

**ÇUKUROVA UNIVERSITY
INSTITUTE OF NATURAL AND APPLIED SCIENCES**

MSc THESIS

Tuğçe DEMİRDELEN

**MODELLING AND ANALYSIS OF MULTILEVEL PARALLEL HYBRID
ACTIVE POWER FILTER**

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

ADANA, 2013

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ABSTRACT

MSc THESIS

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In industrial areas, the harmonics and other power quality problems which is created by nonlinear loads not only have some bad effects such as system loss, efficiency drop, shortening the life of circuit elements but also cause material and natural problems. Therefore, the solutions of reducing power quality problems is required to get both economically and high quality electrical energy. The solution of harmonic distortion generated by nonlinear loads is a quite serious problem. One of these solutions is hybrid active power filters. The main aim of the development of hybrid active power filter is to reduce the cost and capacity of active filter by using passive filter that filters the dominant harmonics caused by non-linear loads and supplies reactive power requirement.

In this thesis, Hybrid Active Power Filter is modeled in PSCAD/EMTDC. The developed topology is a multilevel topology that achieves both harmonic and reactive power compensations. All controllers are written by FORTRAN programming language.

According to the results obtained using PSCAD/EMTDC, it is observed that Multilevel Parallel Hybrid Active Power Filter can compensate both harmonic and reactive power successfully.

Key words: Multilevel Hybrid Active Power Filter, Harmonic Compensation, Reactive Power Compensation

ÖZ

YÜKSEK LİSANS TEZİ

ÇOK SEVİYELİ PARALEL MELEZ AKTİF FİLTRE' NİN
MODELLENMESİ VE ANALİZİ

Tuğçe DEMİRDELEN

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Endüstriyel alanlarda, doğrusal olmayan yüklerin oluşturduğu harmonik ve diğer güç kalitesi problemleri sistem kayıpları, verimin düşmesi, devre elemanlarının ömrünün kısılması, işlev bozuklukları vb. olumsuz etkilere sahip olup, maddi ve doğal birçok probleme neden olmaktadır. Bundan dolayı hem ekonomik hem de kaliteli elektrik enerjisi elde etme konusunda güç kalitesi problemlerini azaltacak çözümler gerekli kılınmaktadır. Doğrusal olmayan yüklerin oluşturduğu harmonik bozulmaların çözümü oldukça ciddi bir problemdir. Bu çözümlerden biri Melez Aktif Güç Filtresi' dir. Melez aktif güç filtrelerinin geliştirilmesindeki temel amaç doğrusal olmayan yüklerin oluşturduğu baskın harmoniklerin filtrelenmesi ile birlikte reaktif güç ihtiyacını pasif filtreler ile sağlayarak aktif güç filtresinin kapasitesini ve dolayısıyla maliyetlerini düşürmektir.

Bu tezde melez aktif güç filtresi PSCAD/EMTDC programı kullanılarak modellenmiştir. Tasarlanan topoloji çok seviyeli bir topoloji olup kontrolcü hem reaktif güç kompanzasyonu hem harmonik kompanzasyon sağlamaktadır. Tüm kontrolcüler FORTRAN programlama diliyle yazılmıştır.

PSCAD/EMTDC simulasyon programında elde edilen sonuçlarda, Çok seviyeli Paralel Melez Aktif Filtrenin hem harmonik kompanzasyon hem de reaktif güç kompanzasyonunu başarılı biçimde gerçekleştirdiği gözlenmiştir.

Anahtar Kelimeler: Çok Seviyeli Paralel Melez Aktif Filtre, Harmonik Kompanzasyon, Reaktif Güç Kompanzasyonu

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CONTENTS	PAGE
ABSTRACT.....	I
ÖZ	II
ACKNOWLEDGEMENTS	III
CONTENTS	IV
LIST OF TABLES	VI
LIST OF FIGURES	VIII
LIST OF SYMBOLS	X
LIST OF ABBREVIATIONS	XIV
1. INTRODUCTION.....	1
1.1. Overview	1
1.2. Scope of Thesis	2
1.3. Outline of the Thesis	3
2. HARMONICS	5
2.1. Harmonics	5
2.2. Definition of Harmonic Problems	5
2.3. Harmonic Mitigation Techniques.....	9
2.3.1. Passive Filter.....	9
2.3.2. Active Power Filter.....	11
2.3.3. Hybrid Active Power Filter.....	13
2.3.3.1. Classification of Hybrid Active Power Filter	14
2.3.3.1.(1). Topology Based.....	14
2.3.3.1.(2). Converter Configuration.....	17
2.3.3.1.(3). Supply System.....	23
2.3.3.1.(4). Passive Filter Type	25
2.3.3.2. Control Strategies	27
2.3.3.2.(1). Signal Conditioning.....	28
2.3.3.2.(2). Generation of Reference Signals.....	28
2.3.3.2.(3). DC Link Control.....	29
2.3.3.2.(4). Generation of Firing Signals	29
3. MODELLING AND ANALYSIS OF PROPOSED HAPF.....	31

3.1. Circuit Topology	31
3.2. Design Circuit Elements.....	34
3.2.1. Passive Filter Capacitor and Inductor	34
3.2.2. Power Converter	35
3.2.3. DC Link.....	35
3.2.4. Diode Rectifier	36
3.2.5. RL Load	36
3.2.6. Supply	37
3.2.7. Active Power Filter.....	38
3.3. Control Techniques	39
3.3.1. Calculation of Harmonic & Reactive Current References.....	39
3.3.1.1. DQ Theory.....	39
3.3.2. Control and Waveform Modulation Method	42
3.3.2.1. Control Method	42
3.3.2.1.(1). Harmonic Current Control.....	43
3.3.2.1.(2). Reactive Power Control.....	46
3.3.2.1.(3). DC Link Voltage Control	47
3.3.2.2. Waveform Modulation Method.....	48
4. SIMULATION Model AND RESULTS OF THE SYSTEM.....	53
4.1. Simulation Models	53
4.2. Analysis of Case Studies	55
5. CONCLUSIONS.....	77
REFERENCES.....	79
BIOGRAPHY	91

LIST OF TABLES	PAGE
Table 2.1. Voltage Distortion Limits (Uçak, 2010)	7
Table 2.2. Current Distortion Limits for General Distribution Systems (Uçak, 2010)	8
Table 2.3. Advantages and Disadvantages of Flying Capacitor Converter (Khomfoi et. al.).....	18
Table 2.4. Possible Switching Configurations in a three-level Cascaded Converter using the binary notations (Galvan,2006)	19
Table 2.5. Advantages and Disadvantages of Cascaded Converter (Galvan,2006)..	19
Table 2.6. Possible switching configurations in three level DCC (Galvan,2006)	21
Table 2.7. Advantages and Disadvantages of Diode Clamped Converter (Galvan,2006).....	21
Table 4.1. Simulation Parameters for Case-1	56
Table 4.2. Simulation Parameters for Case-2	59
Table 4.3. Simulation Parameters for Case-3	63
Table 4.4. Simulation Parameters for Case-4	66
Table 4.5. Simulation Parameters for Case-5	69
Table 4.6. Simulation Parameters for Case-6	73

LIST OF FIGURES	PAGE
Figure 2.1. Harmonic currents flowing through the system impedance result in harmonic voltages at the PCC (Cheng,2006).....	9
Figure 2.2. Series passive filter configuration (Zubi,2005)	10
Figure 2.3. Common shunt passive filter configurations (Zubi,2005).....	10
Figure 2.4. Low pass broadband filter configurations (a): LC type, (b): LLCL type (Zubi,2005).	11
Figure 2.5. a) Series APF b)Shunt APF (Tan, 2011)	12
Figure 2.6. Classification of HAPF (Demirdelen et. al., 2013)	14
Figure 2.7. HAPF Topologies (a)series active power filter +shunt passive filter, (b)shunt active power filter + shunt passive filter, (c)active power filter connected in series with shunt passive filter (Demirdelen et. al., 2013)	16
Figure 2.8. Multilevel inverter based Hybrid APF	22
Figure 2.9. Hybrid APF (a) Single Phase Two Wire, (b) Three-Phase Three Wire and (c) Three Phase Four Wire (Demirdelen et. al., 2013).....	24
Figure 2.10. Classification according to filter: (a) LC, (b) Parallel resonant , (c) RLC, (d) LCL and (e) Injection- Type (Demirdelen et. al., 2013)	27
Figure 3.1. Parallel Hybrid Active Power Filter	32
Figure 3.2. (a) Single Phase Equivalent Circuit (b) Harmonic Equivalent Circuit.	32
Figure 3.3. (a) Three Phase Current Vectors (b) DQ Transformation	40
Figure 3.4. Current Reference Calculation Based on SRF Method	42
Figure 3.5. Power Calculation Based on SRF Method	42
Figure 3.6. Block Diagram of the Sogi-PLL (Demirdelen et. al., 2013)	43
Figure 3.7. Single Phase Equivalent Circuit of HAPF (Harmonic Compensation applied)	45
Figure 3.8. Reactive Power Equivalent Circuit.....	46
Figure 3.9. Control Block Diagrams of Proposed HAPF	51
Figure 4.1. Simulation Model of Parallel Hybrid Active Power Filter.....	54
Figure 4.2. Simulation Model of Multilevel Parallel Hybrid Active Power Filter ..	55
Figure 4.3. SOGI-PLL Output and Mains Voltage.....	56

Figure 4.4.	PHAPF Operates.....	57
Figure 4.5.	DC Link Voltage of PHAPF.....	57
Figure 4.6.	Source Active and Reactive power, Load Active and Reactive Power	58
Figure 4.7.	Source and Load Harmonics and THD.....	58
Figure 4.8.	Multilevel-PHAPF Operates.....	60
Figure 4.9.	DC Link Voltage of Multilevel-PHAPF.....	60
Figure 4.10.	Source Active and Reactive power, Load Active and Reactive Power	61
Figure 4.11.	Simulation Results	61
Figure 4.12.	PHAPF Operates.....	64
Figure 4.13.	DC Link Voltage of PHAPF.....	64
Figure 4.14.	Source Active and Reactive power, Load Active and Reactive Power	65
Figure 4.15.	Simulation Results	65
Figure 4.16.	Multilevel-PHAPF Operates.....	67
Figure 4.17.	DC Link Voltage of Multilevel-PHAPF.....	67
Figure 4.18.	Source Active and Reactive power, Load Active and Reactive Power	68
Figure 4.19.	Simulation Results	68
Figure 4.20.	PHAPF Operates.....	70
Figure 4.21.	DC Link Voltage of HAPF.....	70
Figure 4.22.	Source Active and Reactive power, Load Active and Reactive Power	71
Figure 4.23.	Simulation Results (First Load Connected).....	71
Figure 4.24.	Simulation Results (First and Second Loads Connected).....	72
Figure 4.25.	Multilevel- PHAPF Operates.....	74
Figure 4.26.	DC Link Voltage of HAPF	74
Figure 4.27.	Source Active and Reactive power, Load Active and Reactive Power	75
Figure 4.28.	Simulation Results (First Load Connected).....	75
Figure 4.29.	Simulation Results (First and Second Load Connected)	76

LIST OF SYMBOLS

C	: Capacitor
C_{DC}	: DC Link Capacitor Value
C_F	: Passive Filter Capacitor
F	: Farad
f	: Fundamental Supply Frequency
f_{tuned}	: Tuning frequency of Passive Filter
h	: Order of Harmonics
H_d	: Closed Loop Transfer Function of SOGI-PLL
H_q	: Closed Loop Transfer Function of SOGI-PLL
i_a	: Phase a Current
I_{APF}	: Injected Current of Active Power Filter
i_b	: Phase b Current
i_c	: Phase c Current
I_{cxf}	: Fundamental Compensation Current
I_{cxfp}	: Fundamental Active Compensation Current
I_{cxfq}	: Fundamental Reactive Compensation Current
I_d	: Direct Current
I_{dh}	: Harmonic Component of Quadrature Current
I_F	: Fundamental Current
I_{fh}	: Fundamental Harmonic Current
I_g	: Source Current
I_h	: Harmonic Current
I_L	: Load Current
I_{Load}	: Load Current
I_o	: Zero Sequence Component of Current
I_q	: Quadrature Current
I_{qh}	: Harmonic Component of Quadrature Current
I_{sc}	: Short Circuit Current
I_{sh}	: Harmonic Component of Source Current

I_{Total}	: Total Current
ms	: Milliseconds
k	: Gain of Sogi-PLL
K_c	: Gain of Reactive Power Compensation Loop
K_h	: Feedback Gain of PHAPF
L	: Inductance
L_F	: Inductance of Passive Filter
L_{Load1}	: Inductance of First Load
L_{Load2}	: Inductance of Second Load
L_{ac}	: Inductance of Nonlinear Load
L_s	: Source Inductance
μ	: Micro
P	: Active Power
Q	: Reactive Power
Q_{cxf_PF}	: Fundamental Reactive Power of Passive Filter
Q_{Lxf}	: Fundamental Reactive Power of Load
qv'	: Output Signal with a Phase Shift of $\pi/2$ rad (Sogi-PLL)
R	: Resistance
R_{Load1}	: Resistance of First Load
R_{Load2}	: Resistance of Second Load
R_s	: Source Resistance
S	: Apparent Power
$S_{activefilter}$: Apparent Power of Active Filter
S_{RL}	: Apparent Power of Linear Load
U_K	: Short Circuit Voltage of Transformer in Percentage
v	: Output Signal with the Same Phase and Magnitude Input Signal of Sogi-PLL
v'	: Input Signal of Sogi-PLL
V_{APF}	: APF Voltage
V_{cap}	: Actual Value of DC link Capacitor Voltage
V_{cappi}	: Error between Actual and Reference Values of DC link Capacitor

Voltage

$V_{cap,ref}$: DC link Capacitor Voltage Reference Value
V_d	: Direct Voltage
V_{dc_minx}	: Minimum DC Link Voltage
V_h	: Harmonic Component of Voltage
V_{invxf}	: Fundamental Inverter Voltage
V_{invxfp}	: Fundamental Active Inverter Voltage
V_{invxfq}	: Fundamental Reactive Inverter Voltage
V_q	: Quadrature Voltage
V_{sh}	: Harmonic Component of Source Voltage
V_x	: Output Voltage of Inverter
X_{cf}	: Fundamental Reactance of Capacitor
X_{LF}	: Fundamental Reactance of Inductance
X_{PPFf}	: Fundamental Reactance of Passive Filter
Z	: Impedance
Z_c	: Capacitor Impedance
Z_L	: Inductance Impedance
Z_{fh}	: Harmonic Component of Fundamental Impedance
Z_{sh}	: Harmonic Component of Source Impedance

LIST OF ABBREVIATIONS

AC	: Alternative Current
APF	: Active Power Filter
ASD	: Adjustable Speed Drives
BJT	: Bipolar Junction Transistor
CSI	: Current Source Inverter
DC	: Direct Current
DF	: Distortion Factor
DSP	: Digital Signal Processor
FFT	: Fast Fourier Transform
GTO	: Gate Turn-off Thyristor
HAPF	: Hybrid Active Power Filter
HF	: Harmonic Factor
HVDC	: High Voltage Direct Current
HZ	: Hertz
IEEE	: Institute of Electrical and Electronics Engineers
IGBT	: Insulated Gate Bipolar Transistor
IHD	: Individual Harmonic Distortion
IRPT	: Instantaneous Reactive Power Theory
LPF	: Low Pass Filter
MOSFET	: Metal Oxide Semiconductor Field Effect Transistor
MV	: Medium Voltage
PCC	: Point of Common Coupling
PD	: Phase Detector
PHAPF	: Parallel Hybrid Active Power Filter
PI	: Proportional Integral
PLL	: Phase Locked Loop
PQ	: Power Quality
PSCAD/EMTDC	: Power System Computer Aided Design / Electromagnetic Transient DC Program

PU	: Per Unit
PWM	: Pulse Width Modulation
RDFT	: Recursive Discrete Fourier Transform
RMS	: Root Mean Square
RT	: Resolution Time
SHAPF	: Shunt Hybrid Active Power Filter
SIT	: Static Induction Thyristor
SOGI	: Second Order Generalized Integrator
SRF	: Synchronous Reference Frame
SVM	: Space Vector Modulation
TDD	: Total Demand Distortion
THD	: Total Harmonic Distortion
UPS	: Uninterruptable Power Supplies
VCO	: Voltage Controlled Oscillator
VSC	: Voltage Source Converter
VSI	: Voltage Source Inverter

1. INTRODUCTION

1.1.Overview

In recent years, with the increase of nonlinear loads in industrial manufacturers, the power quality issue has become more serious. There are various custom power devices to solve these power quality problems. In the past, the passive power filters were often used to solve serious harmonic problems of the grid. Although passive filters were preferred because of their economic and simple structures, new methods are needed due to the disadvantages of passive filter such as requirement of a separate filter for each harmonic current, having limited filtering characteristics, the negative effects caused by parallel and series resonance between the grid and the filter impedance. The active power filter which is developed to remedy the shortcomings of the passive filter consists of a voltage or current source inverter, a DC link storage and an output filter. The basic principle of APF is to utilise power electronics technologies to produce current components that cancel the harmonic currents from the nonlinear loads. When an active filter is compared to a passive filter, although the active filter has a complex structure and more costly, today they can solve various power quality problems such as harmonic compensation, reactive power compensation, voltage imbalance and flicker. Even though the active power filter is an effective compensation system, their cost is increasing seriously with the proportion of increasing power capacity. As a solution to this situation, the hybrid active power filters have been developed by using active and passive filters together. The harmonics filtering task is divided into these two filters. The APF cancels the lower order harmonics, while the passive filters cancels the higher order harmonics. The main aim in the development of HAPF is to reduce the cost and the rating of an active filter by using a passive filter that filters the dominant harmonics caused by non-linear loads and supplies reactive power requirements.

1.2.Scope of Thesis

Parallel hybrid active power filter is proposed by Akagi in 1998. The function of proposed topology not only reduces the harmonic voltage and current but also damps the harmonic resonance in the industrial power system (Akagi et. al., 2007). Firstly, PHAPF had a transformer and two level inverter. Then the transformer was removed from the topology. To reach high voltage levels, two level inverter topologies converts to multilevel topologies. Thanks to this, PHAPF is connected to a grid without a transformer in high voltage levels. In studies, by using diode clamped multilevel inverter topology in PHAPF, it is shown as a simulation study that SHAPF can be connected directly to the grid voltage. But the experimental or real applications are continued in low voltage levels. In the articles related to this subject, it is studied to correct the voltage imbalance of dc link capacitor in the diode clamped multilevel inverter (Hatti et. al.,2009).

In studies related to PHAPF, its reactive power compensation property is indicated in lots of article. But in this article, either the passive filter of PHAPF can realize the constant compensation or PHAPF can realize dynamic compensation according to the demanding variable reactive power of SHAPF. However, the dynamic compensation is not presented in detail. Dynamic reactive compensation property of PHAPF is represented only (Lam et. al.,2012) article with a detailed description and analysis.

In this thesis work, a Multilevel HAPF is modeled in PSCAD/EMTDC simulation program. According to the lack of relevant studies based on reactive power compensation, the control method related to this subject has been investigated and applied to the Multilevel HAPF. Firstly, the base hybrid active power filter is developed and the reactive power compensation of this filter is supplied. Then the base hybrid active filter is converted to multilevel hybrid active power filter. Therefore, transformless HAPF is designed. Thanks to this, the transformer loss is removed and the capacity of the system is reduced. Finally, the reactive power compensation of this multilevel filter is demonstrated in PSCAD/EMTDC.

1.3. Outline of the Thesis

After the introduction section, the outline of the thesis is organized as follows;

In second chapter, the general definitions about harmonics are presented and their impacts on power systems are discussed. In addition, harmonic mitigation techniques and extraction methods are introduced.

In the third chapter, firstly the circuit topology of the proposed HAPF are investigated. Secondly, the design of circuit elements are presented and finally the control techniques for harmonic and reactive power compensation are presented in detail.

The fourth chapter presents probable HAPF based compensation systems for the power quality problems of linear and nonlinear loads. In this chapter firstly harmonic compensation performance of the proposed HAPF is demonstrated in simulation results. Afterwards, reactive power compensation performance of proposed HAPF is demonstrated in simulation. Their power circuit configurations and control methods are presented in detail. Finally, the compensation of both harmonic and reactive power compensation performances of the proposed HAPF systems on the PQ problems of linear and nonlinear loads are demonstrated by the simulation results.

In the fifth chapter, the conclusions of the thesis are given and the future work studies are discussed.

Finally all references used in this thesis study are presented.

2. HARMONICS

2.1. Harmonics

Electrical loads, drawing sinusoidal current from a sinusoidal voltage source, are called as linear loads. They consist of only resistive (R), inductive (L) and capacitive (C) passive elements. Non-linear loads draw non-sinusoidal current waveform, although they are fed from a sinusoidal voltage source. In order to indicate the undesirable effects and the severity of these non sinusoidal signals, the harmonic terminology was introduced by Institute of Electrical and Electronics Engineers (IEEE) in 1981 for these non-sinusoidal signals which can be represented as the sum of the sinusoidal signals in different frequencies by Fourier series. According to IEEE Std. 519 reported in 1981, “ A sinusoidal component of a periodic wave or quantity having a frequency that is an integral multiple of the fundamental frequency is defined as harmonic" (Uçak,2010).

2.2. Definition of Harmonic Problems

Due to the proliferation of nonlinear loads from power electronics converters, one of the electric PQ issues that received much attention is the harmonic distortion. These nonlinear loads control the flow of power by drawing currents only during certain intervals of the 50/60 Hz period. Thus, the current drawn by the nonlinear load is non sinusoidal and appears chopped or flattened. Any periodic, distorted waveform can be expressed as a sum of pure sinusoids. The sum of sinusoids is referred to a *Fourier series*, named after the great mathematician who discovered this concept. The Fourier analysis permits a periodic distorted waveform to be decomposed into an infinite series containing DC component, fundamental component (50/60 Hz for power systems) and its integer multiples called the harmonic components. The harmonic number (h) usually specifies a harmonic component, which is the ratio of its frequency to the fundamental frequency (Cheng,2006).

In order to set some practical limitations about harmonics and to offer some recommendations, a standard named (IEEE Std. 519, 1981) “ Guide for Harmonic Control and Reactive Power Compensation of Static Power Converters” was revealed in 1981 by IEEE society. After the adverse effects of non linear loads on the neighborhood loads had been discovered, in 1992 the standard was revised and updated (IEEE Std. 519, 1992). The severity of the harmonic magnitude is indicated by some quantities such as harmonic factor (HF), Total Harmonic Distortion (THD), Total Demand Distortion (TDD).

Harmonic factor which is used for not only the current but also the voltage is the ratio of the root sum square value of all harmonics to the root mean square value of the fundamental (2.1),(2.2). It is also called as distortion factor (DF).

$$\text{Harmonic Factor(Voltage)} = \frac{\sqrt{\sum_{h=2}^{\infty} V_h^2}}{V_1} \quad (2.1)$$

$$\text{Harmonic Factor(Current)} = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_1} \quad (2.2)$$

Another quantity called Total Harmonic Distortion (THD) has been used in low-voltage, medium-voltage and high-voltage systems to extinguish the distortion factor of a voltage or a current waveform (2.3).

$$\text{Total Harmonic Distortion (THD}_F) = \frac{\sqrt{\sum_{h=2}^h V_h^2}}{V_1} \quad (2.3)$$

where $h = 2,3,4 \dots, h$

While the voltage distortion limitations are based on THD values, the current distortion limitations are based on a different variable as Total Demand Distortion (TDD) which is defined in (2.4). The TDD limit defines how much a load can allocate the utility resource in terms of the harmonic current, and it is directly the

proportional with the size of the load with respect to the capacity of the utility at PCC. The capacity of the utility is defined by the short circuit current I_{sc} at PCC, and the size of the load is the maximum demand load current calculated by the average of the last twelve monthly peak demand. Therefore, the load can inject harmonic current to the utility at higher percentages as the size of the load decreases with respect to the capacity of the system.

$$\text{Total Demand Distortion (TDD)} = \frac{\sqrt{\sum_{h=2}^h I_h^2}}{I_L}. \quad (2.4)$$

where $h = 2,3,4\dots,h$

In Table 2.1, the voltage distortion limit values are presented. In Table 2.2, the current distortion limits for general distribution systems are shown.

Table 2.1 Voltage Distortion Limits (Uçak, 2010)

Bus Voltage at PCC	Individual Voltage Distortion (%)	Total Voltage Distortion THD (%)
69kV and below	3.0	5
69.001kV through 161kV	1.5	2.5
161kV and above	1	1.5
Note: High Voltage systems can have up to 2.0% THD where the cause is an HVDC terminal that will attenuate by the time it is tapped for a user		

For nearly all analyses, it is sufficient to treat nonlinear loads simply as a harmonic current source. As Figure 2.1 shows, the voltage distortion is the result of the distorted currents passing through the linear, series impedance of a power distribution system. Although the source bus is a pure sinusoid, there is a nonlinear load that draws a distorted current. The harmonic currents passing through the impedance of the system cause a voltage drop for each harmonic. This results in harmonic voltages appearing at the PCC. The amount of the voltage distortion

depends on the source impedance and the current. Harmonics have a number of undesirable effects on electric PQ. These falls into two basic categories: short-term and long-term. Short-term effects are usually the most noticeable and are related to an excessive voltage distortion. On the other hand, long-term effects often go undetected and are usually related to increased resistive losses or voltage stresses. In addition, the harmonic currents produced by nonlinear loads can interact adversely with a wide range of power system equipment, most notably capacitors, transformers, and motors, causing additional losses, overheating, and overloading. These harmonic currents can also cause interferences with telecommunication lines and errors in metering devices (Cheng,2006).

Table 2.2. Current Distortion Limits for General Distribution Systems (Uçak, 2010)

Individual Harmonic Order (Odd Harmonics), h						
I_{sc}/ I_L	Max. Harmonic Current Distortion for h					TDD
	h<11	11≤h<17	17≤h<23	23≤h<35	35≤h	
Below 20	4.0	2	1.5	0.6	0.3	5.0
Between 20-50	7.0	3.5	2.5	1.0	0.5	8.0
Between 50-100	10.0	4.5	4.0	1.5	0.7	12.0
Between 100-1000	12.0	5.5	5.0	2.0	1.0	15.0
Above 1000	15.0	7.0	6.0	2.5	1.4	20.0
Even Harmonics are limited to 25% of the odd harmonics limit above						
Current distortions that result in a dc offset, e.g., half wave converters, are not allowed						
All power generation equipment is limited to these values of current distortion, regardless of actual I _{sc} / I _L						
I _{sc} = Maximum short circuit current at PCC, I _L = Maximum demand load current (fundamental frequency component) at PCC						

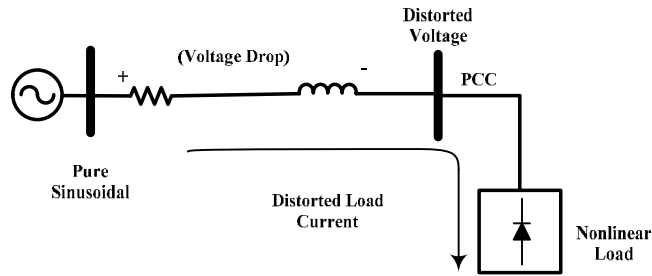


Figure 2.1. Harmonic currents flowing through the system impedance result in harmonic voltages at the PCC (Cheng,2006).

2.3.Harmonic Mitigation Techniques

Various harmonic reduction techniques have been developed to meet the requirements imposed by the current harmonic standards. In general these techniques can be classified into three broad categories:

- § Passive Filters
- § Active Power Filters
- § Hybrid Active Power Filters

The intent of these techniques is to make the input current a pure sinusoidal waveform, so as to reduce the overall current THD.

2.3.1. Passive Filter

In passive filters, the flow of the undesired harmonic currents into the power system can be prevented by the usage of a high series impedance to block them or by diverting them to a low impedance shunt path. These two methods represent the concept of the series and the shunt passive filters, respectively.

The tuned series passive filter, shown in Fig 2.2, is connected to the series with the load. The filter consists of a parallel inductance and a capacitance that are tuned to provide high impedance at a selected harmonic frequency. The high impedance then blocks the flow of the harmonic current at the tuned frequency only. At fundamental frequency, the filter is designed to yield low impedance, thereby

allowing the fundamental current to flow. For blocking multiple harmonics, multiple series filters are needed.

They must be designed to carry a full rated load current as they are connected to series to full the line voltage. Therefore, they can create significant losses at the fundamental frequency. In contrast, shunt passive filters carry only a fraction of the current that a series filter must carry. Given the higher cost of a series filter, and the fact that shunt filters may supply reactive power at the fundamental frequency, the most practical approach usually is the use of shunt filters (Zubi,2005).

A shunt filter offers a very low impedance path at the frequency to which it is tuned and it shunts most of the harmonic currents at that frequency. Most Common shunt filter types are the single tuned and high pass filters. These two filters are relatively simple to design and implement among the other shunt types. The layout of common shunt filter types is shown in Fig 2.3.

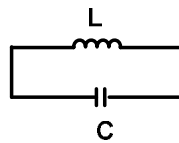


Figure 2.2. Series passive filter configuration (Zubi,2005)

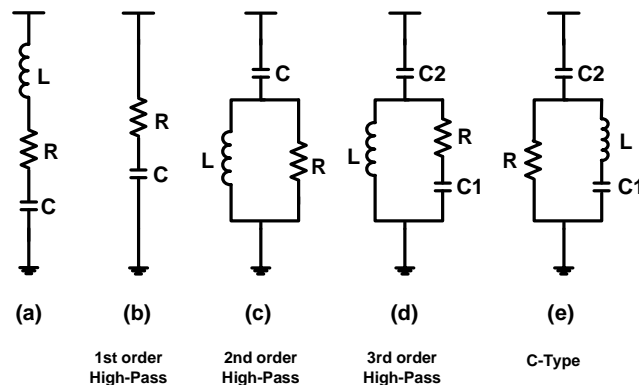


Figure 2.3. Common shunt passive filter configurations (Zubi,2005)

Unlike the shunt and series filters that have a narrow band of harmonic suppression, broadband filters have a wider range of harmonics suppression property. Broadband filters employ a combination of the two passive techniques, with a high series impedance to block the undesired current harmonics (from flowing through the

grid) and a low shunt impedance path to divert their flow through the shunt filter. They can be in different structures, shown in Fig 2.4, LC and LLCL type .

They are tuned to a low cut off frequency so that only fundamental component will pass from the input to the output. Therefore, they are called low pass broadband filters. Both shown low pass broadband filters use only one shunt filter to suppress all the harmonic broadbands. On the contrary, classical shunt filters are tuned to a single harmonic frequency to be suppressed and multiple stages are used to suppress all injected current harmonics.

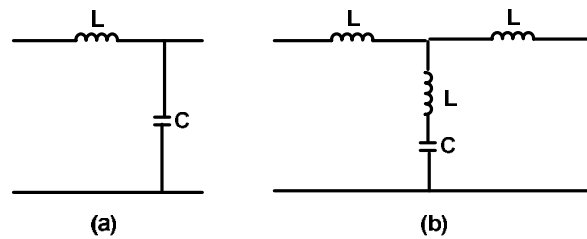


Figure 2.4. Low pass broadband filter configurations (a): LC type, (b): LLCL type (Zubi,2005).

2.3.2. Active Power Filter

The APF technology is now mature for providing compensation for harmonics, reactive power, and/or neutral current in ac networks. It has evolved in the past quarter century of development with varying configurations, control strategies, and solid-state devices. APF's are also used to eliminate voltage harmonics, to regulate terminal voltage, to suppress voltage flicker, and to improve voltage balance in three-phase systems. This wide range of objectives is achieved either individually or in combination, depending upon the requirements and control strategy and configuration which have to be selected appropriately. Starting in 1971, many configurations, such as the active series filter, the active shunt filter as shown in Fig 2.5 and the combination of the shunt and the series filter have been developed and commercialized also for uninterruptible power supply (UPS) applications (Singh et. al.,1999).

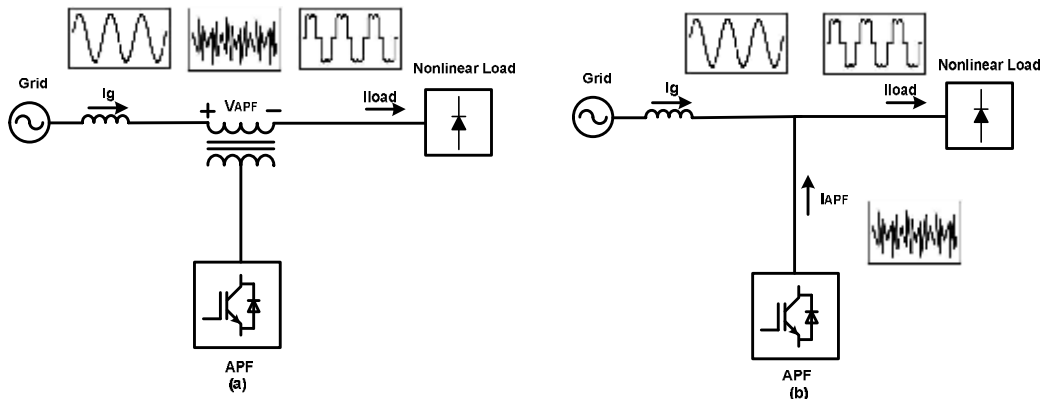


Figure 2.5. a) Series APF b) Shunt APF (Tan, 2011)

The power circuit of APFs is mainly formed from three parts; output filter, inverter and DC link. Output filter is used for linking the inverter to the power system and eliminating the switching ripples created by the inverter. The inverter is the main part of the power circuit and various inverter topologies are used for generating compensation currents or voltages. The switching devices used in inverters are selected according to the power ratings of APF. The most common switching devices used in inverters are MOSFETs and IGBTs. MOSFETs are low power devices and they have high switching frequency capabilities. Adversely IGBTs can work under higher powers but their switching frequency is lower than MOSFETs. DC link of active power filter is formed from inductor or capacitor depending on the type of inverter. DC link is used as an energy storage device. APF eliminates harmonics and/or other power quality problems by supplying reactive energy to the DC link and/or consuming reactive energy from the DC link and additional DC supply is not necessary. The only active power requirement of an active power filter is for the losses of its power circuit (Tan, 2011).

Many control strategies such as instantaneous reactive power theory initially developed by Akagi *et al.*, synchronous frame $d-q$ theory, synchronous detection method, and notch filter method are used in the development of three-phase APFs.

APF development has resulted from the microelectronics revolution. Starting from the use of discrete analog and digital components, the progression has been to microprocessors, microcontrollers, and digital signal processors (DSPs). Now, it is possible to implement complex algorithms on-line for the control of the APF at a reasonable cost. This development has made it possible to use different control

algorithms such as, proportional integral (P– I) , variable-structure control fuzzy logic, and neural nets for improving the dynamic and steady-state performance of the APF. With these improvements, the APF' s are capable of providing fast corrective action, even with dynamically changing nonlinear loads (Singh et. al.,1999).

2.3.3. Hybrid Active Power Filter

In recent years, with the increase of nonlinear loads in industrial manufacturers, the power quality issue has become more serious. There are various custom power devices to solve these power quality problems. Hybrid Active Power Filter is one of them and available in literature surveys. In the past, the passive power filters were often used to solve serious harmonic problems of the grid (Cheng at. al. , 2000). Although passive filters were preferred because of its economic and simple structure, new methods are needed due to the disadvantages of passive filter such as the requirement of a separate filter for each harmonic current, having limited filtering characteristics, the negative effects caused by parallel and series resonance between the grid and the filter impedance (Wua et. al., 2012). The active power filter which is developed to remedy the shortcomings of the passive filter consists of a voltage or a current source inverter, a DC link storage and an output filter. When an active filter is compared to a passive filter, although the active filter has complex structure and more costly, today they can solve various power quality problems such as harmonic compensation, reactive power compensation, voltage imbalance, voltage flicker (Akagi, 2007). Even though the active power filter is an effective compensation system, their cost is increasing seriously with the proportion of increasing power capacity (Shuai et. al., 2009). As a solution to this situation, the hybrid active power filters have been developed by using active and passive filters together. The main aim in the development of HAPF is to reduce the cost and the rating of an active filter by using a passive filter that filters the dominant harmonics caused by non-linear loads and supplies reactive power requirement (Luo et. al.,2009).

2.3.3.1. Classification of Hybrid Active Power Filter

General classification of HAPF is shown in Figure-1.

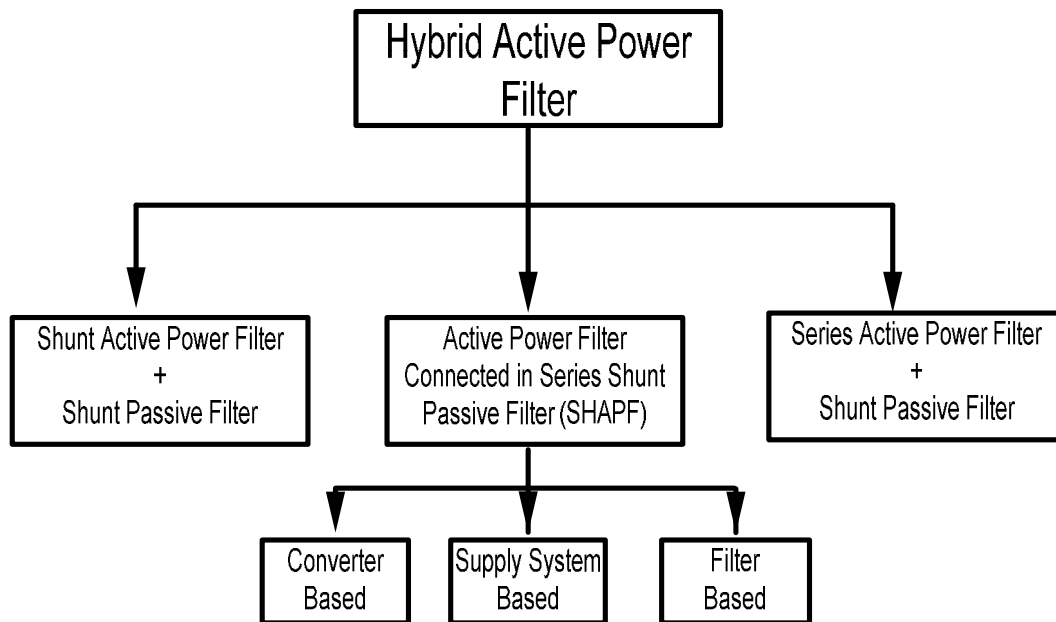


Figure 2.6. Classification of HAPF (Demirdelen et. al., 2013)

2.3.3.1.1. Topology Based

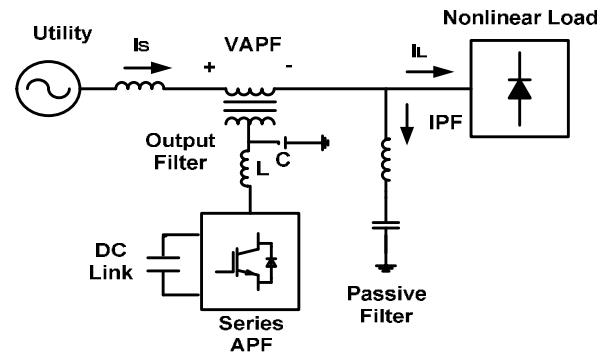
Three basic topologies in literature exist for HAPF. These are series active power filter +shunt passive filter, shunt active power filter + shunt passive filter, active power filter connected to the series with shunt passive filter. Fig 2.6 illustrates these topologies.

-Series active power filter +shunt passive filter: This topology combines the series active filter and the shunt passive filter (Salmeron et. al., 2010). Series active filter indicates a high impedance with the supplying harmonic isolation and enabling the harmonic current to flow on passive filter. This type of filter is designed to compensate reactive power, harmonics and unbalanced loads in the medium voltage level of a power distribution system. In recent studies, the multilevel inverter has been used to reduce the switching losses (Varschavsky et. al., 2010). This topology

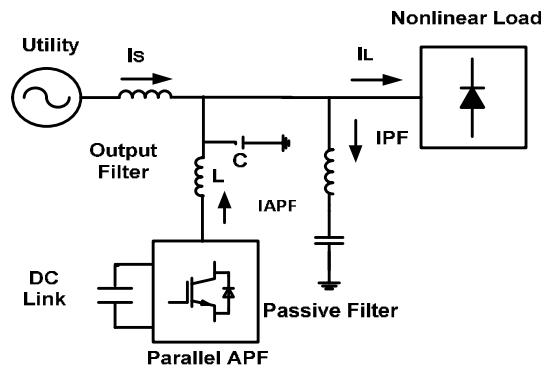
isn't preferred for the practical application because of the disadvantages of series active filter. Therefore, there are limited number of studies on this filter.

-Shunt active power filter+shunt passive filter: This type of filter is combined with a passive and an active power filter in a parallel configuration (Singh et. al.,2005). The aim of using a passive filter is to both filter dominant harmonics of nonlinear loads in low frequency and supply reactive power compensation (Corasaniti et. al.,2009). Besides, the parallel active power filter not only compensates the harmonics that the passive filter couldn't filter but also supports reactive power compensation. With this topology, the rated current of APF is reduced.

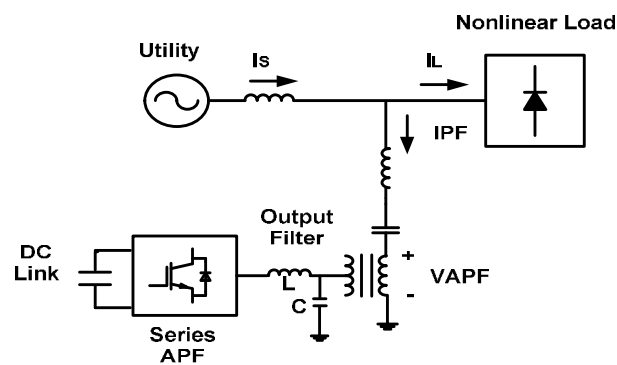
The aim of this topology is that while the passive part compensates the fundamental reactive power and the low order harmonics, the active part compensates the high order harmonics (Wang et. al., 2011). In this topology, the resonance problem between the passive part and the power system is disappeared. In addition, the compensation capacity of active power filter is decreased. With this topology, the compensation capacity of active filter is greatly smaller when reactive compensation is necessary. In addition, the attenuation and phase shift of the compensation current which is occurred by the passive filter will not exist anymore.



(a)



(b)



(c)

Figure 2.7. HAPF Topologies (a)series active power filter +shunt passive filter, (b)shunt active power filter + shunt passive filter, (c)active power filter connected in series with shunt passive filter (Demirdelen et. al., 2013)

-Active power filter connected in series with shunt passive filter: This type of filter is the most common to others. This topology consists of a shunt passive filter in series with an active power filter (Lin et. al., 2002). The active power filter part supplies hold on a DC link voltage that only requires for harmonic compensation. The passive filter holds on the fundamental component of the voltage. The rated voltage of APF can be reduced the ratio of 1/10 compared to a parallel active power filter. Therefore, not only the inverter of APF and the dc link capacity but also the cost is significantly decreased. In addition, the switching loss of the inverter can reduce with decreasing the rated voltage of APF. This topology is examined in details in this section.

2.3.3.1.2. Converter Configuration

HAPF topologies consist of an active power filter and a passive filter. The active part includes inverters. These inverter topologies are as follows:

One of them is a three phase voltage source inverter (Sing et. al.,2006). VSI which has a self supporting voltage bus with a large dc capacitor has many advantages. This type of inverter is lighter, cheaper and easily converted to multilevel to increase the performance for achieving a low switching frequency (Hong et. al.,2011). The other converter used in HAPF is current source inverter. This inverter acts as a non sinusoidal current source in order to satisfy the harmonic current which the nonlinear load requires. The output current is kept constant irrespectively of the load on the inverter. The output voltage is forced to change. The drawbacks of this inverter are that it has higher losses and requires higher values of parallel ac power capacitors. In addition, it is not expandable to multilevel to improve a performance in higher ratings. Besides, it requires an extra control stage to control the current. The dynamic response is slower. The last type is multilevel inverter (Akagi et. al.,2000). The multilevel inverters have become popular in the power industry. In high power and high voltage applications, they have some drawbacks such as switching loss and constraints of device ratings in operations. Multilevel structures can succeed a high power and high voltage inverter without requiring higher ratings. In addition, with this structure, the use of a transformer or a

synchronized switching device isn' t required (Akagi et. al.,2012). In literature, there are three types of multilevel converters: Diode clamped, flying capacitor, cascaded. Figure 2.8 shows multilevel inverter topologies.

-Flying Capacitor Converter (FCC): Meynard and Foch introduced a flying-capacitor-based inverter in 1992. The structure of this inverter is similar to that of the diode-clamped inverter except that instead of using clamping diodes, the inverter uses capacitors in their place. The circuit topology of the flying capacitor multilevel inverter is shown in Figure 2.8(a). This topology has a ladder structure of dc side capacitors, where the voltage on each capacitor differs from that of the next capacitor. The voltage increment between two adjacent capacitor legs gives the size of the voltage steps in the output waveform (Khomfoi et. al.).

Table 2.3. Advantages and Disadvantages of Flying Capacitor Converter (Khomfoi et. al.)

Advantages:	Disadvantages:
Phase redundancies are available for balancing the voltage levels of the capacitors.	Control is complicated to track the voltage levels for all of the capacitors. Also, precharging all of the capacitors to the same voltage level and startup are complex.
Real and reactive power flow can be controlled.	Switching utilization and efficiency are poor for real power transmission.
The large number of capacitors enables the inverter to ride through short duration outages and deep voltage sags.	

-Cascaded Converter: The cascaded converter or full-bridge converter is formed by two single-phase inverters with independent voltage sources. In Figure 2.8(b), a phase of a three-level cascaded converter is shown.

Considering the three-level basic cell, it is clear that only one transistor of each leg (S_1 - S_{11} , S_2 - S_{22}) can be switched on at the same time. In order to facilitate the notation of the possible switching configurations, for each basic cell in phase x , binary factors H_{xi} can be defined as follows (Galvan,2006):

Table 2.4. Possible Switching Configurations in a three-level Cascaded Converter using the binary notations (Galvan,2006)

H_{x1}	H_{x2}	V_{AB}
0	0	0
0	1	$-V_{DC}$
1	0	V_{DC}
1	1	0

Table 2.5. Advantages and Disadvantages of Cascaded Converter (Galvan,2006)

Advantages	Disadvantages
This topology is based on basic cells (full-bridge converters) connected each other. So, its modularity is important and the controller can be distributed.	This topology has not been applied at low power levels to date because of the need to provide separate isolated DC supplies for each full-bridge converter element.

-Diode-Clamped Converter (DCC): In 1980s, power electronics concerns were focused on the converters power increase (increasing voltage or current). In fact, Current Source Inverters were the main focus for researchers in order to increase the current. However, other authors began to work on the idea of increasing the voltage instead the current. In order to achieve this objective, authors were developing new converter topologies. In 1981, A. Nabae, I. Takahashi and H. Akagi presented a new neutral-point-clamped PWM inverter (NPC-PWM). This converter was based on a modification of the classic two-level converter topology. In conventional two-level

case each transistor must have at the most a voltage stress equal to V_{DC} and they should be dimensioned to tolerate this voltage (Galvan,2006).

The proposed modification to get the three-level converter added two new transistors per phase . Using this new topology, each transistor tolerates at the most a voltage equal to $V_{DC}/2$. So, if these new transistors have the same characteristics than the transistors in two-level case, the DC-Link voltage can be doubled achieving a value equal to $2V_{DC}$ (Galvan,2006).

But, this converter topology still has a problem. If transistors S_1 and S_2 are switched on and transistors S_3 and S_4 are switched off, V_{DC} voltage should be equally shared between transistors S_3 and S_4 . But, there is not any mechanism that assures it. The solution of this problem appears thanks to use the “ clamping diodes” . In each phase, two diodes clamp each transistor voltage. Finally, in Figure 2.8.(c), a three-level Diode Clamped Converter (DCC) is shown. In this converter topology, the DC-Link voltage is equally shared between capacitors C_1 and C_2 (Galvan,2006).

It can be explained why this converter is named three-level converter. In order to show it, possible switching configurations of this converter topology can be presented. There are only three possible switching configurations in the three level DCC. Other switching possibilities are not allowed because they create short-circuit in some DC-Link capacitor or they let the output opened. For instance, if S_1 , S_2 and S_3 are switched on, a short-circuit is created in capacitor C_2 . Besides, the voltage in transistor S_4 is V_{DC} being its maximum admissible voltage equal to $V_{DC}/2$. The possible switching configurations are shown in Table 2.6. Only three possible output phase voltages with respect to 0 (middle point of the DC-Link) appear using this converter and this is the reason to name this converter as a “ three-level” converter (Galvan,2006).

Table 2.6. Possible switching configurations in three level DCC (Galvan,2006)

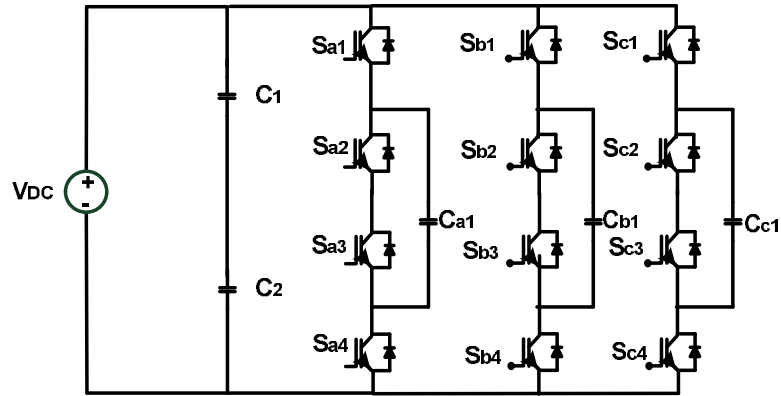
S₁	S₂	S₃	S₄	Phase-0 Voltage
ON	ON	OFF	OFF	$V_{DC}/2$
OFF	ON	ON	OFF	0
OFF	OFF	ON	ON	$-V_{DC}/2$

Table 2.7. Advantages and Disadvantages of Diode Clamped Converter (Galvan,2006)

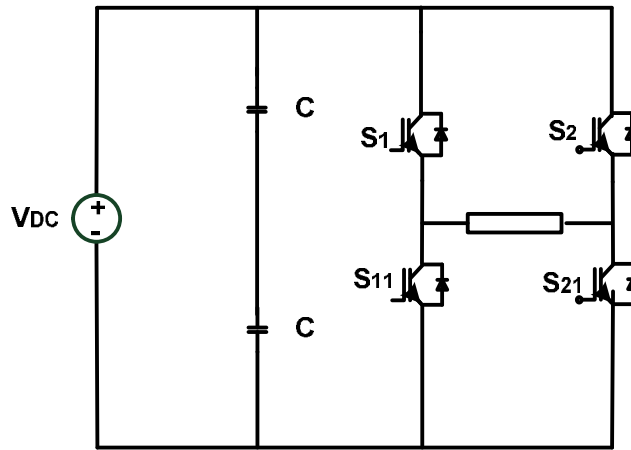
Advantages	Disadvantages
The number of capacitors is low compared with other topologies as the flying capacitor converter. This fact is very important due to the cost of these reactive devices.	The possibilities to control the balance of the DC-Link capacitors voltage are limited. In fact, other topologies as the Flying Capacitor topology present more possibilities to achieve the balance.
This topology does not require any transformer	
There is only one DC-Link bus	
The change between adjacent states is done changing only the state of two transistors.	

DCC topology has become very popular between researchers all over the world and other hybrid topologies have been developed trying to improve the converter features.

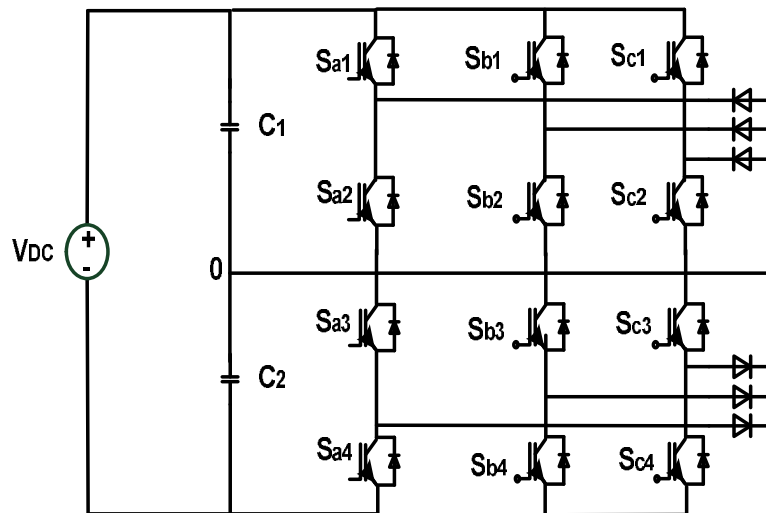
So this multilevel topology is preferred to use for this thesis.



(a)



(b)



(c)

Figure 2.8. Multilevel inverter based Hybrid APF
 (a) Flying Capacitor Converter, (b) Cascaded Converter, (c) Diode Clamped Converter

2.3.3.1.3. Supply System

There are three configurations based on a supply system. These configurations are shown in Figure 2.9. The first configuration is two-wire. Two wire hybrid active power filters are generally available in low power ratings (Rahmani et. al. 2006). The advantage of two wire hybrid active power filter is that they have to deal with a low power. Besides, they are able to be operated at relatively higher frequencies leading to an improved performance.

Another configuration is three-wire (Fujita et. al., 1991). Three wire active power filters are suitable not only for low power but also medium and high power applications. In literature, most publications are on three wire HAPF's with different topologies. The last configuration is four-wire (Rodriguez et. al.,2009). Single phase loads which are supplied from three phase mains with causing unbalance. To overcome these problems, the four wire HAPF has been developed. The most widely used four wire topologies are the capacitor midpoint type and the four leg switch type . The capacitor midpoint type is used for lower ratings (Lam et. al.,2012). All neutral current flows through dc-bus capacitors. The four leg switch type is operated to stabilize the neutral of HAPF (Wua et. al.,2012).

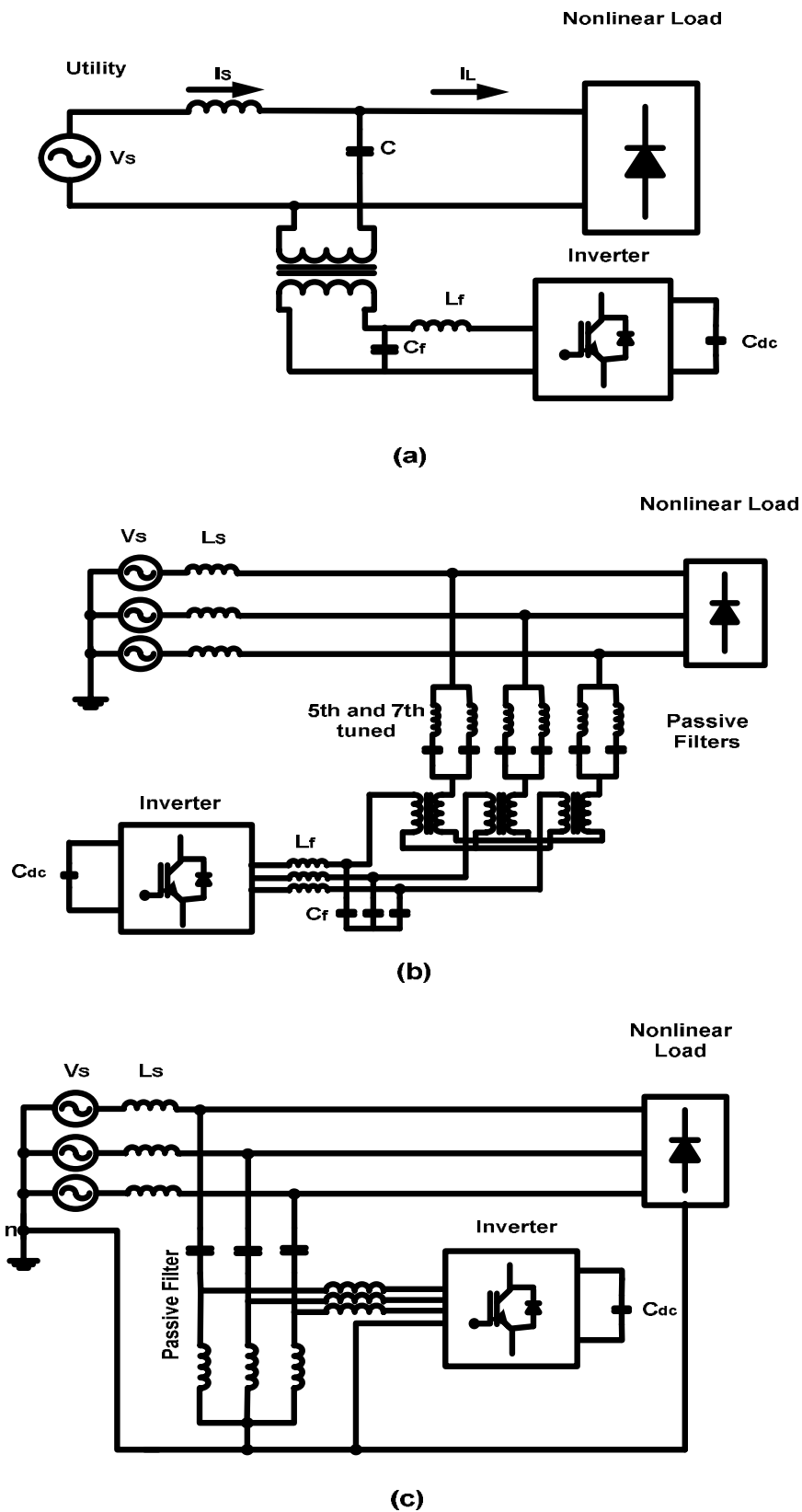
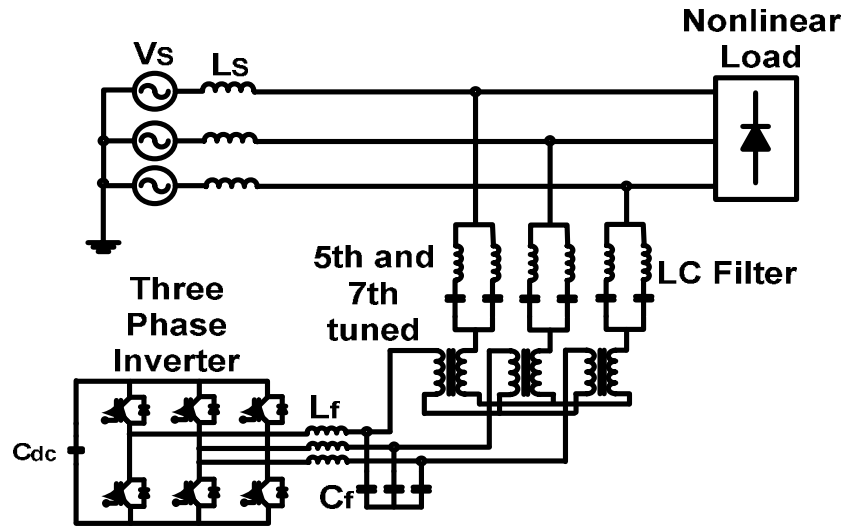


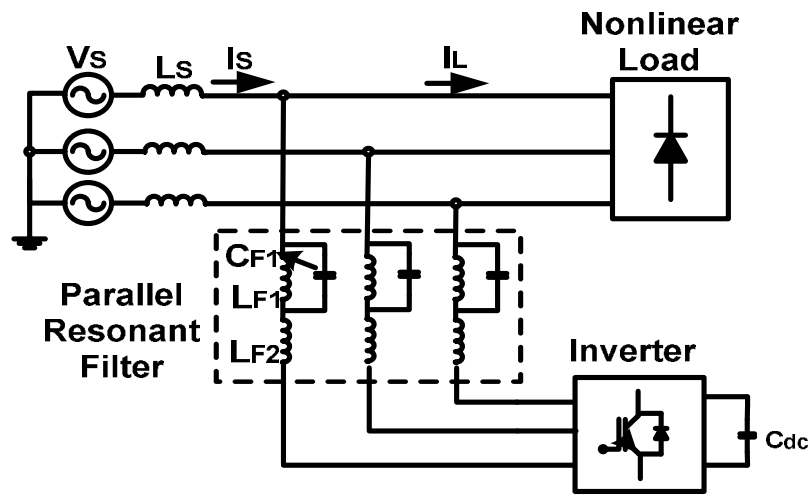
Figure 2.9. Hybrid APF (a) Single Phase Two Wire, (b) Three-Phase Three Wire and (c) Three Phase Four Wire (Demirdelen et. al., 2013)

2.3.3.1.4. Passive Filter Type

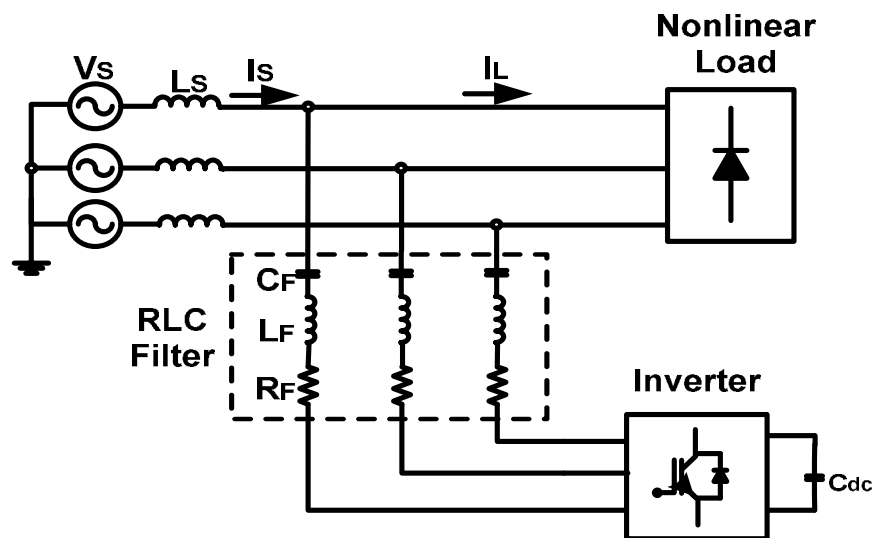
Hybrid active filter topologies consist of passive and active filters. The passive filters have an important role to tune at the fundamental frequency and reduce the power rating of APF. In literature many types of passive filters are applied. Fig 2.10 illustrates this type of filters. One of the most common filter is the LC filter. The LC filter (Bhattacharya et. al.,1997) consists of an inductor and a capacitor in series tuned a single frequency. The LC circuit provides a zero impedance path for a selective harmonic current to be filtered. LCL output filters shows more effective performance than LC output filters (Han et. al., 2011). Some studies prefer this type of filters. A RLC filter consists of a resistor, an inductor and a capacitor connected in series (Rahmani et. al., 2012). It constitutes a harmonic isolator (Rahmani et. al., 2009). The resistor is used for damping. The injection type of filter is created by adding a LC circuit that is tuned to fundamental frequency of the transformer (Luo et. al.,2010). It prevents the flow of the leading current occurring because of the passive filter of HAPF over the inverter of an active filter so the current rating of the active filter is significantly reduced (Shuai et. al., 2011). In addition, this topology can be applied for high voltage levels because the current at the fundamental frequency doesn't flow over the active filter. Another type filter topology is a parallel resonant filter. A new passive filter topology that is tuned at the fundamental frequency of the system is used instead of the conventional passive filter topology (Marques et. al., 2010). This filter consists of the parallel LC with series. The LC is tuned at the fundamental frequency of the system. C in parallel LC filter and series L is tuned at desired a harmonic frequency. This filter demonstrates high impedance at fundamental frequency component so it prevents the flow the fundamental frequency component over the active power filter. For the harmonic frequency, this filter demonstrates a low impedance so the current harmonics flow over active power filter. The power capacity and loss of the inverter are decreased.



(a)



(b)



(c)

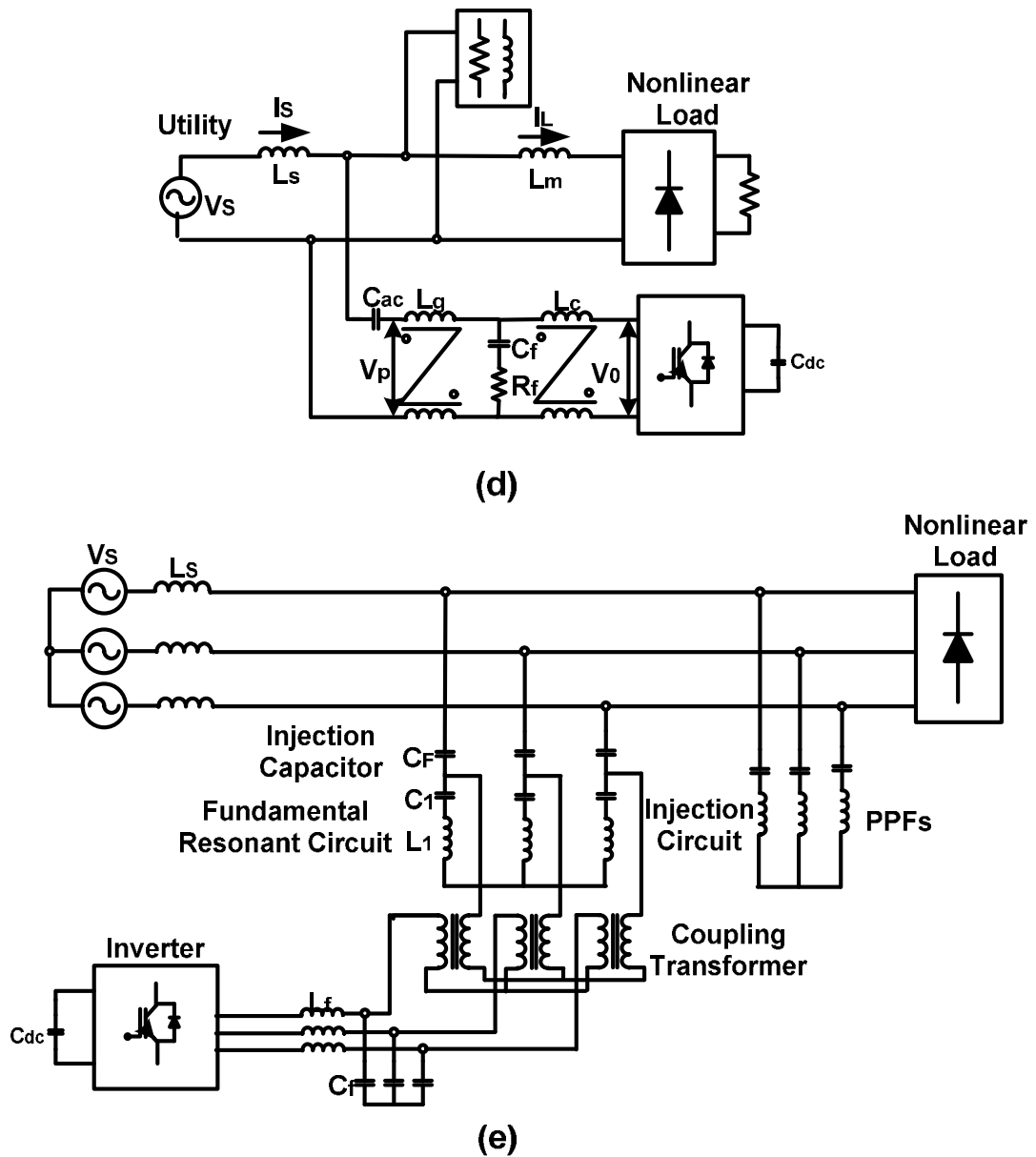


Figure 2.10. Classification according to filter: (a) LC, (b) Parallel resonant, (c) RLC, (d) LCL and (e) Injection-Type (Demirdelen et. al., 2013)

2.3.3.2. Control Strategies

The control strategy is a fairly critical issue in a hybrid active power filter. All control strategies consist of the four stages which are called as the detection of signals, the generation of compensating signals, the dc link voltage control and the generation of firing signals.

2.3.3.2.1. Signal Conditioning

In the control strategy, for the calculation of reference signals to achieve harmonic and reactive power compensation, instantaneous voltages and current signals need to be measured. Instrumentation transformers and Hall-effect sensors are used to measure the voltage and current signals in system. Then, these measured signals are used to generate the reference signals for harmonic and reactive power compensation.

2.3.3.2.2. Generation of Reference Signals

Reference signals are generated using time domain and frequency domain methods in literature.

-Frequency Domain Methods: Frequency domain methods uses Fourier Transform (FT) to generate reference signals. The Fast Fourier Transform (FFT) which is a method based on The Fourier transform, is used to estimate harmonics (Rahmani et. al., 2006). Even though it enables the selective harmonic elimination and provides the generating the reference signals rapidly, it has main drawbacks such as a requirement at least one cycle to estimate the reference current and control complexity compared to control methods in the time domain which will be explained more detailed in next topics.

-Time Domain Methods: Synchronous Reference Frame (SRF) and Instantaneous Reactive Power Theory (IRPT) are the most common and popular control techniques to determine the reference signals based on the time-domain. IRPT also called as p-q theory transforms voltage and current signals from a stationary reference system in abc coordinates, to a system with coordinates α - β (Afonso et. al., 2003). So it determines the harmonic distortion by calculating instantaneous power in a three phase system. To generate reference signals, Dividing Frequency Control (Luo et. al., 2009), Lagrange Interpolator (Luo et. al., 2009), Optimal Linear Prediction Theory (Li et. al., 2011), Generalised Integral PI Controller (Shuai et. al., 2011) and Extension PQ Theorem (Tan et. al., 2005) are also control methods based on p-q method. SRF also called as d-q theory looks likes $\alpha\beta$ transform. However, d-q theory

calculates reference signals of voltage/current in rotating reference frame unlike p-q theory. The notch filter-based method (Basic et. al., 2000), the Indirect Current Control (Singh et. al., 2006), the adaptive fuzzy-dividing frequency control (Luo et. al., 2009), the Recursive Integral combined with Fuzzy Controller (Zhao et. al., 2011), the Recursive Integral Controller (Luo et. al., 2009), the Neural network (Dai et. al., 2007), the RL (Salmeron et. al., 2010) , the Sliding-Mode Controller (Guo et. al., 2009), the Deadbeat Control (Han et. al., 2011), the Integer Lifting Wavelet Transform (Chandrasekar et. al., 2011), the PI-Type Iterative Learning Control Strategy (Luo et. al., 2010) are also control methods used in Hybrid APF.

2.3.3.2.3 DC Link Control

DC link control is one of the significant subjects which draw attention in literature. Although Hybrid APF uses up lower dc link voltage and has less noise compared to conventional APF, It is very important to keep the voltage magnitude at required level or constant in order to stabilise the power exchange. The PI Controller (Tangtheerajaronwong et. al., 2007), Sliding Mode (Guo et. al., 2009), Fuzzy (Luo et. al., 2009), Adaptive DC link Controller (Lam et. al., 2012) are employed to control dc link voltage in Hybrid APF topologies.

2.3.3.2.4 Generation of Firing Signals

The fourth step is the generation of the firing signals for switching devices. There are several techniques to generate the firing signals for solid-state devices in an inverter. These techniques play an important role in the effective performance of Hybrid APF. The PWM (Srianthumrong et. al., 2003) and Hysteresis Controller (Singh et. al., 2006) are the most common techniques which are used to generate gate signals. The Conventional Sine Triangle PWM (Wuo et. al., 2011), The Modified Sine-triangle PWM (Cheng et. al., 1998), The Modified PWM (Rahmani et. al., 2006), The Unipolar PWM (Lai et. al., 1994) are controllers based on pulse-width-modulation. The Space Vector Modulation (SVM) is also another control technique

(Lai et. al., 1994). For instance, The SVM-based hysteresis current controller (Blorfan et. al., 2011) and The Deadbeat Current Controller based SVM (Nishida et. al., 2006) are preferred to control the generation of firing signals. The Adaptive Fuzzy Dividing Frequency Controller (Luo et. al., 2009) and The Fuzzy Controller (Jiang et. al.,2009) are implemented to obtain the control signals for the solid-statedevices.

3. MODELLING AND ANALYSIS OF PROPOSED HAPF

Both multilevel diode clamped topology and three phase voltage source PWM topology are used in simulation model. Mathematical analysis and controllers are same both of them. The only difference is firing signals. The detailed analysis is given below.

3.1 Circuit Topology

Parallel hybrid power filter which is the main concern of this research is formed by the use of a three phase voltage source PWM converter, and a series connected LC passive filter. The series connection between the passive filter and the voltage source converter is made directly, without using a transformer (Fig 3.1). The series connected LC filter is tuned to the dominant harmonic component of the load. It absorbs the current harmonics arising from the non-linear load; however, the filtering characteristic of just the passive filter itself is not satisfactory. Hence, the active power filter is used to improve the filtering performance of the overall system and to suppress the resonance risk of the passive filter. The power circuit of the inverter includes an energy storage element of a DC link capacitor and controllable semiconductor switches with their antiparalel diodes. The active power filter injects compensation currents by operating as a current controlled voltage source. In the conventional voltage source active power filter topology, the DC link capacitor voltage is required to be higher than the peak value of the utility voltage; otherwise the generated compensation currents cannot be injected to the mains. However, the presence of filter capacitor in this topology (Fig 3.1) ensures a reduced DC link voltage and a low rated voltage source converter at the expense of additional fundamental current, passing through the converter. As a result, for low voltage applications, PWM converter can be formed by power MOSFETs instead of using IGBTs. So that, the initial cost of the converter can be decreased by using MOSFETs instead of IGBTs. Similar to the conventional VSC based APFs; hybrid power filter does not require a DC power supply for its DC link voltage regulation. In order to clarify the compensation characteristic of the Parallel Hybrid Power Filter, the

system can be simplified by obtaining its single phase equivalent circuit as indicated in (Fig 3.2) where Z_s represents the source impedance and Z_f represents the passive filter impedance. The non linear load is shown as an ideal current source (I_L), and the APF is considered as a voltage source.

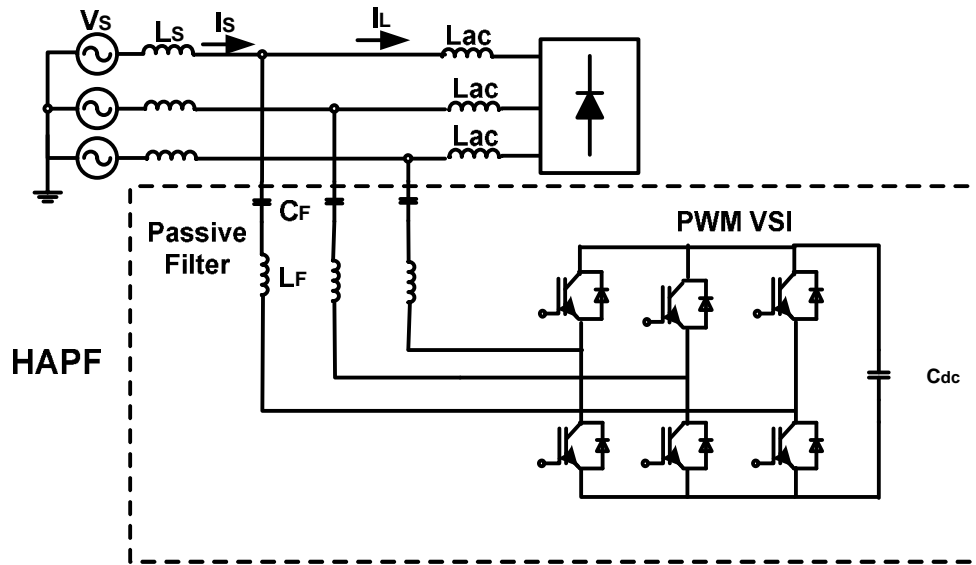


Figure 3.1. Parallel Hybrid Active Power Filter

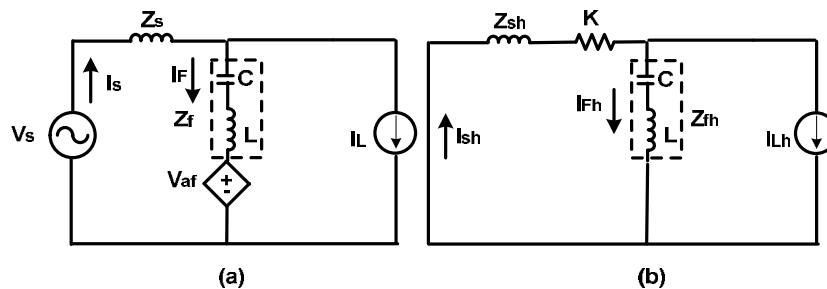


Figure 3.2. (a) Single Phase Equivalent Circuit (b) Harmonic Equivalent Circuit

If the active power filter terminal voltage is assumed to have no fundamental component, the voltage across the PWM inverter can be represented as $K \times I_{sh}$ at harmonic frequencies where ‘h’ stands for the harmonic components and K represents the feedback gain. Hence, assuming the source voltage to be pure 50Hz and considering the current directions as in Fig 3.2, the following equations can be obtained by applying Kirchoff’s voltage law. The harmonic equivalent circuit

shows that source voltage (V_s) is short circuited. So the harmonic component of the source voltage (V_{sh}) is equal to zero.

$$V_{sh} - I_{sh}Z_{sh} - I_{fh}Z_{fh} - V_{af} = 0 \quad (3.1)$$

Where

$$V_{sh} = 0 \quad \text{and} \quad V_{af} = KI_{sh} \quad (3.2)$$

$$I_{sh} = I_{Lh} + I_{fh} \quad (3.3)$$

$$I_{sh} = \frac{Z_{fh}}{Z_{fh} + Z_{sh} + K} \quad (3.4)$$

The equation (3.4) indicates that as the active power filter is connected to the system, the feedback gain K acts as a damping resistor which suppresses the resonance between the supply and the passive filter. Theoretically, as K approaches to infinity, the harmonic content of the source current goes towards zero. However due to stability problems in the control loop, the gain K should be limited to certain values. Hence the design procedure of parallel hybrid active power filter can be divided into 2 groups as the design of the passive filter and the design of the active filter part. The design of the passive filter is mainly identifying the L_f , C_f parameters considering the harmonic content of the load. It is clear that, tuning frequency of the passive filter is chosen to be the most dominant harmonic component of the non linear load. Today' s industrial loads generally consist of three phase diode rectifiers as AC/DC converters instead of PWM converters due to their low cost and efficiencies. As a result, in the case of a diode rectifier, the passive filter should be adjusted to eliminate the 5th or 7th harmonic current content. The 5th harmonic current content of a diode rectifier is higher than its 7th harmonic components, so it is more reasonable to tune the passive filter around 250Hz. The LC filter for his work is tuned 250 Hz.

3.2. Design Circuit Elements

3.2.1. Passive Filter Capacitor and Inductor

The series connected capacitor (C_F) and the filter reactor (L_F) forms a LC passive filter. So that, the LC filters should be chosen to eliminate the most dominant 5th or 7th harmonic of the diode rectifier load. The passive filter is tuned to 250 Hz. The characteristic impedance of the passive filter (Z) is defined as given in (3.5). The filtering performance of the passive filter is determined by this impedance except for resonant frequency. Therefore, the capacitance value should be as high as possible and inductance value should be as low as possible to obtain low characteristic impedance.

$$Z = \sqrt{\frac{L_F}{C_F}} \quad (3.5)$$

However the large capacitance value makes the passive filter bulky and results in a high reactive current. Selecting a low inductance value also increases the switching ripples. By considering all these criteria and to minimize the initial cost of the system, a 8 kVAR passive filter at 380V line voltage tuned around 250Hz is decided to used in the hybrid power system. In addition, HAPF which will be done same power rating as this work is accepted by 112R028 TUBITAK Project. L_F , C_F parameters are calculated as follows:

$$Q = \frac{V^2}{|Z_F|} \quad (3.6)$$

$$Z_F = X_L - X_C \quad \text{Where } X_L = 2pfL_F \quad \text{and } X_C = \frac{1}{2pfC_F} \quad (3.7)$$

$$f_{tuned} = \frac{1}{2p\sqrt{L_F C_F}} \quad (3.8)$$

3.2.2. Power Converter

The power converter of the hybrid power filter is a three phase voltage source PWM converter. It is composed of six semiconductor switches (IGBTs) with their antiparallel diodes, and the DC link capacitor (Fig 3.1). Each IGBT is directly subjected to hybrid filter current and DC link voltage. The harmonic current capacity of the hybrid power filter is decided to be $20A_{RMS}$ by considering the load condition of system. Moreover, the selected passive filter capacitor also introduces nearly $15A_{RMS}$ leading current component at a fundamental frequency. Therefore, at steady state operation, the nominal current passing through at each line is about $45A_{RMS}$.

3.2.3. DC Link

For reactive power compensation, the most important part is to decide DC link voltage value. The minimum dc link value (V_{dc_min}) is dependent on both load reactive power (Q_{Lxf}) and passive filter reactive power (Q_{cx_PF}) which is described as in (3.9a). This equation is developed by Lam et. al., 2012 for three phase four wire system LC-HAPF. For this thesis work, this equation is converted for three phase three wire conventional HAPF.

$$V_{dc_min} = \sqrt{2}V_{pcc} \left| 1 - \frac{Q_{Lxf}}{Q_{CXf - PF}} \right| \quad (3.9a)$$

In addition the equation is improved for three level diode-clamped multilevel topology which is described as in

$$V_{dc_min} = 2\sqrt{\frac{3}{2}}V_{pcc} \left| 1 - \frac{Q_{Lxf}}{Q_{CXf - PF}} \right| \quad (3.9b)$$

For only harmonic compensation, the required DC link voltage value is:

$$\sum_{h \neq 1}^n Z_{F,h} \times I_{filter,h} < V_{DC} \quad (3.9c)$$

Where h represents the order of the harmonic, $I_{filter,h}$ is the filter current and $Z_{F,h}$ is the impedance of the LC filter at the corresponding harmonic frequency.

3.2.4. Diode Rectifier

A non-linear load on a power system is typically a rectifier (such as used in a power supply), or some kinds of arc discharge devices such as a fluorescent lamp, an electric welding machine, or an arc furnace. Because the current in these systems is interrupted by a switching action, the current contains the frequency components that are multiples of the power system frequency. Non-linear loads change the shape of the current waveform from a sine wave to some other forms. Non-linear loads create harmonic currents in addition to the original (fundamental frequency) AC current. In this thesis a diode rectifier is used as a nonlinear load. The equations about the diode rectifier inductance as follow:

$$S_{rectifier} = \frac{V^2}{Z_{rectifier}} \quad (3.10)$$

$$Z_L = 0.03 \times Z_{rectifier} \quad \text{and} \quad L = \frac{Z_L}{2\pi f} \quad (3.11)$$

$$P_{rectifier} = V_{dc} I \quad \text{and} \quad V_{dc} = \frac{3V_{line,max}}{p} \quad (3.12)$$

3.2.5. RL Load

In a purely resistive AC circuit, voltage and current waveforms are in step (or in phase), changing polarity at the same instant in each cycle. All the power entering the load is consumed. Where reactive loads are present, such as with capacitors or inductors, energy storage in the loads results in a time difference between the current

and voltage waveforms. During each cycle of the AC voltage, the extra energy, in addition to any energy consumed in the load, is temporarily stored in the load in electric or magnetic fields, and then returned to the power grid a fraction of a second later in the cycle. A circuit with a low power factor will use higher currents to transfer a given quantity of the real power than a circuit with a high power factor. A linear load does not change the shape of the waveform of the current, but may change the relative timing (phase) between the voltage and current. The calculations about R and L value of the load as follow:

$$S_{RL} = S_{Total_load} - S_{nonlinear_load} \quad (3.13)$$

$$S_{RL} = \frac{V^2}{Z_{RL}} \quad (3.14)$$

$$R = Z_{RL} \times \cos f \quad \text{where} \quad \cos f = 0.85 \quad (3.15)$$

$$Z_L = Z_{RL} \times \sin f \quad (3.16)$$

$$L = \frac{Z_L}{2pf} \quad (3.17)$$

3.2.6. Supply

The existing system includes a 1 MVA transformer at the AC line. In the simulation work, it is modelled as an AC voltage source (380 V_{line}, 50 Hz, U_k= % 5, X/R=10) in series with the transformer' s leakage reactance. The parameters L_s and R_s are calculated as given below:

$$Z_s = \frac{V^2}{S} \times U_k \quad (3.18)$$

$$L_s = \frac{Z_s}{2pf} \quad (3.19)$$

$$R_s = \frac{Z_s}{10} \quad (3.20)$$

3.2.7. Active Power Filter

The load reactive power is equal to 8 kVAR and the apparent power is 15 kVA. The value of the power factor is 0.85. So,

$$S_{Load} = \sqrt{3}VI_1 \quad (3.21)$$

Then the THD value is 25%. So the load current is fourth time greater than the active filter current.

$$I_1 = 4I_2 \quad (3.22)$$

The total current of the active filter is equal to;

$$I_{total} = \sqrt{I_1^2 + I_2^2} \quad (3.23)$$

$$S_{active_filter} = \sqrt{3}VI_{total} \quad (3.24)$$

The value of active power dc link capacitor is;

$$Q_{active_filter} = S_{active_filter} \times \cos f \quad (3.25)$$

$$Q_{active_filter} = \frac{V^2}{Z} \quad (3.26)$$

$$C = \frac{1}{2pZ} \quad (3.27)$$

3.3. Control Techniques

3.3.1. Calculation of Harmonic & Reactive Current References

3.3.1.1. DQ Theory

In hybrid filter topology, PWM converter generates compensation voltages by operating as a current controlled voltage source. So, the performance of the system is highly dependent on the accurate measurement and the calculation of the compensation current references. Once the current references are obtained, the voltage reference for each phase is produced by an appropriate control method in which the gate signals of semiconductor switches are also produced in the modulation part.

The synchronous reference frame method is based on the transformation of vectors into synchronously rotating direct (d), and quadrature axis (q) reference frames. In order to calculate the harmonic components of the mains current. Initially three phase supply current vectors are mapped into synchronously rotating reference frame in (3.28). The phase angle θ defines the fundamental frequency phase information of the utility voltage and it is obtained from a phase locked loop circuit which is investigated.

$$\begin{bmatrix} i_d \\ i_q \\ i_o \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos \Phi & \cos(\Phi - 2p/3) & \cos(\Phi + 2p/3) \\ -\sin \Phi & -\sin(\Phi - 2p/3) & -\sin(\Phi + 2p/3) \\ \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} \end{bmatrix} \quad (3.28)$$

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos \Phi & -\sin \Phi & \frac{\sqrt{2}}{2} \\ \cos(\Phi - 2p/3) & -\sin(\Phi - 2p/3) & \frac{\sqrt{2}}{2} \\ \cos(\Phi + 2p/3) & -\sin(\Phi + 2p/3) & \frac{\sqrt{2}}{2} \end{bmatrix} \quad (3.29)$$

Once the current vectors are transformed into synchronously rotating d-q reference frame, the fundamental component of the mains current turns out to be a DC signal, and the harmonic components which are still AC signals are rotating with a corresponding angular frequency.

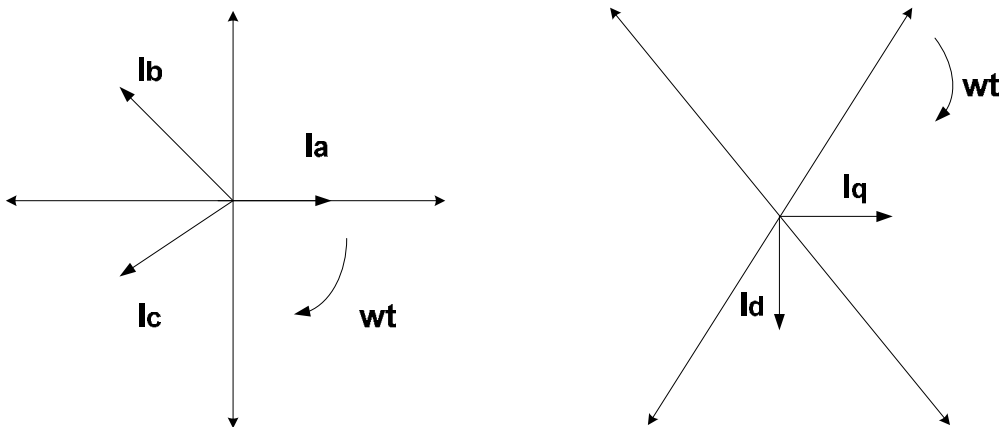


Figure 3.3. (a) Three Phase Current Vectors (b) DQ Transformation

The active and reactive power for the three phase balanced system can be written in dq coordinates as follows, where V_d , V_q , I_d and I_q are the voltages and currents in dq coordinates:

$$P = V_d I_d + V_q I_q \quad (3.30)$$

$$Q = V_d I_q - V_q I_d \quad (3.31)$$

Power calculation based on the SRF method is summarized in Fig 3.5.

For instance; the 5th and 7th harmonic components of a distorted source current turns out to be a 300Hz signal for a 50Hz AC mains. Since the rotation angle of the reference frame is positive, positive and negative sequence harmonic components are transformed to 300Hz and its multiples in synchronous d-q reference frame. Therefore, the method is specifically named as a positive sequence SRF method.

The AC signals are extracted via a high pass filter (HPF) or by subtracting the DC quantity obtained from a low pass filter (1-LPF). Low pass filters with low cut off frequencies (20Hz-30Hz) are sufficient to extract the DC component. Since the extracted signal is a DC quantity, the SRF method is insensitive to phase errors introduced by the filters. The inverse transformation of the obtained AC signals reproduces the supply harmonic current components in the stationary abc frame in (3.29).

If the supply voltage is not balanced and the source current contains a fundamental negative sequence component, it turns out to be a 100Hz component in the synchronous d-q reference frame, and it is not extracted by the LPF. Therefore, the fundamental negative sequence component appears in the references of the active power filter. However, the utilizing negative sequence SRF method, in which the vectors are produced by $-\theta$, prevents the appearance of fundamental negative sequence component in the reference currents of the APF. The method is similar to the positive sequence SRF. The current vectors are transformed into a negative sequence d-q reference frame. In this case, the fundamental negative sequence current component turns out to be a DC signal and extracted via a LPF. The extracted DC signal is back transformed into the stationary α - β reference frame, and subtracted from the references of the positive sequence SRF method in the α - β reference frame.

The current reference calculation based on SRF method is summarized in Fig 3.4.

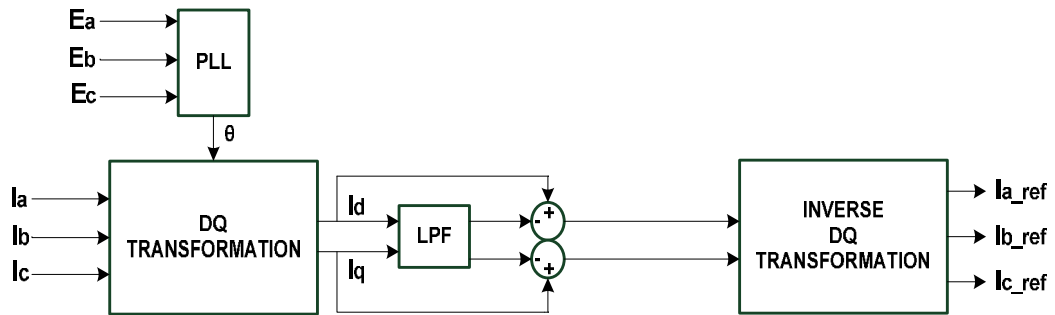


Figure 3.4. Current Reference Calculation Based on SRF Method

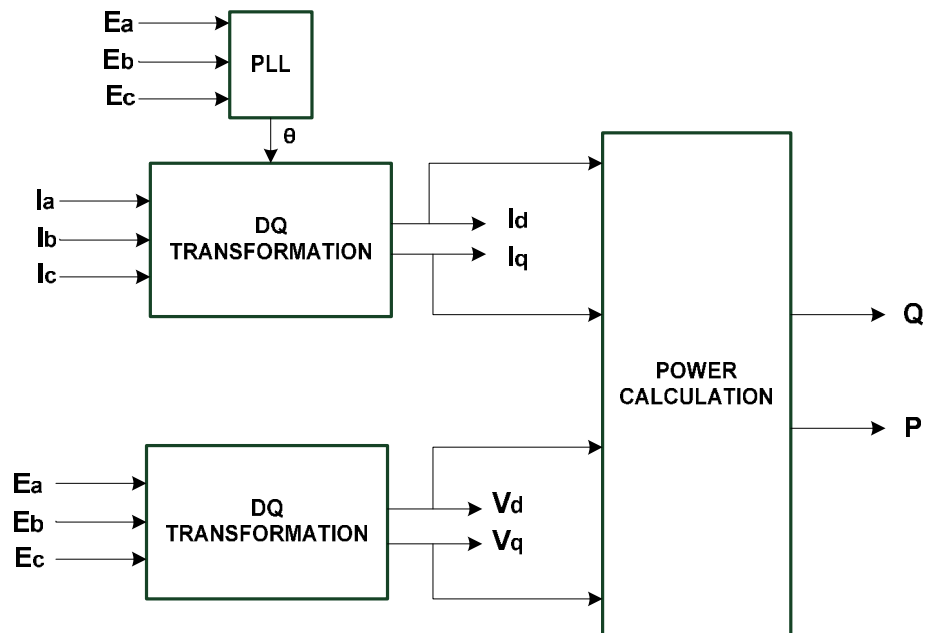


Figure 3.5. Power Calculation Based on SRF Method

3.3.2. Control and Waveform Modulation Method

3.3.2.1. Control Method

The control methods used for VSC based Hybrid Power Filters are based on the generation of voltage references. Firstly, for the harmonic reference current extraction control which is proposed by H. Akagi is described. Then, the proposed reactive power control is presented. In addition, the proposed dc voltage control is described. Finally, the proposed voltage reference generation method is explained.

3.3.2.1.1. Harmonic Current Control

The harmonic current control is based on the calculation of voltage reference by utilizing the source current harmonic references. In this method, the 50Hz component of the source current is extracted and the remaining oscillating part in the d-q reference frame is treated as reference compensation currents.

In this control, the synchronous reference frame method is used to calculate the harmonic components of the mains current. The phase angle (θ) of the supply voltage is required which affects the performance of the control method. Hence, an accurate phase tracking system is the key point of the control method to transform the measured current vectors into the synchronously rotating d-q reference frame. So Sogi- PLL (second order generalised integrator) is selected for extracting the phase angle (θ).

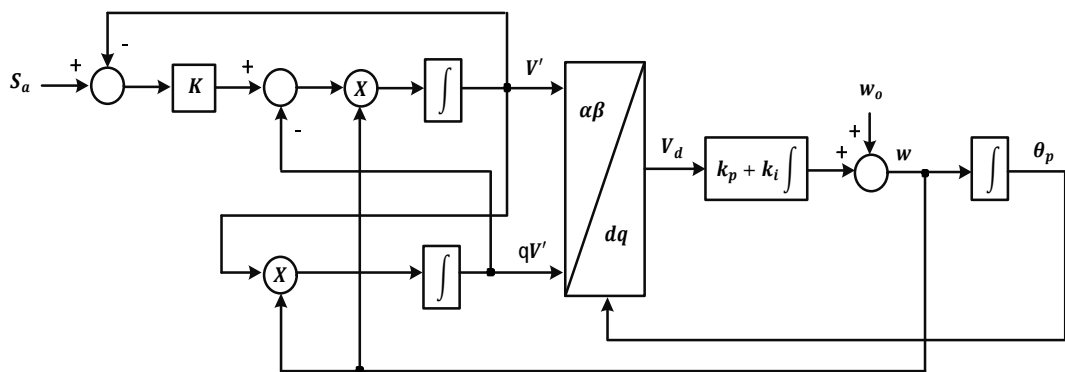


Figure 3.6. Block Diagram of the Sogi-PLL (Demirdelen et. al., 2013)

The phase tracking system indicated above includes the transformation of utility voltages into the d-q reference frame and a PI controller. The system is a closed loop controller in which the transformation of the utility voltage is performed by using the θ output of the PI controller.

As output signals, two sine waves (v' and qv') with a phase shift of 90° are generated. The component V' has the same phase and magnitude as the fundamental of the input signal(v) (Ferreira et. al., 2011).

The presented structure is based on SOGI, which is defined as:

$$GI = \frac{ws}{s^2 + w^2} \quad (3.32)$$

where w represents the resonance frequency of the SOGI.

The closed-loop transfer functions ($H_d = \frac{v'}{v}$ and $H_q = \frac{qv'}{v}$) of the structure presented in Fig 3.6 are defined as:

$$H_d(s) = \frac{kws}{s^2 + kws + w^2} \quad (3.33)$$

$$H_q(s) = \frac{kw^2}{s^2 + kws + w^2} \quad (3.34)$$

where k affects the bandwidth of the closed-loop system.

The level of filtering can be set from gain k as follows: if k decreases the band pass of the filter becomes narrower resulting in a heavy filtering, but in the same time the dynamic response of the system will become slower.

As given in the block diagram of the harmonic current control method (Fig 3.9), the harmonic content of the source current is calculated by utilizing the synchronous reference frame method. Firstly, three phase source currents are transformed into the d-q reference frame by employing the phase angle output of the PLL where $w=\theta$. I_d represents the instantaneous reactive current and I_q represents the instantaneous active current component. The fundamental component of the mains current turns out to be a DC signal, and the harmonic components which are still AC signals are rotating with respect to the reference frame. Harmonic current components I_{dh} and I_{qh} can be extracted by a high pass filter with a low cut off frequency. Another approach to extract harmonic components is applying 1-LPF (Low pass filter) operation. The dc link control signal which will be presented next section is added to I_{qh} . After obtaining the oscillating parts of the source current (I_{dh} , I_{qh}) in rotating the d-q reference frame, inverse dq transformations are applied to reproduce the harmonic current components in stationary abc frames. So the reference harmonic currents is produced.

Each harmonic component is amplified by “ K” to obtain a voltage reference for each phase. Thus hybrid power filter is controlled to produce a voltage at its terminals(V_{AF}) which can be simplified as given in :

$$V_{AF} = K \times I_{sh} \quad (3.35)$$

Thus, single phase equivalent of the hybrid power filter at harmonic frequencies can be represented as indicated in figure:

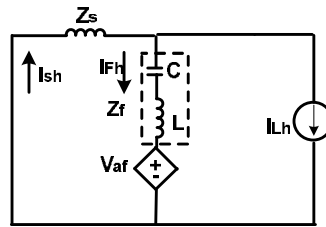


Figure 3.7. Single Phase Equivalent Circuit of HAPF (Harmonic Compensation applied)

So, harmonic content of the source current can be calculated as follows:

$$I_{sh} = I_{Lh} + I_{fh} \quad (3.36)$$

$$V_{AF} + Z_f I_{fh} + Z_s I_{sh} = 0 \quad (3.37)$$

$$I_{sh} = \frac{Z_{fh}}{Z_{fh} + Z_{sh} + K} \times I_{Lh} \quad (3.38)$$

As it can be deduced from (3.38) the equation, when the harmonic compensation control is applied, the active power filter behaves as a pure resistor which is connected in series with the source impedance (Z_s). Hence, the feedback gain K suppresses the resonance between the supply and the passive filter. Therefore, the amplification phenomenon of the passive filter is diminished. Theoretically as K goes to infinite values, the harmonic content of the source current disappears totally.

However, the feedback gain K is limited to the certain values due to the stability problems of the system.

3.3.2.1.2. Reactive Power Control

When the loading reactive power Q_{Lxf} is greater than Q_{cxf_PF} , in order to generate a larger I_{cxfq} , the inverter should output a negative inverter fundamental active voltage ($V_{invxfp} < 0$). The related equations as follows (Lam et. al., 2012):

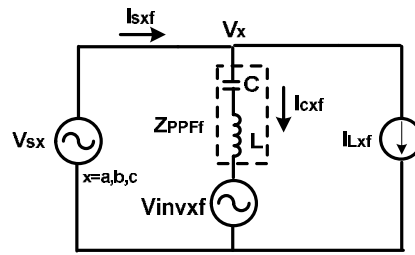


Figure 3.8. Reactive Power Equivalent Circuit

$$V_{invxf} = V_x - Z_{PPF} I_{Cxf} \quad (3.39)$$

$$V_{invxf} = V_{invxfp} - jV_{invxfq} \quad (3.40)$$

$$V_{invxfp} = V_x + I_{Cxfq} X_{PPF} \quad (3.41)$$

$$V_{invxfq} = -X_{PPF} I_{Cxfp} \quad (3.42)$$

The fundamental compensating active current I_{cxfp} and the reactive current I_{cxfq} are

$$I_{cxfp} = -\frac{V_{invxfq}}{X_{PPF}} \quad (3.43)$$

$$I_{cxfq} = \frac{V_{invxfp} - V_x}{X_{PPF}} \quad (3.44)$$

To compensate reactive power, the steady-state active fundamental current I_{cxfp} from the inverter is small ($I_{cxfp} \approx 0$). Thus, $V_{invxfq} \approx 0$.

$$X_{PPFf} = -|X_{cf} - X_{Lf}| \quad (3.45)$$

The reactive power provided by the passive part

$$Q_{cxf_PF} = -\frac{V_x^2}{|X_{cf} - X_{Lf}|} < 0 \quad (3.46)$$

3.3.2.1.3. DC Link Voltage Control

Initially, the loading reactive power are calculated by using the dq theory. Then, the required minimum dc-link voltage V_{dcminx} for the compensating each phase Q_{Lxf} can be calculated using (3.9), where V_x is the rms load voltage and Q_{cxfPF} is the passive filter reactive power. The adaptive minimum dc-link voltage will be equal to V_{dc_min} . During the balanced loading case, the three-phase fundamental reactive power consumptions are the same ($Q_{Laf} = Q_{Lbf} = Q_{Lcf}$), and therefore, $V_{dcmin} = V_{dcmina} = V_{dcminb} = V_{dcminc}$. In order to implement the adaptive dc-link voltage control function for the three-phase three-wire LC-HAPF, V_{dcmin} can be simply treated as the final reference dc-link voltage V_{dc_ref} . It is obvious that when the loading reactive power consumption (Q_{Lxf}) is changing, the system will adaptively yield different V_{dcminx} and V_{dcmin} values (Lam et. al., 2012).

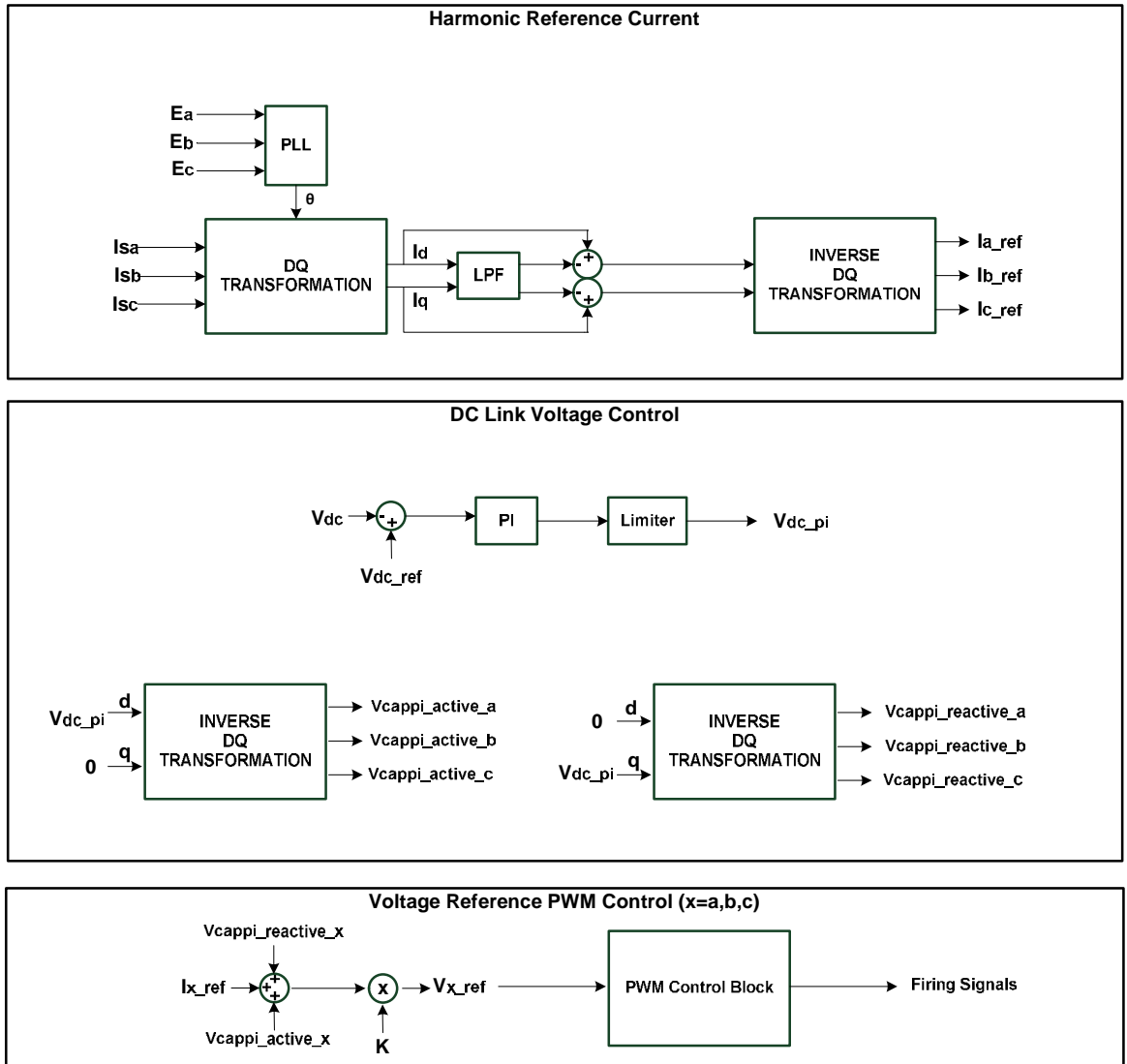
However, this adaptive control scheme may frequently change the dc voltage reference V_{dc}^* in practical situations, as the loading is randomly determined by electric users (different Q_{Lxf}). Then, this frequent change would cause a rapid dc voltage fluctuation, resulting in the deterioration of the HAPF operational performances. In order to alleviate this problem, a final reference dc-link voltage level determination process is added as shown in Fig. 3.9. The final reference dc-link voltage V_{dc}^* is classified into certain levels ($V_{dc1}, V_{dc2}, \dots, V_{dcmax}$, $V_{dc1} < V_{dc2} < \dots < V_{dcmax}$) for selection, so that V_{dc}^* can be maintained as a constant value within a specific compensation range. From Fig. 3.9, when the input V_{dcmin} is less than the lowest dc voltage level V_{dc1} , the final reference dc-link voltage will be $V_{dc}^* = V_{dc1}$. Ifnot, repeat the steps until V_{dc} minis found to be less than a dc-link voltage level. However, if V_{dc} min is greater than the maximum voltage level V_{dcmax} , the final

reference dc-link voltage will be $V_{dc}^* = V_{dcmax}$. Therefore, the proposed adaptive dc-link voltage control scheme for the HAPF can be implemented under various inductive linear loading conditions. The adaptive control scheme can apply either P or PI controller for the dc-link voltage control (Lam et. al., 2012).

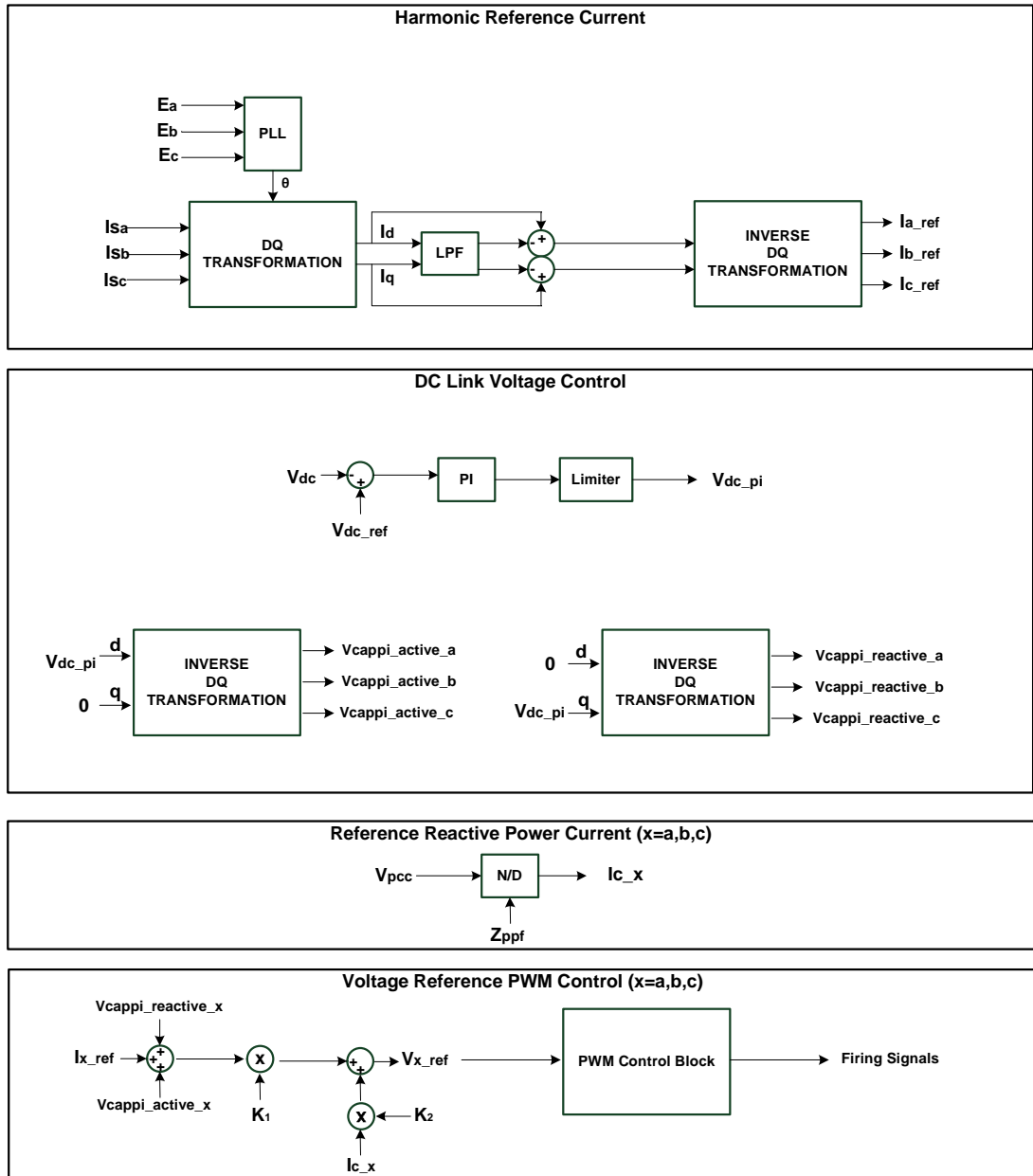
3.3.2.2. Waveform Modulation Method

The triangular carrier-based sinusoidal PWM method with a current error limiter is applied, so that the voltage references must be within the triangular wave. And the frequency of the triangular wave is set to $f_{tri} = 10$ kHz. After the process of instantaneous power compensation and proposed adaptive dc-link voltage control blocks as in Fig. 3.9, the PWM trigger signals for the switching devices can be generated. The proposed adaptive dc-link voltage-controlled HAPF can compensate the dynamic reactive power and reduce the switching loss and switching noise.

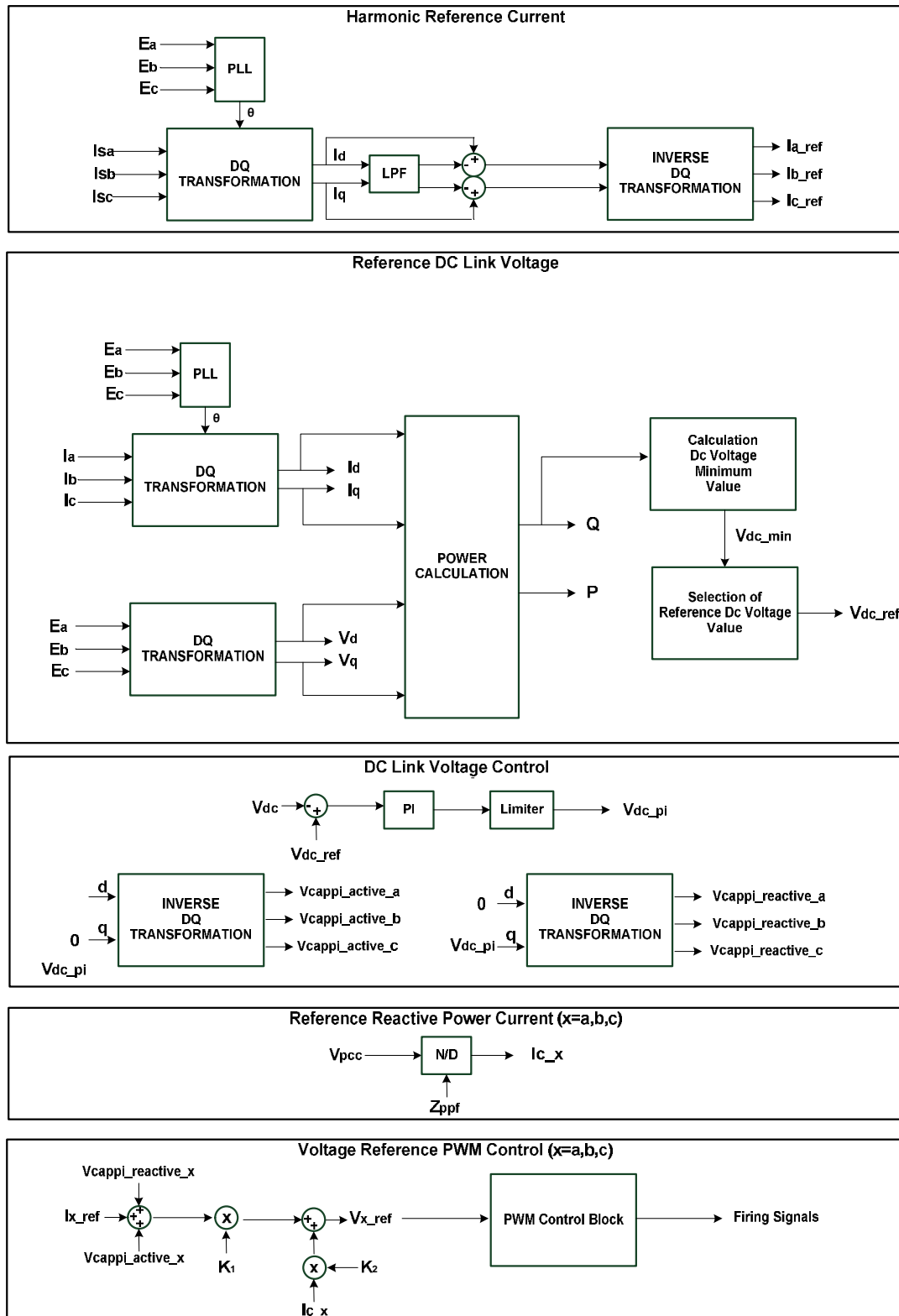
The voltage references can be obtained by summing the reference reactive current and reference harmonic currents with multiplying their gains. Then the voltage references will be sent to the PWM control part.



(a) Only Harmonic Compensation Control Block



(b) Both Harmonic and Reactive Power Compensation with Constant DC Link



(c) Both Harmonic and Reactive Power Compensation with Dynamic DC Link
 Figure 3.9. Control Block Diagrams of Proposed HAPF

4. SIMULATION MODEL AND RESULTS OF THE SYSTEMS

In this thesis, the simulation model of the system is formed by using EMTDC/PSCAD 4.2.0 Professional software. The Parallel Hybrid Power Filter system and Multilevel Hybrid Active Power Filter are modeled, simulated and analyzed in PSCAD 4.2.0 environment. All control methods are developed in FORTRAN language.

4.1. Simulation Models

The simulation results are obtained from the systems given in Figure 4.1 and Figure 4.2 using PSCAD software in a way to minimize the DC link voltage and the rating of the PHAPF, while keeping the filtering performance satisfactory.

In this part of thesis, firstly simulation results obtained from PHAPF and the Multilevel-PHAPF are represented for only harmonic compensation. Then the proposed control methods which combines not only the harmonic compensation but also the reactive power compensation are investigated for PHAPF. Finally, the proposed control method are provided for medium voltage levels using the Diode-Clamped Multilevel topology based PHAPF.

Both the conventional and the proposed control method have startup procedure. The startup procedure of the systems is as follows:

-Initially, the three upper IGBTs are turned on and the three lower IGBTs are turned off. During this time interval, PHAPF is not operating and the DC side of PHAPF is seen as a short circuit by mains side.

-After the DC link voltage is built up to the specified reference value, the compensation current references are activated in the control loop of the system and the PHAPF totally operates.

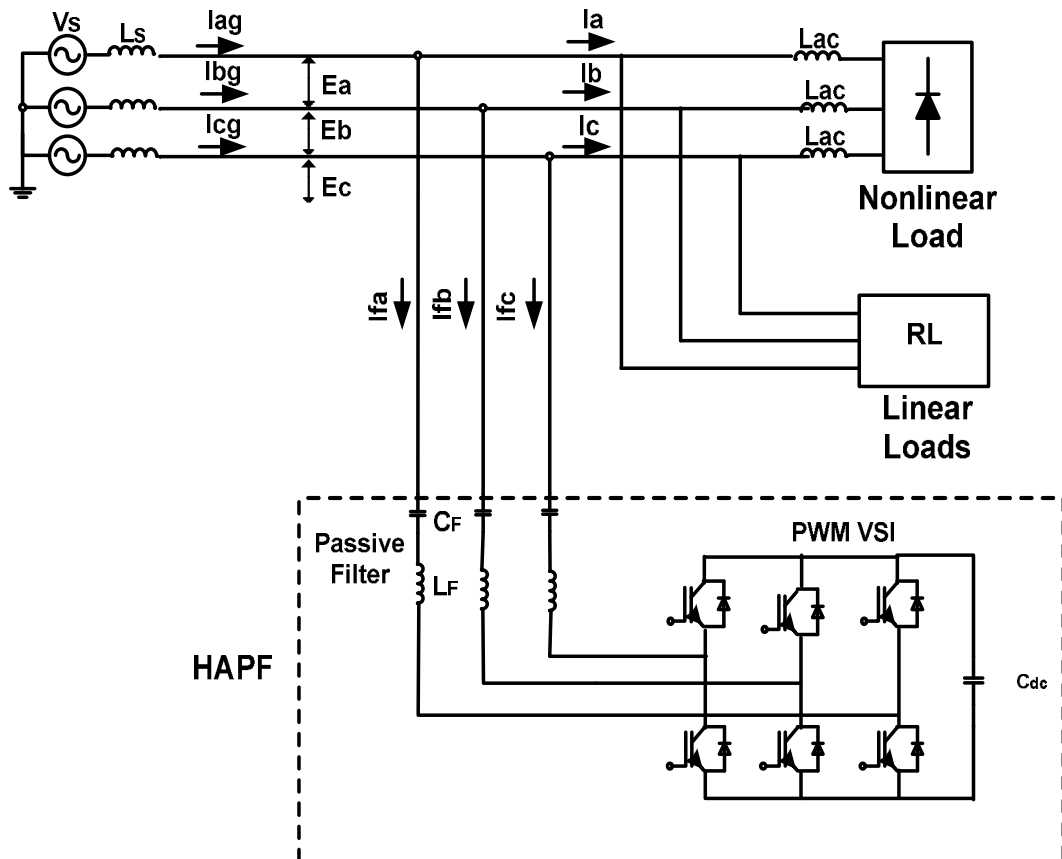


Figure 4.1. Simulation Model of Parallel Hybrid Active Power Filter

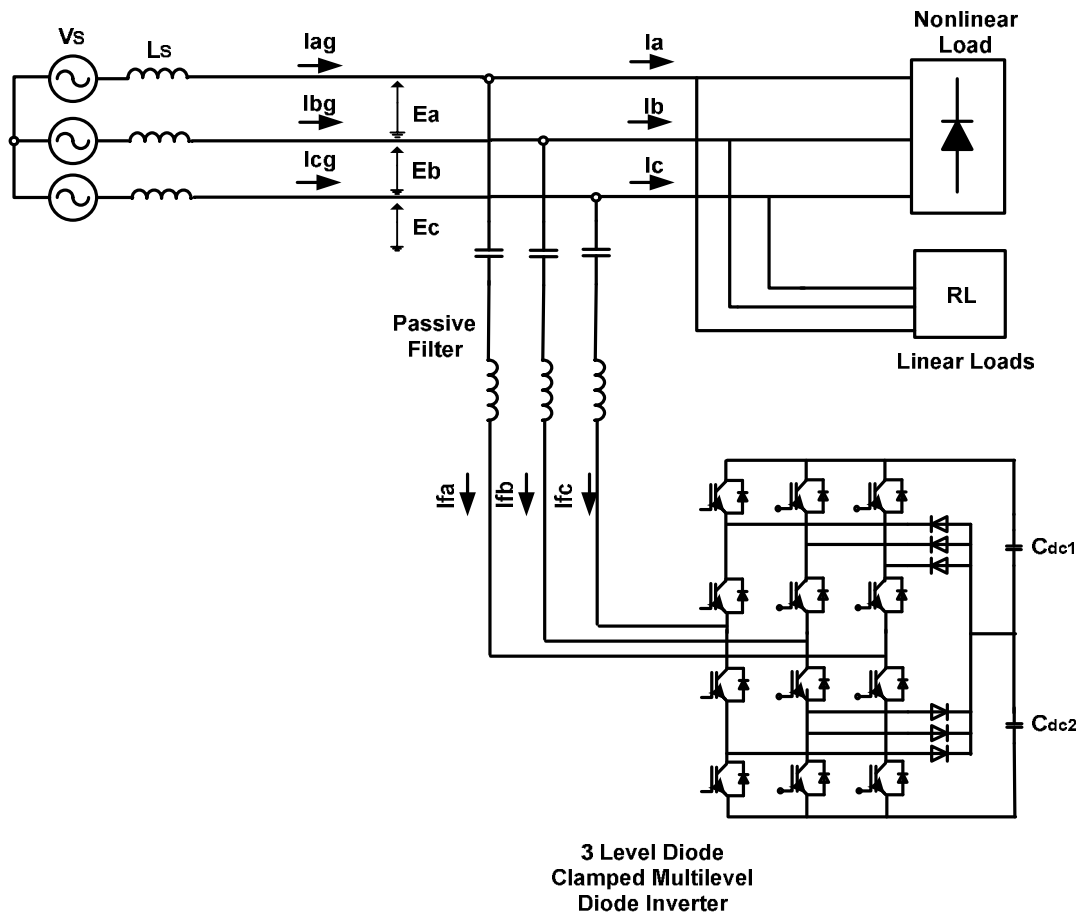


Figure 4.2. Simulation Model of Multilevel Parallel Hybrid Active Power Filter

4.2. Analysis of Case Studies

Case-1: Only Harmonic Compensation for PHAPF: In this part, the PHAPF topology shown in Figure 4.1 is used. The performance for only the harmonic compensation is observed. The passive filters are tuned at 5th harmonics. Both single RL loads and three phase diode rectifiers are used. The simulation parameters of the system are given Table 4.1 respectively.

The harmonic content of the supply current is obtained by the Synchronous Reference Frame method. The phase information of the supply voltage is obtained by a SOGI-PLL system as described in the previous section

As it can be seen from Figure 4.3 the phase angle information is locked to the supply voltage between $0-2\pi$ which is utilized in transformation matrices.

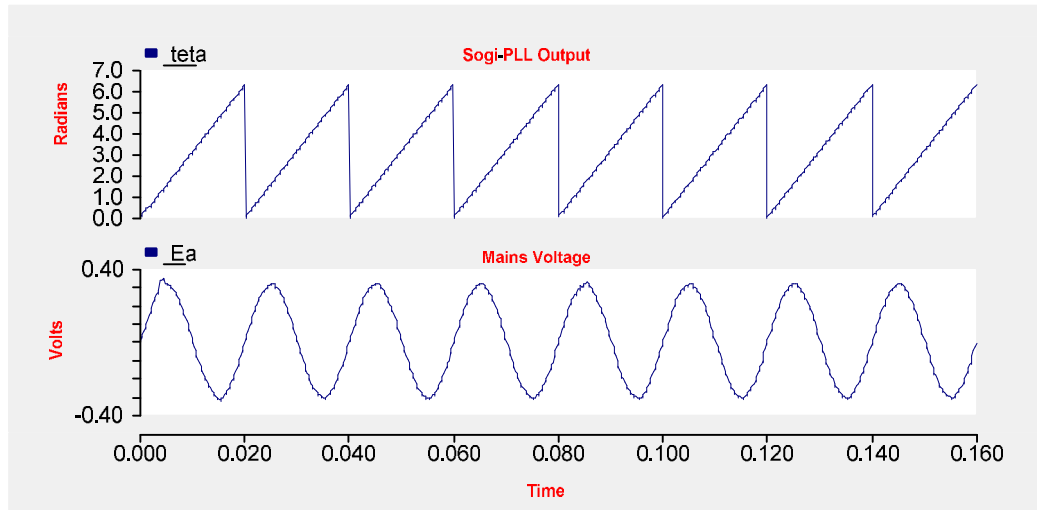


Figure 4.3. SOGI-PLL Output and Mains Voltage

Firstly, the startup procedure is begun. The PHAPF is not operating so the mains current is obtained from the non-sinusoidal waveform. After the DC link voltage is built up, the compensation current references are activated and the PHAPF operates. The mains current becomes a sinusoidal waveform, the DC link voltage kept constant at 100 V. The filtering performance of the system and the DC link voltage are shown in Figure 4.4 and Figure 4.5.

Table 4.1. Simulation Parameters for Case-1

Line Voltage	380 V
Line frequency	50 Hz
Supply inductance (L_s)	0.0005 H
Rectifier inductance (L_l)	0.6 mH
Filter Capacitor (C_F)	170 μ F
Filter Inductance (L_F)	2.39 mH
Tuned freq. of series filter (f_{tuned})	250 Hz
DC link capacitor (C_{DC})	3000 μ F
Load Resistances(R_{load1})	9.75 Ω
Load Inductances(L_{load1})	65 mH
Load Inductances(L_{ac1})	1.3 mH
Switching frequency ($f_{\text{switching}}$)	10 kHz
Simulation Step Time	40 μ s
DC Link Gain (K)	1
Harmonic Voltage Reference gain K1	50

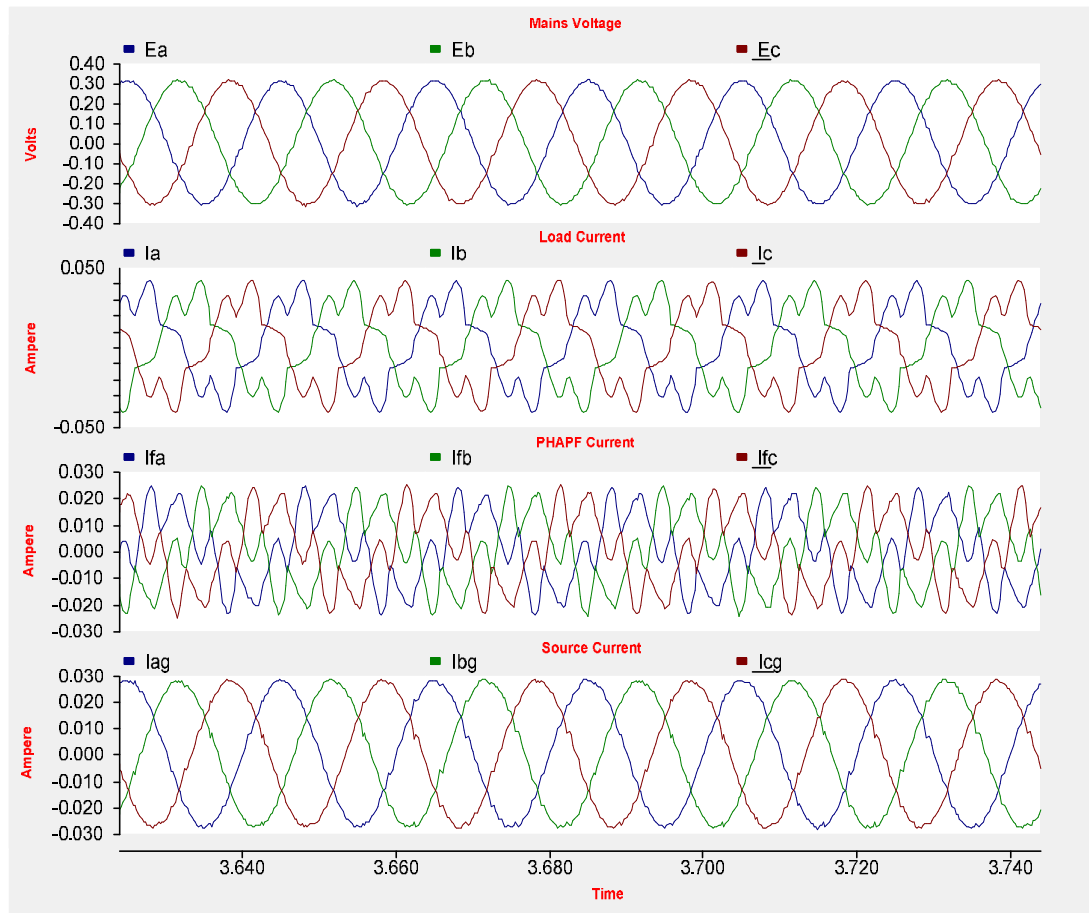


Figure 4.4. PHAPF Operates

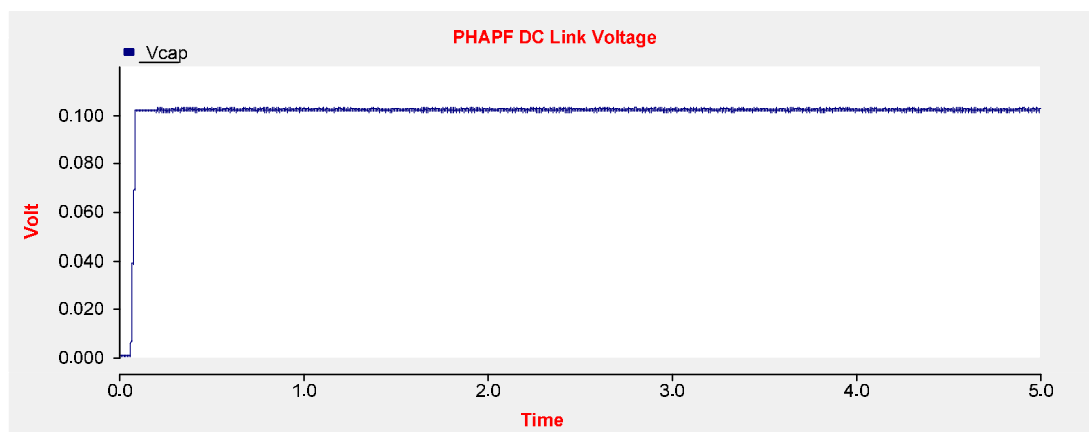


Figure 4.5. DC Link Voltage of PHAPF

In this case, the reactive power compensation is supplied by the passive filter part of PHAPF. The passive filter is selected the same reactive power as loads.

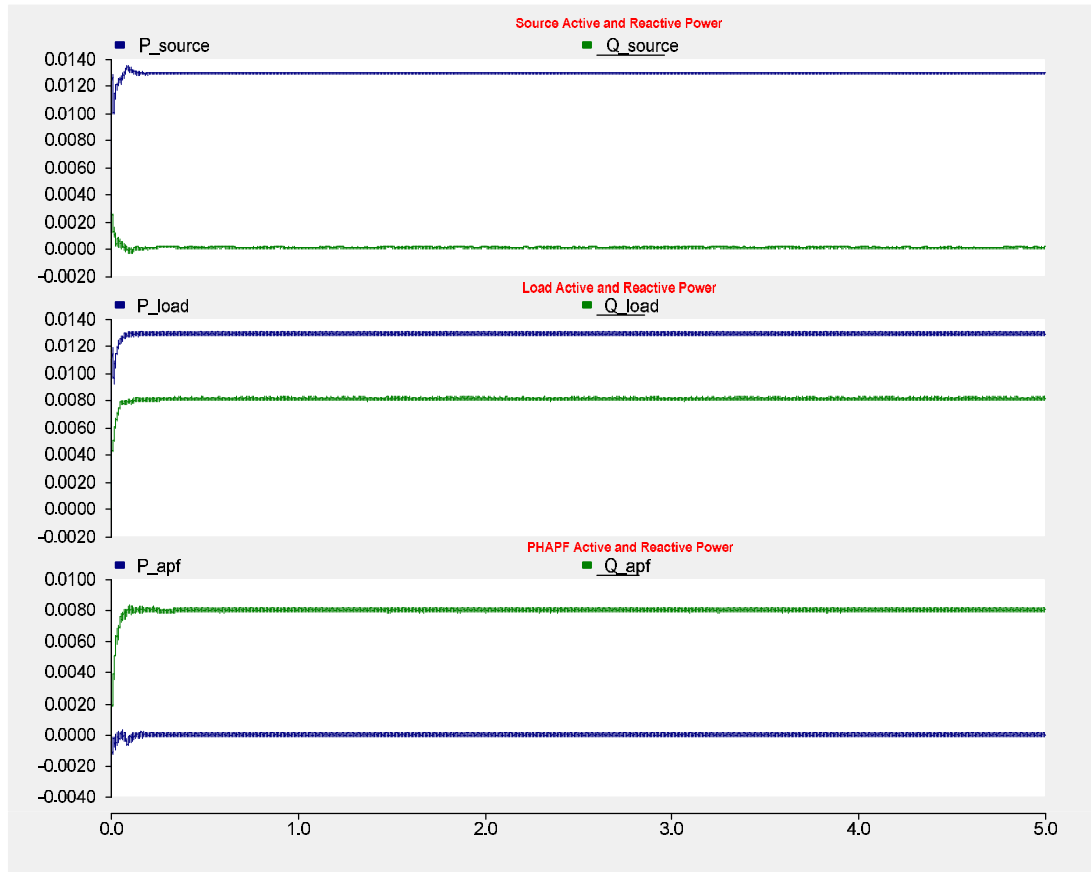


Figure 4.6. Source Active and Reactive power, Load Active and Reactive Power

The total harmonic distortion (THD) is reduced from 27% to 2.5% .

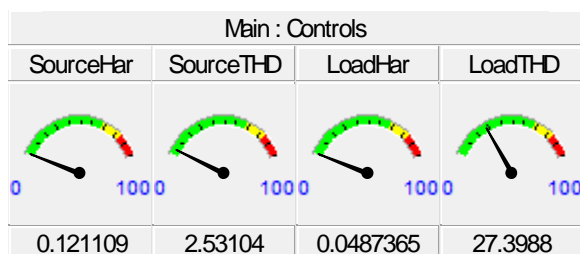


Figure 4.7. Source and Load Harmonics and THD

Case-2: Only Harmonic Compensation for Multilevel-PHAPF: In this case, the Multilevel PHAPF topology which is suitable for medium voltage levels is used. The performance for only the harmonic compensation is observed. The passive filter is tuned at 5th harmonics. Both single RL loads and the three phase diode rectifier are used. The simulation parameters of the system are given in Table-4.2 respectively. The startup procedure, the extraction of harmonic content are the same as the previous case.

The DC link voltage is kept constant at 1 kV. The filtering performance of the system and the DC link voltage are shown in Figure 4.8 and Figure 4.9.

Table 4.2. Simulation Parameters for Case-2

Line Voltage, frequency	6300 V, 50 Hz
Supply inductance (L_s)	0.001 H
Rectifier inductance (L_l)	0.6 mH
Filter Capacitor (C_F)	16 μ F
Filter Inductance (L_F)	0.025 H
Tuned freq. of series filter (f_{tuned})	250 Hz
DC link capacitors (C_{DC1} , C_{DC2})	5000 μ F
Load Resistances(R_{load1})	130 Ω
Load Inductances(L_{load1})	0.6 H
Load Inductances(L_{ac1})	13 mH
Switching frequency ($f_{\text{switching}}$)	10 kHz
Simulation Step Time	40 μ s
DC Link Gain (K)	1
Harmonic Voltage Reference gain K1	400

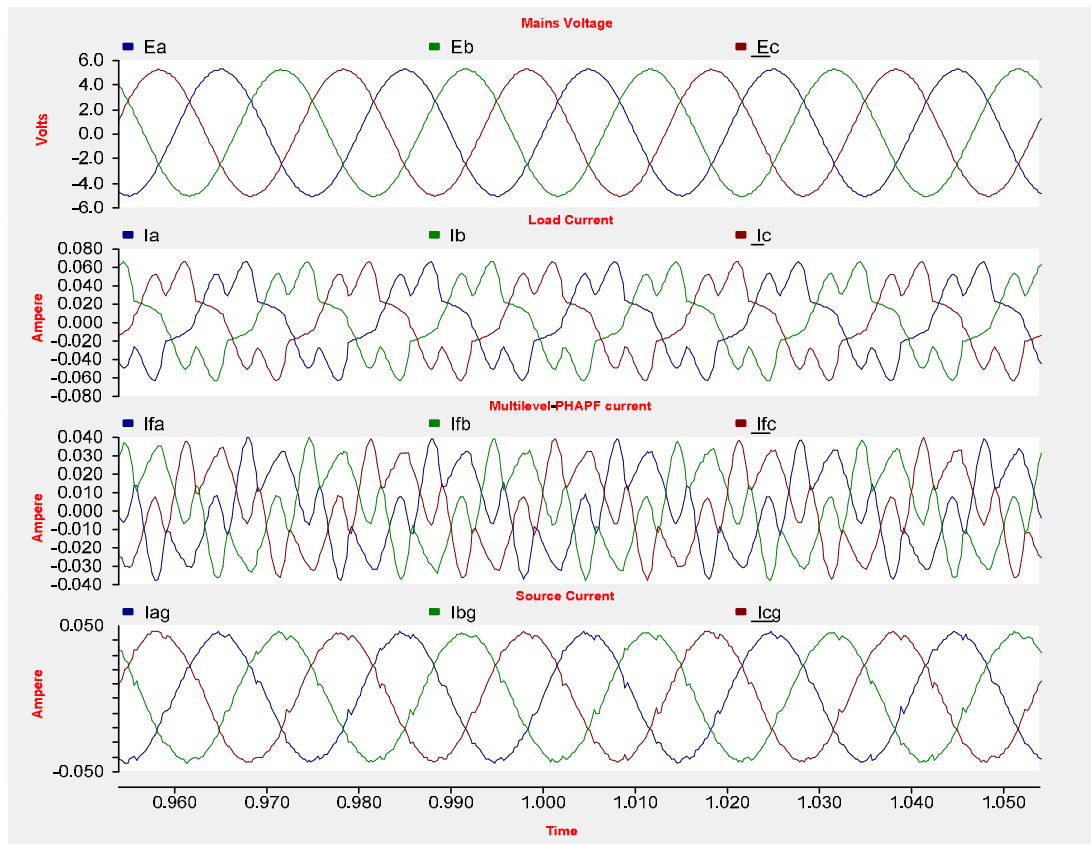


Figure 4.8. Multilevel-PHAPF Operates

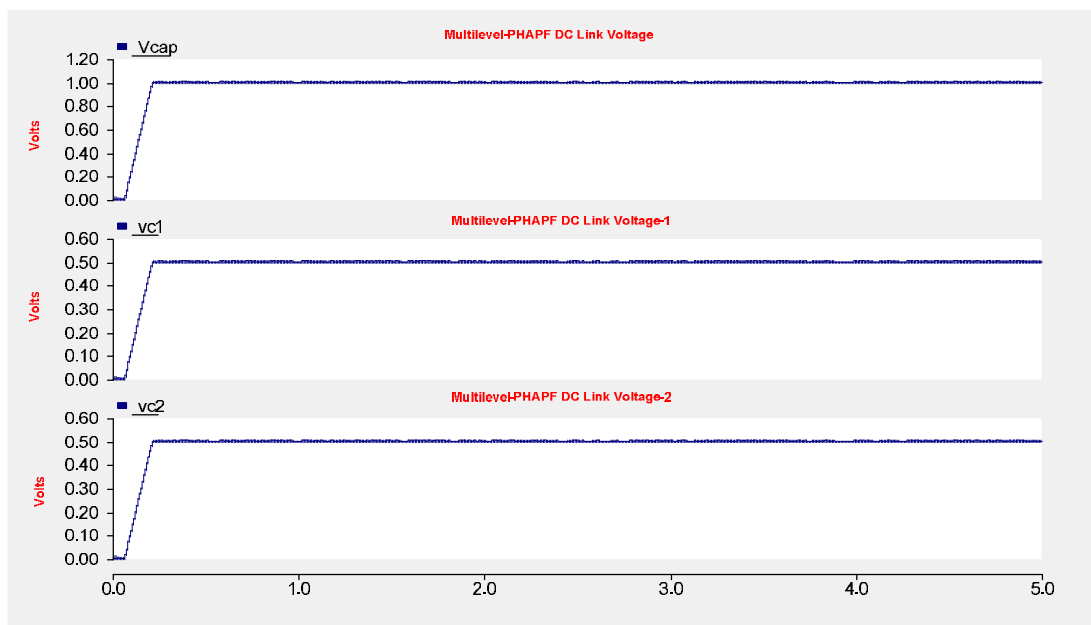


Figure 4.9. DC Link Voltage of Multilevel-PHAPF

Reactive power compensation is supplied by the passive filter part of PHAPF. The passive filter is selected the same reactive power as loads.

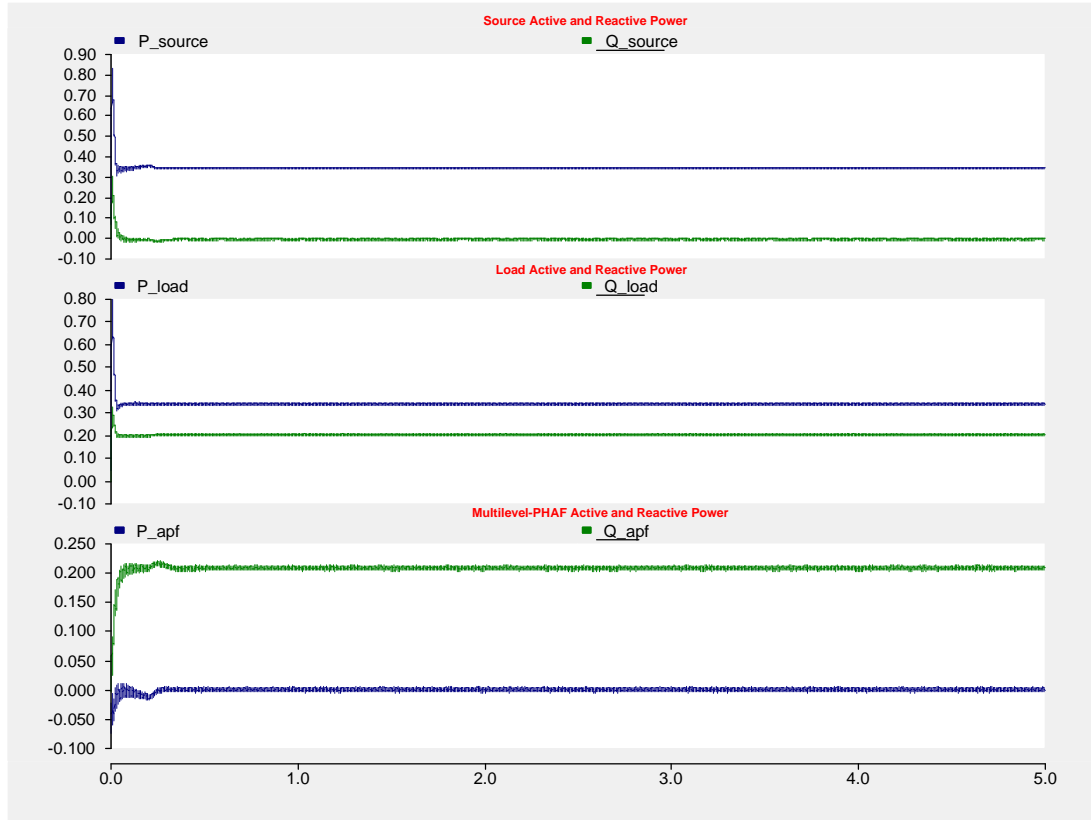


Figure 4.10. Source Active and Reactive power, Load Active and Reactive Power

The total harmonic distortion (THD) is reduced from 28.5% to 4.7% .

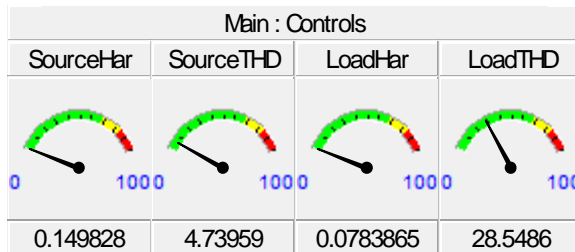


Figure 4.11. Simulation Results

Case-3:Both Harmonic and Reactive Power Compensation with Constant DC Link For PHAPF:According to the most of articles in literature, PHAPF has reactive power compensation capability that is limited with the capacity of the used passive filter.

With the simulation of this case, it is clearly shown that the reactive power compensation capability is added to PHAPF by using APF part. In this case, the capacity of passive filter is nearly 8 kVAR. The load capacity is nearly 9kVAR. The simulation results shows that the APF part of PHAPF compensates nearly 1 kVAR reactive power with the constant DC link voltage.

The simulation parameters of the system are given in Table-4.3 respectively.

The startup procedure, the extraction of harmonic content are the same as the previous case. For the reactive power compensation, the fundamental reactive compensation current is calculated for the three phase that is described in previous section. Then this current is multiplied by K_c which adjusts the reactive power amount. Then this multiplication is added to the firing signal.

The DC link voltage is kept constant at 100 V. The filtering performance of the system and the DC link voltage are shown in Figure 4.12 and Figure 4.13.

Table 4.3. Simulation Parameters for Case-3

Line Voltage	380 V
Line frequency	50 Hz
Supply inductance (L_s)	0.0005 H
Rectifier inductance (L_l)	0.6 mH
Filter Capacitor (C_F)	170 μ F
Filter Inductance (L_F)	2.39 mH
Tuned freq. of series filter (f_{tuned})	250 Hz
DC link capacitor (C_{DC})	5000 μ F
Load Resistances(R_{load1} , R_{load2})	9.75 Ω , 50 Ω
Load Inductances(L_{load1} , L_{load2})	65 mH
Load Inductances(L_{ac1})	1.3 mH
Switching frequency ($f_{\text{switching}}$)	10 kHz
Simulation Step Time	40 μ s
DC Link Gain (K)	1
Harmonic Voltage Reference gain K1	30
Reactive Power Compensation gain K2	5

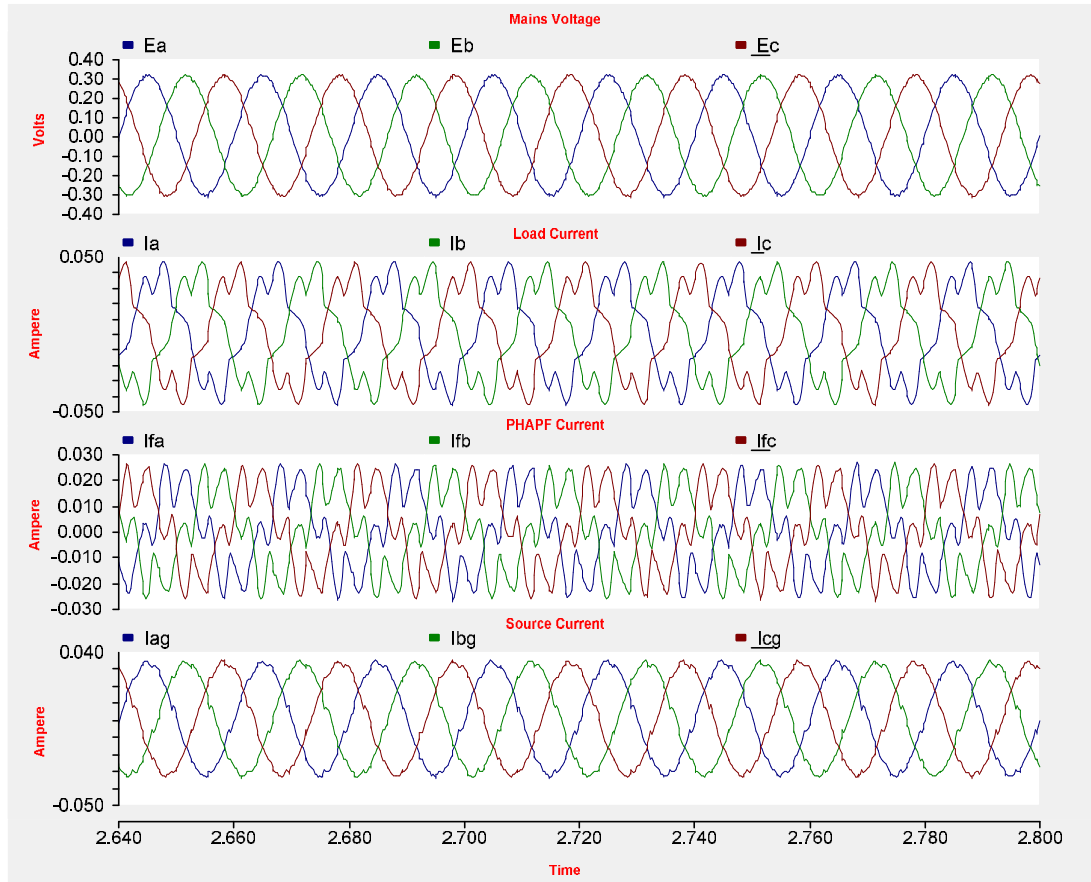


Figure 4.12. PHAPF Operates

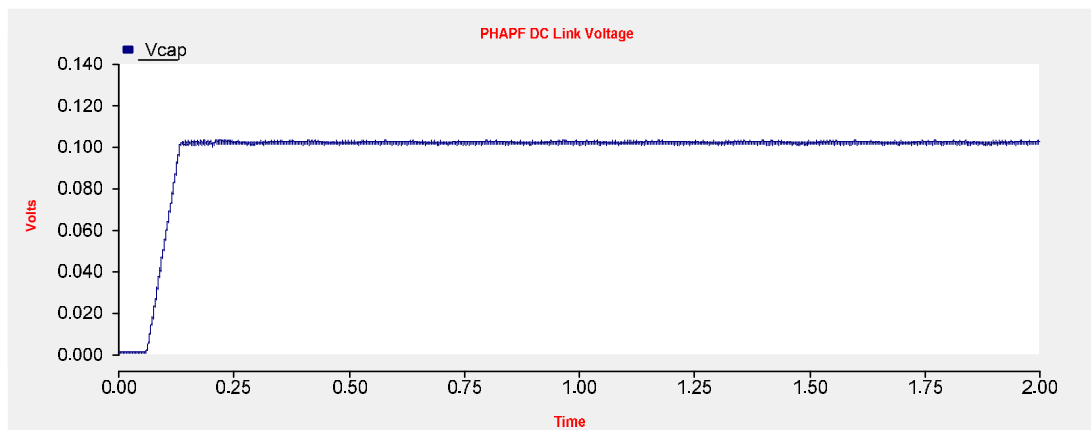


Figure 4.13. DC Link Voltage of PHAPF

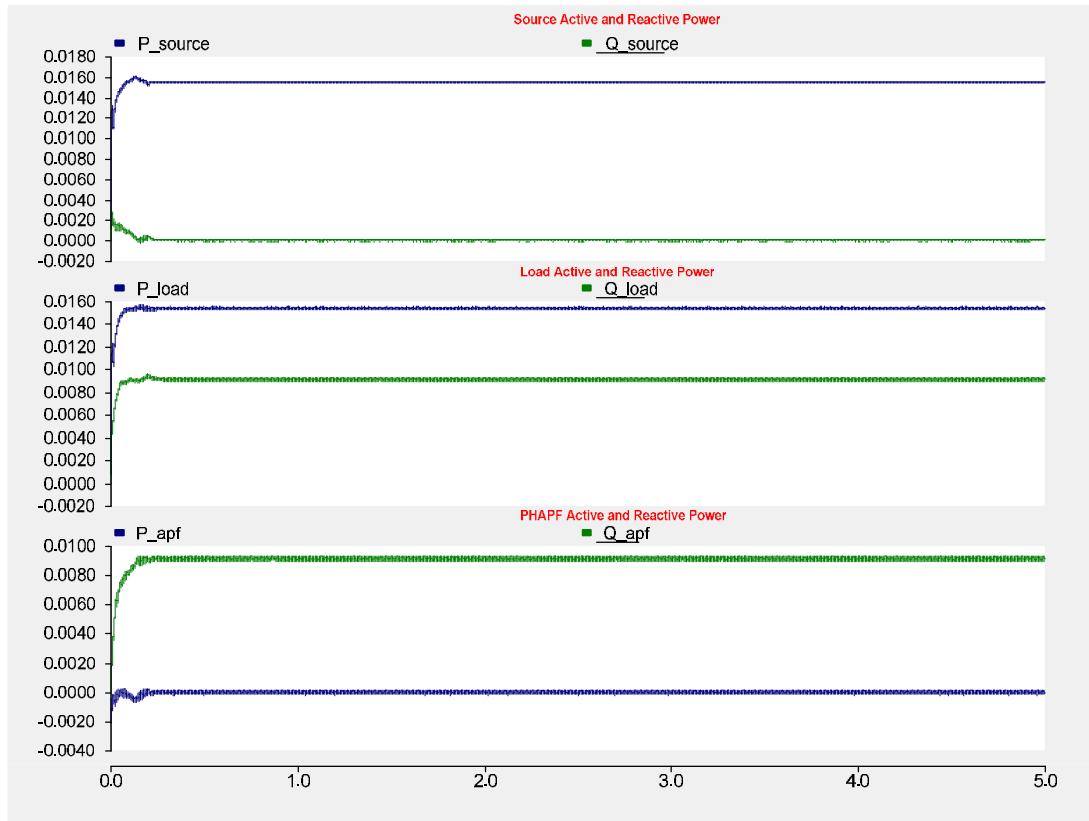


Figure 4.14. Source Active and Reactive power, Load Active and Reactive Power

The total harmonic distortion (THD) is reduced from 23% to 4.4% .

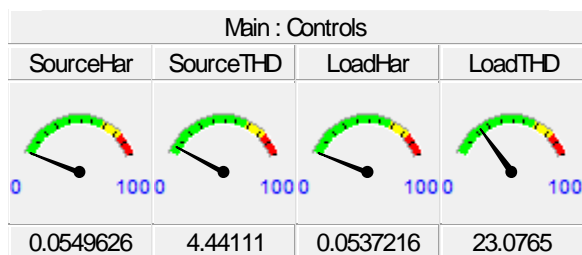


Figure 4.15. Simulation Results

Case-4: Both Harmonic and Reactive Power Compensation with Constant DC Link For Multilevel-PHAPF: With the simulation of this case, it is clearly shown that the reactive power compensation capability is added to Multilevel-PHAPF by using the APF part. In this case, the capacity of the passive filter is nearly 205 kVAR. The load capacity is nearly 220 kVAR. The simulation results show that the

APF part of Multilevel-PHAPF compensates nearly 15 kVAR reactive power with the constant DC link voltage.

The simulation parameters of the system are given in Table-4.3 respectively.

The startup procedure, the extraction of harmonic content are the same as the previous case. For the reactive power compensation, the fundamental reactive compensation current is calculated for the three phase that is described previous section. Then this current is multiplied by K_c which adjust the reactive power amount. Then this multiplication is added to firing signal.

The DC link voltage is kept constant at 1 kV. The filtering performance of the system and the DC link voltage are shown in Figure 4.16 and Figure 4.17.

Table 4.4. Simulation Parameters for Case-4

Line Voltage	6300 V
Line frequency	50 Hz
Supply inductance (L_s)	0.001 H
Rectifier inductance (L_l)	0.6 mH
Filter Capacitor (C_F)	16 μ F
Filter Inductance (L_F)	0.025 H
Tuned freq. of series filter (f_{tuned})	250 Hz
DC link capacitors (C_{DC1} , C_{DC2})	10000 μ F
Load Resistances(R_{load1})	100 Ω
Load Inductances(L_{load1})	0.6 H
Load Inductances(L_{ac1})	13 mH
Switching frequency ($f_{\text{switching}}$)	10 kHz
Simulation Step Time	40 μ s
DC Link Gain (K)	1
Harmonic Voltage Reference gain K_1	1500
Reactive Power Compensation gain K_2	50

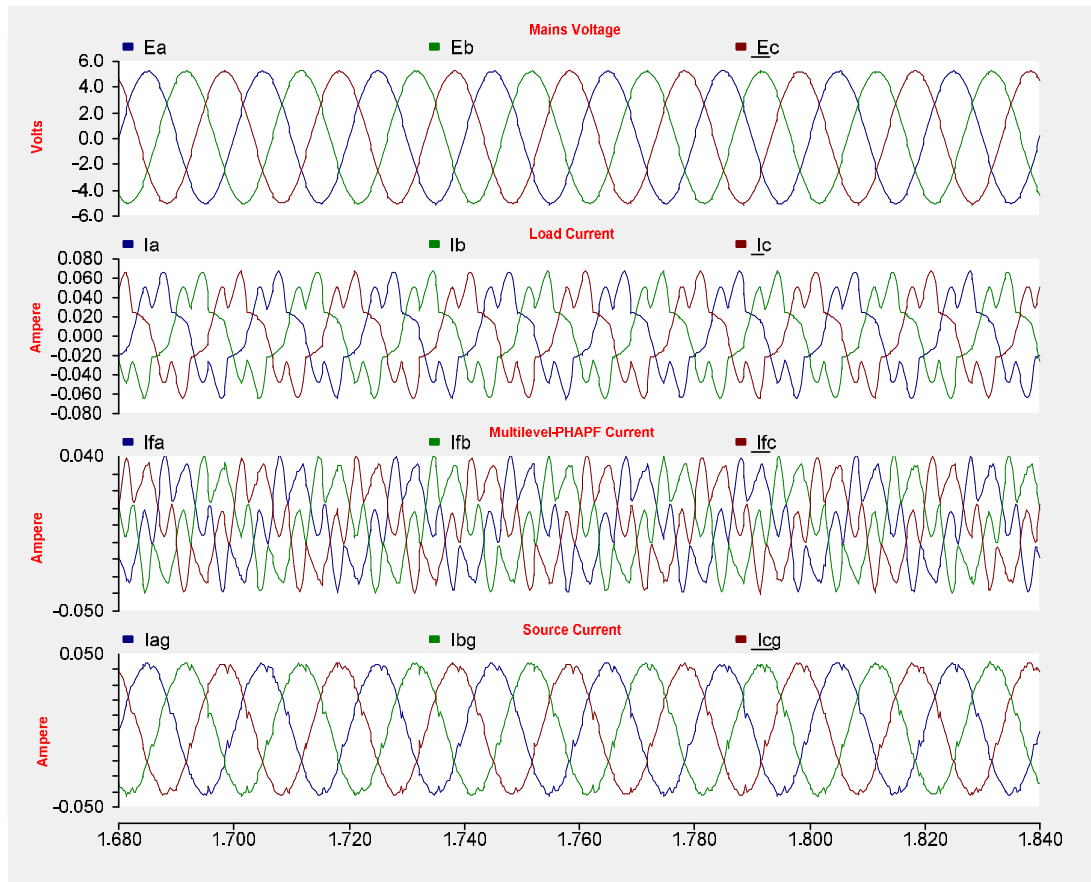


Figure 4.16. Multilevel-PHAPF Operates

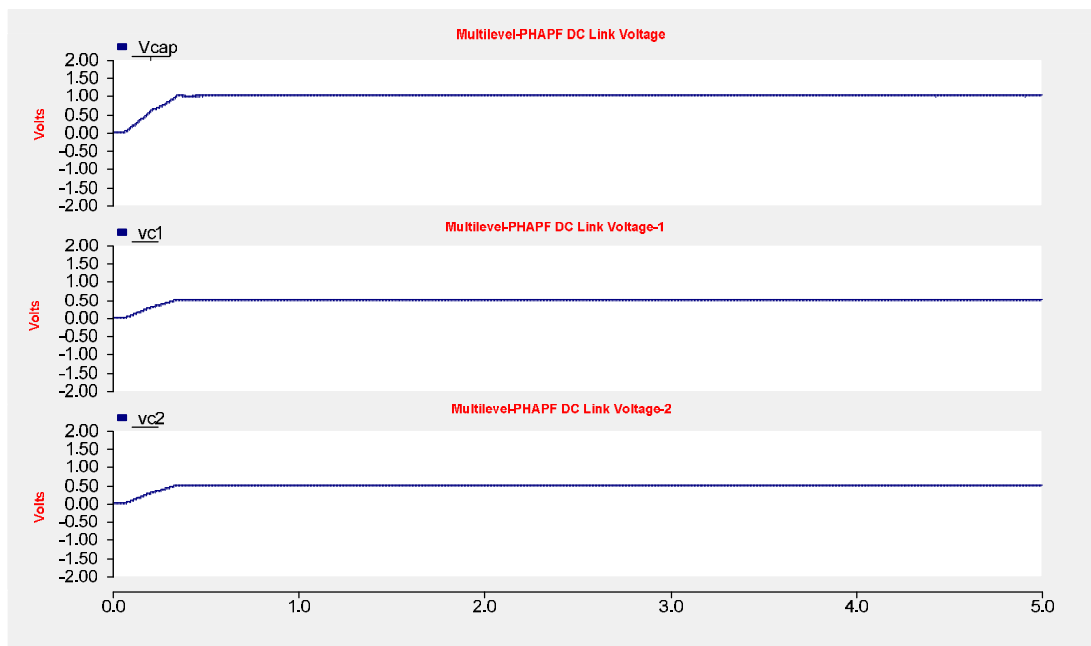


Figure 4.17. DC Link Voltage of Multilevel-PHAPF

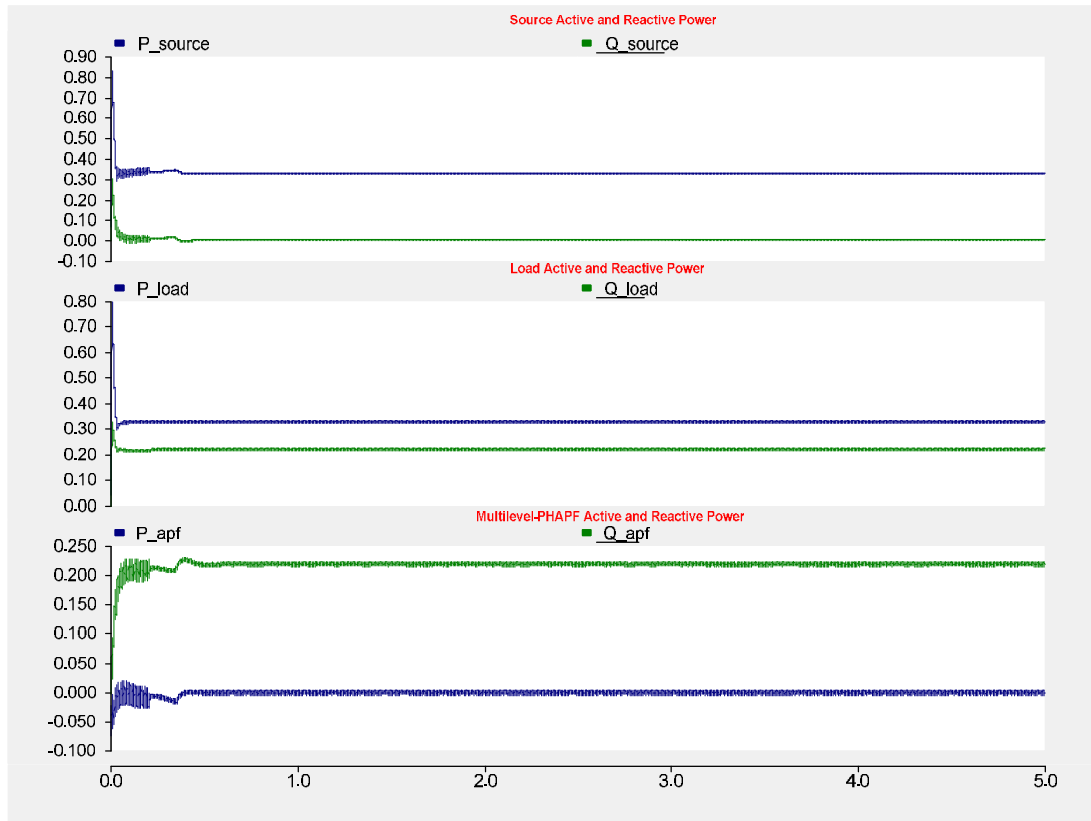


Figure 4.18. Source Active and Reactive power, Load Active and Reactive Power

The total harmonic distortion (THD) is reduced from 238.4% to 4.36% .

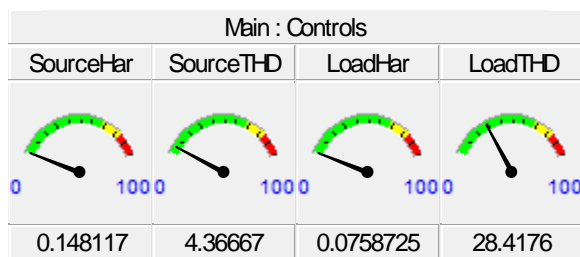


Figure 4.19. Simulation Results

Case-5: Both Harmonic and Reactive Power Compensation with Dynamic DC Link For PHAPF:With the simulation of this case, it is clearly shown that the reactive power compensation capability is added to the PHAPF by using the APF part and also dynamic dc link. In this case, the capacity of passive filter is nearly 8 kVAR. When the first load is connected, the load capacity is nearly 9 kVAR. The

simulation results shows that the APF part of PHAPF compensates nearly 1 kVAR reactive power with the adjusted DC link voltage which is nearly 130 V. When the first and the second loads are connected, the load capacity is nearly 11 kVAR. The simulation results show that the APF part of PHAPF compensates nearly 1.5 kVAR reactive power with the adjusted DC link voltage which is nearly 210 V.

The simulation parameters of the system are given in Table-4.4 respectively.

The startup procedure, the extraction of harmonic content is the same as the previous case. For the reactive power compensation, the fundamental reactive compensation current is calculated for three phase that is described in the previous section. Then this current is multiplied by K_c which adjust the reactive power amount. Then this multiplication is added to firing signal.

The DC link voltage is adjusted itself by changing the load capacity. The filtering performance of the system and the DC link voltage are shown in Figure 4.20 and Figure 4.21.

Table 4.5. Simulation Parameters for Case-5

Line Voltage	380 V
Line frequency	50 Hz
Supply inductance (L_s)	0.0005 H
Rectifier inductance (L_1)	0.6 mH
Filter Capacitor (C_F)	170 μ F
Filter Inductance (L_F)	2.39 mH
Tuned freq. of series filter (f_{tuned})	250 Hz
DC link capacitor (C_{DC})	10000 μ F
Load Resistances(R_{load1} , R_{load2})	9.75 Ω , 20 Ω
Load Inductances(L_{load1} , L_{load2})	65 mH
Load Inductances(L_{ac1})	1.3 mH
Switching frequency ($f_{\text{switching}}$)	10 kHz
Simulation Step Time	40 μ s
DC Link Gain (K)	1
Harmonic Voltage Reference gain K_1	50
Reactive Power Compensation gain K_2	5

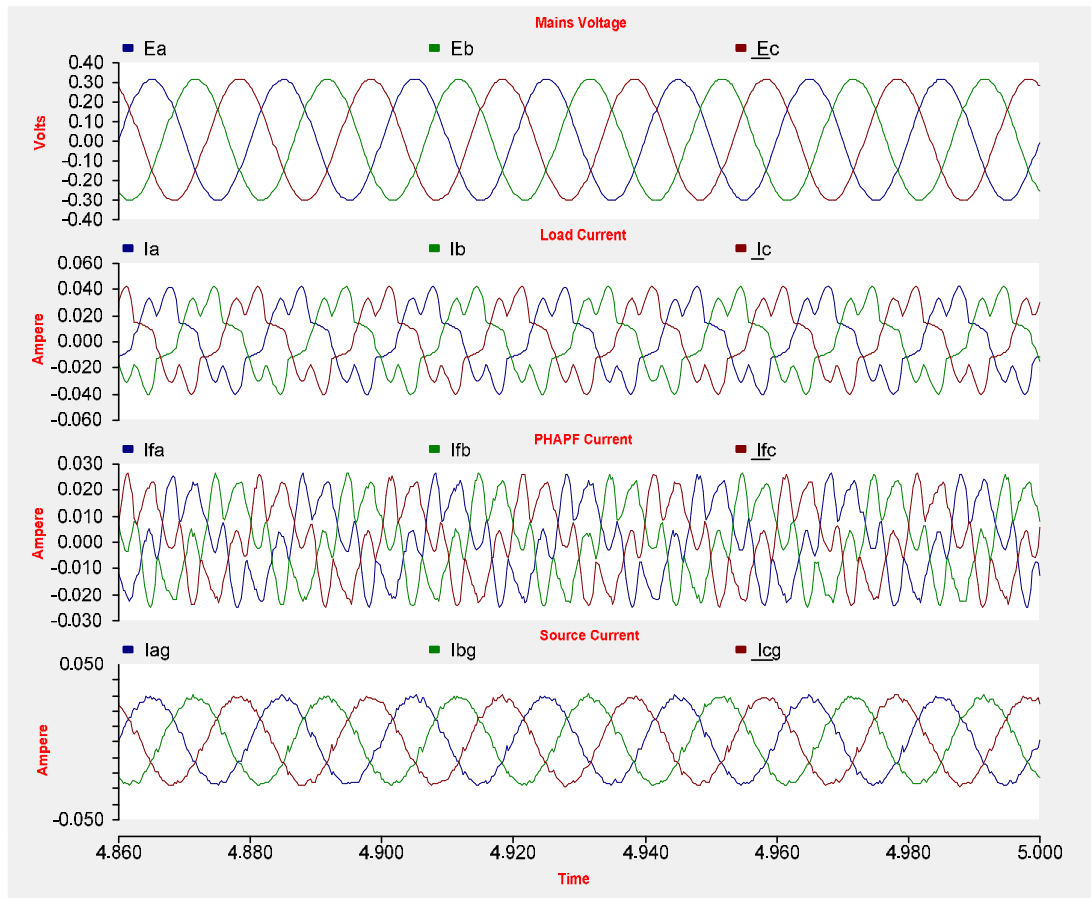


Figure 4.20. PHAPF Operates

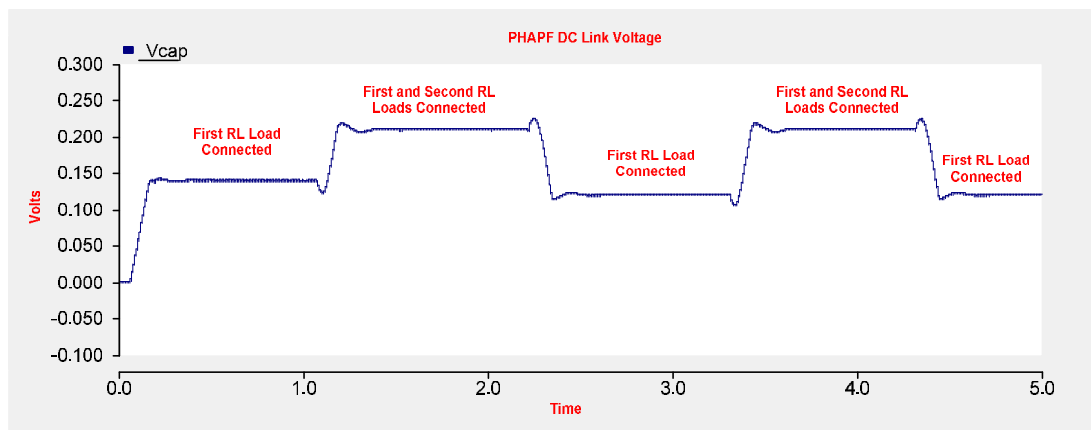


Figure 4.21. DC Link Voltage of HAPF

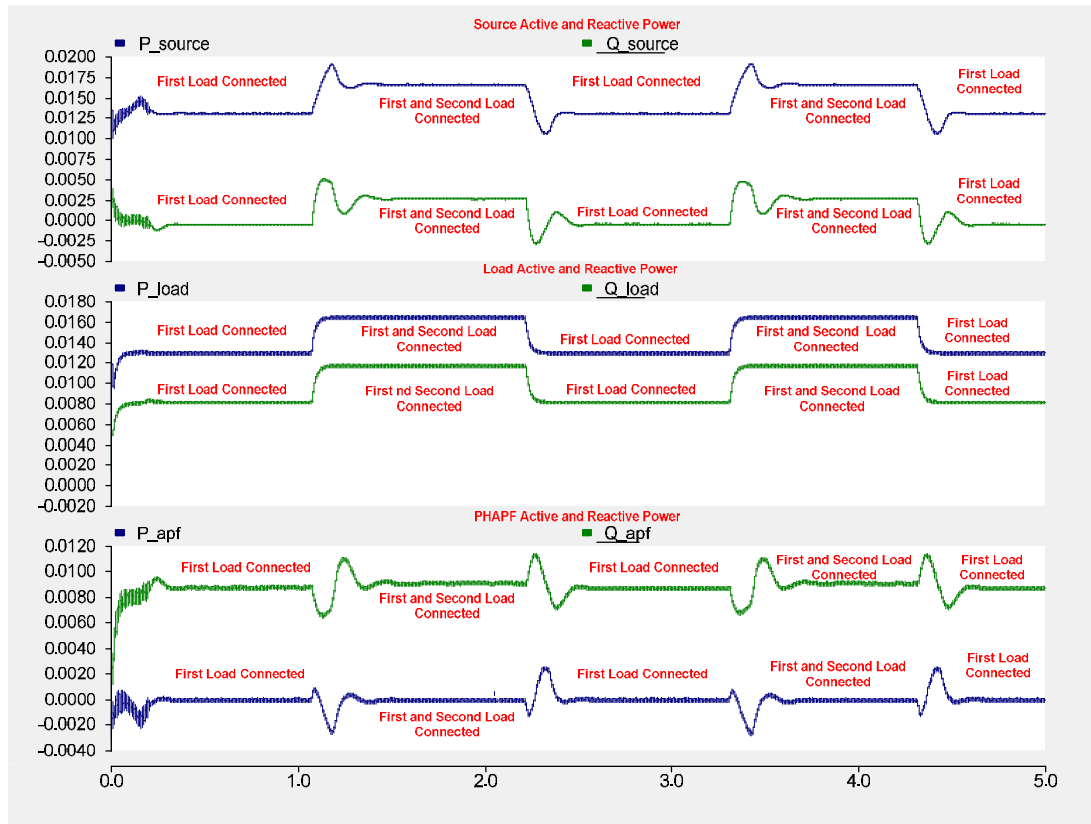


Figure 4.22. Source Active and Reactive power, Load Active and Reactive Power

The total harmonic distortion (THD) is reduced from 27.5% to 4.28% when first load is connected.

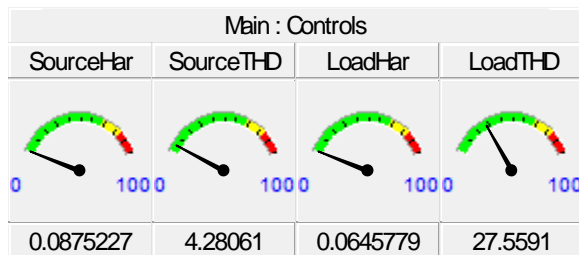


Figure 4.23. Simulation Results (First Load Connected)

The total harmonic distortion (THD) is reduced from 20.8% to 3.25% when the first and the second loads are connected.

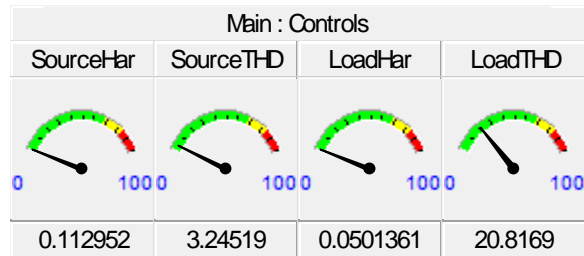


Figure 4.24. Simulation Results (First and Second Loads Connected)

Case-6: Both Harmonic and Reactive Power Compensation with Dynamic DC Link For Multilevel-PHAPF: With the simulation of this case, it is clearly shown that the reactive power compensation capability is added to the Multilevel-PHAPF by using the APF part and also the dynamic dc link. In this case, the capacity of the passive filter is nearly 205 kVAR. When the first load is connected, the load capacity is nearly 220 kVAR. The simulation results show that the APF part of Multilevel-PHAPF compensates nearly 15 kVAR reactive power with the adjusted DC link voltage which is nearly 1 kV. When the first and the second loads are connected, the load capacity is nearly 380 kVAR. The simulation results show that the APF part of Multilevel-PHAPF compensates nearly 20 kVAR reactive power with the adjusted DC link voltage which is nearly 1.5 kV.

The simulation parameters of the system are given in Table-4.4 respectively.

The startup procedure, the extraction of harmonic content are the same as the previous case. For the reactive power compensation, the fundamental reactive compensation current is calculated for the three phase that is described previous section. Then this current is multiplied by K_c which adjust the reactive power amount. Then this multiplication is added to the firing signal.

The DC link voltage is adjusted itself by changing the load capacity. The filtering performance of the system and the DC link voltage are shown in Figure 4.21 and Figure 4.22.

Table 4.6. Simulation Parameters for Case-6

Line Voltage	6300 V
Line frequency	50 Hz
Supply inductance (L_s)	0.001 H
Rectifier inductance (L_l)	0.6 mH
Filter Capacitor (C_F)	16 μ F
Filter Inductance (L_F)	0.025 H
Tuned freq. of series filter (f_{tuned})	250 Hz
DC link capacitors (C_{DC1} , C_{DC2})	10000 μ F
Load Resistances(R_{load1})	100 Ω
Load Inductances(L_{load1})	0.6 H
Load Inductances(L_{ac1})	13 mH
Switching frequency ($f_{\text{switching}}$)	10 kHz
Simulation Step Time	40 μ s
DC Link Gain (K)	1
Harmonic Voltage Reference gain K_1	1500
Reactive Power Compensation gain K_2	50

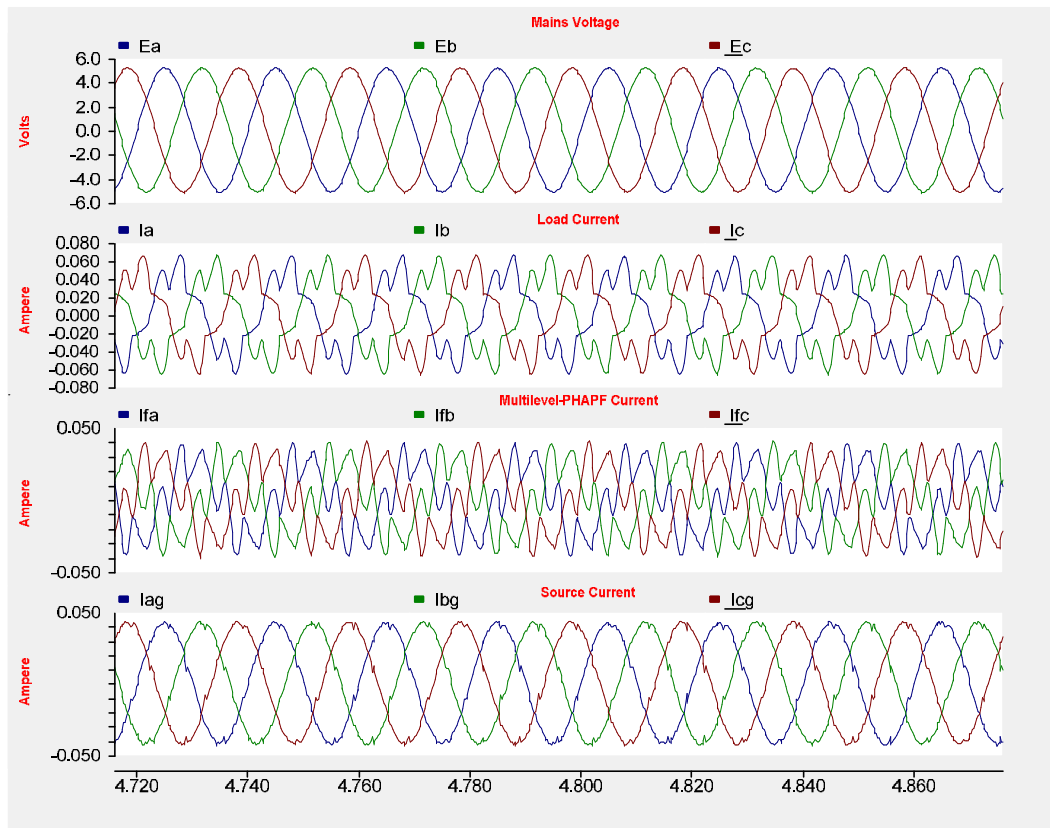


Figure 4.25. Multilevel- PHAPF Operates

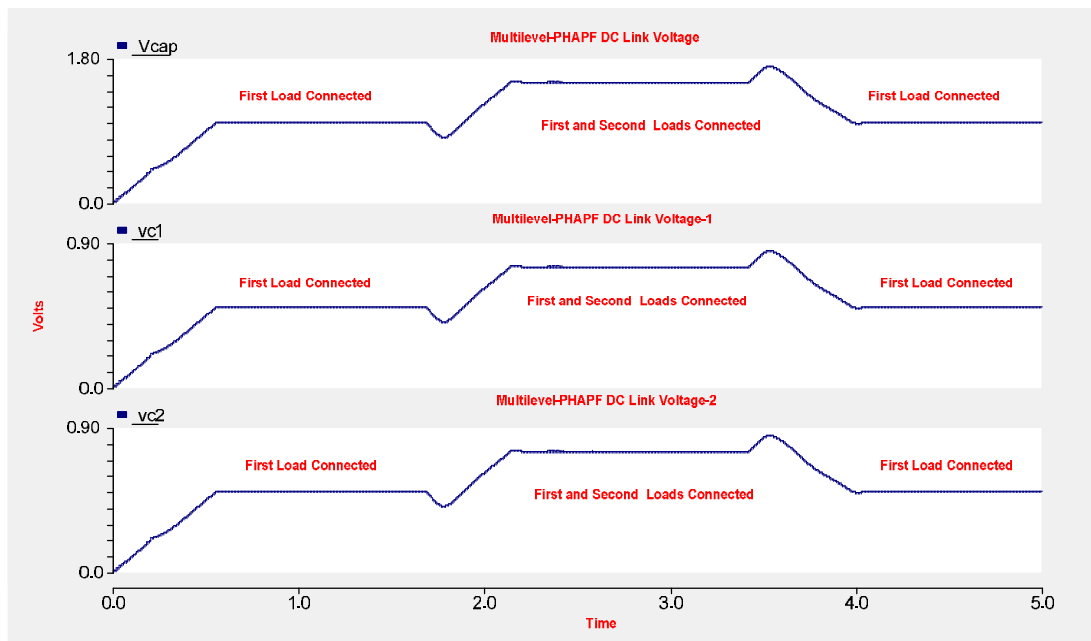


Figure 4.26. DC Link Voltage of HAPF

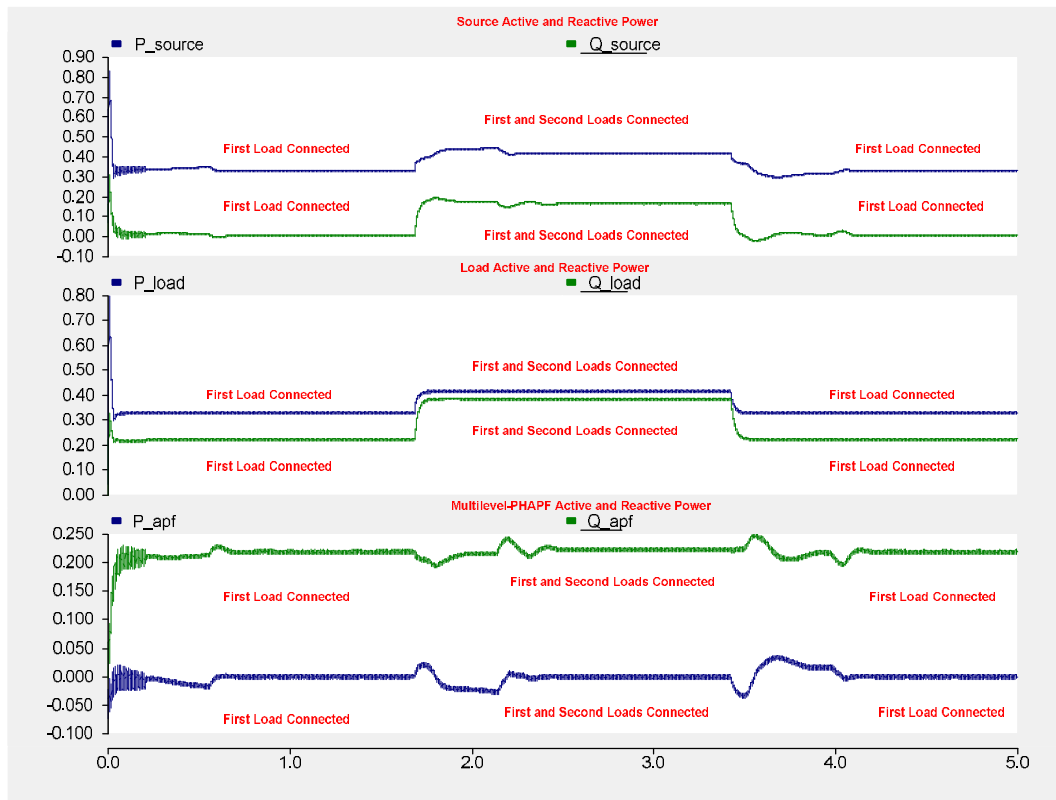


Figure 4.27. Source Active and Reactive power, Load Active and Reactive Power

The total harmonic distortion (THD) is reduced from 28.4% to 3.88% when the first is connected.

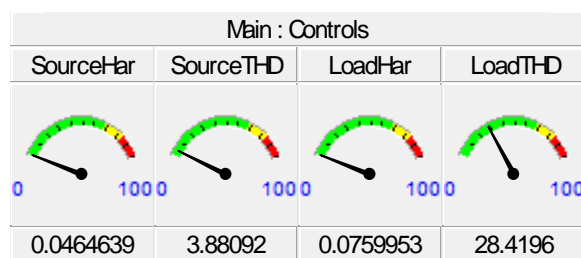


Figure 4.28. Simulation Results (First Load Connected)

The total harmonic distortion (THD) is reduced from 20% to 1.63% when the first and the second loads are connected.

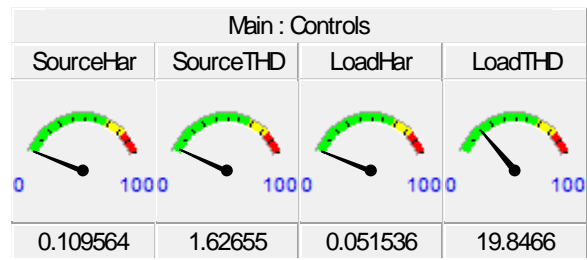


Figure 4.29. Simulation Results (First and Second Load Connected)

5. CONCLUSIONS

This thesis has presented the development of a new controllers of the multilevel parallel hybrid active power filter. Firstly, the previous research works and related literatures are reviewed to give a better understanding of the related research area. This is followed by the theoretical analysis and the design of the proposed HAPF. The detailed description of the proposed HAPF is provided to offer an overview of the operation principle and its overall control system. The emphasis is given to the design of HAPF and the proposed controller using the dq theorem. The results obtained from the simulation by the help of that different cases are compared, analyzed and verified with the theoretical results. The analyzed results conclude that the proposed HAPF improves the harmonic filtering and the reactive power compensation performance.

This research work has led to these important contributions:

- During this work, the performance of the parallel hybrid active power filter is analyzed using the proposed technique for minimizing harmonics, compensation of the reactive power and improving power factor in the power system.
- The dq theory is used to generate the reference current form the distorted load current.
- The dq-abc transformation is used to generate dc link control signals to convert three phase signals.
- Also PI controller is used to maintain the PWM VSI DC side capacitor nearly constant.
- Also the dq theory is used to calculate the instantaneous reactive power of loads. The proposed controller is used to generate reactive power against to this power.
- Also the proposed DC link controller is adaptive and when load is changed, the DC link value is also changed. So the controller has a dynamic property.

- The THD value of the source current after the compensation is less than 5%, the harmonic limit imposed by IEEE-519 & IEC-6000-3 standard.
- With using the multilevel topology, it has shown that the controller can be used for medium voltage levels. In addition, the disadvantages of using the transformer is removed with this topology.

Suggestion and Future Works:

- Experimental investigations can be done on the multilevel parallel hybrid active power filter by developing a prototype model in the laboratory to verify the simulation results for both conventional and digital controllers.
- The controllers can be improved different multilevel topologies.
- For harmonic compensation, different controllers can be applied.

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BIOGRAPHY

Tuğçe DEMİRDELEN was born in Adana, Turkey in 1988. She received her B.S. degree in Electrical and Electronics Engineering Department from Çukurova University in 2011. After completion his B.S. education, she started MSc education in Electrical and Electronics Engineering Department in Çukurova University. She has been working as a Research Assistant in Electrical and Electronics Engineering Department of the ÇukurovaUniversity since 2011. Her research areas are Power Quality, Power Electronics and Energy Efficiency.

APPENDIX

Publication Arose Form This Thesis Work

1.International Conference Papers:

- DEMİRDELEN T., İNCİ M., BAYINDIR K. Ç., TÜMAY M., 2013. Review of Hybrid Active Power Filter Topologies and Controllers, 4th International Conference on Power Engineering, Energy and Electrical Drives
- TAN A., DEMİRDELEN T., İNCİ M., BAYINDIR K. Ç., TÜMAY M., 2013. Analysis of Power Quality Problems of Coreless Induction Melting Furnace with Exact Simulation Model Based on Field Measurements, 4th International Conference on Power Engineering, Energy and Electrical Drives

2.National Conference Papers:

- DEMİRDELEN T., TAN A., İNCİ M., KÖROĞLU T., BÜYÜK M., TERCİYANLI A., BAYINDIR K. Ç., TÜMAY M., 2013. Şebekeye Bağlı Sistemler için Üç Faz ve Tek Faz PLL' lerin Performans Değerlendirmesi, V. Enerji Verimliliği ve Kalitesi Sempozyumu