate zero-crossing information, so phase shift and waveshape are important. AC motor contactors are not as sensitive to phase shift and waveshape; however voltage magnitude and point in wave of the initiation of the event play a key role in tripping the contactor (Middlekauff *et al.*, 1998).

5. CONTROL STRATEGY OF DVR

5.1. General

One of the most important power quality problems facing industrial customers is the voltage sag. The main source of voltage sags is short circuit faults in the grid system. The voltage sags are related with the clearing time of the faults by protective devices and fault impedance. The first approach can be modification of sensitive devices to voltage sags. But better solution is obtained by using a Dynamic Voltage Restorer for certain group of sensitive devices.

In order to provide the reliable DVR operation and excellent voltage regulation, the control strategy of DVR should satisfy the following criterions:

- Reliable and fast response for transient states as well as steady states
- Compensation of different types of sags at deep variation and different load connection
- Robustness for non-linear load conditions, sudden load changes and system parameter variations

The basic compensation strategies for a DVR are pre-sag compensation, in-phase compensation, phase advance compensation and voltage tolerance compensation. The voltage and power limit of the DVR and characteristics of the load determine the optimum selection of control strategy. Before selecting a control method to be used, further issues have to be addressed, which are closely linked to the chosen control strategy.

In this thesis, in-phase voltage injection method is preferred for compensation of voltage sags. This model has following advantages:

- Quick calculation ability during the compensation process of sag
- Less complex control strategy than phase advance and voltage tolerance method
- Fewer disturbances to the load
- Optimum solution when the DVR has limited voltage injection capability

A DVR has limited capabilities and the DVR will most likely face the voltage sag outside the range of full compensation. Three important limitations for a DVR are (Mohan *et al.*, 2001):

- Voltage limit: The design of the DVR is limited in the injection capability to keep the cost down and reduce the voltage drop across the device in normal operation.
- Power limit: Power is stored in the DC link, but the bulk power is often converted from the supply itself or from a larger DC storage. An additional converter is used to maintain a constant DC link voltage and the rating of the converter introduces a power limit to the DVR.
- Energy limit: Energy is used to maintain the load voltage fixed and it is normally sized as low as possible in order to reduce cost. Some sags will deplete the storage fast and the control can reduce the risk of load tripping caused be insufficient energy storage. All the limits should be included in the control to fully utilize the investment of a DVR. Figure 5.1 illustrates how the power flows in the system.

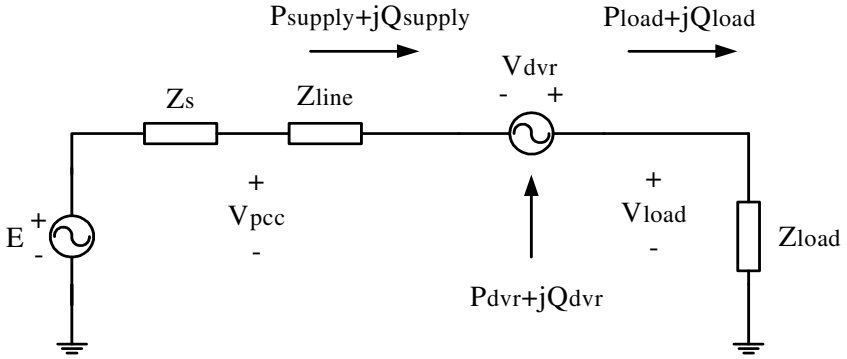


Figure 5.1 The flow of active and reactive power with a DVR inserted

E is the voltage of infinite bus; Z_{line} is the line impedance.

The generated voltage that is perpendicular to the load current can be used to bring the current in-phase with the supply voltage or can make the DVR and load appear as a capacitive load. A capacitive load current tends to raise the supply voltage V_{supply} and by raising the supply voltage more power can be taken from the

grid and hence saved from the energy storage. It is possible to control the injected active and reactive power flow with well designed control algorithm. Direct feedforward type control model is used to minimize the response time and maximize the dynamic performance (Nielsen *et al.*, 2003; Zhan *et al.*, 2001). Voltage regulation, low harmonics distortions and no interruptions are realized with this type of control harmonics architecture.

5.2. Fuzzy Logic Control (FLC) of DVR

Lotfi Zadeh, a professor at the University of California at Berkley, introduced the mathematical foundations of fuzzy set theory and Mamdani first used fuzzy algorithm to control a system.

The general requirement of proposed control scheme is to obtain an ac waveform with low total harmonic distortion and good dynamic characteristics against supply and load disturbances. Although conventional sinusoidal PWM schemes and programmed optimal PWM schemes have performed reasonably well for linear loads, the voltage waveforms tend to get distorted for non-linear loads (Vilathgamuwa *et al.*, 1999).

The increased use of power semiconductor switches in custom power devices makes the system non-linear, difficult to model mathematically and complicated. Fuzzy Logic (FL) is a problem solving control system methodology that lends itself to implementation in systems ranging from simple, small, embedded microcontroller to large, networked, multi-channel PC or workstation based data acquisition and control systems (Elmitwally *et al.*, 2000; Jurado *et al.*, 2003; Fuzzy Logic Toolbox Documentation, 2005).

Fuzzy Logic provides a simple way to arrive at a definite conclusion based upon vague, ambiguous, imprecise, noisy or missing input information. Traditional control systems are based on mathematical models in which the control system is described using one or more differential equations that define the system response to its inputs. Such systems are often implemented as proportional-integral (PI) controllers. They are the products of decades of development and theoretical analysis

is highly effective. The PI control of DVR is the most general techniques used in DVR applications (Kim *et al.*, 2004). For the common PI control, the control parameters are fixed, so the PI law can only guarantee good performance in a local area since the DVR is non-linear. When the operation point of the converter is changed, the parameters of PI should be designed again. Generally speaking, when designing a PI controller, some prior information of the converter is necessary and some trials are needed to design the parameters of PI (Jurado *et al.*, 2003).

The growing sophistication in modern technologies has increased the demand for FL controlled applications. In many cases, the mathematical model of the control process may not exist or may be too expensive in terms of computer processing power and memory and a system based on empirical rules may be more effective. Furthermore, fuzzy logic is well suited to low cost implementations based on cheap sensors, low-resolution analog to digital converters and 4-bit or 8-bit one-chip microcontroller chips. Such systems can be easily upgraded by adding new rules to improve performance or add new features. In many cases, fuzzy control can be used to improve existing traditional controller systems by adding an extra layer of intelligence to the current control method.

A control system may also have various types of switch or "on-off", inputs along with its analog inputs and such switch inputs of course will always have a truth value equal to either 1 or 0, but the scheme can deal with them as simplified fuzzy functions that are either one value or another.

FLC is a new addition to control theory and it incorporates a simple, rule based IF X AND Y THEN Z approach to a solving control problem rather than attempting to model a system mathematically. The Fuzzy Logic model is empirically based, relying on an operator's experience rather than their technical understanding of the system. The fuzzy controller designer must define what information/data flows into the system (control/input variable), how the information/data is processed (control strategy and decision) and what information/data flows out of the system (solution/output variable) (Hilloowala *et al.*, 1996). Fuzzy Logic offers several unique features that make it a particularly good choice for many control problems (Zadeh *et al.*, 1987):

- It is inherently robust since it does not require precise, noise free inputs and can be programmed to fail safely if a feedback sensor quits or is destroyed. The output control is a smooth control function despite a wide range of input variations.
- Since the Fuzzy Logic controller processes user defined rules governing the target control system, it can be modified and tweaked easily to improve or drastically alter system performance. New sensors can easily be incorporated into the system simply by generating appropriate governing rules.
- Fuzzy Logic is not limited to a few feedback inputs and one or two control outputs, nor is it necessary to measure or compute rate of change parameters in order for it to be implemented. Any sensor data that provides some indication of a system's actions and reactions are sufficient. This allows the sensors to be inexpensive and imprecise thus keeping the overall system cost and complexity low.
- Because of the rule based operation, any reasonable number of inputs can be processed (1-8 or more) and numerous outputs (1-4 or more) generated, although defining the rule base quickly becomes complex if too many inputs and outputs are chosen for a single implementation since rules defining their interrelations must also be defined. It would be better to break the control system into smaller chunks and use several smaller Fuzzy Logic controllers distributed on the system, each with more limited responsibilities.
- Fuzzy Logic can control non-linear systems that would be difficult or impossible to model mathematically. This opens doors for control systems that would normally be deemed unfeasible for automation.
- Fuzzy Logic is much closer to human thinking than traditional logical systems. It requires less rule and data storage than traditional controllers and gives reliable and fast response.

The fuzzy logic controller is used as a substitute for the conventional PI controller. In (Jurado *et al.*, 2003), the three-phase source voltages are transformed into d and q coordinate. The references 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 PWM inverter signals.

In this thesis, a new method for the generation of reference voltage for a DVR is adopted to the control system. The proposed method 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. The proposed DVR has the capability of both balanced and unbalanced voltage sag compensation. Figure 5.2 shows the implementation of proposed control system for single-phase.

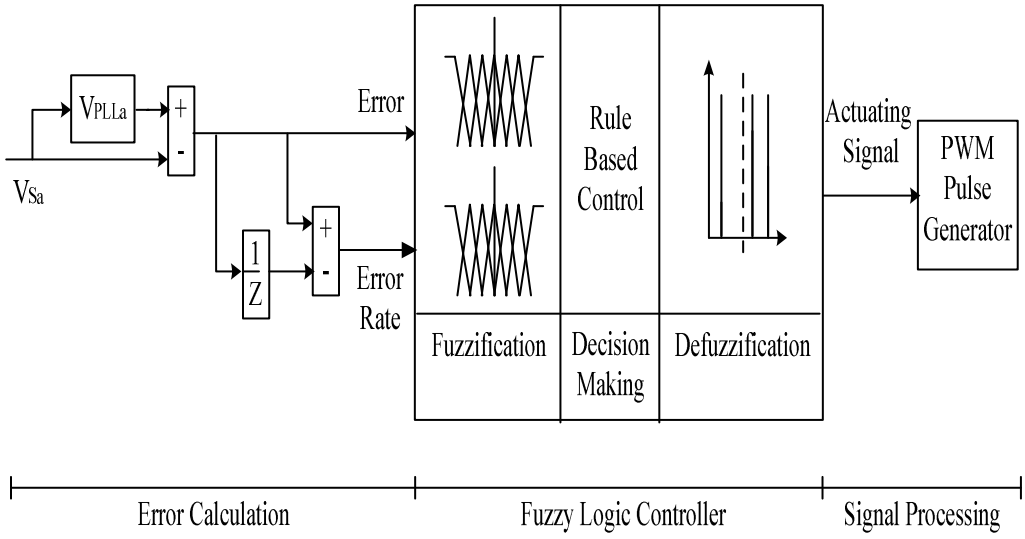


Figure 5.2 Block diagram of proposed control system

The fuzzy logic controller has two real time inputs measured at every sample time, named error and error rate and one output named actuating signal for each phases. The input signals are fuzzified and represented in fuzzy set notations by membership functions. The defined 'If … Then …' rules produce output (actuating) signal and these signals are defuzzified to analog control signals for comparing with a carrier signal to control PWM inverter. The detailed description of each subsection is given as follows:

5.2.1. Error Calculation

The supply voltage for each phase is converted to per-unit value. 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 5.3. The error rate is the rate of change of error. For phase A, the error and error rate are defined as:

$$err_A = V_{PLLa} - V_{Sa} \tag{5.1}$$

$$\Delta err_A = err_A(n) - err_A(n-1) \tag{5.2}$$

V_{PLLa} is the A phase PLL voltage; V_{Sa} is the A phase source voltage; n is the sampling time.

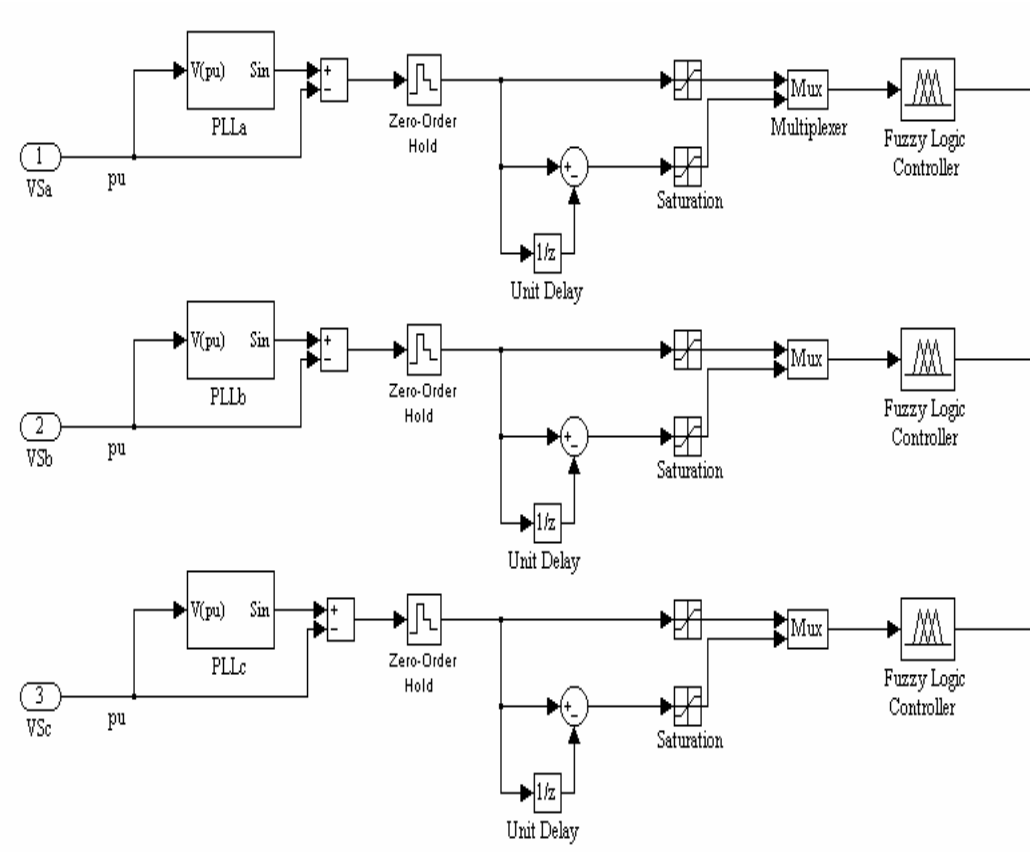


Figure 5.3 Block diagram of the control system

The zero order hold block implements a sample and hold function operating at the specified sampling rate. The error rate is obtained by the use of unit delay block which delays and holds its input signal by one sampling interval. The saturation block imposes upper and lower bound on a signal, the multiplexer block (mux) combines its inputs into a single output. The modified error and error rate are now inputs for FL process.

The method should not affect from the harmonics, flickers, frequency variations and unbalanced voltages because the correct detection of the phase of the source voltage is very important for DVR (Elnady *et al.*, 2005). Using a PLL algorithm satisfies these requirements. The PLL generates a reference signal during a voltage dip, which is needed to produce the control signals.

5.2.2. Fuzzy Logic Controller

The FLC involves three steps and detailed description of each step is as following:

5.2.2.1. Fuzzification

This unit transforms the non-fuzzy (numeric) input variable measurements into the fuzzy set (linguistic) variable that is a clearly defined boundary, without a crisp (answer). In this simulation study, the error and error rate are defined by linguistic variables such as large negative (LN), medium negative (MN), small negative (SN), very small (VS), 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 inputs map the appropriate membership functions. The most common membership functions are triangular, trapezoidal, bell shaped and constant functions. The shape is generally less important than the number of curves and their placement. From three to seven curves are

generally appropriate to cover the required range of an input value. The distribution of input membership functions is uniform which is listed in Figure 5.4.

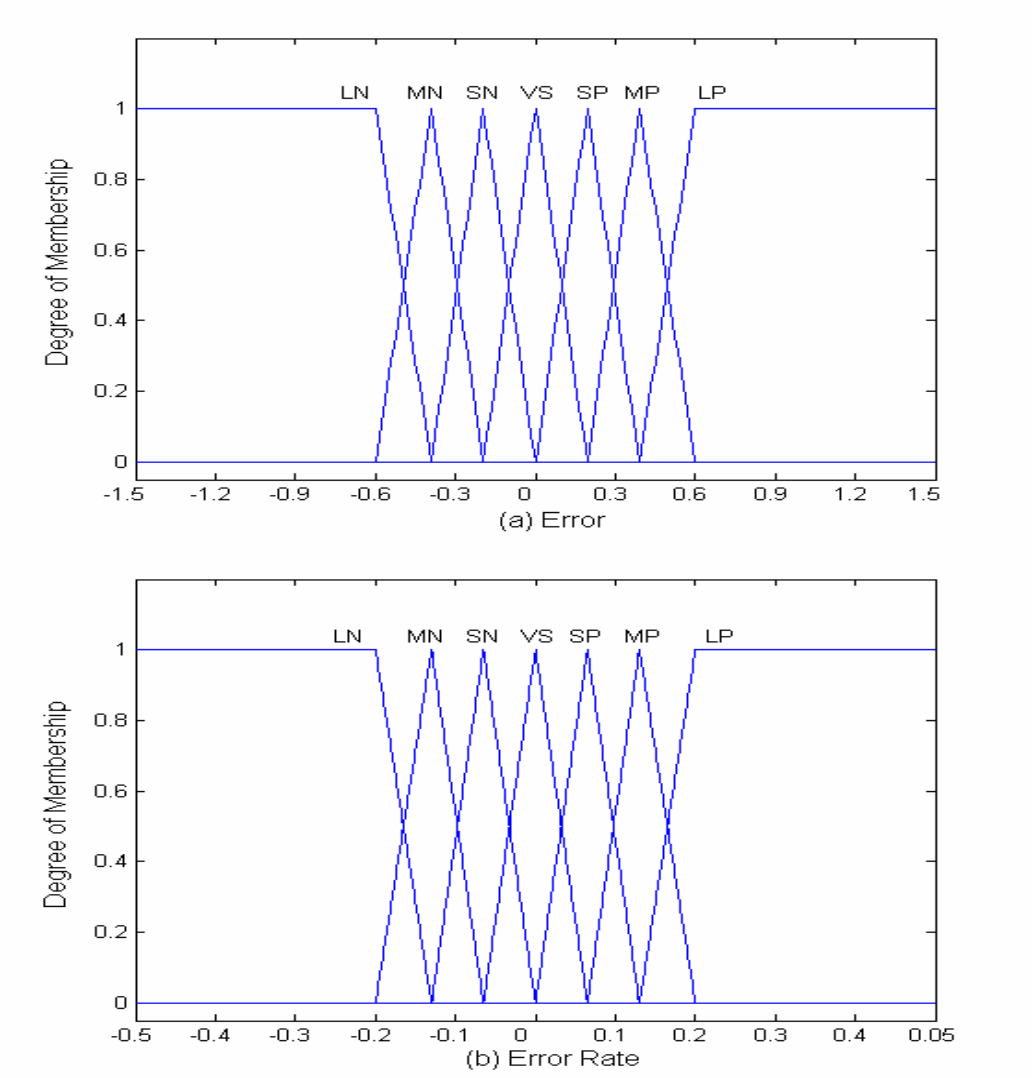


Figure 5.4 Fuzzy membership functions of (a) error and (b) error rate

With this scheme, the input state of variable no longer jumps abruptly from one state to the next. The membership functions change gradually from one state to the next. A certain amount of overlap is desirable otherwise the controller may run into poorly defined states, where it does not return a well-defined output. Table 5.1 shows the weights of input membership functions.

Table 5.1 The weights of the input membership functions

Input	Error	Error Rate	Function
LP	[0.4 0.6 1.5 1.5]	[0.13 0.2 0.5 0.5]	Trapezoidal
MP	[0.2 0.4 0.6]	[0.065 0.13 0.2]	Triangular
SP	[0 0.2 0.4]	[0 0.065 0.13]	Triangular
VS	[-0.2 0 0.2]	[-0.065 0 0.065]	Triangular
SN	[-0.4 -0.2 0]	[-0.13 -0.065 0]	Triangular
MN	[-0.6 -0.4 -0.2]	[-0.2 -0.13 -0.065]	Triangular
LN	[-1.5 -1.5 -0.6 -0.4]	[-0.5 -0.5 -0.2 -0.13]	Trapezoidal

The membership functions belonging to the other phases are identical. Trapmf (trapezoidal) and trimf (triangular) membership functions are used in the input of fuzzy controller. These functions have chosen to be to satisfy the output needs of the fuzzy controller.

5.2.2.2. Decision Making

Fuzzy inference process is realized by one of the Mamdani or Takagi-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 Takagi-Sugeno method are linear or constant.

Takagi and Sugeno's model can express a highly non-linear functional relation using small number of fuzzy rules. It is a more compact and computationally efficient representation than a Mamdani system. It works well with linear techniques and it is suited for modeling non-linear systems by interpolating multiple linear models (Youssef, 2004). It provides higher performance and accuracy to non-linear dynamic systems under various operating conditions.

The Sugeno system is preferred for constructing fuzzy models. The *ith* rule is given in the following form (Takagi *et al.*, 1985):

$$L^{(l)} : If\ x_1\ is\ F_1^l\ and\ ....\ and\ x_n\ is\ F_n^l,\ then$$
$$y^l = c_0^l + c_1^l x_1 + c_2^l x_2 + ... + c_n^l x_n \tag{5.3}$$

F_i^l is the fuzzy set; c_i^l is the real valued parameter; y^l is the system output due to the rule c_i^l; $x_1,..., x_n$ are the real valued inputs; $l = 1, 2, 3 \ldots M$.

A simple if-then rule is defined as follows:

If error is A, error-rate is B; then output $y = B$

A is the linguistic value defined by fuzzy sets on the range error; B is the linguistic value defined by fuzzy sets on the range error-rate; y is the output.

A slightly more complex rule is:

If error is very small and error rate is very small then output

$y = a * error + b * error \cdot rate + c$

Here, a, b and c are all constant.

The If-then rules define a Fuzzy Inference System (FIS) by connecting the input to the output. Sugeno inference method can easily obtain the relationship between its inputs and output. 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 5.5.

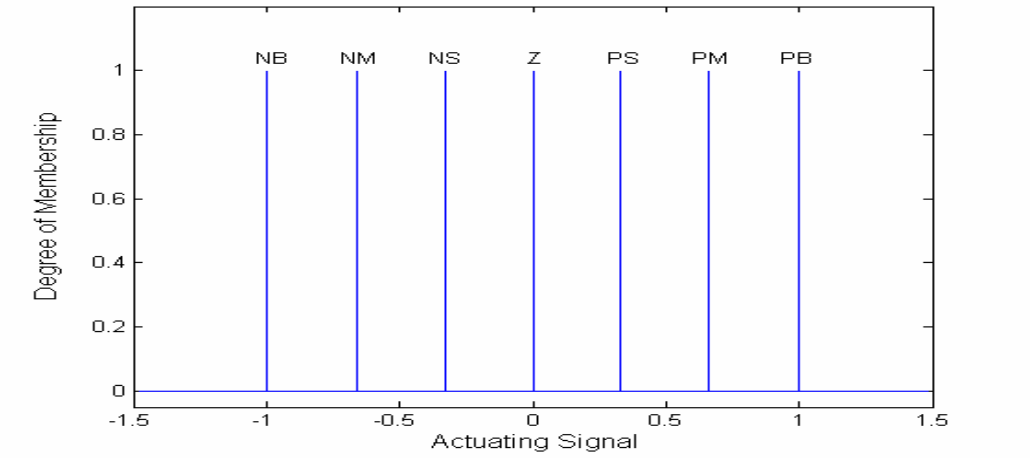


Figure 5.5 Fuzzy membership function of output

The weights of the output membership function are shown in Table 5.2.

Table 5.2 The weights of the output membership function

Actuating Signal	**PB**	**PM**	**PS**	**Z**	**NS**	**NM**	**NB**
	[1]	[0.66]	[0.33]	[0]	[-0.33]	[-0.66]	[-1]

In this application, in order to get good control accuracy on the one hand and not complicate the rule base on the other hand, the symmetry of the positive and negative half-waves of the ac variables is used. The rules are created for only one half-wave but can be used by the other one taking into account the polarity of the system variables. This may be imagined as the insertion of a third controller input variable. The task of this variable would be to switch between two rule tables at every zero-axis crossing of the reference voltage (Osterholz, 1995). Table 5.3 shows the decision table for fuzzy logic control rules.

Table 5.3 Fuzzy decision table

		Error Rate						
		LP	MP	SP	VS	SN	MN	LN
Error	LP	PB 1	PB 2	PB 3	PM 4	PM 5	PS 6	Z 7
	MP	PB 8	PB 9	PM 10	PM 11	PS 12	Z 13	NS 14
	SP	PB 15	PM 16	PM 17	PS 18	Z 19	NS 20	NM 21
	VS	PM 22	PM 23	PS 24	Z 25	NS 26	NM 27	NM 28
	SN	PM 29	PS 30	Z 31	NS 32	NM 33	NM 34	NB 35
	MN	PS 36	Z 37	NS 38	NM 39	NM 40	NB 41	NB 42
	LN	Z 43	NS 44	NM 45	NM 46	NB 47	NB 48	NB 49

Each input of the above fuzzy system is assigned to 7 membership functions. So, fuzzy system consists of $7^2=49$ rules. These rules carry out optimum control action and each rule expresses an operating condition in the system as shown in Table 5.3.

The person's experience and knowledge about the plant behavior help to define the rules. All rules are appreciated in parallel and the order of the rules is not important. The correct combinations of these rules improve the system performance. The algorithm for generating the appropriate control action can be imagined as follows:

The status of the system is the voltage error (magnitude and sign): if it is large (small) it means that the voltage is far (near) its reference value; if it is positive (or negative), it means the phase voltage is smaller (or bigger) than the reference one. A sample rule from Table 5.3 is:

Rule 20: IF the error is (SP) AND error rate is (MN),

THEN the output is (NS).

The increased number of rules can improve the accuracy of the control system but it can cause to increase in the data size or complexity of the control system.

The output is produced by the fuzzy sets and fuzzy logic operations by evaluating all the rules. The first step is to take the inputs and determine the degree to which they belong to each of the appropriate fuzzy sets via membership functions. Once the inputs have been fuzzified, the degree to which each part of the antecedent has been satisfied for each rule is obtained. If the antecedent of a given rule has more than one part, the fuzzy operator is applied to obtain one number that represents the result of the antecedent for that rule. This number will then be applied to the output function. The input to the fuzzy operator is two or more membership values from fuzzified input variables. The output is a single truth value.

Large amount of experiment shows that the distribution of the membership functions of input and output has different effect on the system performance. If the same distribution for all the membership functions is chosen, the optimal result cannot be obtained (Xu *et al.*, 2004). Fuzzy logic helps to obtain the optimized distribution of membership functions adjusting the control surface for very different operation conditions. The three dimensional control curves for the derived rule base are plotted in Figure 5.6.

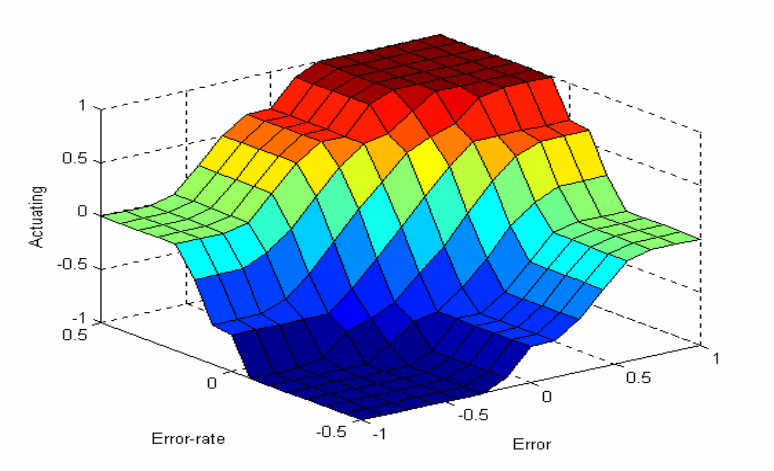


Figure 5.6 Control surface of fuzzy controllers

The surface viewer has a special capability that is very helpful in cases with two (or more) inputs and one output. The axes can be actually grabbed and repositioned to get a different three-dimensional view on the data (Fuzzy Logic Toolbox Documentation, 2005). Increased number of rules can result better adjustment of control surface. In practical applications, providing optimum results with minimum rule is essential.

5.2.2.3. Defuzzification

It is the process of converting the controller outputs in linguistic labels represented by fuzzy set to real control (analog) signals. Sugeno's wtaver (weighted average) method is selected for defuzzification and it is a special case of Mamdani model. For real valued inputs $x_1,...,x_n$, the output y of the Sugeno fuzzy system is a weighted average of the outputs of all the rules. The solution of defuzzification process results from Equation (5.4).

$$y = \frac{\sum_{l=1}^{M} w^l y^l}{\sum_{l=1}^{M} w^l} \tag{5.4}$$

$$w^l = \prod_{i=1}^{n} M_{F_i^l}(x_i) \tag{5.5}$$

w^l is the overall truth value of the premise of the rule $L^{(l)}$; $M_{F_i^l}$ is the membership function that describes the meaning of the linguistic value F_i^l.

If the fuzzy set used for the controller output variable y is as shown in Figure 5.7, the output of the proceeding inference algorithm is:

NS = 0.2; PM = 0.4; PB = 0.7

The output of the fuzzy controller is the exact (non-fuzzy) value of y=0.69. Figure 5.7 illustrates this process graphically.

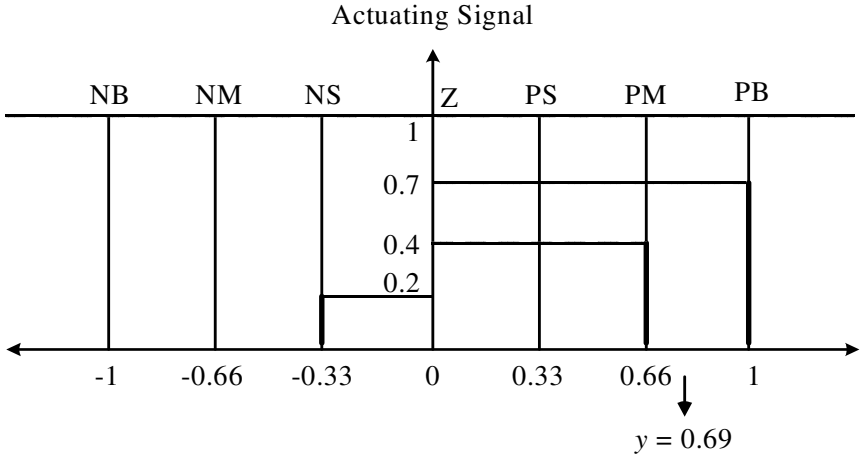


Figure 5.7 Graphical representation of defuzzification process

$$y = \frac{-0.33*0.2 + 0.66*0.4 + 1*0.7}{0.2+0.4+0.7} = 0.69$$

5.2.3. Signal Processing

The outputs of FLC process are the control signals that are used in generation of switching signals of the PWM inverter by comparing a carrier signal as shown in Figure 5.8.

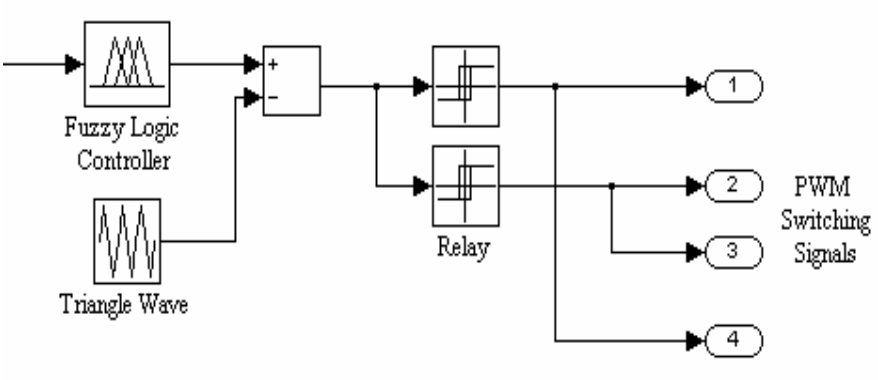


Figure 5.8 Generation of PWM switching signals

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 complement of upper one. The output of the fuzzy controller is set to take values between –0.7 to 0.7. The carrier signal is set to take values between –0.7 to 0.7 with a frequency of 2 KHz.

5.3. Constructing a FIS File in MATLAB

The rule structure of FIS makes it easy to incorporate human expertise with the target system directly into the modeling process. When the input/output data of a target system is available, conventional system identification techniques can be used. A process for constructing a FIS can be summarized as follows:

- Choose a specific type of FIS (Mamdani or Sugeno)
- Select relevant input-output variables
- Determine the number of linguistic terms associated with each input-output variables (determine the membership function for each linguistic term)
- Design a collection of fuzzy if-then rules
- Choose the defuzzification method to extract a crisp value that best represents a fuzzy set
- Run through test suite to validate system, adjust details as required

In this study, the fuzzy controllers for the single fuzzy controller scheme are characterized as follows:

- Seven fuzzy sets for each input
- Seven fuzzy sets for the output
- Triangular and trapezoidal membership functions for each input
- Constant membership function for the output
- Fuzzification using continuous universe of discourse
- Implication using the "min" operator
- Sugeno inference mechanism based on fuzzy implication
- Defuzzification using the "wtaver" method

6. SIMULINK MODELING OF DVR AND SYSTEM DESIGN

6.1. General

Simulink is a software package for modeling, simulating and analyzing dynamic systems. It supports linear and non-linear systems modeled in continuous time, sampled time or a hybrid of the two (Dynamic System Simulation for Matlab, 1998). Simulink includes a comprehensive block library of sinks, sources, linear and non-linear components and connectors. It has an extensive control library that allows easy implementation of any control algorithm, including linear control, fuzzy logic, neural networks and others. Simulink provides a graphical user interface (GUI) for building models as block diagrams, using click and drag mouse operations. Simulink encourages you to try things out. You can easily build models from scratch or take an existing model and add to it. You have instant access to all the analysis tools in MATLAB, so you can take the results and analyze and visualize them.

The Power System Blockset is designed to provide a modern design tool that allows scientists and engineers to rapidly and easily build models that simulate power systems. Models are hierarchical, so you can build models using both top-down and bottom-up approaches. After you define a model, you can simulate it, using a choice of integration methods, either from the Simulink menus or by entering commands in the MATLAB Command Window. Using scopes and other display blocks, you can see the simulation results while the simulation is running. You can change many parameters and see what happens for "what if" exploration.

Some advantages of Simulink program are as following:

- Requires less memory space and CPU run time
- Circuit equations are solved much faster than PSPICE.
- Some mathematical calculations e.g. harmonic magnitude spectrum, are computed with higher steps than PSCAD / EMTDC.
- Access to sophisticated routines embedded in MATLAB toolboxes
- Well suited for the design of industrial applications

6.2. Design Considerations

The design of the DVR is affected by the load, the supply characteristic and by the expected voltage sag (dip) characteristics. When designing for a DVR for certain application, the following items should be considered (Awad *et al.*, 2003).

- Maximum load power and power factor: The load size strongly affects the current rating of the VSI and the injection transformer as well as the amount of energy storage needed.
- Maximum depth and duration of voltage dips to be corrected: These characteristics, together with the load size, dictate the necessary storage capacity of the energy storage device. The maximum depth determines the voltage rating of the VSI and the injection transformer. The maximum depth and duration of voltage dips to be corrected are determined by the statistics of the voltage dips at the DVR location and by the acceptable number of equipment trips.
- Maximum allowed voltage drops of the DVR during the standby mode: This affects the control mode during normal operation and indirectly the reaction speed at beginning of a voltage dip.
- Parameters of the step-down transformer: Coupling of the step-down transformer (Δ/Y, Y/Δ, Y/Y…) at the input and output sides of the DVR
- Harmonic requirements of the load and of the system: These affect the harmonic filtering needed for the DVR and also influence the choice of charging method for the capacitors.

Statistical data on voltage sags such as average number of single and three-phase sags per-year, sag duration, size of sag and the cost of lost production have also to be considered in order to design an economical DVR. Although a DVR may be designed to compensate up to a 90% voltage dip, it does not support complete outages. Moreover, the DVR must be coordinated with other protective equipment such as breakers and bypass switches prevent breaks in the current path required for the DVR to operate and prevent potentially harmful phase shifts for loads upstream of the DVR (Middlekauff *et al.*, 1998).

6.3. Proposed DVR Configuration

The DVR uses self-commutating IGBT solid-state power electronic switches to mitigate voltage sags in the system. The voltage controlled three single-phase full bridge PWM inverters are used to produce compensating voltage. The switching frequency of the inverters is 2 kHz. Three of single-phase inverters are connected to the common DC voltage source. The DC voltage source is an external source supplying DC voltage to the inverter for AC voltage generation.

Inverter side LC filters block high frequency harmonics caused by DC to AC conversion to reduce distortion in the output. The three 140/3464 V (rms) single-phase injection transformers boost the output waveform of the filter unit. The bypass switches and solid-state bypass breakers are placed in parallel with the injection transformers allowing the protection of the DVR.

A proposed DVR built in MATLAB/Simulink and installed into a simple power system to protect a sensitive load in a distribution system is presented in Figure 6.1. 15 kV (rms) main feeder energizes the proposed system. Main feeder is divided into two feeders and each feeder is connected with loads. The sensitive load is rated at 50 kVA at 95% power factor lagging and receives power from the grid at 15 kV. The grid voltage is reduced to 380 V (rms) to allow the utilization of low voltage sensitive load.

There are two numbers of 50 kVA identical power transformers each 15000/380 V (Δ/Yn) connected with solidly grounded neutral. The DC link voltage is 200 V. The system runs 50 Hz frequency. A 100 μs sample time (10 kHz sampling frequency) is used for measurements and controller calculations.

The voltage sags are generated by switching on impedance to the ground at PCC. The DVR is designed to mitigate the three-phase balanced (symmetrical) or unbalanced (unsymmetrical) voltage sags up to 0.4 pu with long duration of voltage sags.

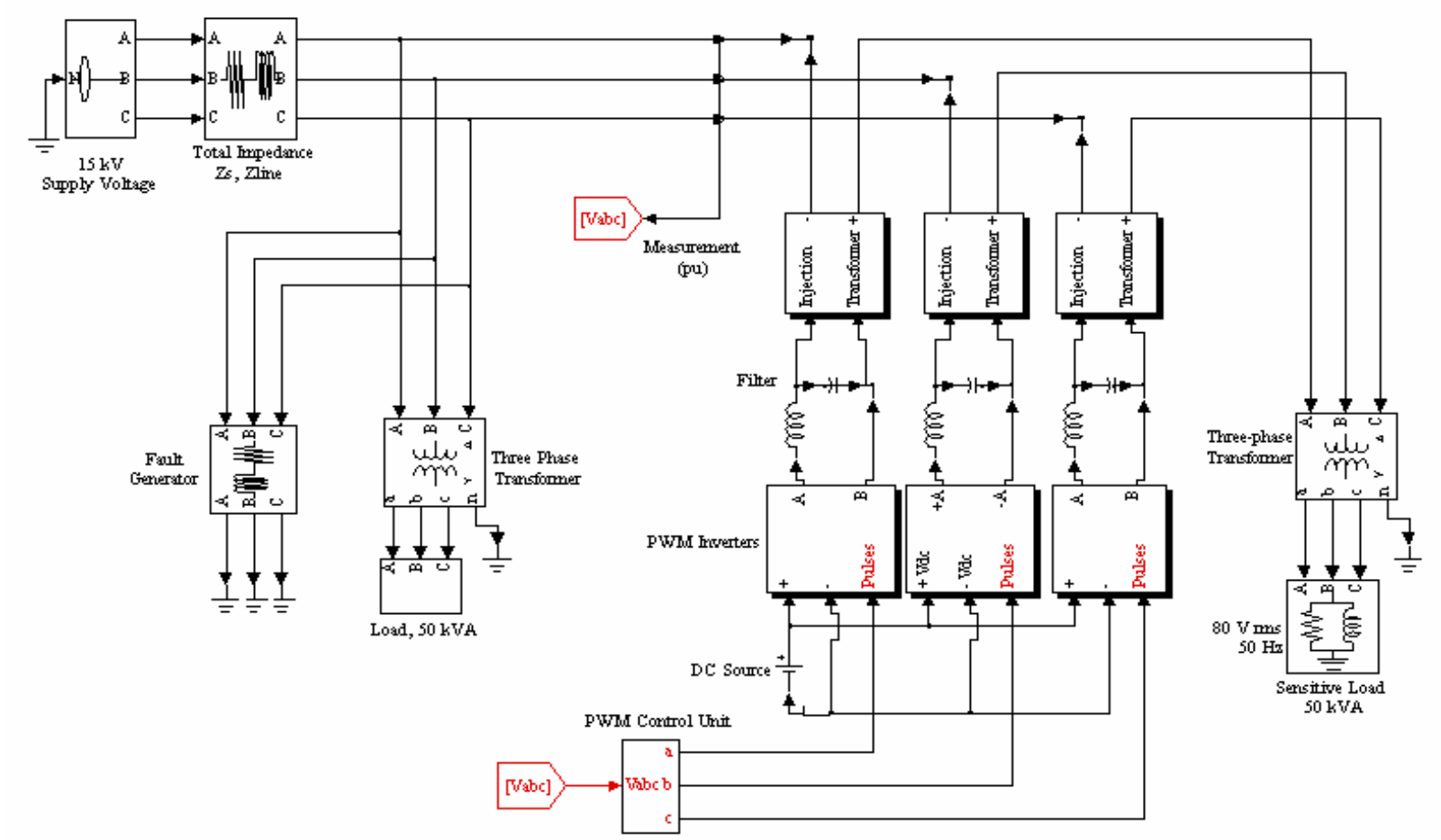


Figure 6.1 MATLAB/Simulink model of DVR

The power circuit of DVR systems can be represented as a single-phase equivalent circuit as shown in Figure 6.2. The compensation voltages on each phase of the DVR system are controlled independently.

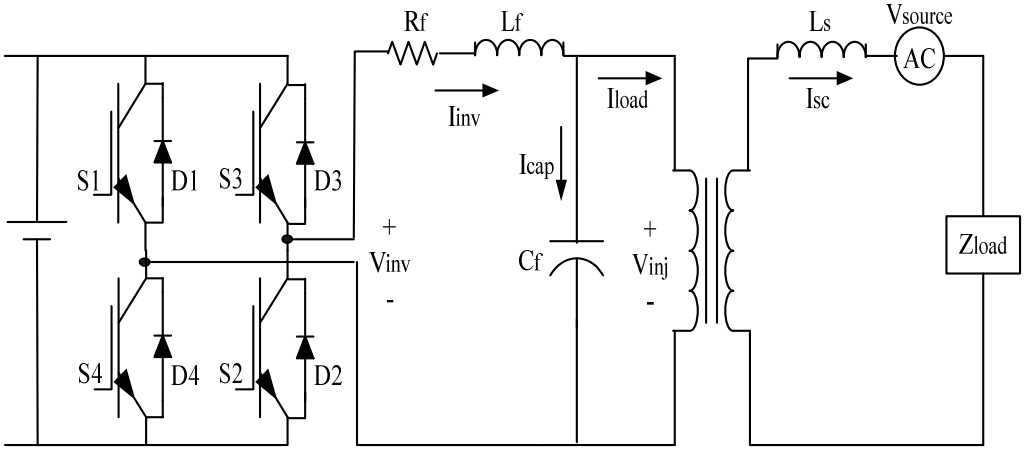


Figure 6.2 Single-phase equivalent circuit of DVR system

V_{inv} is the inverter output voltage; R_f is the series resistance existed in the filter inductor and inverter switches; L_f is the filter inductor; C_f is the filter capacitor; V_{inj} is the injected voltage; L_s is the source inductor.

To understand the feasibility of new topologies and applications, it is required that the characteristics of available system parts should be analyzed. To do this, terminal characteristics, line voltage, current or switching speed capabilities of currently available power devices are required. To mitigate voltage sags the DVR must have excellent dynamic capabilities with response time of less than 0.5 cycles (Chan, 1998). The DVR should be designed to have minimal affect on the system, during faulted and non-faulted system states**.** The ratings of DVR components should be selected properly to ensure fast and reliable response. As seen from the Figure 6.1, there are four main elements, which deserve consideration in the design of a DVR.

- Voltage source PWM inverter
- Injection transformer
- Harmonic filter
- Control system

6.3.1. Voltage Source PWM Inverter

The voltage source PWM inverter operates to control and maintain the desired output voltage. The inverter is fed by DC capacitor and can switch at a high frequency to mitigate the voltage sags from system. The DC capacitor is initially charged before system operation and during operation to maintain a constant DC voltage in the storage element. In industry, the DC energy is already available for DC energy applications. DVR inverter can be connected to currently available DC energy storage device to reduce the rating of DVR and its DC energy storage device. This situation leads to select the DC link voltage as 200 V.

The missing voltage is generated by accurately controlling the switches in the inverter. VSIs based on IGBT devices generate the injection voltages to compensate for the voltage sag. Control of voltage wave shape is limited by the switching frequency of the inverter. The PWM inverter is the most important part of the DVR. MATLAB/Simulink model of the single-phase PWM inverter is shown in Figure 6.3.

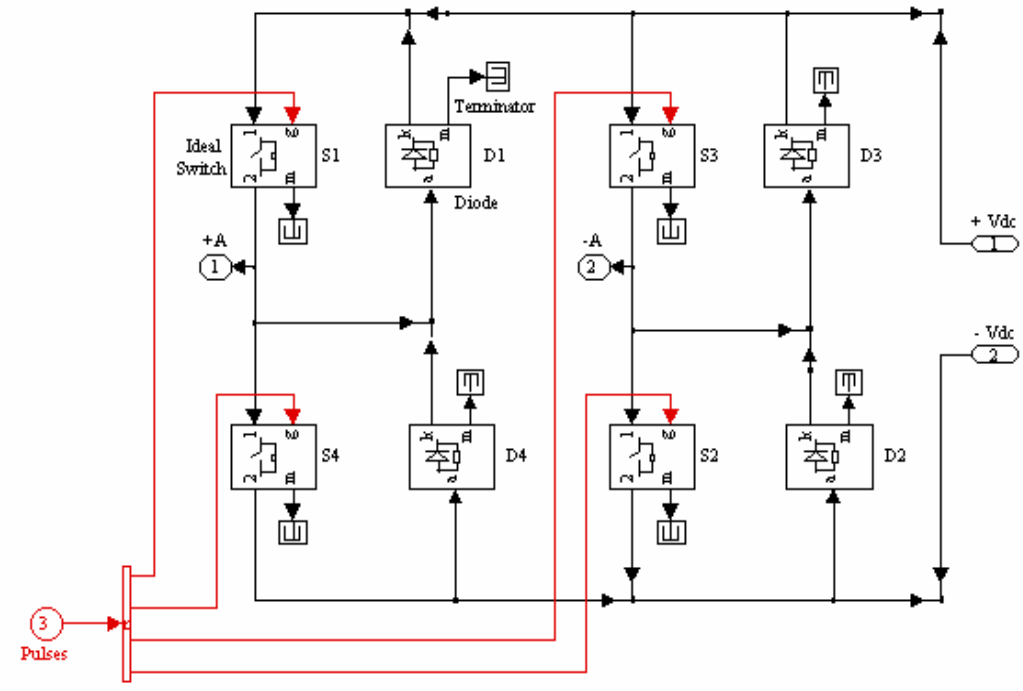


Figure 6.3 MATLAB/Simulink model of the single-phase PWM inverter

The single-phase full wave inverter bridge is built using 4 IGBT switches ($S1, S2, S3, S4$) and 4 anti-parallel diodes ($D1, D2, D3, D4$). The configuration is the same for other phases. The IGBT switch and diode are represented in the MATLAB/Simulink model as an ideal switch and diode respectively. The ideal switches are modeled as a resistor (R_{on}) and inductor (L_{on}) in series with a switch controlled by a logical signal. It switches between on and off state instantaneously when triggered. The diode is modeled as a resistor (R_{Don}), inductor (L_{Don}) and DC voltage source (E_{on}) connected in series with a switch. The anode cathode voltage and current control the switch. Using a diode rectifier as shunt element can cause the generation of extra harmonic currents by the diode bridge during the voltage sag however this cannot cause any problem since the sag duration is limited.

Because of the requirements of Simulink, a snubber circuit is in parallel to assure running of simulation. The snubber circuit limits the voltage spikes produced during reverse recovery of the ideal switch (thyristor) storage charge.

6.3.2. Injection Transformer

The injection transformers connect the DVR to the distribution network via the high voltage windings as shown in Figure 6.4. They transform and couple the injected compensating voltages generated by the VSI to the incoming supply voltage. The ratings of injection transformers are related with the depth of voltage sag, supply current and capacity of DC link. The maximum injection voltage and DC link voltage determine the turn-ratio of the transformer.

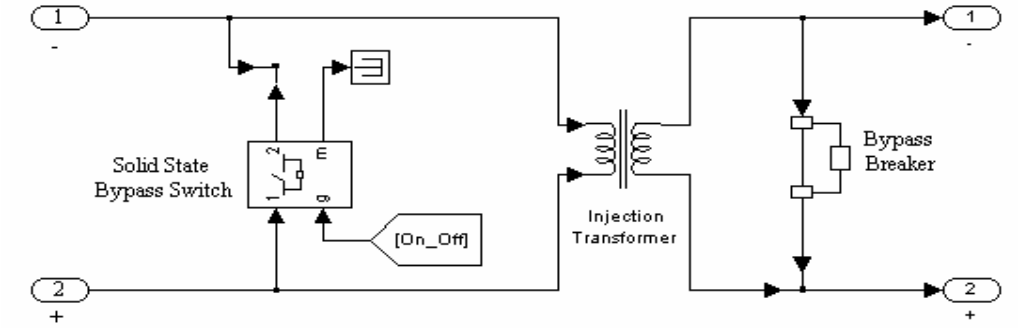


Figure 6.4 Single-phase circuit of injection transformer

In this simulation study, 3 single-phase transformers 6.6 kVA and 3464V/140V (rms) ratings are used. The ratings of the injection transformer are calculated when the system is arranged to perform the worst-case (i.e. three-phase to ground fault with deepest voltage sag magnitude and the longest duration). In this case, the primary (high) side voltage of the single-phase injection transformer is calculated by Formula 3.12. In this study, D=0.4 pu and V_r=8660 Vrms. The theoretical calculation according to the formula results in high side voltage, which is 3464 Vrms. The voltage on filter capacitor at maximum sag (0.4) determines the secondary (low) side voltage, which is 140 Vrms.

In Matlab/Simulink, the resistance, inductance and core parameters of windings are represented in the pu values. The secondary winding parameters of injection transformer are based on P_n= 6.6 (kVA), f_n=50 (Hz) and V_n=140 (Vrms). The default parameters of secondary side of the transformer give the following bases for secondary side winding by using Equation (3.19) and Equation (3.20):

R_{base} = 2.96 Ω, L_{base} = 9.45 mH

In Table 6.2, the secondary winding parameters are R_s=0.056 Ω and L_s=0.067 mH. The corresponding values to be entered in Equation (3.17) and Equation (3.18) are:

$R_{(pu)}$ = 0.019 pu, $L_{(pu)}$ = 0.007 pu

The same procedure is applied to calculate the pu value of primary winding parameters by using the default parameters for primary side in Table 6.2. The primary side parameters are calculated as:

$R_{(pu)}$ = 0.00015 pu, $L_{(pu)}$ = 0.0002 pu

To specify a magnetizing current of 0.5% (resistive and inductive) based on nominal current, the per-unit values of 1/0.005=200 pu for the resistance and the inductance of the magnetizing branch must be entered. Using the base values calculated for secondary side winding, these per-unit values correspond to:

R_m = 588 Ω, L_m = 593 Ω

The parameters of load transformer in pu are calculated by following the same procedures. Applying the same equations for high voltage side with the data given in Table 6.2 yields:

$R_{(pu)} = 0.00048$ pu, $L_{(pu)} = 0.0006$ pu

The low voltage side ratings are calculated as:

$R_{(pu)} = 0.007$ pu, $L_{(pu)} = 0.009$ pu

The bypass breakers are placed in parallel with the injection transformer's primary windings allowing the protection of the DVR in case an overcurrent in the main circuit, due to voltage sags, with durations above the stipulated time, may occur (Ahn *et al.*, 2004). The medium voltage switchgear serves as a bypass circuit breaker allowing continuous power supply during maintenance of the DVR (Chan, 1998). The current could cause an equipment trip or even a long interruption, if fast acting overcurrent protection devices are used (Dong *et al.*, 2004). The solid-state bypass breakers placed in parallel with injection transformer's secondary side (low side) are used to perform short circuit operation during non-faulted times.

To avoid saturation under all conditions, the ratings of injection transformer must be sized to handle at least twice the nominal steady state flux requirement at maximum rms injection voltage without saturation (Middlekauff *et al.*, 1998). The transformers not only reduce the voltage requirement of the inverters, but also provide isolation between the inverters. This prevents the dc storage capacitor from being shorted through switches in different inverters (Ghosh *et al.*, 2002).

6.3.3. LC Filter

The DVR system model is non-linear owing to the presence of power semiconductor switches in the inverter switches. To provide high quality waveforms, an output filter consisting of inductors and capacitors minimizes the modulation components generated by the inverter modules, which otherwise would be imposed on the utility system (Woodley, 2000). Filter circuit allows some signal frequencies to pass while limiting others.

The DVR generally should not actively produce any harmonics but during the sag period, the DVR tends to generate harmonics. In this study, inverter side filtering method is preferred to keep the harmonic voltage content generated by PWM inverter to the permissible level. This scheme is closer to harmonic voltages with low magnitudes but the inverter side filtering can cause phase shift on the system.

The ratings of the inductance (L) and capacitance (C) are related with the maximum injection limit of the DVR. The design procedure of the LC filter is shown in the section 3.5.1. Table 6.1 gives the required values to design the filter.

If the dc source voltage varies widely during the operation, the worst value of the dc voltage that results in the higher value of the output voltage harmonic should be used in this design.

Table 6.1 Parameters used in filter design

E_d (V)	V_o (V)	f_r (Hz)	f_s (Hz)	I_o (A)	$V_{o,av}$
200	180	50	2000	39	0.01 %

Based on the design procedure, the modulation index k is calculated from Equation (3.22) and the factor K is calculated from Equation (3.23). The theoretical calculations result in:

$k = 1.27,\ K = 6.82e^{-3}$

By substituting the obtained values into Equation (3.24) and (3.25), the filter parameters are calculated as:

$L = 2.25$ mH, $C = 84.2$ μF

The obtained closed form expressions of the inductance and capacitance of the LC filter in (Dahono *et al.*, 1995) eliminate the time consuming conventional fourier series method. The obtained L and C values may not give the optimum results due to some initial assumption. The parameters must be verified by analyzing the total harmonic distortion (THD) and harmonic components of the output.

6.3.4. Control System

The main considerations for the control system of a DVR include:

- Quick and accurate characterization of the voltage sags
- Transient and steady state control of the injected voltage
- Protection of the system

The adoption of a proper control strategy to the system can reduce the voltage drops and harmonics so as to improve the voltage restoration performance. Figure 6.5 shows block diagram of control system for single-phase representation.

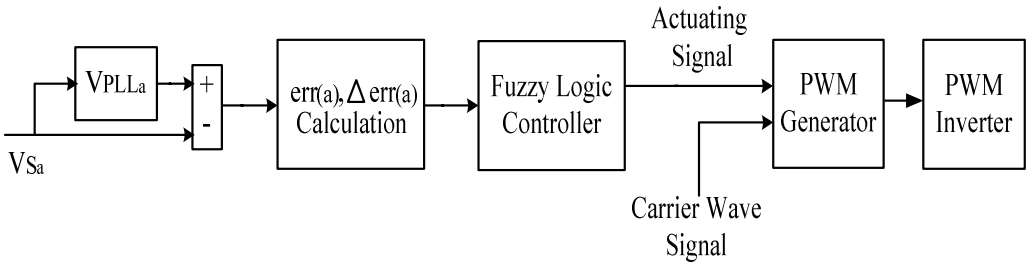


Figure 6.5 DVR control structure

The supply voltage for each phase is converted to pu and error is obtained from the difference of reference PLL generated signal and actual supply voltage converted to per-unit. PLL tracks the phase of network voltage phasor and generates a reference signal with magnitude of 1 locked to supply frequency for each phase. While locking to the phase and frequency of one-phase has the advantage of simplicity, this will lead to the injection of unnecessary voltage and power if the reference phase experiences a phase jump during sag (Fitzer *et al.*, 2001).

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 PWM 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). The proposed DVR uses a feedforward controller to obtain both good transient and steady state response. The in-phase voltage injection strategy is

preferred for generating the compensation voltage. Zero sequence components are not detected and compensated with the proposed control system since the load side step-down transformer (delta connection) blocks the zero sequence voltage caused by a dip.

The proposed method does not appeal to rms calculation of voltages. The rms calculation to analyze the sags does not give reliable and fast results because at least one-half period at the line frequency is required for calculation. The simplicity of the system is improved due to the development of the fuzzy control based DVR model. The developed control strategy with fast power converters and an appropriate modulation method to switch the semiconductor switches will successfully eliminate the disturbances in the system and achieve high efficiency usage of electrical energy.

The DVR has three main operating conditions. When the system is in the normal steady state condition, the DVR operates in standby mode and the PWM inverters inject no voltage to the system. When voltage sag is detected, the DVR starts to inject three single-phase voltages in series with controlled phase and amplitude (on mode). In the event of fault or short circuit in the system, the protection devices provide an alternative path for the fault currents and isolate the DVR from the system (off mode). Figure 6.6 summarizes the operation modes of DVR

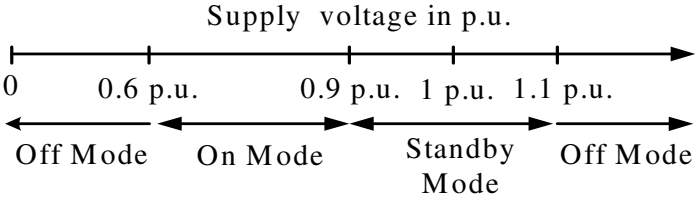


Figure 6.6 Variation of operation modes with sag magnitude

Currents will follow in different directions at outputs depending on the control scheme, eventually supplying AC output power to the critical load during power disturbances. The control of the PWM inverter bridge is indeed the control of thyristor firing angles. Time to open and close gates will be determined by the control system that is governed by a set of rules. The load voltage may not be

compensated to a desirable value owing to voltage drop across the transformer series impedance and the filter.

According to IEEE Standard 519-1992, the objective of the current limit is to limit the maximum individual frequency voltage harmonic to 3% of the fundamental and the voltage THD to 5% for the system without a major parallel resonance at one of the injected harmonic frequency (IEEE Std. 519, 1992). The simulation results should meet the IEEE recommended standard limits.

6.4. Fault Generation

The balanced or unbalanced voltage sags are caused by faults on the transmission or distribution system and by sudden load increases on adjacent feeders. Balanced voltage sags mainly originate from three-phase faults. Unbalanced voltage sags are caused by either single-phase to ground fault or two-phase fault or the combinations of these faults. The location of fault is essentially random and related with the fault distance. In this study, the voltage sags are generated by switching on impedance to the ground or other phases on the PCC at desired time and size. This situation is equivalent to a remote short circuit fault that results in voltage sag with phase shift. Figure 6.7 shows the network fault causing voltage sag.

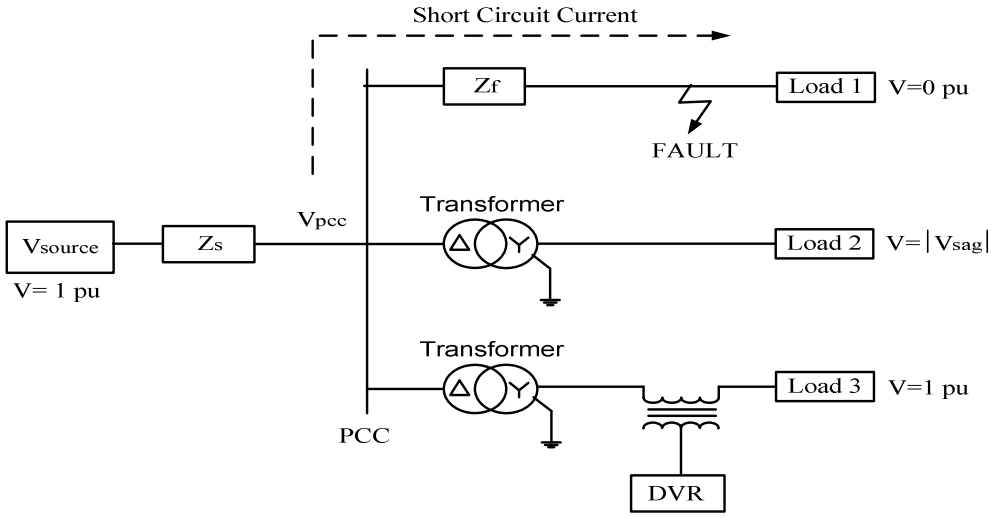


Figure 6.7 Network fault causing a voltage sag

PCC voltage (V_{pcc}) is calculated by Equation (2.1) that is known as effective impedance divider. Sag magnitude very often quantified as a function of the distance to the fault (Dong *et al.*, 2004).

$$Z_f = z * L \tag{6.1}$$

z is the impedance of the feeder per-unit length; L is the distance between the fault and the PCC.

By substituting Equation (6.1) into Equation (2.1) leads to:

$$V_{pcc} = \frac{zL}{zL + Z_s} \tag{6.2}$$

The impedance between the fault and PCC not only consists of lines or cables but also of power transformers. Transformers have large impedance, among others to limit the fault level on the low voltage side, which will lead to relatively shallow sags (Dong *et al.*, 2004).

Figure 6.8 shows the equivalent circuit for common fault condition.

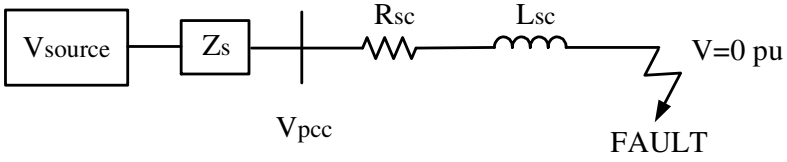


Figure 6.8 Schematic diagram for fault current calculation

R_{sc} is the short circuit resistance of the transformer; L_{sc} is the short circuit inductance of the transformer.

The short circuit current at the secondary side of the transformer is given by:

$$I_{fault} = \bar{I}\left[sin(wt + \varphi - \phi) - sin(\varphi - \phi)e^{\frac{R_{sc}}{L_{sc}}t} \right] \tag{6.3}$$

$$\bar{I} = \frac{V_{pcc}}{\sqrt{R_{sc}^2 + (wL)^2}} \tag{6.4}$$

I_{fault} is the short circuit current; $\bar{I}$ is the peak value of the short circuit after the initial transient; φ is the voltage angle when the fault occurs; ϕ is equal to $\arctan(wL / R_{sc})$.

The fault current consists of a transient ac component, a transient dc component and a load current. It can be observed that the fault current has a decaying part and depending on the angle when the fault occurs.

6.5. Performance Improvement of Voltage Restoration

The critical load should not be exposed to voltage sags in order to maintain a reliable operation. The desired operation is strongly related to the fast and improved transient performance. It is needed to analyze the problems with load voltage compensation to improve the performance (Zhang *et al.*, 2000):

- Voltage drop in the series transformer reduces the load voltage and may cause it to dip below the desired level under heavy load condition.
- If the load is non-linear, the voltage drop across the series transformer will distort the load voltage due to the presence of the harmonics. This causes deterioration in the power supply quality

Analyzing the internal impedance of the DVR eliminates the problems. For all practical purposes, the DVR will have internal impedance. However, it may be possible to optimize the filter parameters and reduce the effects of the impedance. From the power system point of view, the equivalent circuit of the DVR can be simplified to as shown in Figure 6.9.

$R_1 + sL_1$ is the winding impedance of the series transformer; L_f and C_f are the parameters of the filter; R' is the equivalent resistance representing the power loss of the inverter switches; V_h' is the inverter terminal voltage; V_h is the actual output voltage of DVR.

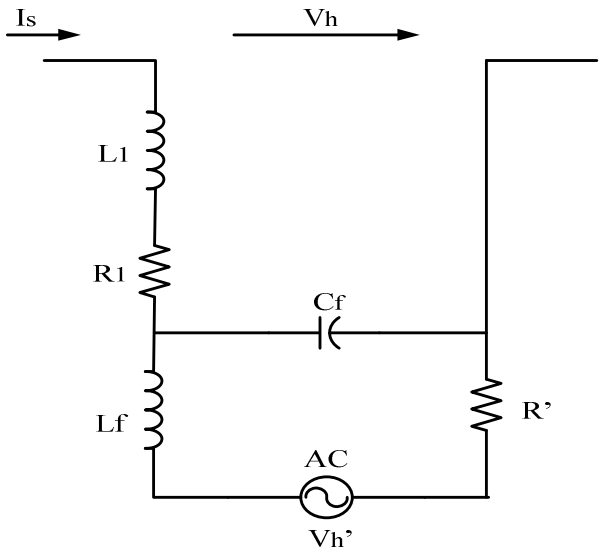


Figure 6.9 The equivalent circuit of DVR

Therefore the internal impedance of the DVR is given by the following expression:

$$Z_{DVR}' = R_1 + sL_1 + \frac{1}{L_f C_f} \frac{sL_f + R'}{s^2 + \frac{R'}{L_f} s + \frac{1}{L_f C_f}} \tag{6.5}$$

The following can be deduced from Equation (6.5):

- The internal impedance can be reduced by making $R_1 + sL_1$ as small as possible.
- The harmonic filter also plays an important role in determining the internal impedance.

Meanwhile, harmonic is more significant when it appears in a fairly longer time, as it is the factor which mainly causes non-useful heat dissipation in load equipment and so forth (Nguyen *et al.*, 2004).

6.6. Summary

The rapid developments in power electronic and advanced control technologies have led to intensive research in the power quality of distribution systems such as voltage sag, voltage swell, interruption and harmonics. Among the disturbances, the voltage sags are considered the dominant disturbances affecting the power quality. In this thesis, it is aimed to mitigate the voltage sags from the system and maintain the operation of sensitive load. The problems have been clearly defined and the researches in this field have mostly been documented in the previous chapters. The chapters have clearly answered the following questions:

- Which of the custom power devices can be best suited to mitigate the voltage sag problem in distribution system?
- Which of the voltage injection methods can be employed in proposed system for mitigation of voltage sags?
- How can the new control strategy control the PWM inverter and improve the power quality of critical load?
- How can the design parameters of DVR be selected?

The new control strategy is integrated to the system and DVR components are theoretically calculated. The designed model should be evaluated with different case studies in order to test and verify the modeled system. The simulation examples will help a more physical understanding of the designed system.

6.7. Parameters of the DVR Used in the Simulation

Table 6.2 The simulation parameters

Data of the System Simulated	
System Fundamental Frequency	50 Hz
Sampling Frequency	10 kHz
Typical Cause of Sags	Line to ground faults
Efficiency in Standby Mode	>99%
Data of the Supply Voltage	
Supply Voltage (phase to phase)	15 kV (rms)
Phase-A Voltage and Resistance	8660 ∠0˚ V (rms), 0.04 Ω
Phase-B Voltage and Resistance	8660 ∠-120˚ V (rms), 0.04 Ω
Phase-C Voltage and Resistance	8660 ∠-240˚ V (rms), 0.04 Ω
DVR Characteristic	
Rated Capacity (three-phase)	20 kVA
Three-Phase Injection Capability	≤40%
Max. Voltage Injection (single-phase)	3464 V (rms)
Data of the Sensitive Load	
Rating	50 kVA
Power Factor	0.95 lagging
Nominal Phase to Phase Voltage	380 V (rms)
Data of the Inverter	
Inverter's Capacity	3 x 6.6 kVA
Semiconductor Voltage	200 V (dc)
Semiconductor Current (peak)	55 A
Switching Frequency	2 kHz
Filter Data	
Capacitance	84.2 μF
Inductance	2.25 mH
Resonance Frequency	350 Hz

DC Link Data	
DC Link Voltage	200 V (dc)
Injection Transformer's Data	
Nominal Power	3 x 6.6 kVA
Standby Losses	0.8% pu
Primary Winding Voltage	3464 V (rms)
Secondary Winding Voltage	140 V (rms)
Primary Winding Resistance	0.28 Ω
Secondary Winding Resistance	0.056 Ω
Primary Winding Inductance	1.11 mH
Secondary Winding Inductance	0.067 mH
Magnetization Resistance and Reactance	588 Ω, 588 Ω
Load Transformer's Data	
Nominal Power	50 kVA
Primary Phase to Phase Voltage	15 kV (rms)
Secondary Phase to Phase Voltage	380 V (rms)
Primary Winding Resistance	2.16 Ω
Secondary Winding Resistance	0.02 Ω
Primary Winding Inductance	8.6 mH
Secondary Winding Inductance	0.08 mH
Connection	ΔY (grounded)
Magnetization Resistance and Reactance	577 Ω, 577 Ω
Data of the Semiconductor Devices	
Ideal Switch Voltage (peak)	200 V
Diode Voltage (peak)	200 V
Forward Voltage	0.4 V

7. SIMULATION RESULTS AND DISCUSSIONS

7.1. Challenges in Computer Simulation

At the beginning, several factors that make simulation of power electronic systems very challenging should be stated (Mohan *et al.*, 1995):

- Solid-state switches including diodes, thyristor, GTO's and metal oxide semiconductor field effect transistors (MOSFET) present extreme non-linearity during their transitions from one state to the other. The simulation program ought to be able to represent this switching of states in an appropriate manner.
- The simulation may take long time, the time constants, or in other words the response time of various parts within the system may differ by several orders of magnitude.
- Accurate models are not always available. This is specially true for semiconductor devices (even for simple diodes) but is also the case for magnetic components such as inductors and transformers.
- The controller in block diagram that may be analog and/or digital needs to be modeled along with the power converters.
- Even if only steady state waveforms are of interest, the simulation time is usually long due to unknown values of the initial circuit states at the start of the simulation.

The challenges listed above dictate that the objective of the simulation is carefully evaluated. In general, it is not desirable to simulate all aspects of the system in detail. The reason is that the simulation time may be very long and the output at the end of the simulation may be overwhelming, thus obscuring the phenomena of interest, in this aspect, the best simulation is the simplest possible simulation that meets the immediate object.

7.2. System Modeling

In this chapter, the performance and effectiveness of the proposed system will be tested with different case studies. The single-line diagram of the modeled system for simulation study of DVR is shown Figure 7.1.

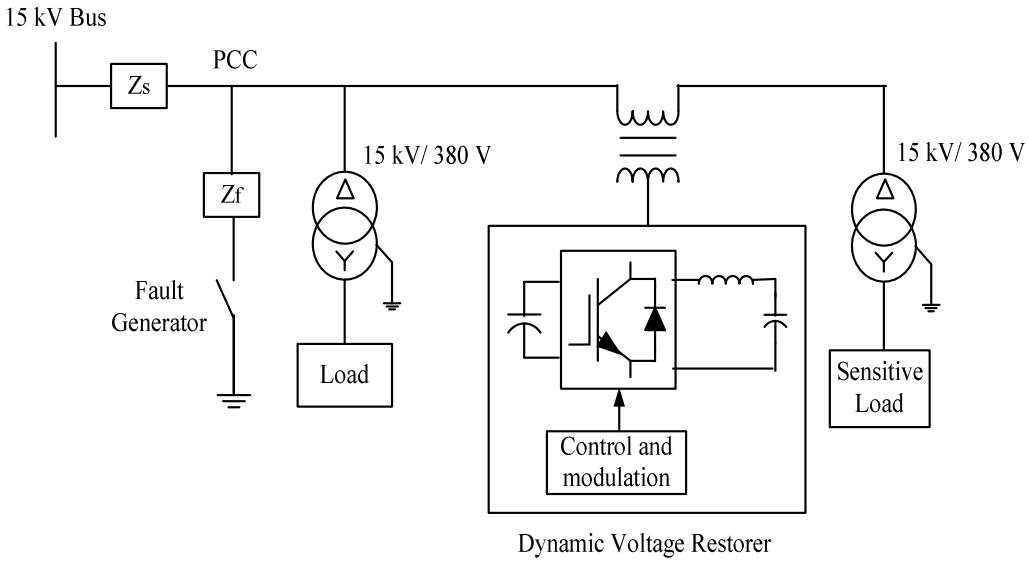


Figure 7.1 Single-line diagram of the test system

In this simulation study, it is aimed to have the following attributes for load voltages:

- Rms voltage recovery grater than 90% of nominal value
- The maximum individual frequency voltage harmonic to 3% of the fundamental value and the voltage THD to 5% for the system
- Load current THD as low as possible for voltage harmonic sensitive applications
- Losses of designed DVR lower than 1% of the nominal rating

7.3. Simulation Examples

To show the restoring function of the proposed DVR and performance of the new control algorithm, the system is tested for the following case studies:

- **Case (1) Single-phase to ground fault:** Most of the faults are single-phase line to ground faults (SLGF). The SLGF occurs on phase A resulting in 40% decrease from nominal value during the period 0.05-0.2 s. Figure 7.2 shows the source voltages, injected voltages and load voltages at SLGF.

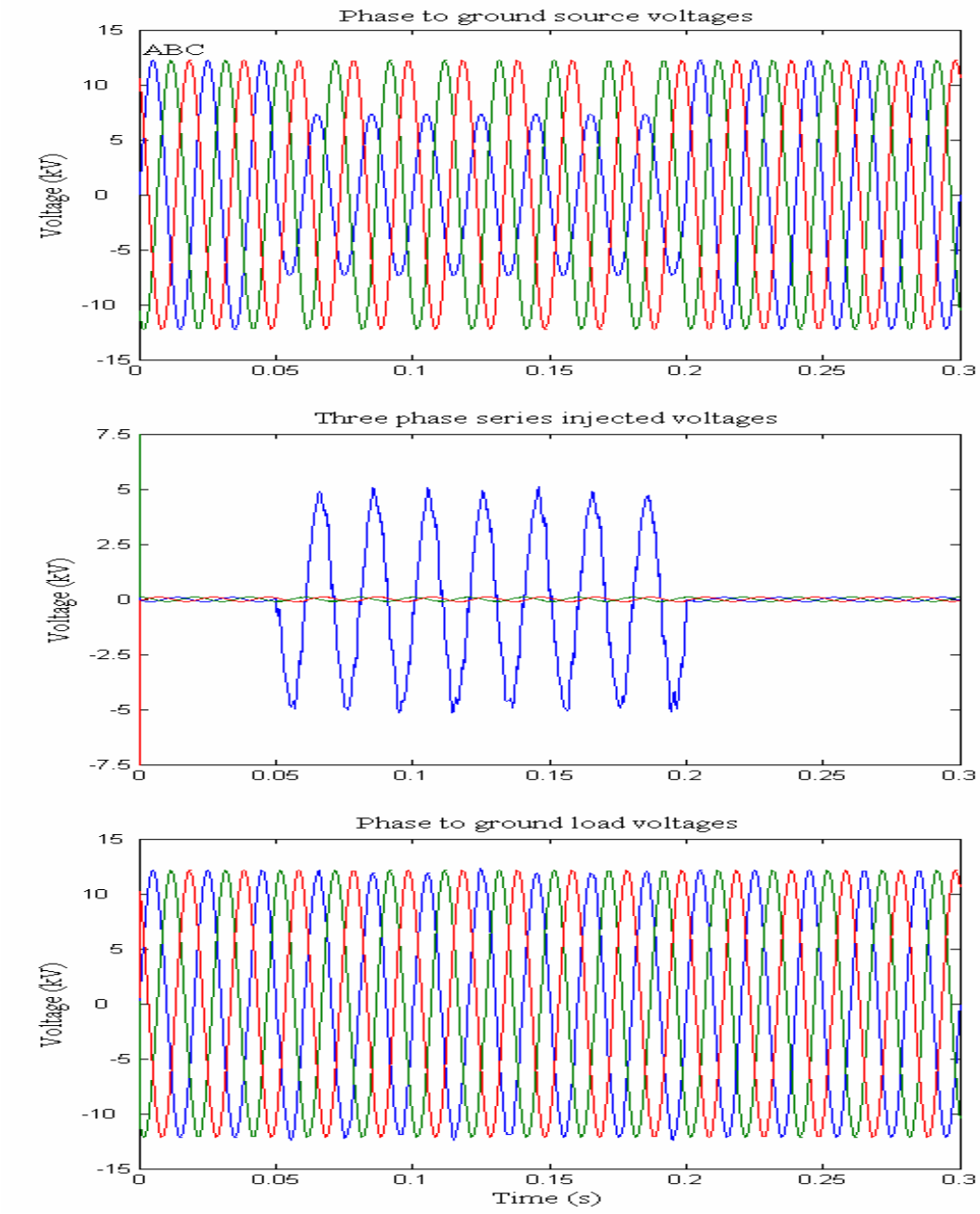


Figure 7.2 Simulation results for Case (1)

Initially there are not any voltage injection and power flow from DVR to the system because no voltage sag is sensed (standby mode). As soon as the sag starts, fuzzy controlled PWM inverter produces the missing voltage so that the voltage sag does not affect the sensitive load (on mode). Table 7.1 summarizes the effects of source, injected and load voltages in standby and on mode.

Table 7.1 Voltage values in standby and on mode

Fundamental Peak Voltage (50 Hz)		**Abbreviation**	**DVR Standby Mode**	**DVR On Mode**
Phase A	Source, V_S	V_S/V_{rs}	1 pu	0.6 pu
	Injected, V_{inj}	V_{inj}/V_{rs}	0.008 pu	0.384 pu
	Load, V_L	V_L/V_{rs}	0.992 pu	0.977 pu

V_{rs} value is 12247 Vmax per-phase, $((15000/\sqrt{3})*\sqrt{2})$; V_s is the measured A phase supply voltage; V_{inj} is the measured injection voltage; V_L is the measured sensitive load voltage.

It is observed that the injected voltages are not equal to zero (~100 V, 0.008 pu) during the standby mode due to the non-linear characteristic of DVR. Phase B and phase C voltages are not affected by the fault because Δ/Yn connected transformers remove the zero sequence components from the system.

The THD level and harmonic content of A phase load voltage are summarized in Table 7.2. The load voltage is nearly perfect sinusoid with low THD of 1.6. The DVR can insert some harmonics to the sensitive load voltage due to oscillations between the filter inductance and the filter capacitance. Other existing harmonics have small magnitude (< 0.6%) with minimal effect to the system.

Table 7.2 THD and harmonic content of phase A

Parameter	**THD**	**Higher Harmonics**	**Harmonic Magnitude**
Phase A	1.6	200 Hz (4^{th})	0.81 %
		150 Hz (3^{rd})	0.62 %

As seen from Figure 7.3, the supply voltage drops, DVR changes its mode from standby (off) to injection (on) mode and load voltage is almost maintained constant. The controller of the DVR rapidly responses to disturbances for keep the voltages in-phase.

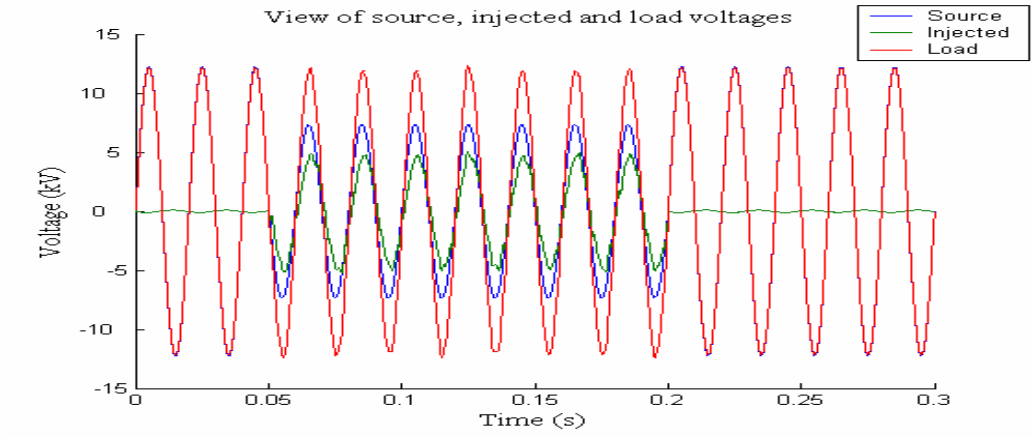


Figure 7.3 The source, injected and load voltages of phase A

Figure 7.4 illustrates the load side currents and Table 7.3 analyzes the load currents. I_{normal} is the normal steady-state load current value. The primary task of DVR is providing the high quality voltage to the critical loads. The load currents remain almost balanced and slightly distorted owing to high quality corrected load voltages.

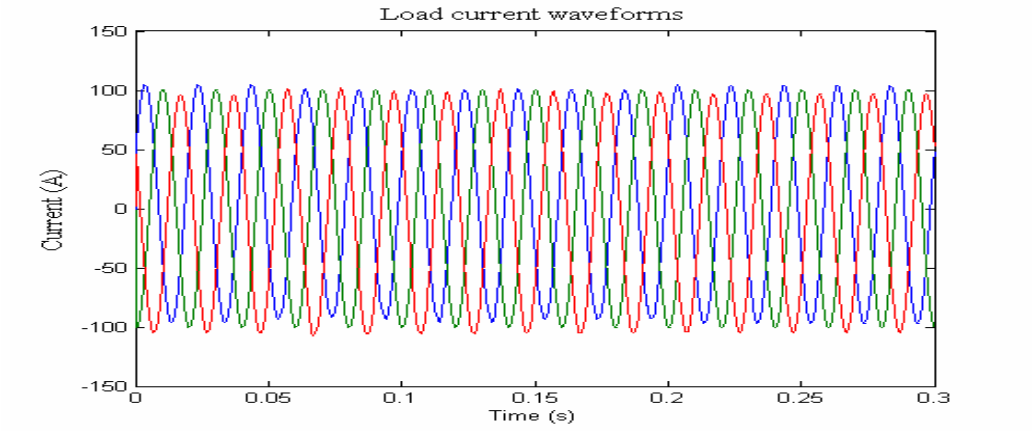


Figure 7.4 Waveform of load currents during simulation period

Table 7.3 Analysis of load currents

Fundamental Peak Current (50 Hz)	**Abbreviation**	**DVR On Mode**	**THD during sag**
Phase A	Iload/Inormal	0.965 pu	0.79 %
Phase B	Iload/Inormal	1 pu	0.01 %
Phase C	Iload/Inormal	1.018 pu	0.76 %

PLL provides the reference voltage for the tracking of source voltage. It generates pure sinusoidal voltage at the same frequency for the system as shown in Figure 7.5.

The fuzzy controllers start to operate in case of a voltage sag is detected lasting 150 ms. The controller inputs are determined by comparing PLL signals and measured source data signals. The controller outputs are compared with triangle wave signals to generate the proper switching pulses. All signal calculations are completed within one sampling cycle.

The fuzzy controllers applied to DVR enable the proposed system for providing a good power and voltage quality to the critical load.

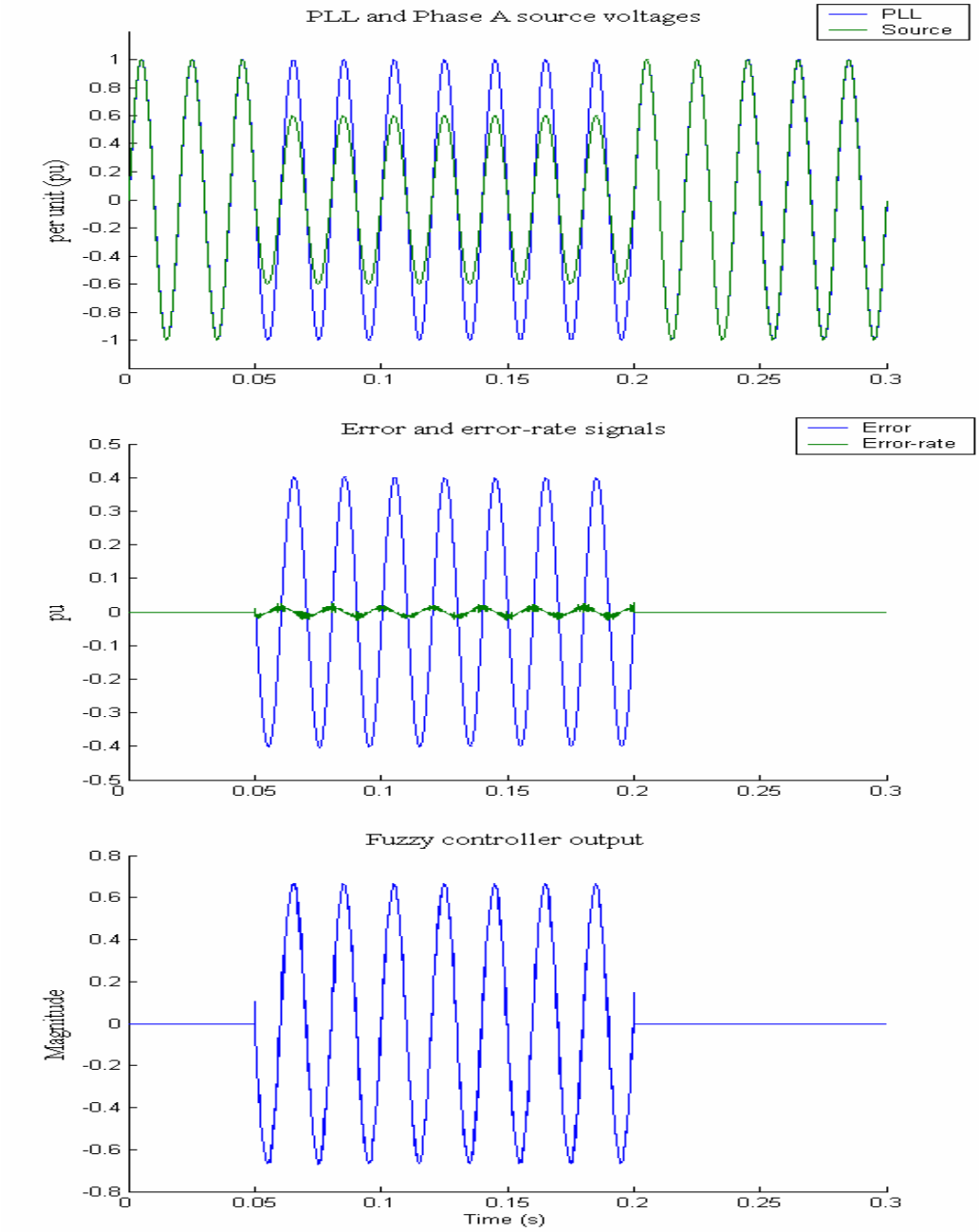


Figure 7.5 The reference and controller signals

- **Case (2) Double-phase to ground fault:** Phase A and phase C voltages are decreased to 60% and 70% from their nominal values during period 0.05-0.2 s. Figure 7.6 shows the source voltages, injected voltages and load voltages under double-phase to ground fault.

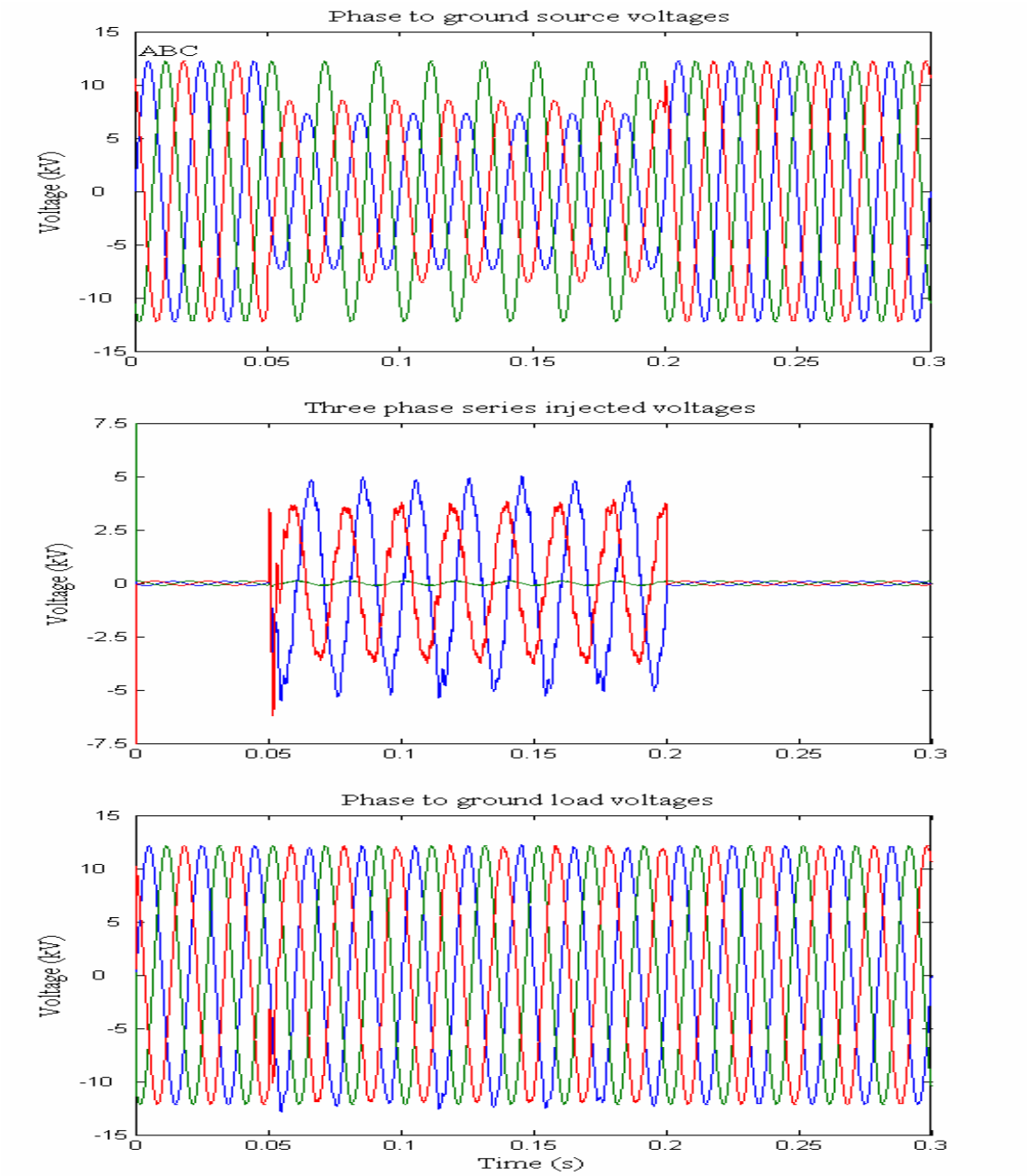


Figure 7.6 Simulation results for Case (2)

Once the voltage sag is detected, the DVR acts increasing the load voltage amplitude to restore the critical load voltage. Figure 7.6 illustrates how quickly the DVR responses for sudden changes to keep the sensitive load voltages at reference value. Table 7.4 analyses the effects of source, injected and load voltages in standby mode and on mode.

Table 7.4 Voltage values in standby and on mode

Fundamental Peak Voltage (50 Hz)		**Abbreviation**	**DVR Standby Mode**	**DVR On Mode**
Phase A	Source, V_s	V_s/V_{rs}	1 pu	0.6 pu
	Injected, V_{inj}	V_{inj}/V_{rs}	0.008 pu	0.382 pu
	Load, V_L	V_L/V_{rs}	0.992 pu	0.975 pu
Phase C	Source, V_s	V_s/V_{rs}	1 pu	0.7 pu
	Injected, V_{inj}	V_{inj}/V_{rs}	0.008 pu	0.291 pu
	Load, V_L	V_L/V_{rs}	0.992 pu	0.981 pu

The THD value and harmonic content of A phase and C phase load voltages are summarized in Table 7.5.

Table 7.5 THD and harmonic content of phase A and phase C

Parameter	**THD**	**Higher Harmonics**	**Harmonic Magnitude**
Phase A	1.89	400 Hz (8^{th})	1.06 %
		350 Hz (7^{th})	0.87 %
Phase C	1.66	350 Hz (7^{th})	1.25 %
		400 Hz (8^{th})	0.58 %

Figure 7.7 shows the source, injected and load voltages of phase C during standby and on mode. The calculated injection voltages exactly compensate the sag because the controller exactly calculates the missing voltage.

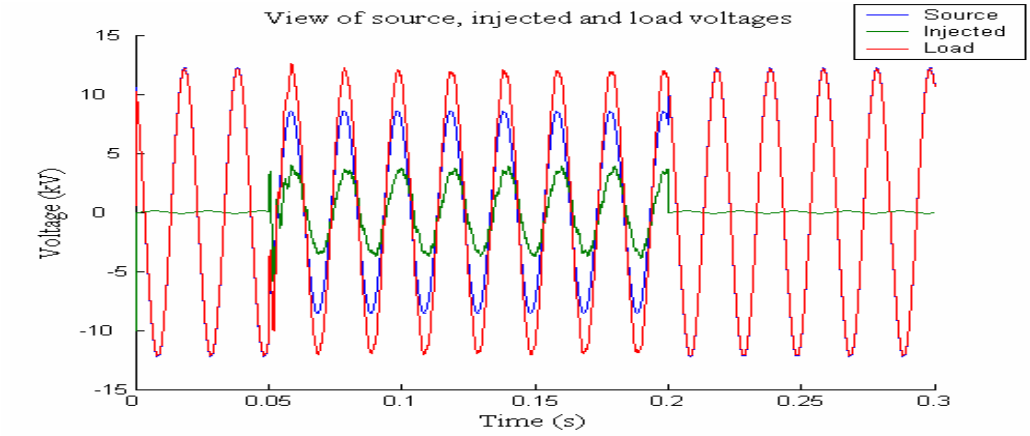


Figure 7.7 The source, injected and load voltages of phase C

The high quality load voltage generates almost constant load current as shown in Figure 7.8. Table 7.6 analyses the quality of load currents.

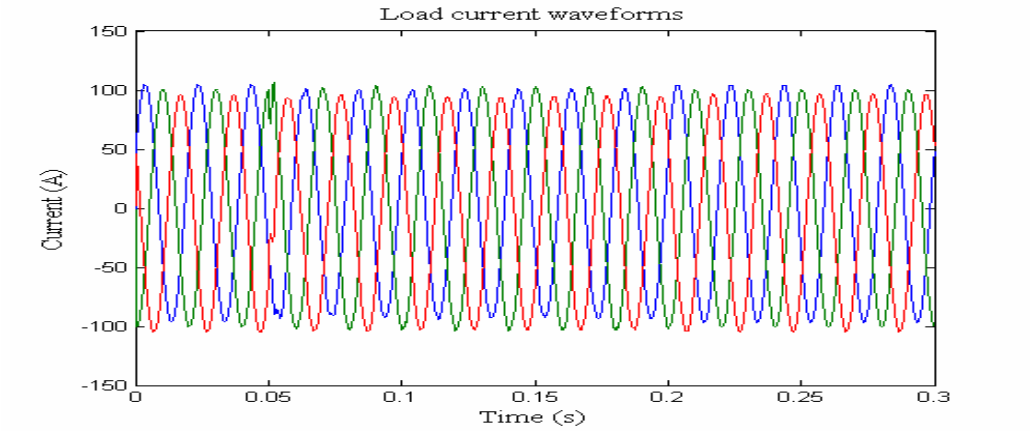


Figure 7.8 Waveform of load currents during simulation period

Table 7.6 Analysis of load currents

Fundamental Peak Current (50 Hz)	**Abbreviation**	**DVR On Mode**	**THD during sag**
Phase A	Iload/Inormal	0.965 pu	1.09 %
Phase B	Iload/Inormal	1.02 pu	0.92 %
Phase C	Iload/Inormal	0.987 pu	1.11 %

The controller inputs are obtained by the instantaneous phase voltage values of the source to obtain a fast and improved transient performance. Figure 7.9 shows the response of control algorithm when presented with a double-phase to ground fault. The controller operates on each supply phase independently.

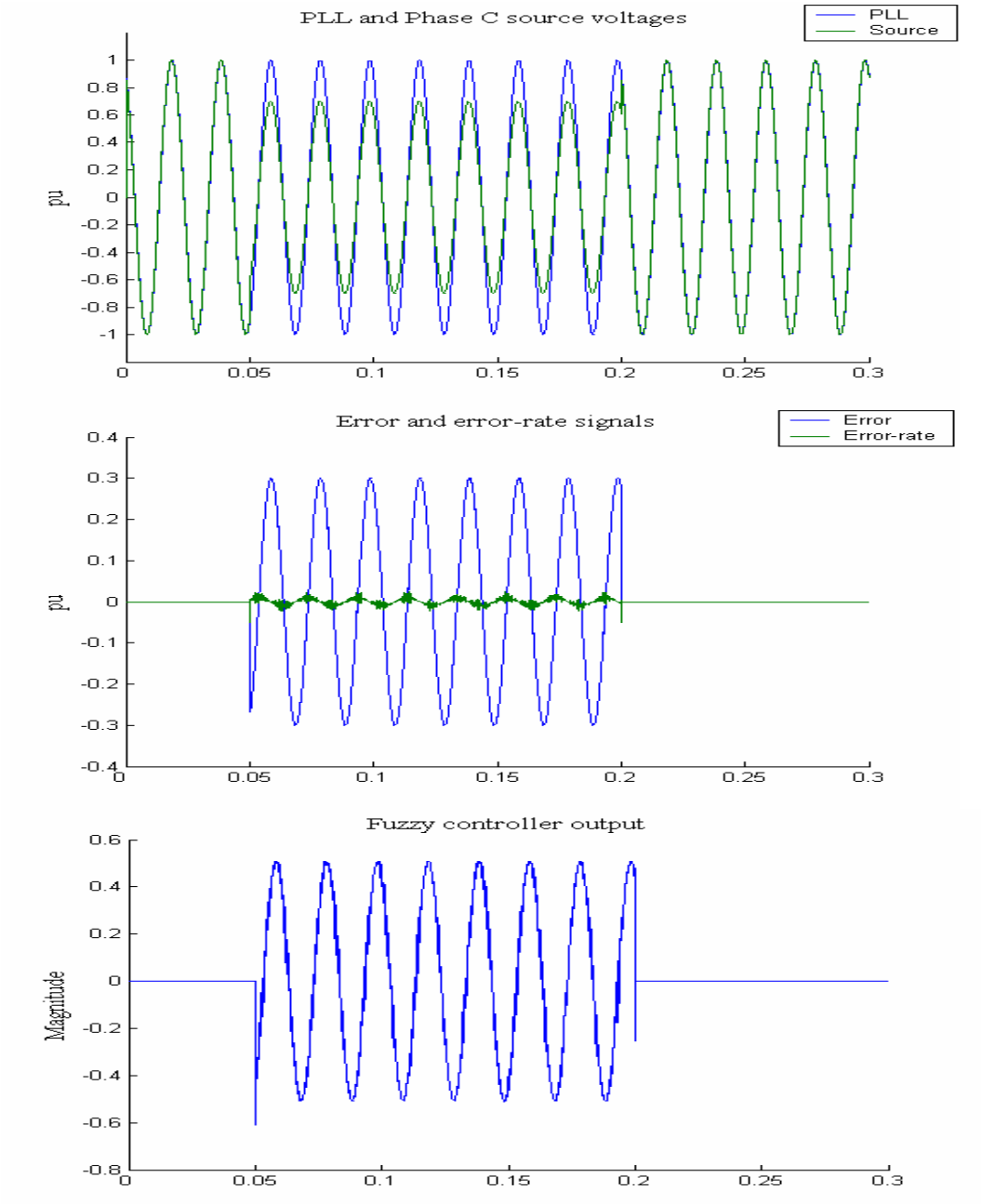


Figure 7.9 The reference and controller signals

- **Case (3) Three-phase unbalanced fault:** In Case 3, A phase, B phase and C phase source voltages are decreased to 60%, 70% and 80% from their nominal values during the period 0.05-0.2 s. Figure 7.10 shows the source voltages, injected voltages and load voltages at three-phase unbalanced sag.

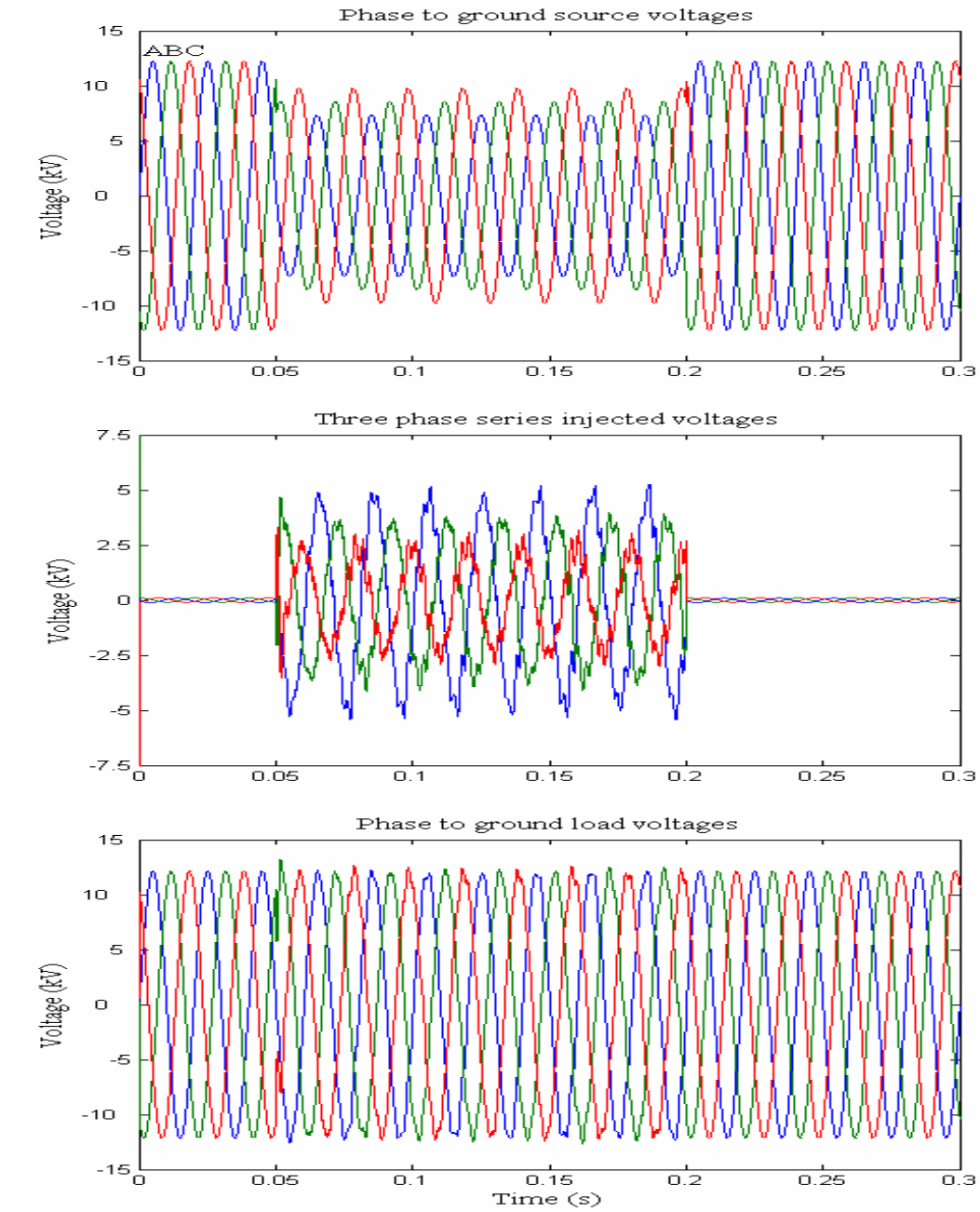


Figure 7.10 Simulation results for Case (3)

The single-phase PWM inverters managed by the control system generate the three distinct series inverter output voltages to compensate the source voltages at different sag level. Table 7.7 summarizes the effects of source, injected and load voltages in standby and on mode.

Table 7.7 Voltage values in standby and on mode

Fundamental Peak Voltage (50 Hz)		**Abbreviation**	**DVR Standby Mode**	**DVR On Mode**
Phase A	Source, V_s	V_s/V_{rs}	1.02 pu	0.6 pu
	Injected, V_{inj}	V_{inj}/V_{rs}	0.008 pu	0.385 pu
	Load, V_L	V_L/V_{rs}	0.992 pu	0.979 pu
Phase B	Source, V_s	V_s/V_{rs}	1.02 pu	0.7 pu
	Injected, V_{inj}	V_{inj}/V_{rs}	0.008 pu	0.286 pu
	Load, V_L	V_L/V_{rs}	0.992 pu	0.977 pu
Phase C	Source, V_s	V_s/V_{rs}	1.02 pu	0.8 pu
	Injected, V_{inj}	V_{inj}/V_{rs}	0.008 pu	0.193 pu
	Load, V_L	V_L/V_{rs}	0.992 pu	0.976 pu

The THD and harmonic content of A phase, B phase and C phase load voltages are summarized in Table 7.8. The results indicate the capability of DVR to deal with unbalanced voltage sags.

Table 7.8 THD and harmonic content of load phases

Parameter	**THD**	**Higher Harmonics**	**Harmonic Magnitude**
Phase A	2.43	350 (7^{th})	1.95 %
		300 (6^{th})	0.98 %
Phase B	2.32	350 (7^{th})	1.79 %
		300 (6^{th})	1.24 %
Phase C	1.64	350 (7^{th})	1.36 %
		300 (6^{th})	0.59 %

As seen from Figure 7.11, the supply voltage drops and DVR almost maintains the load voltage constant.

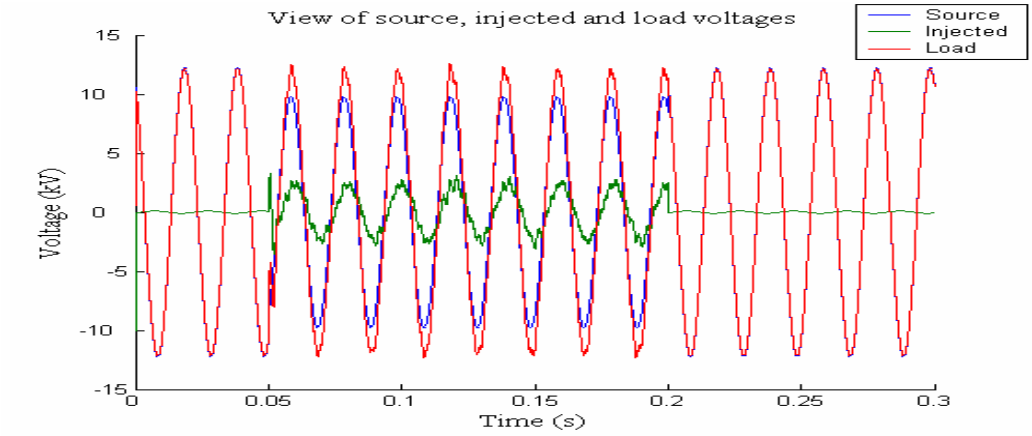


Figure 7.11 The source, injected and load voltages of phase C

Figure 7.12 illustrates the load side currents and Table 7.9 analyzes the load currents.

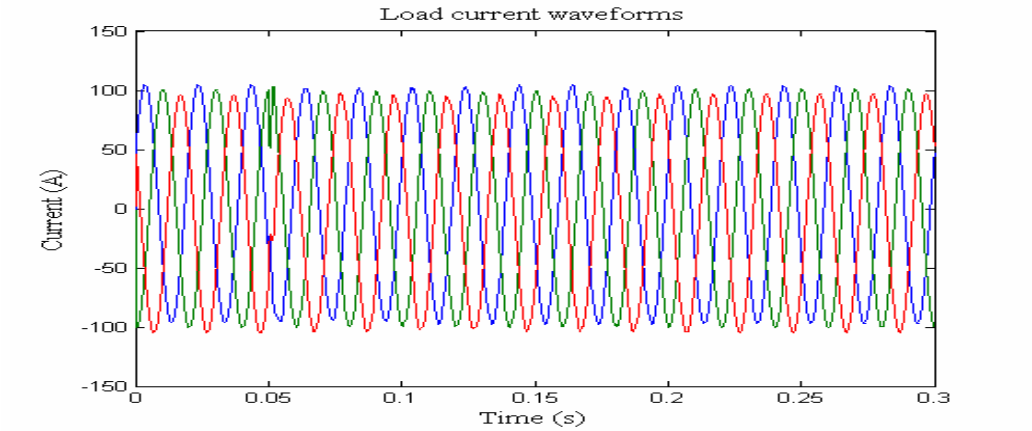


Figure 7.12 Waveform of load currents during simulation period

Table 7.9 Analysis of load currents

Fundamental Peak Current (50 Hz)	**Abbreviation**	**DVR On Mode**	**THD during sag**
Phase A	Iload/Inormal	0.985 pu	1.06%
Phase B	Iload/Inormal	0.985 pu	0.91%
Phase C	Iload/Inormal	0.985 pu	0.77%

Three groups of switching devices work independently from each others. The fuzzy controllers quickly start firing in case the measured phase pu voltages of source are different from the reference values as shown in Figure 7.13. The controller output signals stay at stable condition when all the phase voltages of the load reach to desired value.

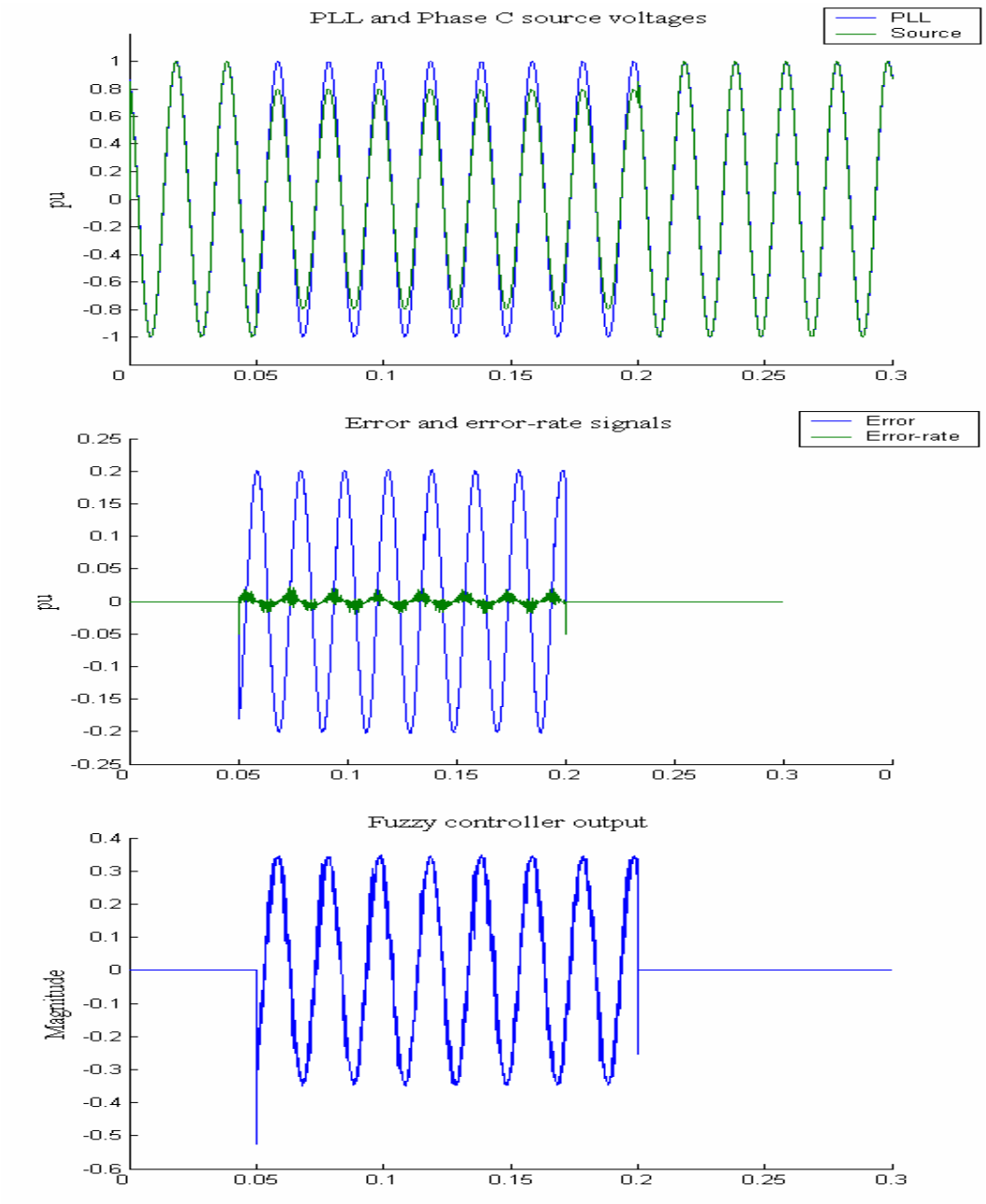


Figure 7.13 The reference and controller signals

- **Case (4) Three-phase balanced fault:** In Case 4, the three-phase balanced fault occurs and 40% voltage sag takes place during the period 0.05-0.2s. Figure 7.14 shows the remaining voltage, injected voltage and load voltage under balanced three-phase sag.

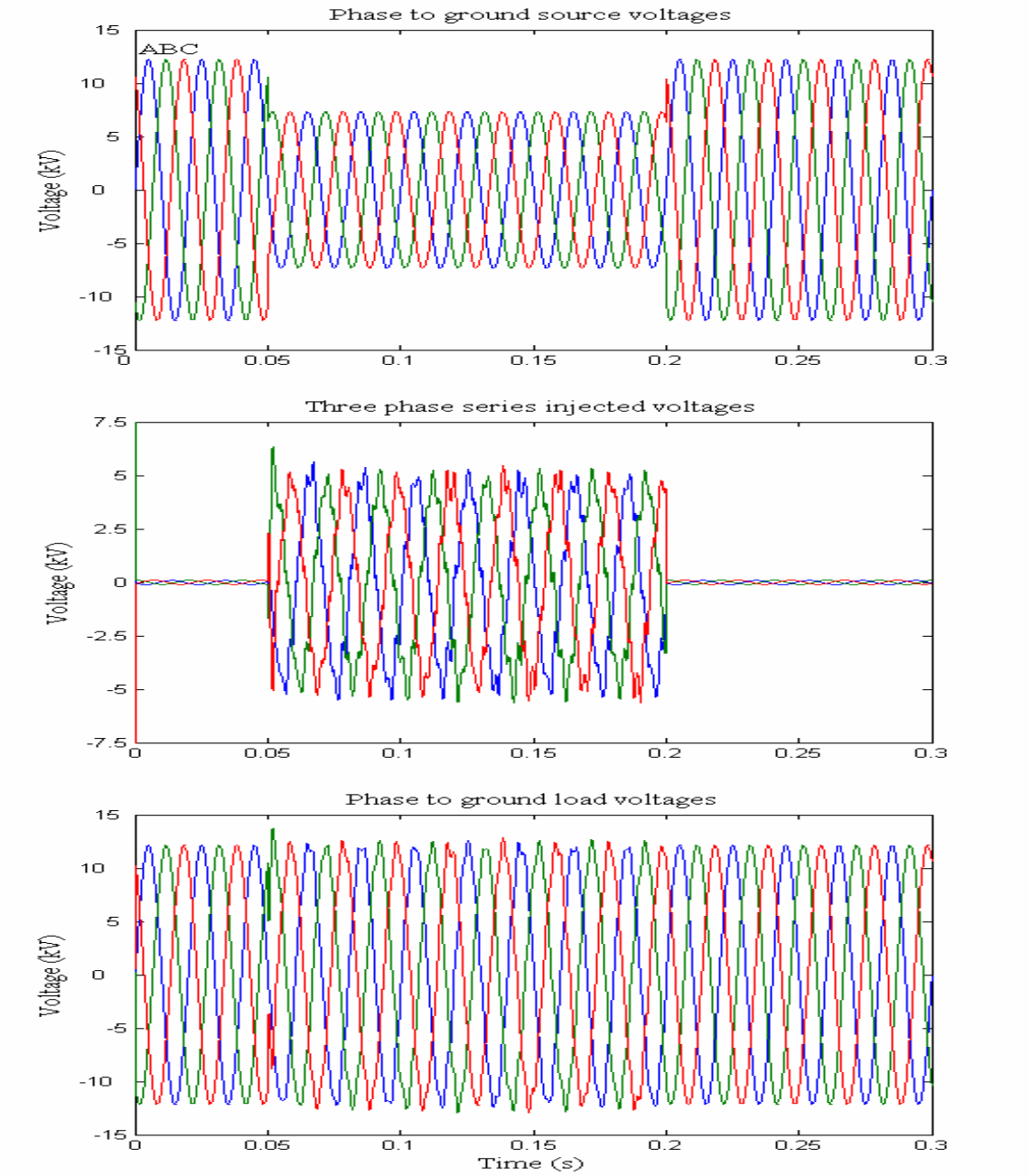


Figure 7.14 Simulation results for Case (4)

The three-phase faults are known as the worst-case fault in the system. As shown from Figure 7.14 and Table 7.10, DVR performs high performance to inject the more in-phase voltage with proper polarity and phase angle. From the three-phase voltage waveforms, the new control strategy of DVR quickly responses to sudden changes and high quality load voltage waveforms are achieved.

Table 7.10 Voltage values in standby and on mode

Fundamental Peak Voltage (50 Hz)		**Abbreviation**	**DVR Standby Mode**	**DVR On Mode**
Phase A	Source, V_s	V_s/V_{rs}	1 pu	0.6 pu
	Injected, V_{inj}	V_{inj}/V_{rs}	0.008 pu	0.387 pu
	Load, V_L	V_L/V_{rs}	0.992 pu	0.98 pu
Phase B	Source, V_s	V_s/V_{rs}	1 pu	0.6 pu
	Injected, V_{inj}	V_{inj}/V_{rs}	0.008 pu	0.38 pu
	Load, V_L	V_L/V_{rs}	0.992 pu	0.975 pu
Phase C	Source, V_s	V_s/V_{rs}	1 pu	0.6 pu
	Injected, V_{inj}	V_{inj}/V_{rs}	0.008 pu	0.384 pu
	Load, V_L	V_L/V_{rs}	0.992 pu	0.979 pu

The THD and harmonic content of A phase, B phase and C phase load voltages are summarized in Table 7.11.

Table 7.11 THD and harmonic content of load phases

Parameter	**THD**	**Higher Harmonics**	**Harmonic Magnitude**
Phase A	3.37	350 (7^{th})	2.61 %
		300 (6^{th})	1.74 %
Phase B	3.49	350 (7^{th})	2.88 %
		300 (6^{th})	1.25 %
Phase C	3.09	350 (7^{th})	2.62 %
		300 (6^{th})	1.05 %

Figure 7.15 shows the source, injected and load voltages during standby and on mode.

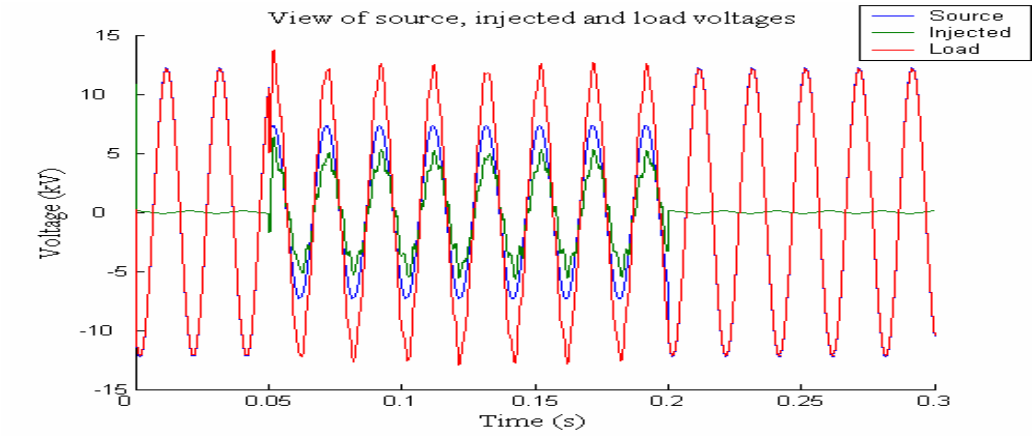


Figure 7.15 The source, injected and load voltages of phase B

The almost constant load current is shown in Figure 7.16 and it is analyzed in Table 7.12.

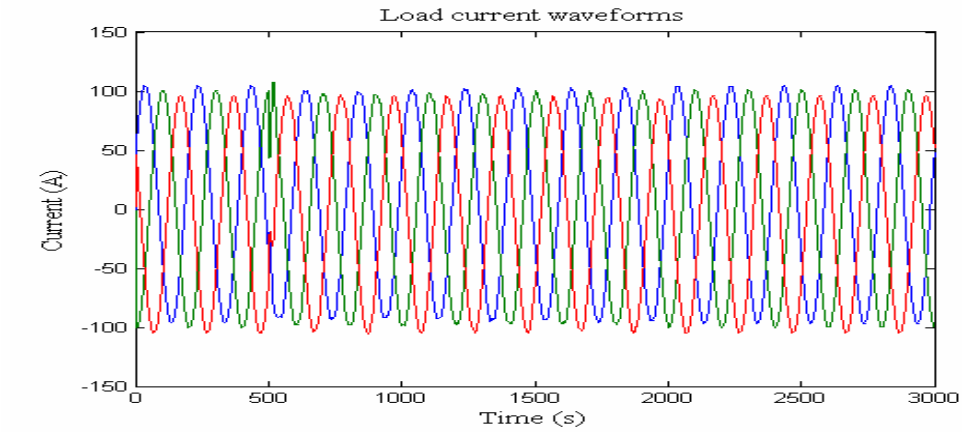


Figure 7.16 Waveform of load currents during simulation period

Table 7.12 Analysis of load currents

Fundamental Peak Current (50 Hz)	**Abbreviation**	**DVR On Mode**	**THD during sag**
Phase A	Iload/Inormal	0.982 pu	0.83%
Phase B	Iload/Inormal	0.985 pu	0.84%
Phase C	Iload/Inormal	0.992 pu	0.97%

Figure 7.17 shows the reference, error and controller output signals. When it is sensed that the source voltage comes outside of a pre-defined range, the control unit quickly starts to generate the reference signals. The fuzzy controller output signals are the inputs to the PWM module to generate the required missing voltages.

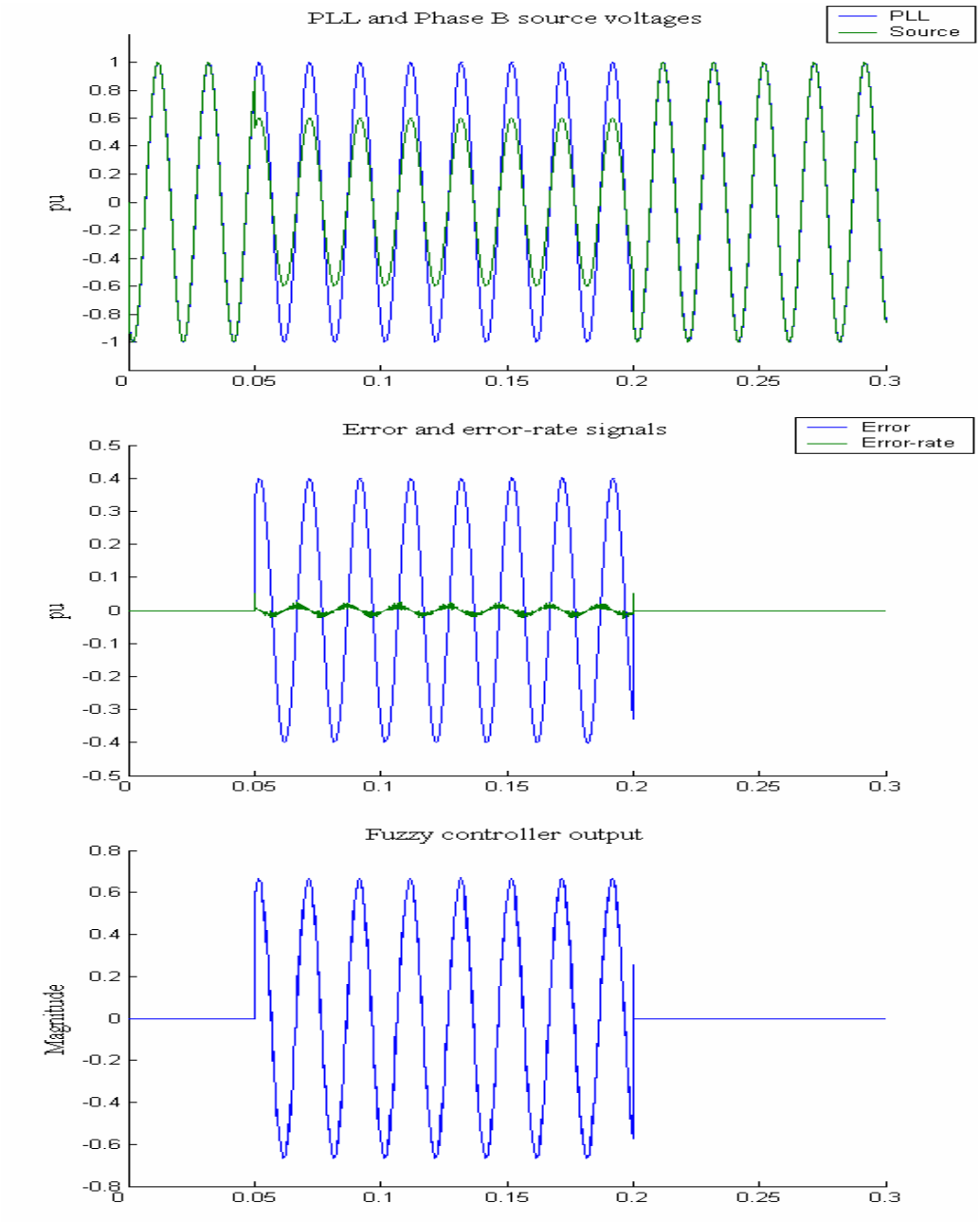


Figure 7.17 The reference and controller signals

7.4. Analysis and Discussions of Case Studies

The control strategy was tested for 4 cases. It is shown that the response time of DVR controller is less than half cycle. This ability confirms the results of proposed DVR control technique for the mitigation of voltage sags. Figure 7.18 shows the waveforms of A phase load voltage and ideal sinusoidal voltage during one-phase fault.

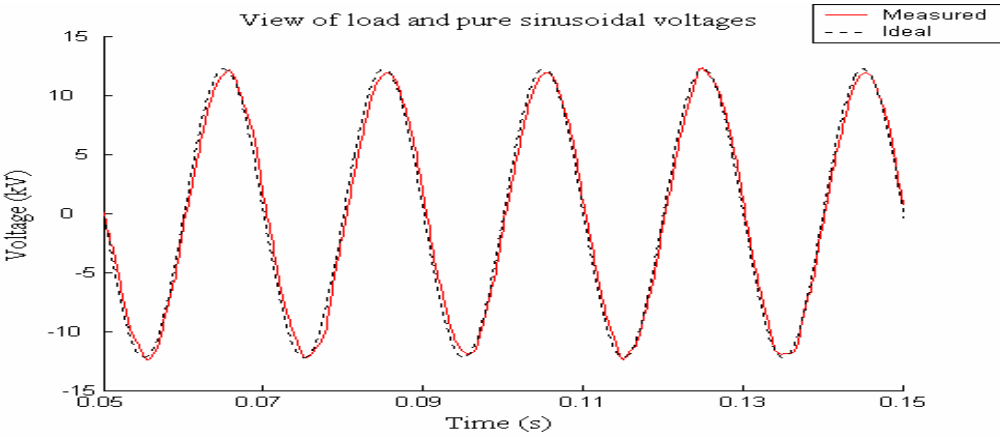


Figure 7.18 Zoomed waveforms of pure sinusoidal and load voltage

DVR prevents the sensitive load from faults and provides high quality system voltage. Figure 7.19 shows the waveform of A phase corrected load and source voltages (rms) during three-phase balanced fault in pu. The critical load voltage (rms) sets between 0.975-0.99 pu.

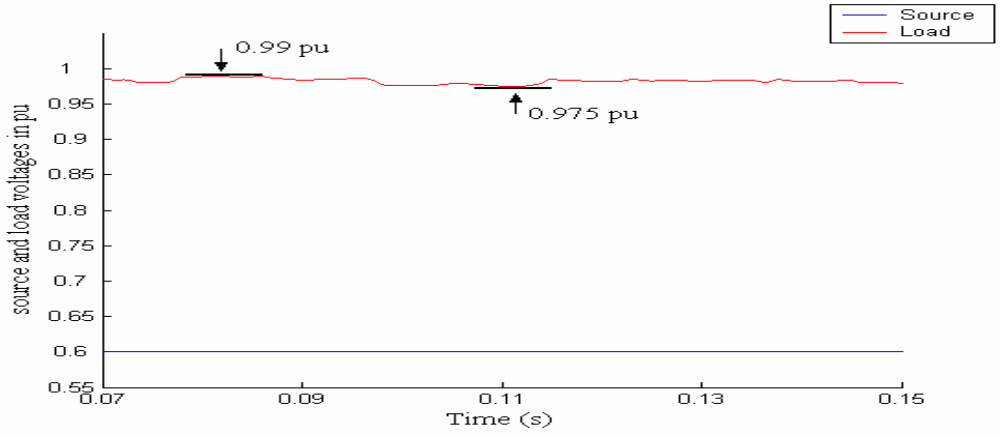


Figure 7.19 View of source and load voltages (pu) in rms terms

In order to compare the case results achieved with fuzzy controlled DVR, Table 7.13 shows the some quantities of A phase load voltage for simulated cases.

Table 7.13 Performance comparisons among study cases

Parameter	**During voltage sag**			
	Case 1	**Case 2**	**Case 3**	**Case 4**
Load rms (pu)	[0.97-0.98]	[0.97-0.98]	[0.97-0.98]	[0.97-0.98]
Load power (pu)	[0.96-0.97]	[0.95-0.96]	[0.95-0.96]	[0.95-0.96]
Power factor (pf)	[0.92-0.934]	[0.914-0.93]	[0.905-0.92]	[0.904-0.91]
THD (%)	1.6	1.89	2.43	3.37
Highest harmonic (%)	0.82	1.06	1.95	2.61

The normal rms value of A phase load voltage is 8660 V ($15000/\sqrt{3}$) and the normal three-phase load power value is 47.5 kW.

The injected active power depends on the voltage sag magnitude, phase angle jump and power factor. The voltage sag is perfectly compensated and no phase jump occurs during sag. This implies that the drop of power factor in pu has small value during sag mitigation.

As shown from Table 7.13, the results approach the standard limits when the amplitude of voltage sag or faulted line number increase. However, THD of the load voltage is always kept below the standard limits by using proper control strategy and applying a LC filter in the circuit. Figure 7.20 shows the inverter output voltage before and after the filter and inverter current after the filter.

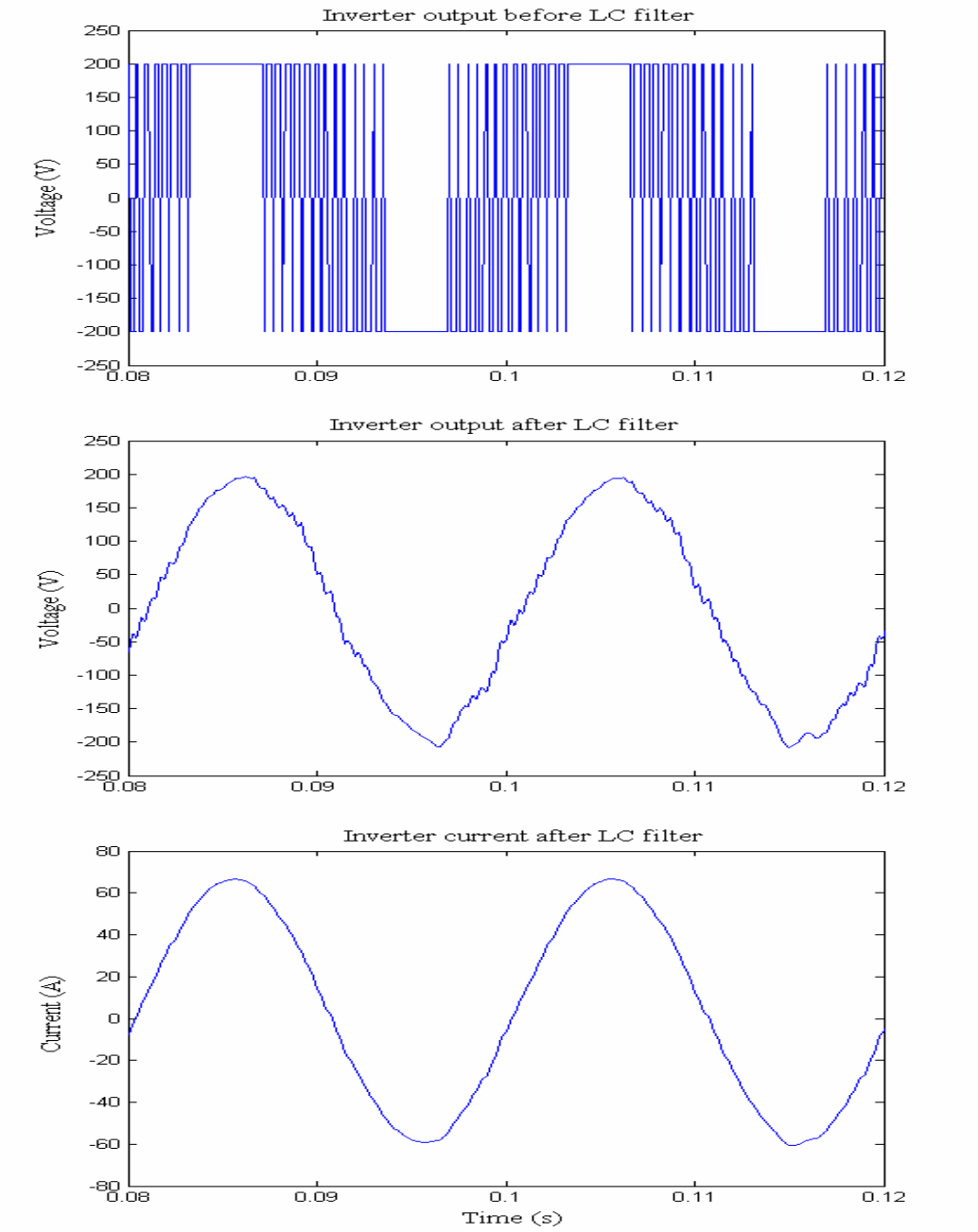


Figure 7.20 Zoomed view of inverter output before and after the filter

As shown from Figure 7.20, with the proper inverter LC filter configuration, the harmonics produced by the inverter will be eliminated and high quality compensation voltage and current will propagate into the distribution system during

voltage sag. With the increasing capacitor value, the voltage waveform of the inverter output can be significantly improved. However, there is no need to increase the size of the capacitor because the designed LC filter has successfully attenuated the harmonics and kept THD value of the load voltages less than 5%. The increasing size of capacitor can result in the ratings of DVR components and total cost of the system to exceed the desired values.

The resonance frequency of the designed DVR is 350 Hz, which is around the 7^{th} harmonic. In case studies, the dominant harmonics are the lower order harmonics. Non-symmetrical conditions (unbalanced fault, sag start and sag end) may produce second order harmonics in the system. The second order harmonic filter can be connected in parallel with the inverter if the values exceed the standard limits. The presented results show that the designed DVR has successfully kept THD of the load side below standard limits and the load voltage nearly 1 pu.

The fuzzy controlled DVR protects the sensitive load voltage against sudden voltage sags in the PCC. Table 7.14 shows the voltage correction ability of DVR for different source voltages. The results show how the DVR dynamically responses to the existing disturbances.

Table 7.14 Sensitive load voltage against source voltage variations

Source Voltage	**60%**	**65%**	**70%**	**75%**	**80%**	**85%**
Load Voltage	0.977 pu	0.987 pu	0.989 pu	0.989 pu	0.99 pu	0.99 pu

Through the simulation cases, at the starting and ending times of faults rapidly damped oscillations can be observed in the voltages. This can be caused by an instantaneous reduction of the voltage reference calculated by the feedforward part and/or the voltage angle when fault occurs.

It is observed from Equation 6.3 that the fault current depends on the angle when the fault occurs. The fault is applied at the zero crossing and at the top value of the voltage waveform, respectively as shown in Figure 7.21.

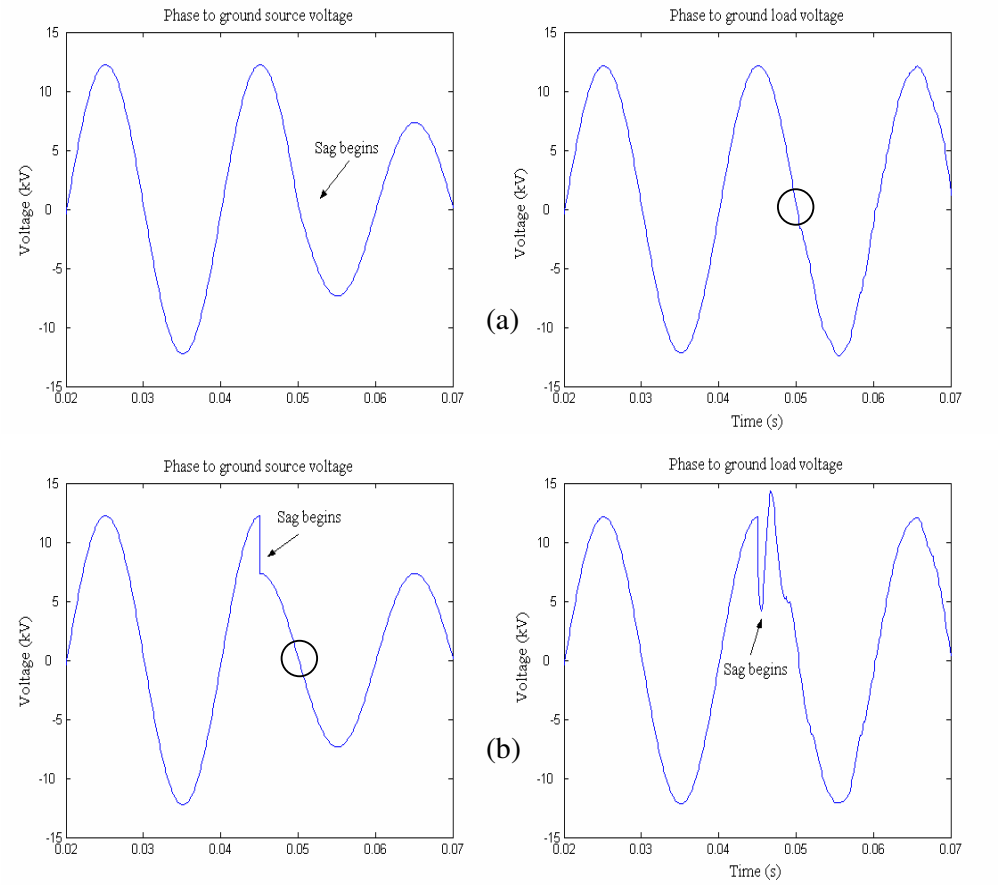


Figure 7.21 Fault occurs at (a) the zero crossing and (b) the peak of the voltage

When the fault occurs at a zero crossing, the transients in the voltage are naturally extinguished. As the fault occurs at a top value, the instantaneous reduction of the voltage is observed.

Throughout the simulation study, the results are compared with IEEE standards to validity the proposed system. The results agree with the standards and theoretical calculations, which indicate that the designed system has superior performance to mitigate the long duration balanced and unbalanced voltage sags.

8. CONCLUSIONS AND FUTURE WORK

The aim of the thesis is to develop a new control strategy to improve the system response and injection capability of the dynamic voltage restorer (DVR) for the mitigation of voltage sags.

The comprehensive literature research was carried out in order to explain and design the studied equipment. The problem was clearly emphasized and the main components and operation principle of DVR were explained in Chapters 1 to 4. In Chapter 5, the new developed control strategy was integrated to adjust the reference signal for the system. In Chapter 6, the DVR was achieved on the basis of the equations to dynamically inject the compensation voltage into the power system. After that, the validity of the designed system was verified by different simulation cases in Chapter 7.

The proposed DVR rated for 20 kVA has been assumed to be located in medium voltage distribution network level and it can mitigate three-phase sags up to 40% of the nominal voltage. The studied DVR is based on forced commutated series connected voltage source inverter (VSI). Pulse width modulation (PWM) technique with switching frequency 2 kHz has been employed in VSI. The DVR has been designed with special importance at the control of PWM inverter. The quick response and high performance have been proposed in the thesis. The traditional control techniques have been analyzed and it has been deduced that they have three main drawbacks: slow transient response, necessity of complex mathematical modeling of the system and requirement of the transformation process.

The fuzzy logic controlled DVR has been developed in this thesis to response quickly (less than 2 ms) and obtain a good dynamic performance. The deriving the mathematical model of the system is not necessary to design a fuzzy controller. The control method does not require a complex computer algorithm. The elimination of transformations, multiplications and divisions makes the control system simple and more reliable. The controller has obtained high performance with relatively low sampling time and switching frequency. The quick response and high performance have been obtained by directly processing the measured source voltages and

employing the direct feed forward control algorithm. A phase locked loop (PLL) has satisfactorily tracked the source voltage and generated reference signal for PWM modulation without experiencing a disturbance. The control system has not deal with the compensation of zero sequence voltages because the faults have occurred in medium voltage system and the shunt transformers connected in delta have eliminated these voltage components.

The DVR has introduced harmonics during mitigation process that needed to be filtered out using LC filter. The LC filter unit has eliminated the dominant harmonics of the inverter output voltage and kept the total harmonic distortion of the load side below the standard limits. The even harmonics can become visible in the load side due to small negative sequence components and natural unbalances in the system. The proper meetings of the LC filter and control algorithm have improved the power quality of PWM inverter output without disregarding duration and magnitude of the sags.

The different voltage compensation strategies have been studied, which are pre-sag compensation, in-phase compensation, phase advance compensation and voltage tolerance compensation methods. It is appropriate before choosing the rating of DVR components to determine a proper compensation strategy. The control algorithm based on in-phase injection method has been employed in the thesis. This method has ensured the minimum injected voltage magnitude and reduced active power injection especially for high power factor loads.

The proposed DVR has shown the ability to mitigate the voltage sags at the PCC. DVR has stayed in standby mode until the sag magnitude exceed the its limit. The small voltage drop on the sensitive load can be seen during standby mode because DVR uses series based topology and is composed of non-linear semiconductor switching devices. The voltage injection has been allowed until the source voltage reached its pre-fault level. The switching devices have correctly been triggered to make the DVR on-line or off-line and protect the DVR especially the injection transformers from the voltage anomalous.

The carefully chosen four case studies have been realized to verify the operation and performance of the designed system in MATLAB/Simulink program.

The voltage sags have been generated by performing controlled short circuits in the grid. It is concluded that the proposed DVR has successfully mitigated the long duration balanced and unbalanced voltage sags and perfectly restored the critical load voltage to nearly 1 pu. In all simulated cases, the fundamental values (50 Hz) of load voltages have been kept higher than 97% of nominal and THD of load voltages have been kept less than 3.5% of nominal.

The results have verified the efficiency, flexibility and transient response capability of the developed control strategy. The designed DVR has provided a regulated and sinusoidal voltage across the sensitive load. The nearly perfect sinusoidal output voltages have resulted in improvements in the current and power quality of the sensitive load.

The proposed system has shown that a high efficiency and reliability can be reached theoretically. The IGBT based VSI technology and dynamic performance capability of fuzzy controlled DVR have improved the quality of critical load quantities by preventing the sags and losses. The suitable settings of DVR parameters have successfully dealt with the different levels and types of voltage sags. The system has eliminated the voltage harmonics and reduced the transient time when switching to the standby mode or the injection mode. The system has successfully met IEEE 519 harmonic standard under all fault conditions.

The DVR is considered the best cost-effective solution against the voltage sags. However, DVR has two main drawbacks which are the need of an energy storage device that could be quickly operated and existence of harmonics in the system during the fault period.

Some studies have proposed to reduce the drawbacks and cost of DVR and improve the response of it. The new researches to reduce the cost and improve the response of DVR are the addition of DC/DC converter for minimizing the energy storage device, transformer-less DVR and absence of energy storage device. The application of voltage tolerance compensation method for injection strategy and three-level converter to minimize the harmonic content are other interesting alternatives.

The DVR is considered a new class of power electronic based equipment for electric power systems. The simulation results of fuzzy controlled DVR are encouraging future research in the fuzzy controller applications. Furthermore, the suggestions for future researches on this topic should be pointed out which are given below:

- The developed control strategy and designed DVR should be tested by connecting the DVR into a real network where the efficiency and accuracy of the proposed system can be better evaluated.
- The efficiency and performance comparison of fuzzy controlled DVR with pqr theory, dq0 theory, neural network and PI controller based DVR.
- Modeling and verifying the proposed control system using PSCAD/EMTDC simulation program.
- The detailed study for the effect of transient characteristics of the system, voltage unbalance, voltage harmonics and various load types on the performance of DVR.
- Application of proposed control algorithm to other kinds of series type voltage compensators such as series active filters, static synchronous series compensators and bootstrap variable inductances.
- Mitigation of zero sequence components from the sensitive load side by improving the proposed control scheme if the transformer is not delta-connected.

By performing the suggestions for future researches on this topic, the DVR technology can be rapidly and efficiently developed and employed.

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BIOGRAPHY

I was born in Osmaniye, Turkey, in 1979. I completed the high school education in Osmaniye. I received the B.S. degree in Electrical and Electronics Engineering from Çukurova University, Adana, Turkey in 2002. After completion my B.S. training, I have started MSc degree in the department of Electrical and Electronics Engineering in Çukurova University and have been working there as a research assistant since 2005.

My areas of interest include power system analysis and modeling, power quality applications, PWM modulation techniques, power system harmonics and control of power converters.

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LIST OF PUBLICATIONS

[1] ELECO 2005, TURKEY

Simulation and Modeling of a Dynamic Voltage Restorer

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Abstract: This paper presents modeling and analysis of a Dynamic Voltage Restorer (DVR) with three-level sinusoidal pulse width modulation (SPWM) based controller by using the Matlab/Simulink program. In addition, the performance of the designed DVR is examined under different sag conditions. The proposed control scheme is simple to design and allows flexibility in cost or robustness constraints.

Index Terms: Dynamic voltage restorer, power quality and voltage sags (dips)

[2] ELMA 2005, BULGARIA

Fuzzy Logic Control of Dynamic Voltage Restorer

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Abstract: This paper presents Fuzzy Logic Control (FLC) of Dynamic Voltage Restorer (DVR). The purpose of this study is detecting voltage sags on the line and injecting the missing voltage to the system. In this study, a new control method for DVR is presented by combining a FLC with a carrier modulated PWM inverter. The proposed control scheme is simple to design, flexible in cost and has excellent voltage regulation capabilities. The simulations under balanced and unbalanced sag conditions verify the performance of the designed DVR.

Keywords: Dynamic voltage restorer, fuzzy logic controller, power quality, voltage sag