

University of Bahrain

College of Engineering



**Department of Electrical
&Electronic Engineering**

**Investigation and Mitigation of Harmonics in
Industrial Power Network of Aluminum Smelters:
An Adaptive Approach**

**A Thesis Submitted in Partial Fulfillment of the Requirements for the
Degree of master's in electrical and Electronic Engineering**

Prepared by

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November 2017

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The Student Mahmood Mohsen Taher, student ID 20052107, has defended the thesis by which he partially fulfilled the requirement for the degree of Master of Science entitled “Investigation and Mitigation of Harmonics in Industrial Power Network of Aluminum Smelters: An Adaptive Approach” on 01/03/2018.

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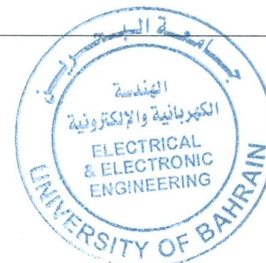
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ABSTRACT

The Aluminum Smelter is basically a series connected electrolytic cells (Pots) supplied by direct current electrical equipment known as Rectifiers. The Rectifier is a combination of rectifier coupled to a transformer and it is used in Aluminum smelters to supply the pot line with direct current. Aluminum Bahrain (ALBA) consumes more than 1.6GW DC power to feed their five pot lines. The conversion from alternating current to direct current unfortunately creates harmonics and causes a power quality issues especially when large amount of power being converted. ALBA and other aluminum smelter nowadays are relying on shunt passive harmonic filter for reactive power compensation and to reduce the harmful effect of harmonics on the AC power network.

In this thesis, ALBA power network with their large rectification systems has been simulated using MATLAB/Simulink to evaluate the harmonic distortions based on different practical operating scenarios. A new pot line Rectifier scheme has been proposed in order to reduce the distortion at Rectifier terminal. In addition, a better harmonic attenuation capability at point of common coupling (PCC) has been found by using parallel delta connected (PDC) tertiary winding between two adjacent Rectifiers. The proposed scheme is modeled and simulated using MATLAB/Simulink and its performance is compared with that of conventional schemes. Finally, a shunt active power filter (SAPF) for large scale Rectifier is introduced. The SAPF is a good solution for harmonics as it is self-adaptive and does not involve any risk of resonant with the power network impedance. The topology and the control technique suits adequately the pot line load behavior.

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Abbreviations

The abbreviation used in this thesis are listed below

A	Ampere
AC	Alternating Current
AESO	Alberta Electric System Operator
AF	Active Filter
ALBA	Aluminum Bahrain
DC	Direct Current
DFT	Discrete Fourier Transform
f	Frequency
HVDC	High Voltage Direct Current
I	Current
I_m	Magnetization Branch Current
IEEE	Institute of Electrical and Electronics Engineers
L	Inductance
MATLAB	Matrix Laboratory
OLTC	On Load Tap Changer
PCC	Point of Common Coupling
PDC	Parallel Delta Connected
PHF	Passive Harmonic Filters
PL	Pot Line
PLC	Programmable Logic Controller

P_{oc}	Open Circuit Test Real Power
PSCAD	Power System Computer Aided Design
Q	Quality Factor
Q_c	Reactive Power
Q_{oc}	Open Circuit Test Reactive Power
R	Resistance
Rectifier	Combination of Rectifier and Transformer
RMS	Root Mean Square
SAPF	Shunt Active Power Filter
SH	Switch House
TDD	Total Demand Distortion
THD	Total Harmonic Distortion
V	Voltage
VA	Apparent Power
VA_{sc}	Short Circuit Apparent Power
Var	Volt Ampere Reactive
V_{oc}	Open Circuit Test Voltage
W	Watt
X	Reactance
X_c	Capacitive Reactance
Z	Impedance

Chapter 1

Introduction

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Chapter 1

Introduction

1.1. Introduction

As per International Aluminium Institute web site, there are more than 200 Aluminum Smelter in the world with total production of more than 58,000 thousand metric tons of Aluminum. The GCC countries represent around 8% of the total world production and Aluminum Bahrain (ALBA) represent around 18% of the total GCC production. ALBA is considered as one of the largest Aluminum Smelter in the world with total production 960,000 metric tons. ALBA has launched potline 6 (PL6) expansion project that will boost the capacity to reach 1,500,000 metric tons per annum bringing ALBA to becomes the biggest single site Aluminum Smelter in the world. The expansion consisting of many projects including a new 1792 MW capacity power plant that will increase the total power plants capacity to more than 3.2GW and new PL6 Rectifiers with total consumption of 900MW DC power for the electrolysis process in PL6.

The Aluminum Smelter is basically a series connected electrolytic cells (Pots) supplied by a direct current electrical equipment known as Rectifier. The Rectifier is combination of rectifier coupled to a transformer which is used in Aluminum Smelters to supply the potline with direct current. The conversion from alternating current to direct current unfortunately creates harmonics due to large capacity Rectifier operation which is classified as a nonlinear load. Nowadays Aluminum Smelter consumption can be more than 2 GW DC power, which means that a large Rectifier is required to provide such power. The large amount

of power being converted from AC to DC creates power quality problem by producing harmonics at the point of common coupling (PCC) in the Smelter electrical network that feeds the Smelter load and other important loads.

The IEEE working group (1992) established a recommended practice and requirements for harmonics limits, control in a power system and large DC power consumers such as Aluminum Smelter tries to satisfy such requirements. In order to deal with harmonics in Aluminum Smelter, multi-pulse method is normally used nowadays. The method basically involve 4 to 6 Rectifiers which are phase shifted in order to achieve 48 to 72 pulse system which effectively reduces the harmonic currents at PCC. However, this scheme is not sufficient to keep the distortions below the recommended standard acceptable limits as discussed by Hemang K. et al., (2015).

Passive harmonic filters (PHF) are mainly used to attenuate harmonics in Aluminum Smelter along with the conventional Rectifiers PL configuration which is connecting the PHF directly to the feeding grid as in Yokoyama et al., (2006); P. Pollock and C. Duffey, (1998); X. Liang, Y. Luy (2011). There is another scheme in which the harmonic filter is connected to the regulating transformer tertiary winding of each Rectifier unit which is considered as the most economical method to keep the distortion level as low as possible as discussed by M. Wiestner (2010) and A. Collier et al, (2012).

In this thesis, ALBA power network will be modeled to study the distortion level at the main substations. In addition, a propose scheme is proposed and compared with ALBA PL6 in terms of harmonic attenuation capability, operational constrains, cost and space requirements. Furthermore, an adaptive shunt active power filter (SAPF) is used instead

of PHF to keep pace of development and trend in Aluminum Smelter harmonic attenuation technology (Siebert, 2002). All parameters used in the modeling has to be extracted from ALBA power network and other related documents. ALBA granted the access to their power network data for this purpose only. The access approval emails are in appendix A. All the simulation works are performed in MATLAB/SIMULINK environment beside the theoretical analysis.

1.2. Research Problem

It is commonly known that the Rectiformers suppliers to Aluminum Smelters that multi-pulse rectifier with phase shift transformers are effective method in reducing harmonics. There are many conditions that must be fulfilled in order to utilize the phase shifting technique to reduce harmonic contents, these conditions can be summarized as follow:

- Phase shift transformer must have exact theoretical angle and the phase differences between them must be the same.
- Converters must be having the same load to ensure the identical DC current.
- The voltage of the AC power system must be symmetrical.
- All Rectiformers must be in service
- All Rectiformers impedances must be same (Operating at the same OLTC tap).
- Source impedance must remain the same.

In practice, the above conditions are never fulfilled in real Aluminum Smelter power system network which cause higher harmonic distortions in the power network.

Hemang K. et al., (2015) project in Dubai Aluminum Smelter involve installation of passive filter which improved the voltage THD. It has been found that transformer phase shifting alone may not be sufficient in view of expansions, complexity and other practical considerations of the Smelters. A study in Boyne Smelter (Australia's largest Aluminum Smelter) done by Gersch (2000) stated that due to non-ideal conditions, unbalances, asymmetry in the system impedances in both supply network and phase shifting transformers, the converter systems produce non-characteristic harmonics. It has been shown that 1% voltage unbalance, which can occur in real practice introduces a significant 3rd harmonic. Noncharacteristic harmonics are also generated due to variation in the system impedance and unbalances in the supply voltage. In ETI Aluminum Smelter (Ermis et al., 2004), the 7th components slightly increase even after the passive filter installation and the paper shows that shunt passive filter with damped resistor will be less effective in suppressing harmonic components produced by the converters at tuning frequency. In (Yokoyama et al., 2006), an investigation on the origin of the harmonic amplification is observed in the fifth order filter of Aluminum reduction plant IV of ALBRAS Smelter by checking the phase angle difference of the rectifier transformers and through the current records and measurements at several points. The high current distortion causes an overheating and damage the tie beam of the reactor which cause a great amount of wasted energy. In (P. Pollock and C. Duffey, 1998), harmonics are amplified by the system resonant due to the present of capacitor banks which are used for power factor correction. The issue was solved by replacing the capacitor banks in the network by tuned harmonic filters which has attenuated the dominant harmonics and shift the undesired parallel resonant to another frequency where characteristic harmonics are not generated. In (R. Fuentes and L.Temicien, 2002), failure of one

transformer got replaced by two transformers in order to ensure the productions and consequently caused an increase in the 5th and 7th harmonic components, which in turn resulted in an overloading of the passive harmonic filter.

Commonly, Aluminum Smelters are equipped with PHF's to attenuate harmonics at certain orders. These PHF must be carefully designed in order to avoid resonances with the source impedance or other equipment in the network. The main reasons for selecting this type of filters is due to economic reasons. SAPF has no resonance issues but still has not been used till now in Aluminum Smelters for the same reason.

Due to expansions, special operating conditions, changes in the network and other problems within the plant, the PHF filter can cause problems. SAPF filters should be considered as a near future to improve the power quality of the supply network as they have many features that overcome PHF weakness. Also, designers should think about different or new Rectifier PL topologies that can make the distortion level minimum.

1.3. Research Questions

The research questions are listed as follows:

1. What are the consequences of running Aluminum Smelter without harmonic filter?
2. What will be the consequences of harmonic generated into the utility main supply in case of change in the power network topology?
3. What will be the consequences of harmonic generated into the utility main supply in case of plant expansions?
4. Are there any other solutions to minimize the main utility supply pollution?

5. What is the configuration of the active filter that can be used in Aluminum Smelter?
6. What are the requirements for designing and implementing the active harmonic filter to suit the Aluminum Smelter network?

1.4. Research Objectives

The main three objectives of this thesis are:

- 1- Study ALBA network harmonic emissions
- 2- Propose a new PL Rectifier scheme and compare it with the new scheme for ALBA PL6.
- 3- Replace the PHF with Rectifier PL with SAPF and study its performance.

The first objective involves modeling ALBA power network with key equipment such as source supplies, main substations, Rectifier PL's and power transformers. Study the harmonic distortion levels with different network configurations and operating conditions. Currently, ALBA network is equipped with 100Mvar PHF tuned at 5th and 11th harmonic order installed in switch house 5 (SH5). In 2005, a new power station with PL5 has been commissioned with no harmonic or reactive power compensation equipment installed. In the same project, PL3 supply is shifted from SH3 to SH6 to ensure PL3 supply reliability. The PHF in SH5 were installed in 1990s which raised the question whether or not the SH5 PHF is adequate.

The second objective is to propose a new PL Rectifiers scheme and compare it with ALBA PL6 in terms of harmonic attenuation capability, operational constraints, cost and space requirements. ALBA PL6 Rectifiers design, which has been approved by the company, is based

on connecting the PHF to the regulating transformer tertiary winding of each unit as shown in Figure 1.1.

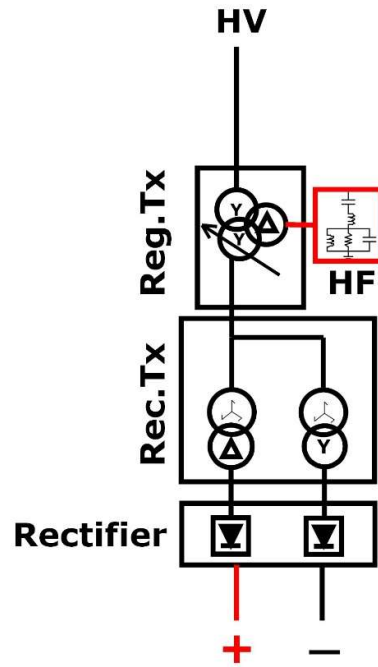


Figure 1.1, Rectifier with PHF connected to the regulating transformer tertiary winding

The third objective is to model SAPF to replace the traditional PHF and incorporate it in PL Rectifiers scheme. The SAPF design is based on Discrete Fourier Transform technique. The results of the simulation study will be compared with ALBA PL6 and the new proposed PL Rectifier scheme.

1.5. Research Significance

Harmonics are undesired phenomena occurring due to existence of non-linear loads. The use of such types of loads is ever increasing, so the power quality concerns is a very important matter nowadays. Harmonics must be eliminated from the system as it has adverse effects on electrical apparatus. Many problems caused by harmonics when it is penetrated into the electrical network is extensively discussed in (IEEE Std., 1992), (S.V.Kulkarni, S.A.Khaparde, 2004), (C. Buddingh, 2017) and (Sykulski et al., 2000).

Smelters are always in continuous improvements for enhancing the efficiency and increasing the production. For that reason, many changes in the power network can occur, such as adding more Rectiformers units to an existing PL or adding extra generators. These changes may lead to a problem to the existing PHF as the power network parameters have been changed from the condition at which the PHF was designed for.

Human being is always looking for improvement by making the technologies more advance, efficient and reliable. The harmonics in industrial power network such as Aluminum Smelter has been always treated by PHF regardless to its flaws because of its low cost compared to other methods. Modern active filters are superior in filtering performance, smaller in physical size, and more flexible in application as compared to PHF, which uses capacitors, inductors and/or resistors (AKAGI, 2006). Based on the principle of keeping pace with the development as discussed in (Siebert, 2002) and (AKAGI, 2006), a SAPF based on DFT algorithm is used to replace the traditional PHF. The SAPF shall react adaptively to changes in the power network of the Aluminum Smelter and react adaptively to those changes and hence force the distortions levels to be

minimum or below the recommended limits. A new PL scheme is also proposed in this thesis which has better performance in terms of harmonic attenuation as compared to the other conventional PL schemes.

1.6. Thesis Outline

This thesis is organized as follows:

Chapter 1: Provides an introduction to the thesis, research problem, research objectives and significant in which collectively represent the literature review of this thesis.

Chapter 2: A comparison between two well-known reputed computer simulation softwares to determine the most suitable software for this thesis. A test system is modeled and simulated using both softwares and their simulation results has been evaluated. The IEEE 519 models also has been verified using the selected software. An introduction to the practical modeling were discussed by introducing the main equipment models.

Chapter 3: An explanation of Rectifier unit with practical simulation was performed. A simulation is performed to the entire power network of ALBA including an assessment to the harmonic distortion on different practical operating scenarios.

Chapter 4: A new potline scheme is proposed in this chapter. The structure of the proposed model is discussed in details. A comparison with the conventional scheme and PHF connected to tertiary winding schemes is carried out in terms of harmonic attenuation capability, operational constraints, cost/space requirements.

Chapter 5: In this chapter, a SAPF for potline Rectifiers is proposed. A DFT control technique was described in detailed and applied on a test

model. The topology of the control technique was found suitable for Aluminum potline load behavior. The performance of the PL with SAPF is compared with schemes discussed in chapter 4.

Chapter 6: The overall conclusion summarizing the work done in this thesis and the future work are presented in this chapter

Chapter 2

Selection of Simulation Software and Model Validation

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Chapter 2

Selection of Simulation Software and Model Validation

2.1. Introduction

The research work carried out in this thesis is based on computer simulations using a commercial software. In order to ensure correct selection of the simulation software, two well-known reputed computer simulation softwares have been tested. Both softwares are based on visual block diagram environment for simulation. A 12 pulse Rectifier has been modeled in Power System Computer Aided Design (PSCAD) and Matrix Laboratory Simulink (MATLAB Simulink). In addition, validation of the 12 pulse Rectifier and 72 pulse Rectifier PL based on the IEEE 519 are also discussed. Practical modeling of the utility source and transformer has been furnished.

2.2. Modeling of 12 pulse Rectifier using PSCAD and MATLAB Simulink

In order to evaluate the PSCAD with MATLAB Simulink results, the electrical parameters in Table 2.1 were used in the modeling in both softwares. The focus of the comparison will be limited to harmonic contents calculations at PCC and the output voltage waveform obtained by both softwares.

The 12 pulse Rectifier model in PSCAD and MATLAB Simulink are shown in Figure 2.1 and Figure 2.2, respectively. Both models consist of three windings transformers with star and delta secondary connections to create a 30° phase shift. The 12 pulse output voltage waveforms from the PSCAD and Simulink are respectively shown in Figure 2.3 and 2.4. The result of the input current waveform with harmonic spectrum from the PSCAD and Simulink are shown in Figure 2.5 and Figure 2.6, respectively.

Table 2.1

Electrical Parameters of the 12 Pulse Rectifier

Parameter	Unit	Value
Input voltage	KV	11.5
Frequency	Hz	50
Three winding Transformer	MVA	50
Transformer Primary Voltage	KV	11.5
Transformer Secondary Voltage (DELTA)	KV	1
Transformer Secondary Voltage (STAR)	KV	1
Load resistance	Ohm	1

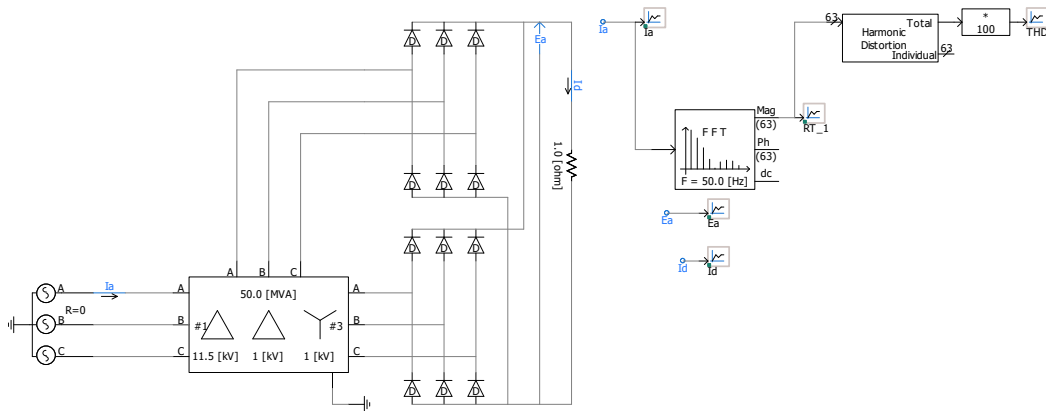


Figure 2.1, 12 pulse Rectifier model in PSCAD

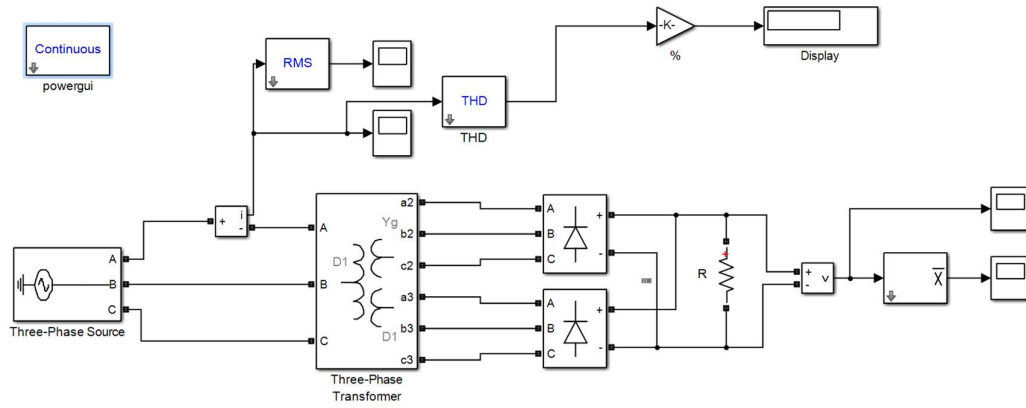


Figure 2.2, 12 pulse Rectifier model in MATABL Simulink

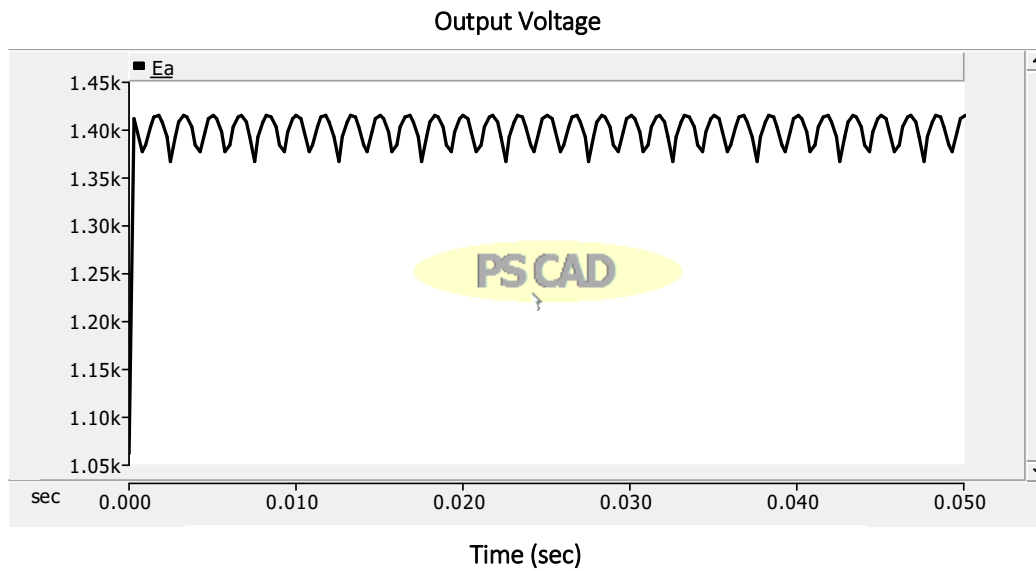


Figure 2.3, Output voltage waveform of PSCAD model

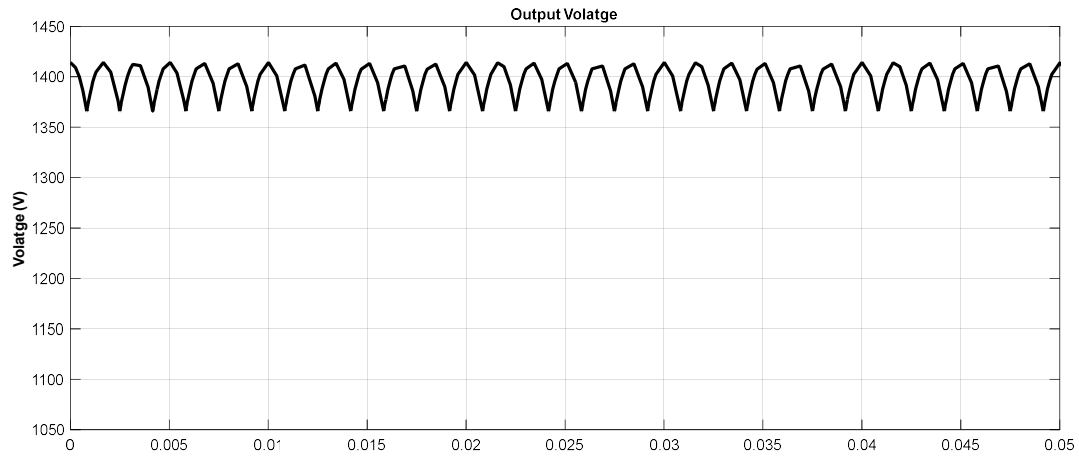


Figure 2.4, Output voltage waveform of MATLAB Simulink model

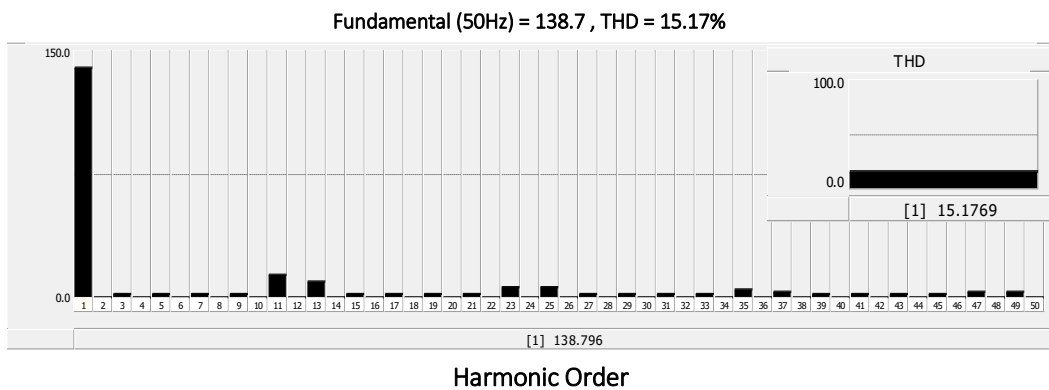
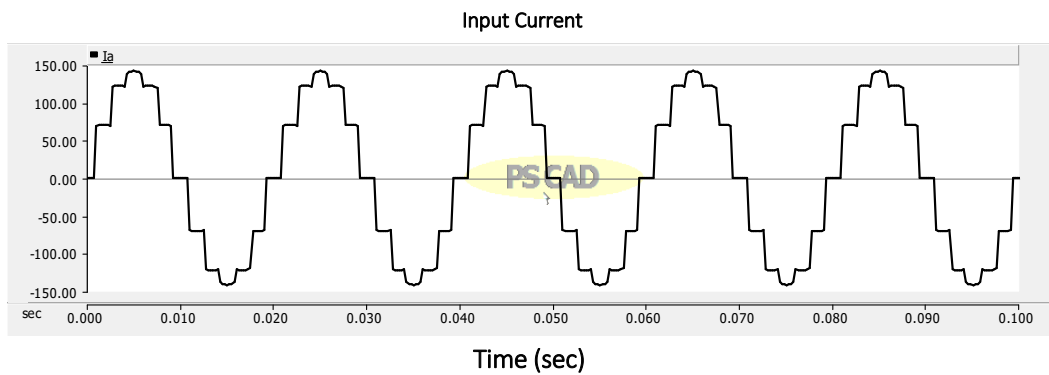


Figure 2.5, Input current waveform of PSCAD model

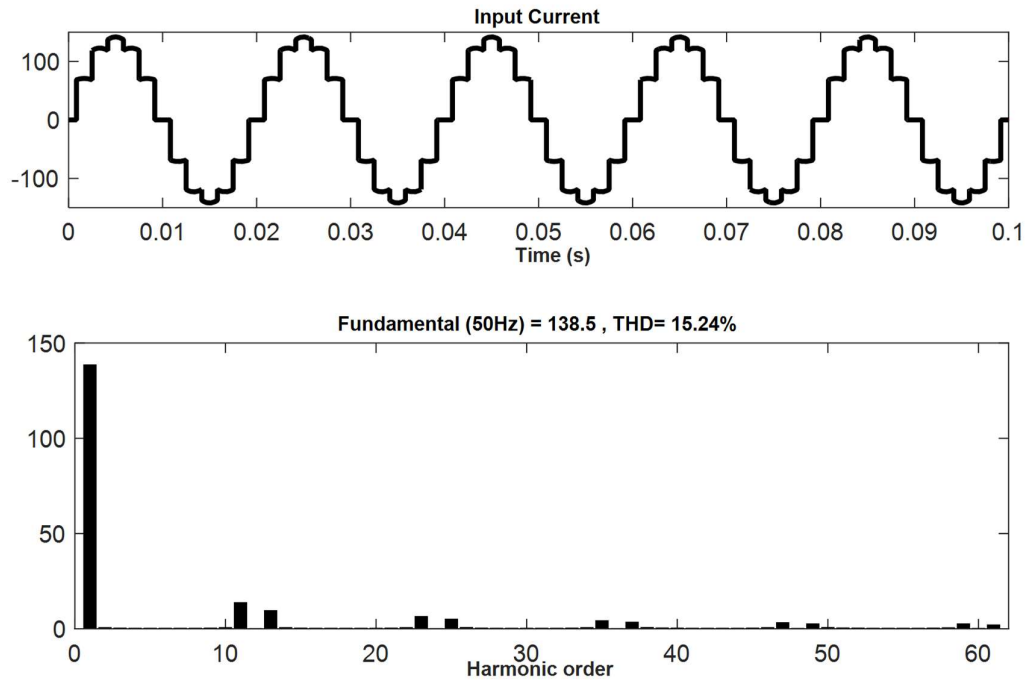


Figure 2.6, Input current waveform of MATLAB Simulink model

At steady state, both softwares produced almost same outputs with negligible differences. PSCAD has calculated 15.179% THD with fundamental current equal to 138.7A while MATABL Simulink has calculated 15.24% THD with fundamental current equal to 138.5A. Figure 2.7 shows characteristic harmonics of the input current of both models, plotted in same graph.

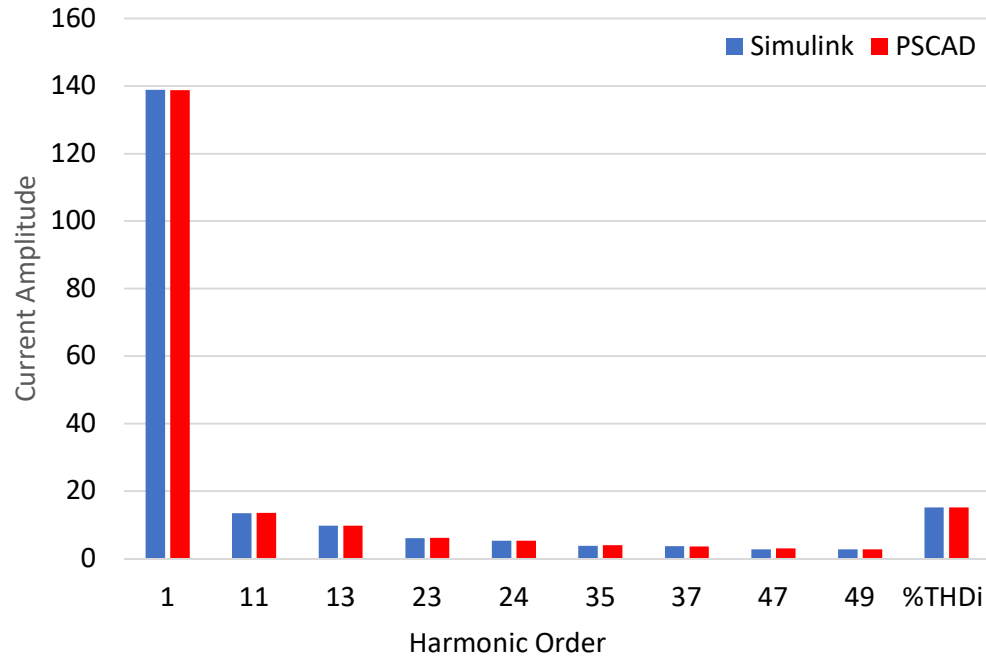


Figure 2.7, Comparison of the input current harmonic components of both models

Since both software are giving same results, it has been decided to use MATLAB Simulink in this thesis due to its flexibility and simplicity. It also allows the user to easily implement the control algorithms and link workspace with Simulink. The results presentation from Simulink are controllable and editable as well as many toolboxes are available for different technical domains.

2.3. IEEE 519 Model of 12 Pulse Unit

In order to ensure valid modeling, Simulink is used to simulate a 12 pulse unit based on the IEEE 519 model to evaluate the steady state current harmonic order values at the point of common coupling. Figure 2.8 shows the IEEE 519 model for 12 pulse unit. In this model, ideal components were used. The electrical data for this model are as in Table 2.2

Table 2.2

Electrical Data of the IEEE 519 Model of 12 Pulse Unit

Parameter	Unit	Value
Input voltage	KV	11.5
Frequency	Hz	50
Three winding Transformer	MVA	50
Transformer Primary Voltage	KV	11.5
Transformer Secondary Voltage (DELTA)	KV	1
Transformer Secondary Voltage (STAR)	KV	1
Load Current	KA	10

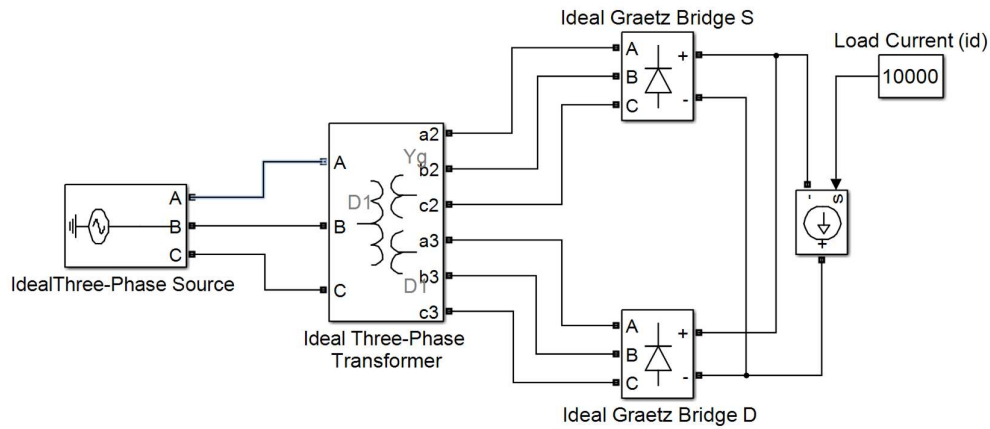


Figure 2.8, IEEE 519 model for 12 pulse unit

The output voltage waveform is shown in Figure 2.9. The average dc voltage obtained from the simulation is 1398 V.

The same can be calculated as described by (Mohan, 1995):

$$V_{dc} = \frac{1}{T} \int_0^T V_m \sin \omega t dt \quad (2.1)$$

$$V_{dc} = \frac{\sqrt{2}V_L}{2\pi/12} \int_{-15^\circ}^{15^\circ} \cos \omega t d\omega t = 1.398V_L = 1398 \text{ V}$$

Where V_L is the supply rms voltage.

The RMS line current output of the transformer secondarys can be calculated by inspection:

$$I_{rms(\Delta,Y)} = \sqrt{\frac{2}{6}} \times I_{dc} = 5773.5 \text{ A} \quad (2.2)$$

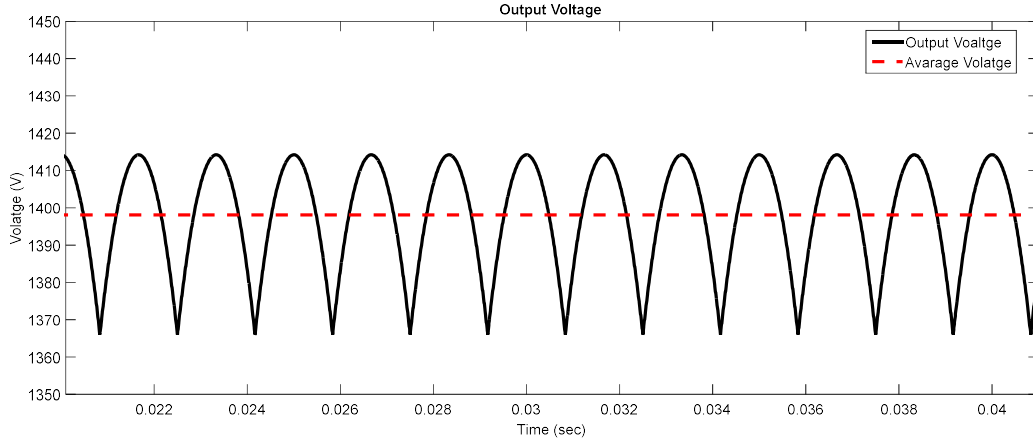


Figure 2.9, Output voltage and average output voltage of 12 pulse unit

The line current in the transformer primary is calculated as:

$$I_{(primary)} = \frac{2 \times I_{rms(\Delta,Y)}}{\text{Transformer ratio}} = 1004.08 \text{ A} \quad (2.3)$$

This is the peak of the input current as shown in Figure 2.10.

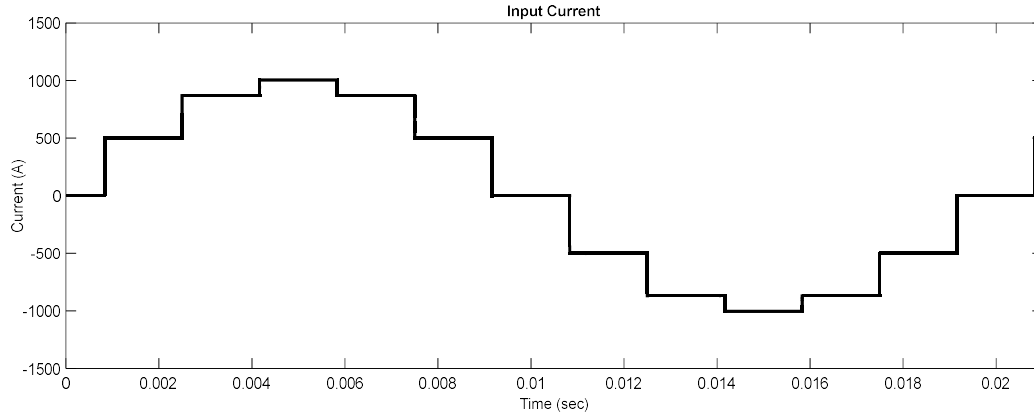


Figure 2.10, Input current waveform of 12 pulse unit

From (2.3), the rms primary input current is:

$$I_{(\text{primary})\text{rms}} = \frac{I_{(\text{primary})}}{\sqrt{2}} = 710 \text{ A} \quad (2.4)$$

The harmonic contents of the input current are in form of

$$h = kp \pm 1 \quad (2.5)$$

Where:

h: is the harmonic order

k: is any positive integer

p: is the pulse number of the rectifier circuit which in this case is 12.

The current harmonic is calculated as

$$I_h = \frac{I_1}{h} \quad (2.6)$$

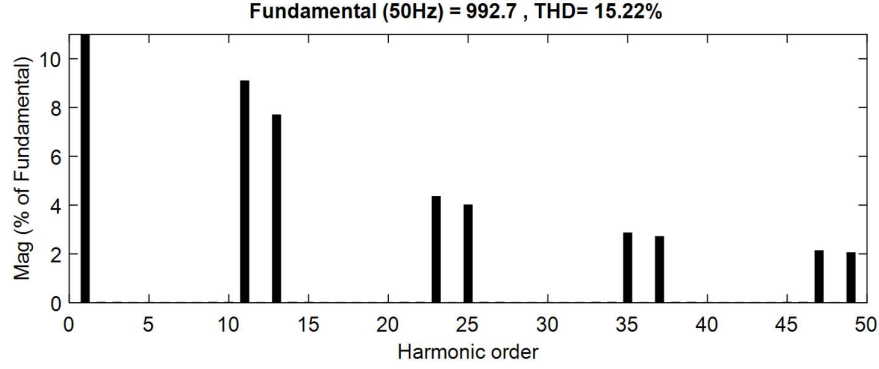


Figure 2.11, Frequency spectrum of the input current of the 12 pulse unit

For example, the rms value of the 11th harmonic is:

$$I_{11} = \frac{I_1}{11} = \frac{992.7/\sqrt{2}}{11} = 63.81 \text{ A} \quad (2.7)$$

Where I_1 was obtained from Figure 2.11.

Consequently, I_{11} represent 9.09% of the fundamental rms current as indicated in Figure 2.11.

2.4. IEEE 519 Model of 72 Pulse System

The typical aluminum smelter pot-line arrangement is shown in Figure 2.12. Normally five or six Rectifiers are connected in parallel in order to supply DC power needed for aluminum production and to eliminate low order harmonics to for the sake of achieving better power quality by using pulse multiplication method. Pulse multiplication can be achieved by using phase shift transformers.

The phase shift in degree can be calculated as in (Marian P et al., 2002):

$$\text{Phase shift}^\circ = \frac{60^\circ}{\text{Number of converters}} = \frac{360^\circ}{\text{Number of pulses}} \quad (2.8)$$

Where, the number of converters is 12 and the corresponding number of pulses is 72 for a 72-pulse system.

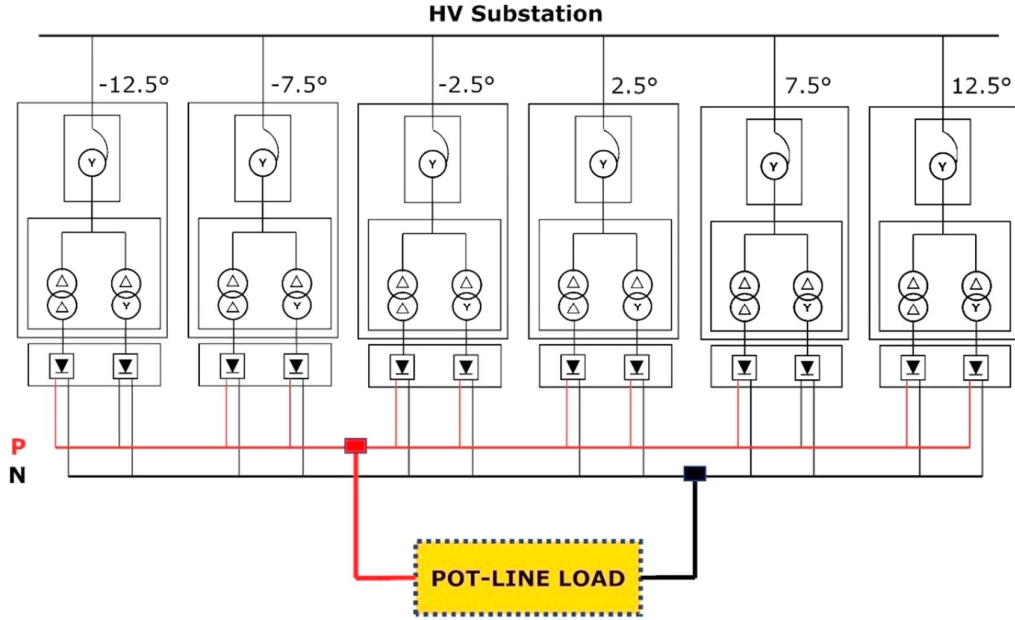


Figure 2.12, Typical arrangement of aluminum smelter PL Rectifiers

The phase-shift is 5° based on an arrangement of $\pm 12.5^\circ$, $\pm 7.5^\circ$ and $\pm 2.5^\circ$. The 5° phase-shift can be achieved by using phase shifting transformer such as zigzag transformer.

The output voltage pulse peak will decrease and the average voltage will increase as shown in Figure 2.13. The average output voltage can be calculated as per equation 2.1:

$$V_{dc} = \frac{1}{T} \int_0^T V_m \sin \omega t \, dt = \frac{\sqrt{2}V_L}{2\pi/72} \int_{-2.5^\circ}^{2.5^\circ} \cos \omega t \, d\omega t = 1.4137V_L$$

$$= 1413.7 \, V$$

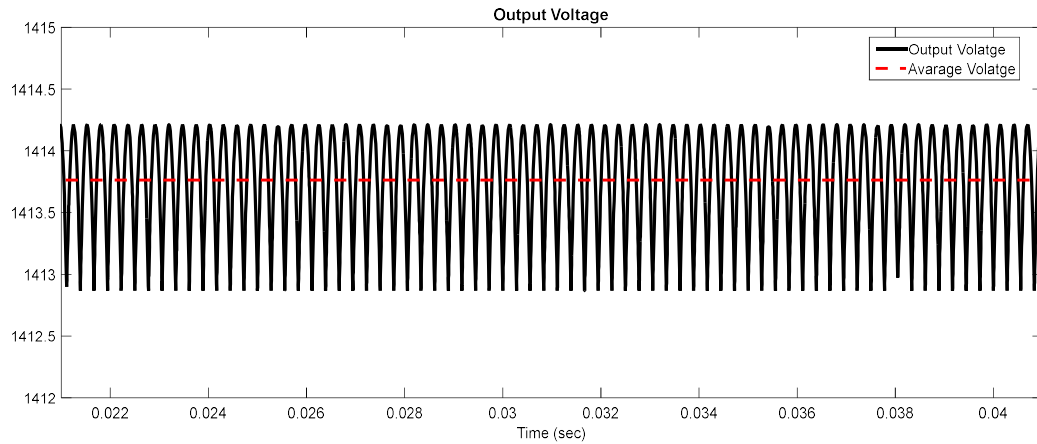


Figure 2.13, Output voltage waveform and average voltage of the 72 pulse system

Figure 2.14 shows the IEEE 519 Simulink model for 72 pulse system. The PL load is 150KA DC. Figure 2.15 shows the output voltage of the 12 pulse unit and the 72 pulse system unit. The ripple voltage is reduced by 97% and the average DC voltage increased by 1.123%.

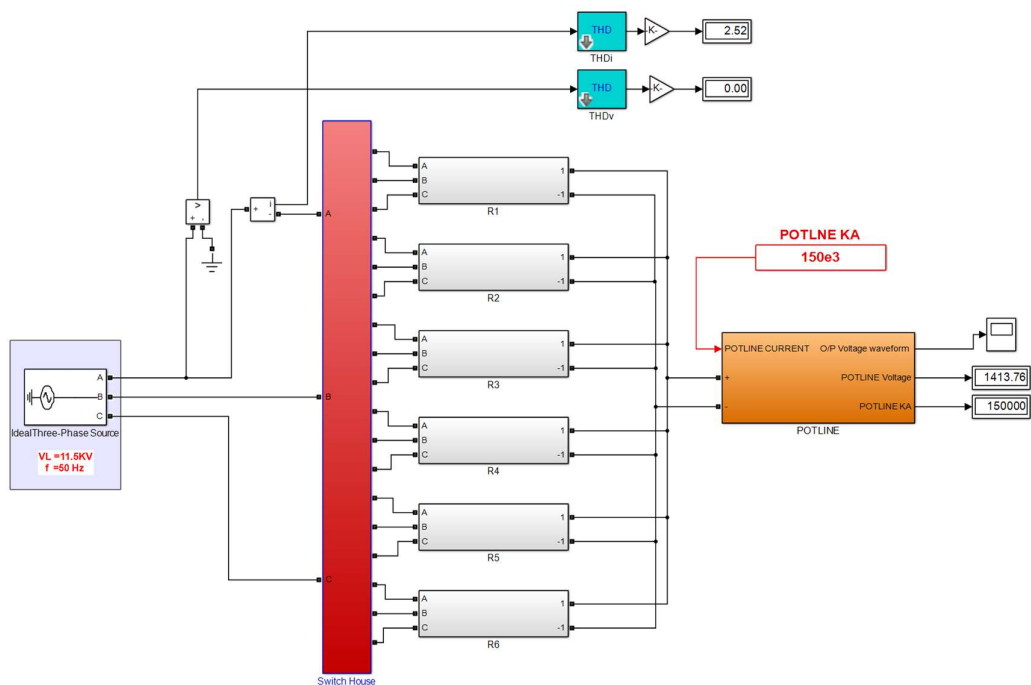


Figure 2.14, IEEE 519 Simulink model for 72 pulse system

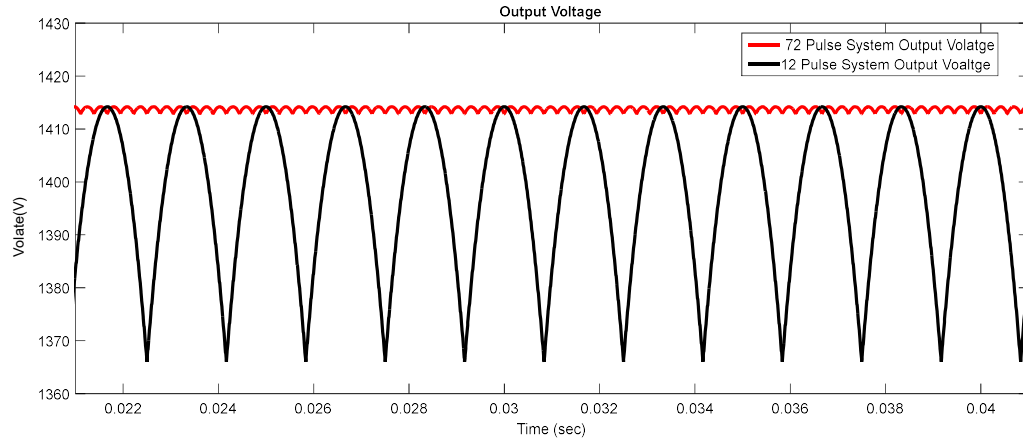


Figure 2.15, Output voltage of 12 pulse unit and 72 pulse system unit

The harmonic orders contained in the input current for the 72-pulse system can be calculated as per equation 2.5, as:

$$h = 72k \pm 1$$

The percentage values of the characteristic harmonics are shown in Table 2.3.

Table 2.3

The Percentage Values of the Characteristic Harmonics
of 72 Pulse System

Harmonic Order	% from fundamental
71	1.408
73	1.369
143	0.699
145	0.686

The theoretical values match with the Simulink model results as shown in Figure 2.16

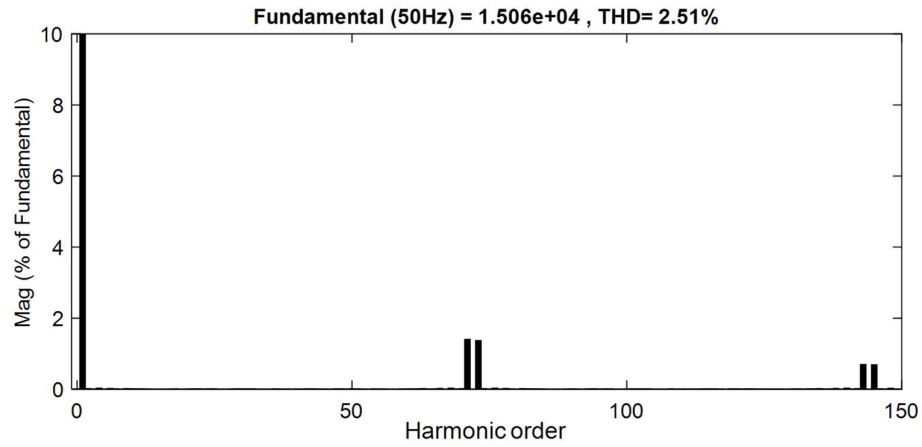


Figure 2.16, Frequency spectrum of input current of 72 pulse unit

The shape of the input current is greatly enhanced due to the phase multiplication method. Figure 2.17 shows the shape of the input current of both the 12 and 72 pulse models running at the same DC load (10KA DC). Figure 2.18 shows the frequency spectrum comparison of both models.

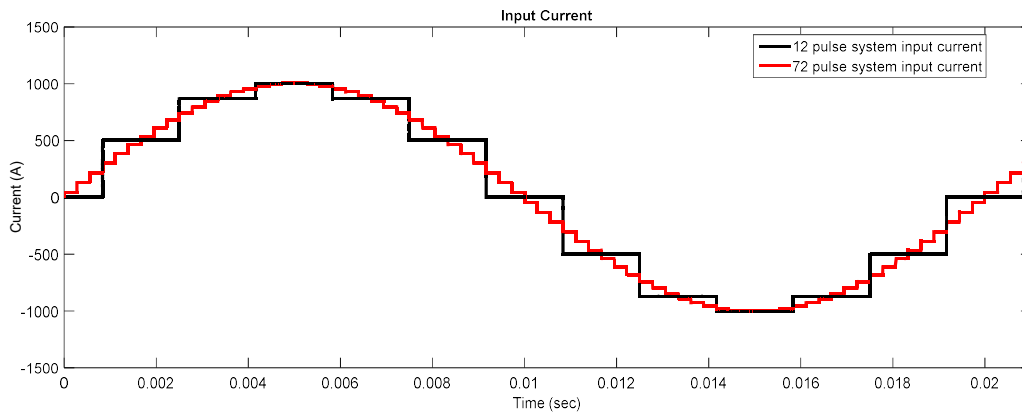


Figure 2.17, 12 pulse and 72 pulse system input current waveform running at same 10KA load

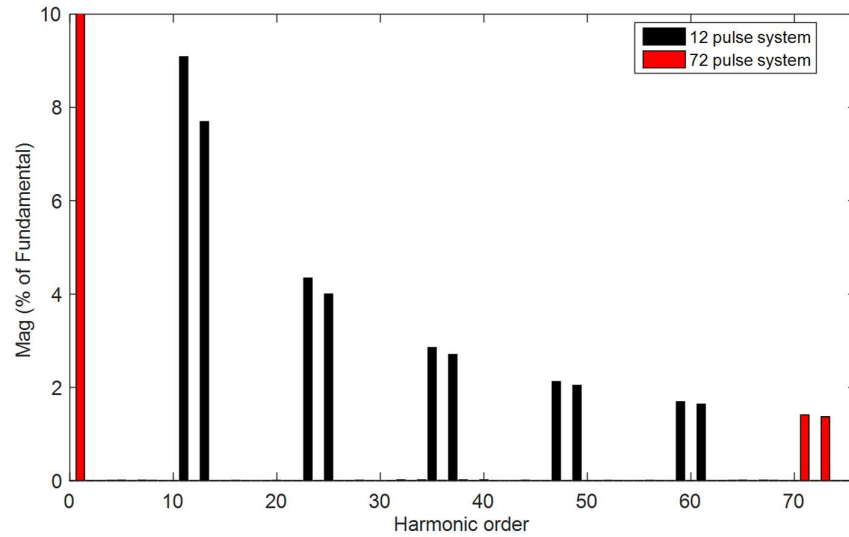


Figure 2.18, Frequency spectrum of the input current for the 12 pulse and 72 pulse running at same 10KA load

When large amount of power required to be converted form AC to DC, 12 pulse rectification unit is mainly used. In order to diminish the harmonic currents at PCC, 4 to 6 units connected in parallel for pulse multiplication. For this reason, aluminum smelter adopting pulse multiplication method would achieve better power quality.

2.5. Practical Modeling

2.5.1. Utility Source Model

Practically, the input source is modeled as a voltage source behind an internal R-L impedance. The R-L impedance can be calculated based on the short circuit level as

$$MVA_{sc} = \sqrt{3} \times V \times I_{sc} \quad (2.9)$$

$$Z = \frac{V^2}{MVA_{sc}} \quad (2.10)$$

$$R = \frac{Z}{\sqrt{1 + \left(\frac{X}{R}\right)^2}} \quad (2.11)$$

$$X = \left(\frac{X}{R}\right) \times R \quad (2.12)$$

$$L = \frac{X}{2\pi f} \quad (2.13)$$

Where

X/R :is the ratio of reactance to resistance (IEEE C37.010, 1979).

MVA_{sc} :is the short circuit power in volt-ampere.

I_{sc} : is the short circuit current in ampere.

2.5.2. Transformer Model

The practical modeling of the Rectifier requires obtaining the data sheets of both the regulating and rectifier transformers. Simulink requires the following parameter to be entered in the transformer model:

- Transformer Rated power
- Primary and secondary winding voltage
- Primary and secondary winding resistances and inductances.
- Magnetization resistance and inductance.

based on the transformer data sheet and the test report, the above parameters can be calculated. In case when some of the parameters can not be obtained from the data sheet or test report, they can be estimated using the standard values. For example, for two winding transformers, the IEEE C37.010 (1979) specified that the X/R ratio of power transformers (Oil forced Oil – Air Forced) range is between 16 and 58 as shown in Figure 2.19. Its low for small rating transformers and high for higher rating transformers.

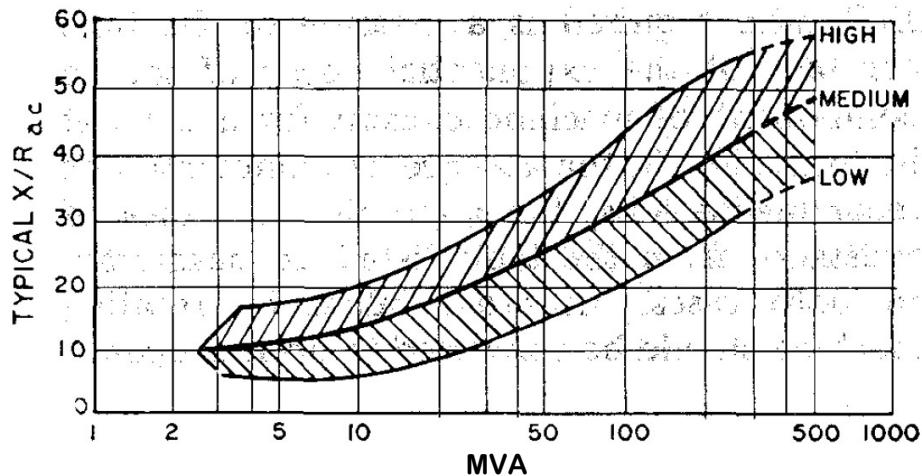


Figure 2.19 IEEE C37.010 typical X/R ratios of power transformer

Alberta Electric System Operator (AESO) conducted a review on 900 transformers and obtained a recommended X/R values (Shaarbafi, 2014). The values given by AESO is higher than that recommended by the IEEE C37.010 because of higher transformer loss evaluations currently used. Both curves are shown in Figure 2.20 for comparison.

For example, the parameters of two windings transformer which are required to calculate the data for Simulink model are given as follows:

- Transformer Rating.
- Primary and secondary voltages.
- Short circuit impedance (%Z).
- X/R ratio.
- Excitation current

These parameters can be calculated by referring to the transformer name plate, test reports, data sheets and as well as by referring to the recommended X/R ratios in case when the X/R ratios are not available.

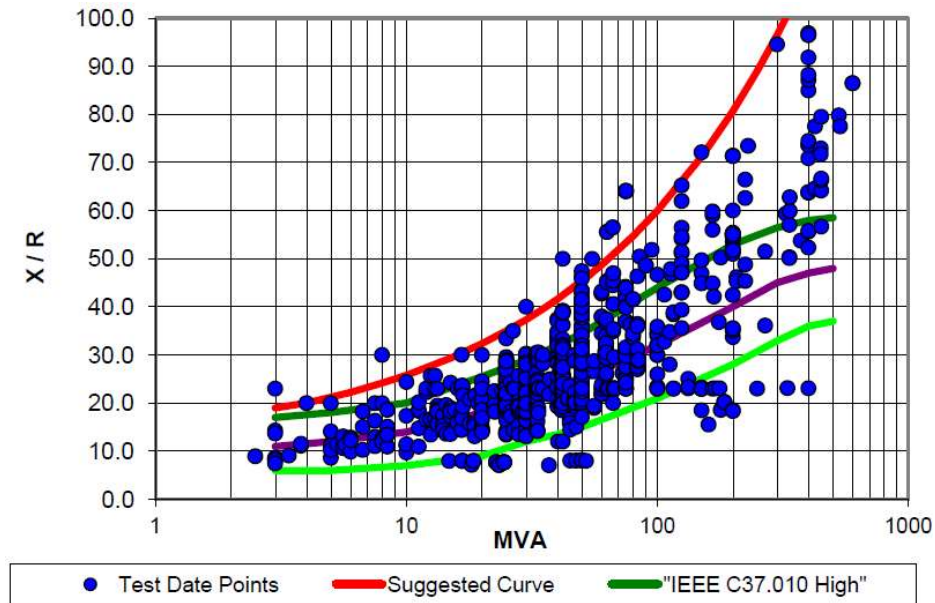


Figure 2.20, Recommended X/R values by AESO

The base impedance, base resistance and base reactance for each winding are defined as:

$$Z_{\text{base}} = R_{\text{base}} = X_{\text{base}} = \frac{V^2}{S} \quad (2.14)$$

The base inductance can be calculated by

$$L_{\text{base}} = \frac{X_{\text{base}}}{2\pi f} \quad (2.15)$$

The per unit (pu) resistance and inductance can be calculated as follows when the winding resistance and inductance are available:

$$R_1 = \frac{R(\Omega)}{R_{\text{base}}} \quad (2.16)$$

$$L_1 = \frac{L(H)}{L_{\text{base}}} \quad (2.17)$$

Based on test reports, the magnetizing branch values can be obtained as follow:

$$Z_m = \frac{V_{\text{oc}}}{I_m} \quad (2.18)$$

$$R_m = \frac{V_{\text{oc}}^2}{P_{\text{oc}}} \quad (2.19)$$

$$X_m = \frac{V_{\text{oc}}^2}{Q_{\text{oc}}} \quad (2.20)$$

In case when the winding resistance and inductance are not available, the percentage resistance can be calculated based on the IEEE Std C57.12.90 (1999) as in (2.21).

The transformer percentage resistance can be calculated as

$$\%R = \frac{\text{Full Load Loss} - \text{No Load Loss}}{\text{Rated VA}} \quad (2.21)$$

The transformer percentage inductance can be calculated as:

$$\%X = \sqrt{\%Z^2 - \%R^2} \quad (2.22)$$

The $Z\%$ can be obtained from transformer name plate or datasheet.

2.5.3. Underground Cable Model

The cable can be represented by a pi equivalent model as shown in Figure 2.21 (T. Koshiduka, et al., 2016) and (J.C. DAS, 2015). The inductance, capacitance and resistance can be calculated from the equations mentioned in the given references. However, since Simulink uses the same pi equivalent model for cables, the readymade cable model will be used.

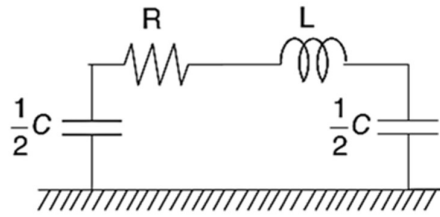


Figure 2.21. Pi equivalent circuit of a power cable

The inductance, capacitance and resistance will be taken from the manufacturer datasheets or can be extracted from the typical values for each cable voltage level. The typical values for 230KV cables are given in (J.C. DAS, 2016).

2.6. Conclusion

This chapter shows the initial step that has been taken to ensure correct start. Two computer simulation softwares were used to simulate a 12 pulse Rectifier unit. The results of both softwares have been compared and found almost similar. MATLAB Simulink software has been chosen over PSCAD to carry the simulation studies in this thesis due to the reasons mentioned in section 2.2. The effect of using pulse multiplication method in aluminum smelter on power quality has been illustrated. Aluminum pot line Rectifiers with 6 units connected in

parallel can reduce the current THD by 80% as compared to that of 12 pulse system. Also, the ripple voltage reduced by 97%.

The calculations required for utility source and transformer models in Simulink has been discussed. The recommended values for the X/R ratios and the calculations of the percentage resistance and inductance has been discussed.

Chapter 3

ALBA Power Network and Harmonic Distortion

Assessment

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Chapter 3

ALBA Power Network and Harmonic Distortion Assessment

3.1. Introduction

ALBA generate more than 2GW to feed their 5 potlines for the aluminum electrolysis process. Potline 1 and 2 were commissioned in 1970s, potline 3 in 1980s, potline 4 in 1990s and potline 5 in 2004. The total number of Rectiformers installed are 33 and they are connected in different switch houses with more than 34 power transformers used for substation interconnection and for smelter axillary load supply. The voltage levels are in the range of 220KV to 11.5KV in which 5 potlines are connected to different switch houses. Figure 3.1 shows the single line diagram of ALBA power network. Each potline consists of 5 to 7 Rectiformers unit and each one is basically a rectifier coupled to a transformer. MATLAB Simulink default solver is 'ode45', which is recommended for models with continuous states. This solver is accurate but its speed is affected by the number of continuous state and dynamics which makes it not suitable for large systems. On the other hand, the discrete solver is performing less computation steps depending on the sampling time. Its fast and suitable for large systems and detailed power electronic studies.

In this chapter, an explanation of Rectiformer unit with practical simulation was performed. A Simulation to the entire power network of ALBA with harmonic distortion assessment on different practical

operating scenarios will be presented. Potline 6 is still under construction and it has not considered in the simulation.

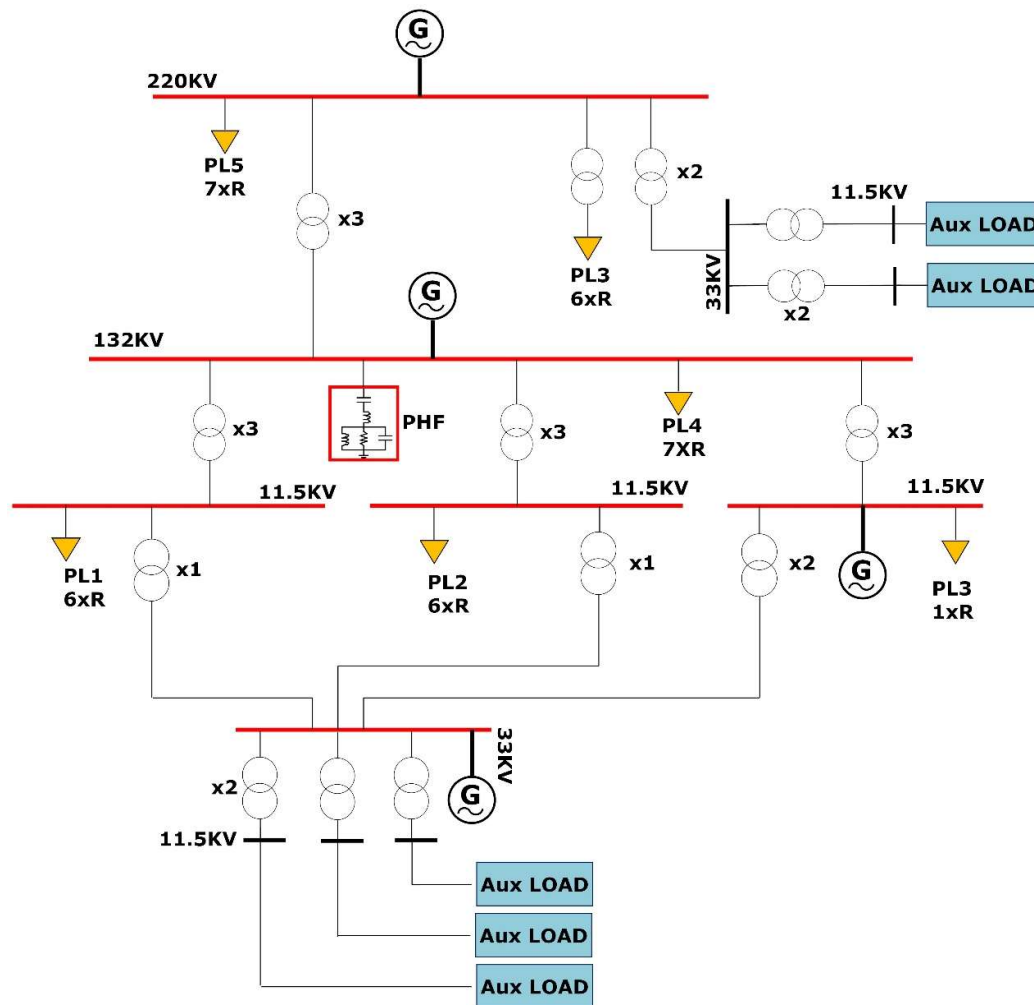


Figure 3.1, Single line diagram of ALBA Power network

3.2. Aluminum Smelter Rectifier

In aluminum smelters, diode base rectifiers are mostly used rather than thyristor based rectifier. The main reason behind the usage of diode based unit is that it can work manually in case of emergencies even when controls fail and has better performance in terms of power quality (S. Jhajharia 2013).

In general, the Rectifier unit shown in Figure 3.2 and 3.3 consist of (Siebert, 2002; Areva T&D, 2008; A. Agalgaonkar, 2009):

- Regulating Transformer
- Rectifier Transformer
- Rectifier
- Cooling system
- Local control equipment

In general, for unit power less than 120MVA, the regulating transformer can be located in the same tank as shown in Figure 3.2. However, for higher rating, it can be located in separate tanks as shown in Figure 3.3.

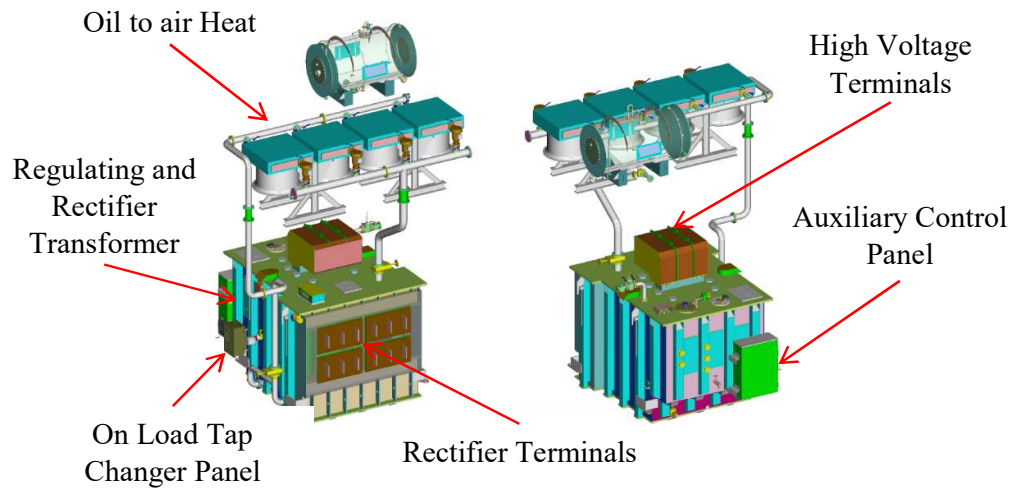


Figure 3.2, Rectifier unit with regulating and rectifier transformer in the same tank

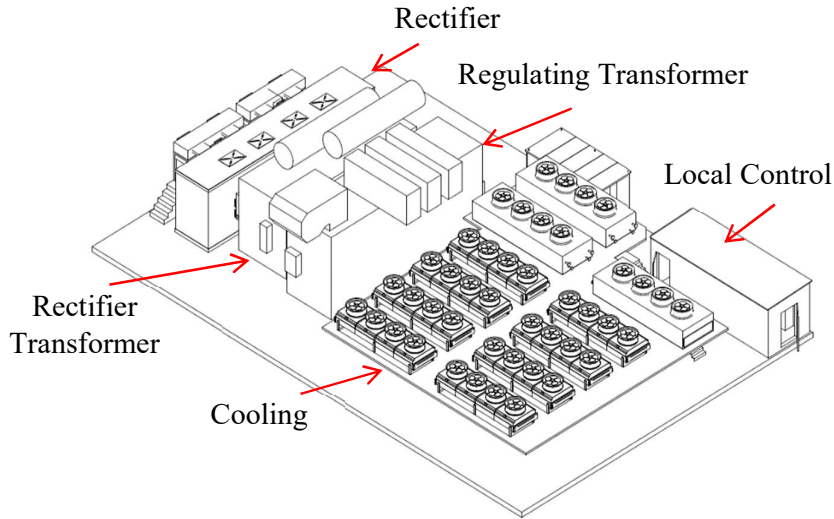


Figure 3.3, Rectifier unit with regulating and rectifier transformers in separate tanks

3.2.1. Regulating Transformer

The regulating transformer is fitted with on load tap changer for the regulation range of the secondary voltage by stepping the regulation transformer on load tap changer upwards or downwards depending on the voltage set value.

3.2.2. Rectifier Transformer

The rectifier transformer with two secondary windings, each is connected to a separate three phase bridge rectifier in order to get twelve pulse output. For a complete potline Rectifiers, the primary of the rectifier transformer is phase shifted in order to achieve 72 pulses for six units connected in parallel scheme.

The saturable reactors installed in the rectifier transformer are used for fine current control between on load tap changer step by acting like a variable

impedance to the rectifier input. The Feature of the saturable reactor are discussed by Hao Jiang et al., (2013). The saturable reactors are not considered in the simulation because the harmonics will be evaluated at steady state operating conditions at which the reactor characteristic is not varying.

3.2.3. Rectifier

The 12-pulse diode rectifier is constituted by two “Graetz” bridges connected in parallel and housed in a sealed shelter to prevent the entrance of dust, sand and other contaminations. The rectifier diodes and fuses are cooled by deionized water circulating through the aluminum extruded profile. The main function of the cooling system is to cool both the rectifier frames and the air in the rectifier container.

3.2.4. Cooling Equipment

The cooling equipment is provided with oil to air heat exchangers installed remote from the transformer as shown in Figure 3.3 or on the top of it as shown in Figure 3.2. Most designers are maintaining one redundant heat exchanger bank or at least on redundant fan for each bank.

3.2.5. Local Control

The local control could be housed in a control building or near to the unit itself depending on the design. The local control is equipped with all of the necessary apparatus for local rectifier control, metering and protection. The rectifier is controlled by a programmable logic controller (PLC) in order to do rectifier operation, fast current regulation and rectifier

protection. Auxiliaries of low voltage supply are also controlled by the local control equipment.

3.3. Practical Modeling of Rectifier Unit

A 12-pulse Rectifier unit modeled in simulink is shown in Figure 3.4. The parameters entered in the model has been calculated as discussed in chapter 2, section 2.5.

The 11.5KV utility source is modeled with 50KA short circuit level and with the recommended IEEE C37.010 X/R ratio which is equal to 10. R. Vedam et al., (2009) provided a guidance regarding the details of the network that must be represented for harmonic studies in which the utility source is represented by its short-circuit impedance. The load has been modeled as pure DC current source drawing 28KA at 1552V. The three phase input voltages and currents are shown in Figure 3.5. It can be seen that both signals are affected by harmonics generated by the non linear load. The harmonic spectrum for the input voltage and current are shown in Figure 3.6 and the DC output voltage is shown in Figure 3.7.

The order of characteristic harmonics that will present in a 12-pulse rectifier unit can be expressed as (Ma Zhiheng et al., 2014):

$$h = 12n \pm 1 \quad (3.1)$$

However, it can be noticed from Figure 3.6 that the noncharacteristic harmonics (5th and 7th) have also appeared due to the unbalance between both rectifier output voltages. The unbalance between the two rectifiers selected to be 1% in the simulation.

Such uncharacteristic harmonics can also increase when the short circuit impedances are not perfectly equal. The unbalance in practice will not exceed 3.9% (S.Furuki et al., 2008). However, this voltage unbalance can be reduced by different methods depending on the designer.

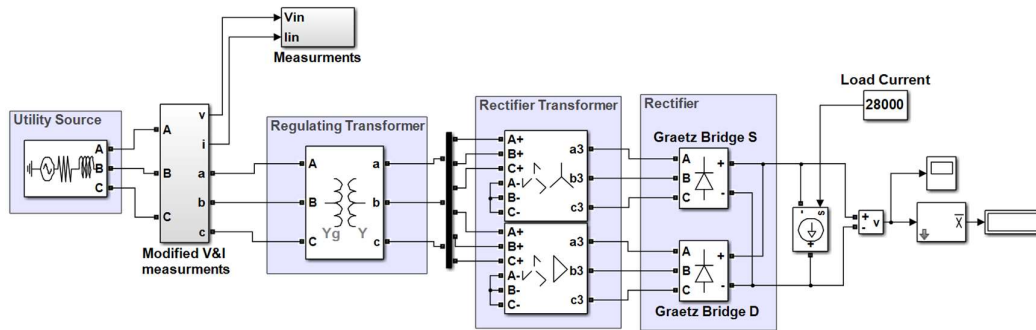


Figure 3.4, Simulink model of Rectifier Unit

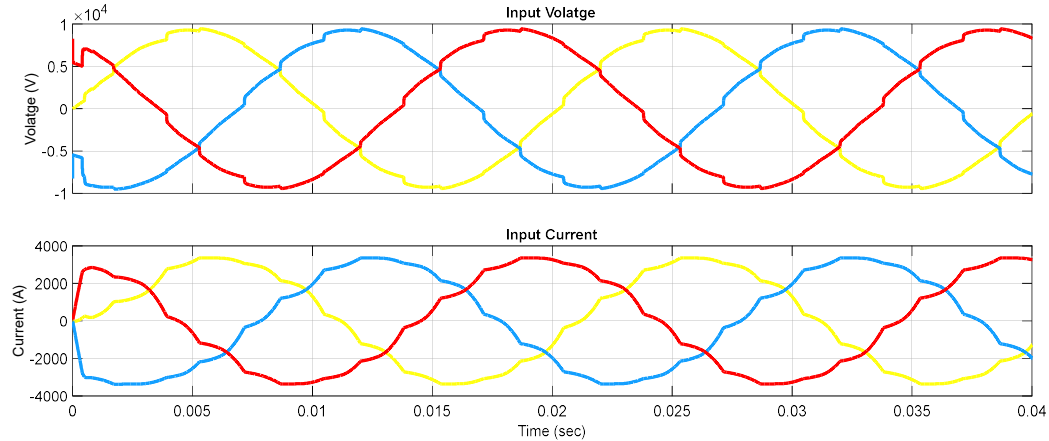


Figure 3.5, Three phase Input voltage and current waveforms

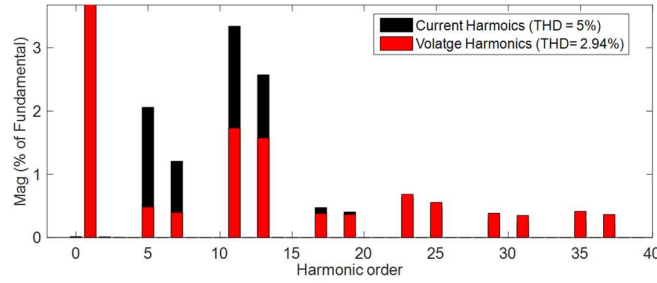


Figure 3.6, Harmonic spectrum of the input voltage and current

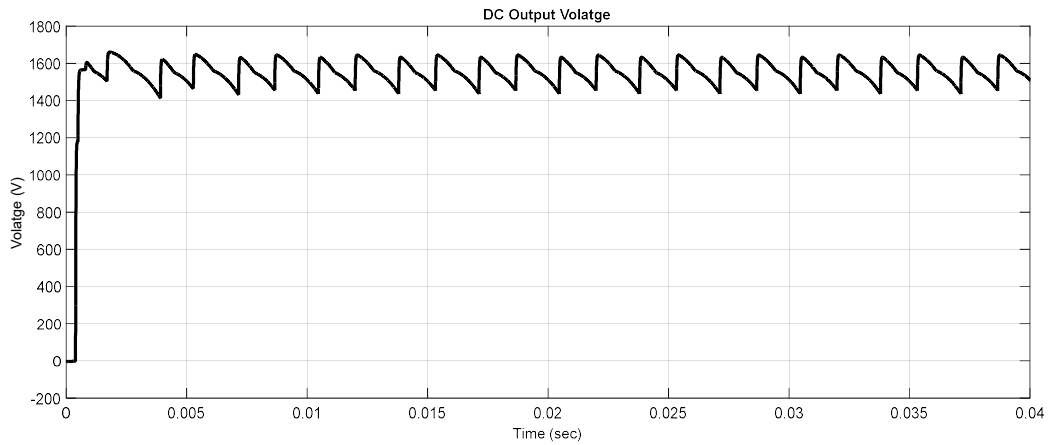


Figure 3.7, Output DC voltage of a practical Rectifier model

3.4. Modeling of ALBA Power Network

The complete power network shown in Figure 3.1, is simulated using the Simulink as shown in Figure 3.8. The power network consists of 5 potlines, 5 auxiliary substaion for smelter auxialry power requirements. A passive harmonic filter (PHF) connected to the 132KV switchgear with 100Mvar reactive power compensation capability and tunned at the 5th and 11th harmoic orders.

The short circuit level is very important in the modeling because the strength of the feeding grid can influence the distortion level as illustrated in Figure 3.9. The short circuit levels of each switch house are shown in Table 3.1.

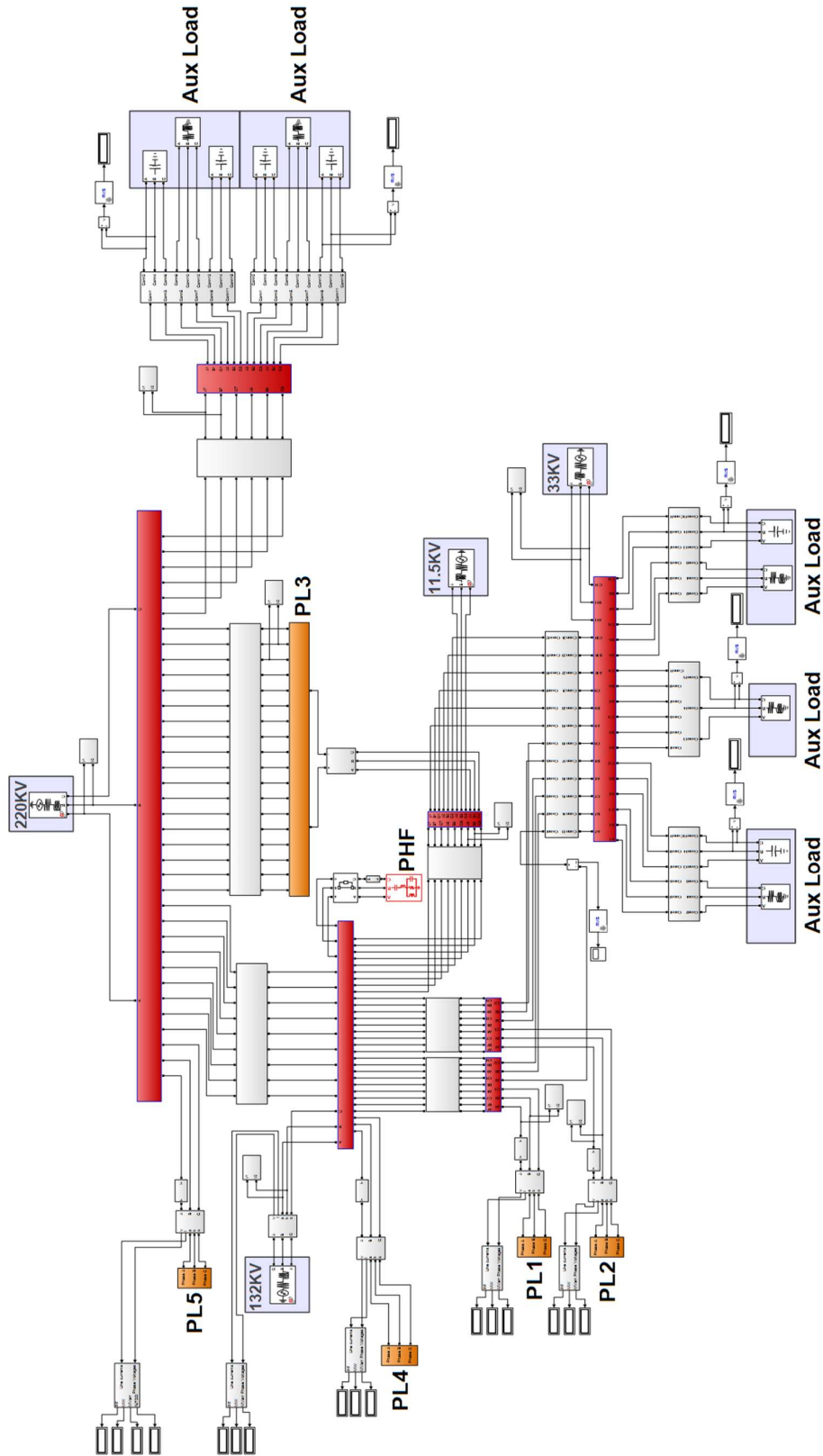


Figure 3.8, ALBA power network

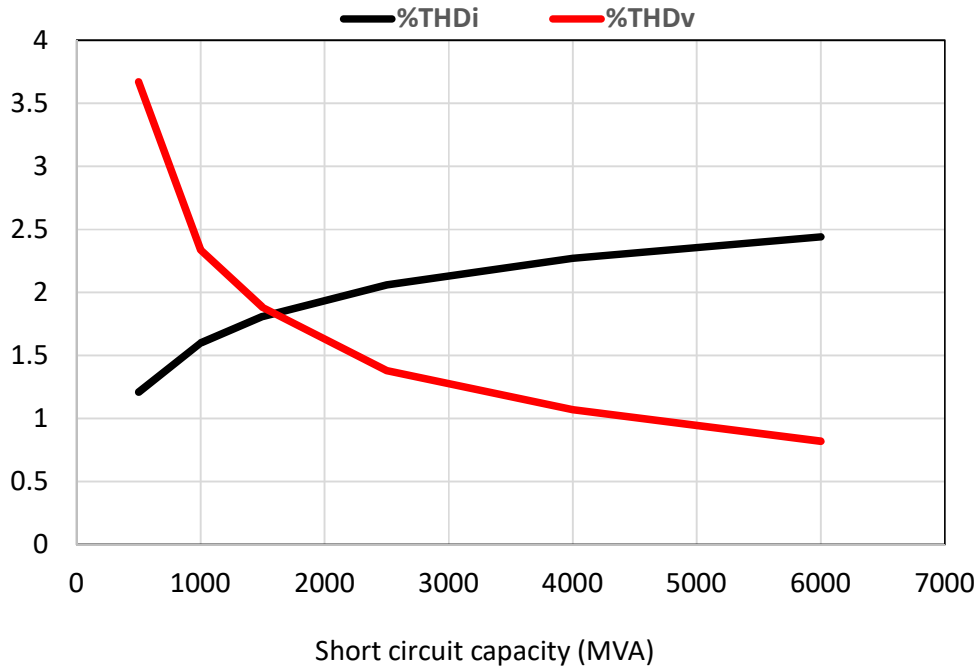


Figure 3.9, Short circuit capacity verses THD

Table 3.1
Switch Houses Short Circuit Current

Switch House No.	Voltage Level (KV)	Short Circuit Current (KA)
6	220	40
5	132	40
3	11.5	40
2	11.5	90
1	11.5	90

3.4.1. ALBA 132KV Harmonic Filter

The PHF which is connected to switch house 5 has been installed before commissioning of switch house 6 that is feeding potline 5 Rectiformers. The PHF was required to attenuate the harmonic currents and to support the generators by feeding 100Mvar into the network.

The one phase diagram of the PHF is shown in Figure 3.10. It was decided that the required tuning frequency shall be set to target the 5th and 11th harmonic orders. The decision was made based on computer simulation at that time by a power system design consultant.

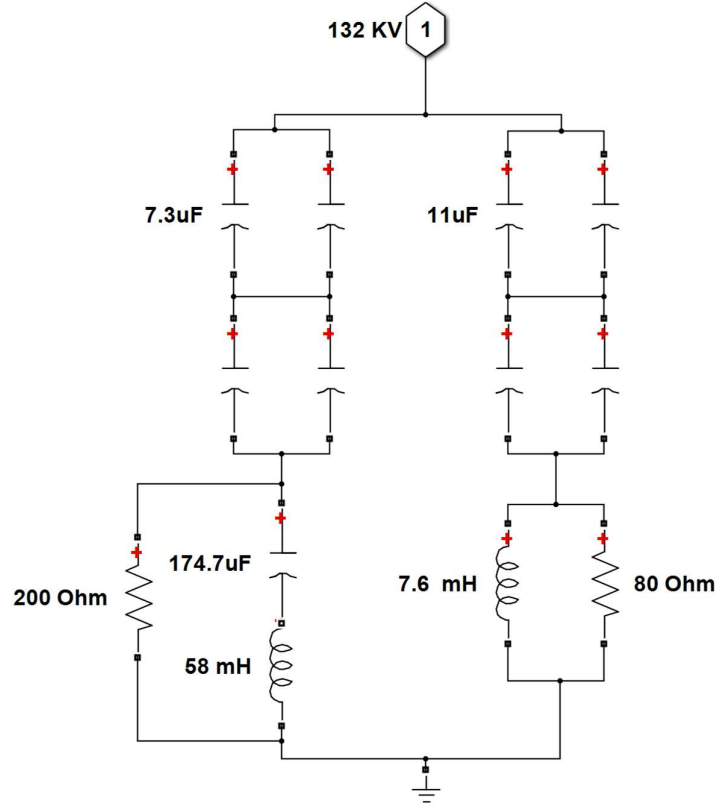


Figure 3.10, ALBA 132KV harmonic filter one phase diagram

The 5th order PHF is a C-type with the following parameters:

$$X_c = \frac{1}{2\pi fC} = 436.041 \, \Omega \quad (3.2)$$

$$Mvar = \frac{V^2}{X_c} = 40 \quad (3.3)$$

The 11th order PHF is a high pass type with the following parameters:

$$X_c = \frac{1}{2\pi f C} = 289.37 \Omega \quad (3.4)$$

$$Mvar = \frac{V^2}{X_c} = 60 \quad (3.5)$$

The quality factor is the measure of the sharpness of the tuning frequency which is determined by the resistance value as:

$$Q = \frac{R}{L \cdot 2\pi f_n} \quad (3.6)$$

where f_n is the tuning frequency, so the 5th and 11th filter quality factor can be calculated as:

$$Q_5 = \frac{R}{L \cdot 2\pi f_n} = \frac{200}{0.058 \times 2 \times \pi \times 250} = 2.195 \quad (3.7)$$

$$Q_{11} = \frac{R}{L \cdot 2\pi f_n} = \frac{80}{0.0076 \times 2 \times \pi \times 550} = 3.046 \quad (3.8)$$

To confirm the above calculations, simulink was used to plot the frequency response of the PHF. The frequency response is shown in Figure 3.11. It can be seen that, the PHF with higher quality factor ($Q=16$), a parallel resonance can occur. However, with lower quality factor as calculated in 3.7 and 3.8, the resonance has been reduced.

It can be noted from Figure 3.11 that the impedance at the fundamental frequency is:

$$Z_{50Hz} = 174.25\Omega \quad (3.9)$$

Then, the total reactive power supplied by the PHF is:

$$Q_c = \frac{(132KV)^2}{174.25} = 100Mvar \quad (3.10)$$

Which is the same results of the addition of reactive power of both filters.

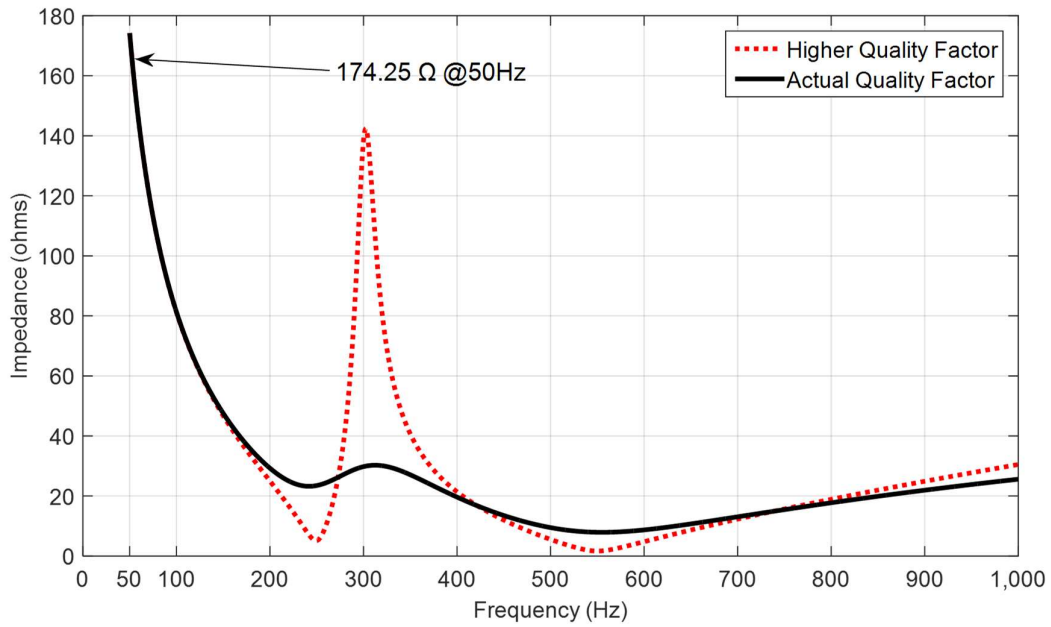


Figure 3.11, PHF impedance frequency response

3.4.2. Simulation Results and Discussion

The power network shown in Figure 3.1 is simulated to assess the voltage and current harmonic distortions at the switch houses that feeds the potlines. The five potlines are connected as per Table 3.2. So, the harmonic distortion measurements were taken at switch house 1, 2, 5 and 6. The four practical operating scenarios that has been considered in the simulation are listed as follows:

- 1- Normal operating condition
- 2- PHF is out of service
- 3- Rectifier out of service
- 4- PHF and Rectifier are out of service

These considered scenarios were selected based on previous harmonic studies performed by consultants on ALBA power network. These scenarios will reflect possible practical operating conditions including the worst operating condition.

As mentioned in section 3.4, the utility source short circuit level can influence the harmonic distortions. So, it is reasonable to repeat the simulation and obtain the results at maximum and minimum short circuit levels. The minimum short circuit level chosen based on previous studies performed on ALBA power network. The selected minimum short circuit level is equal to one third of the maximum value.

Table 3.2
Potline Supply Sources

Switch House	Voltage Level (KV)	Potline
1	11.5	1
2	11.5	2
3	11.5	One Rectifier connected to 3
5	132	4
6	220	5 and 3

The normal operating scenario means that all units in all potlines are in service and the PHF also in service. The second scenario means that the PHF is taken out of service, and the third scenario is to take out of service one Rectifier. The fourth scenario is to take one Rectifier and the PHF out of service which is considered as the worst operating condition.

Figure 3.12 and Figure 3.13 show the percentage TDD at minimum and maximum short circuit level, respectively. It can be seen that the percentage TDD at maximum short circuit level is higher as the source impedance in this case becomes lower. The percentage TDD at switch house 6 (SH6) exceeded the recommended IEEE 519 set value when the system is running at maximum short circuit level in the third and fourth scenario. The percentage TDD of the switch houses is within the IEEE 519 recommended values in all the operating scenarios.

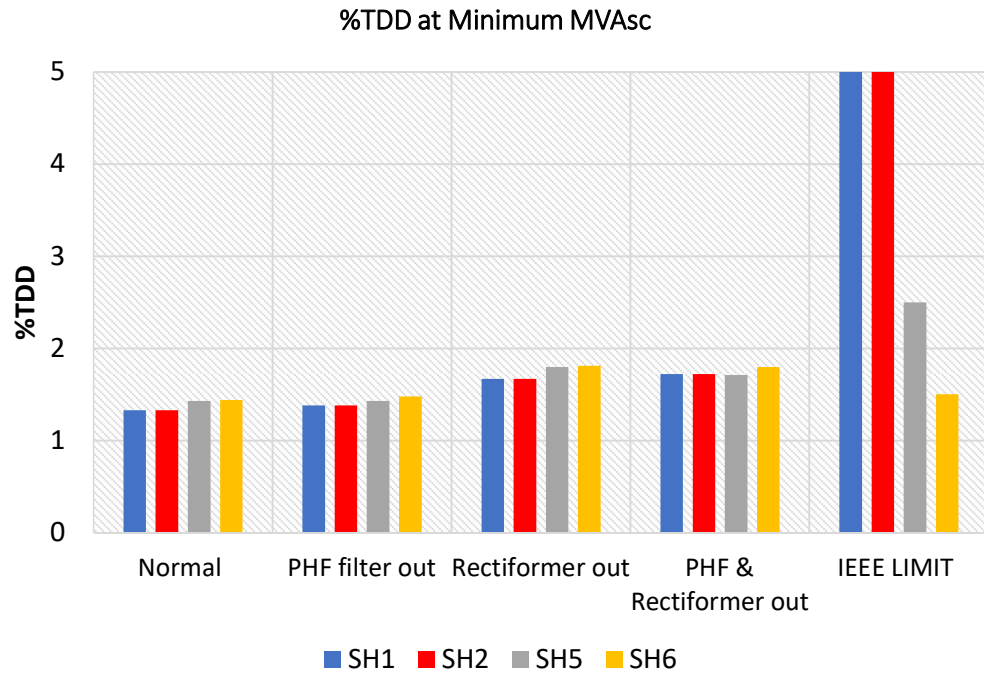


Figure 3.12, Percentage TDD at minimum short circuit level

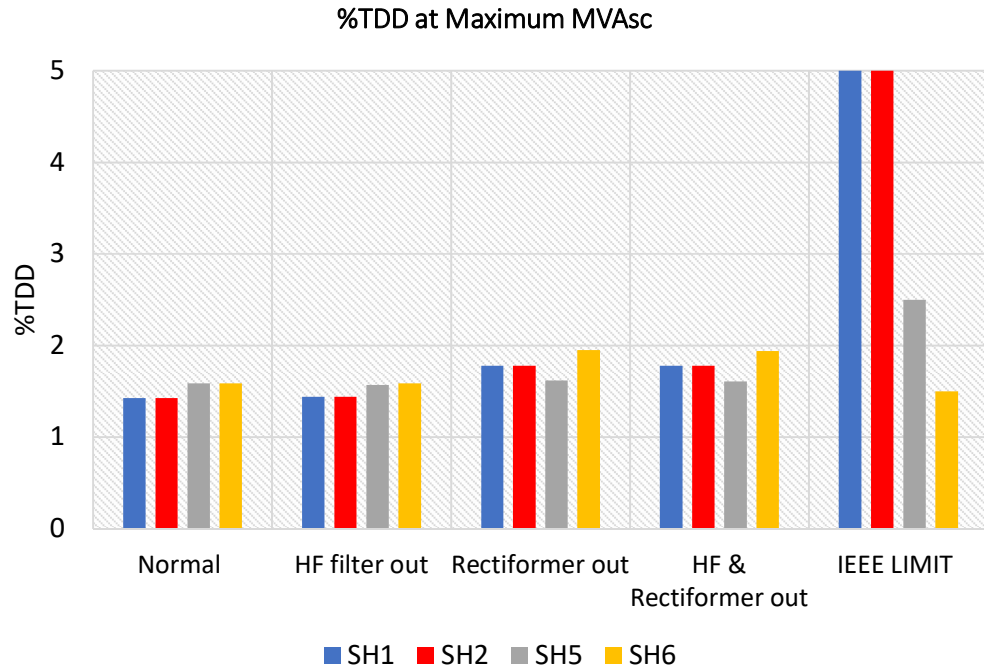


Figure 3.13, Percentage TDD at maximum short circuit level

On the other hand, the percentage THD behave in opposite as compared to TDD, As the short circuit level decreases, the percentage THD increases as shown in Figure 3.14 and Figure 3.15. At minimum short circuit level, the percentage THD in all scenarios are higher than the cases when the system is running with maximum short circuit level. It can be seen that the harmonic distortions in all switch houses are within IEEE 519 recommended values for all the scenarios.

The PHF effect on reducing the harmonic distortion becomes insignificant after the commissioning of power station 4. Power station 4 strengthen the power network forcing the overall harmonic distortions to reduce. Now, the PHF is required for reactive power support to reduce the load on the generators in power station 3 and 4. If we assume that there is no PHF and ALBA would obey the IEEE 519, the PHF should be installed in switch house 6 as the percentage TDD in scenarios 3 and 4 has exceeded the recommended values as well as the percentage THD has also exceeded the recommended values when the system is running with minimum short circuit level.

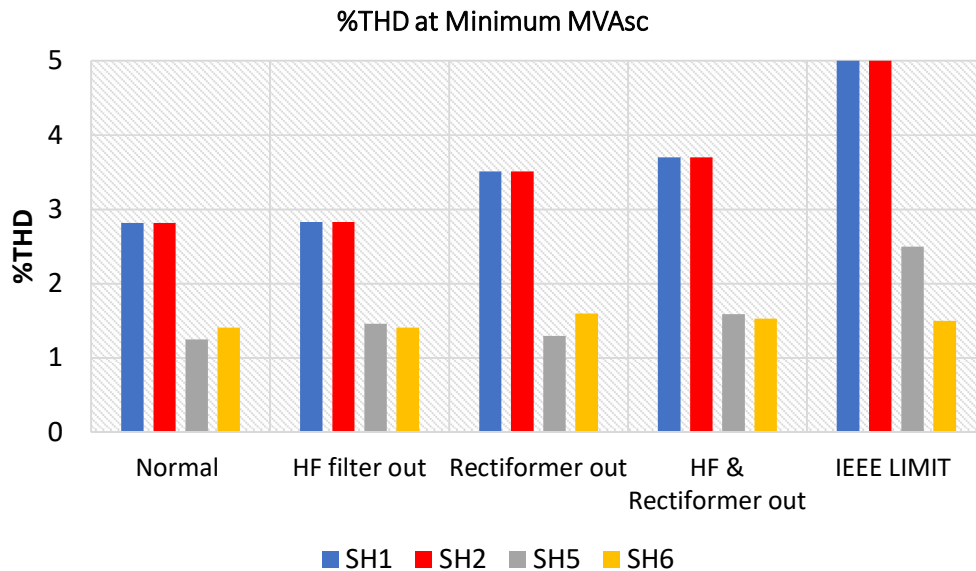


Figure 3.14, Percentage THD at minimum short circuit level

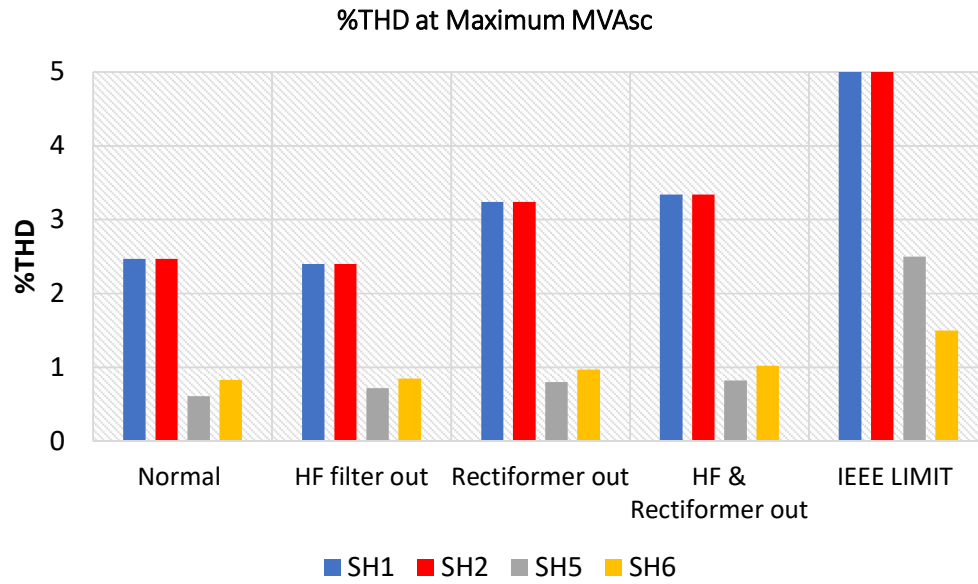


Figure 3.15, Percentage THD at maximum short circuit level

3.5. Conclusion

An explanation of Rectifier unit with all auxiliaries have been discussed along with practical simulation to show the effect of source impedance and unbalance in the rectifier output on harmonics contents.

The assessment results show that the PHF which is connected to SH5 will be more effective if it is connected to SH6 due to the percentage TDD as well as THD in scenarios 3 and 4 exceeded the IEEE 519 recommended limits when the system is running with minimum short circuit level.

Chapter 4

Proposed Aluminum Pot Line Rectifiers Scheme

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Chapter 4

Proposed Aluminum Pot Line Rectifiers Scheme

4.1. Introduction

Conventional potline scheme is consisting of six Rectifiers connected in parallel and each is phase shifted in order to achieve 72 pulse system which effectively reduces the harmonic currents at PCC. The PHF which is connected directly to the feeding grid is mostly employed to attenuate the harmonic distortions and to provide reactive power compensation (Hemang K. et al., 2015; N. Gersch, 2000; P. Pollock and C. Duffey, 1998; Ermis et al., 2004; Yokoyama et al., 2006). The conventional scheme is shown in Figure 4.1. In this scheme, the harmonics will always flow in the regulating transformer.

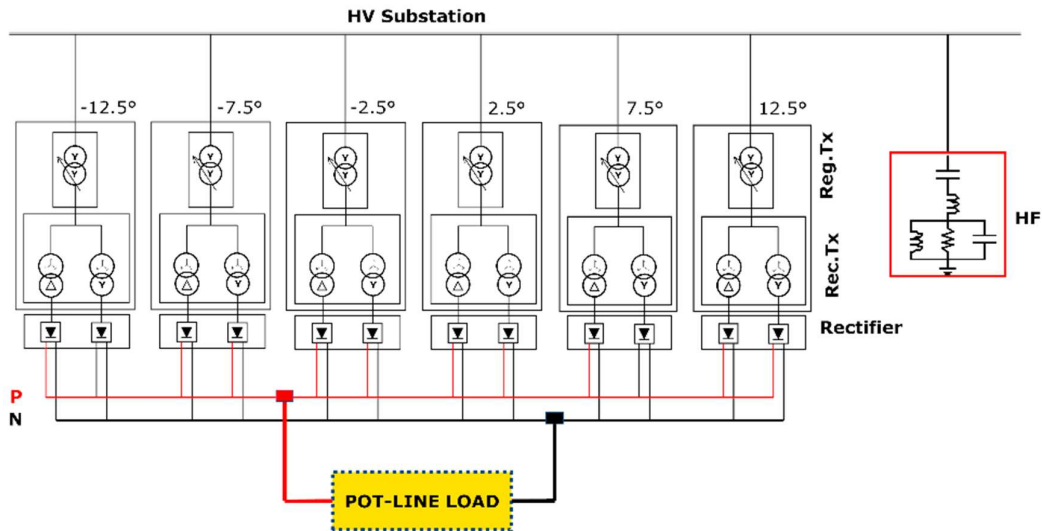


Figure 4.1, Conventional potline Rectifier scheme

Another scheme in which the PHF is connected to the regulating transformer tertiary winding of each Rectifier unit is shown in Figure 4.2. Max Wiestner (2010) discussed the most economical method to maintain the voltage THD at around 2% by connecting the PHF to the regulating transformer tertiary winding. The connection of PHF to the tertiary winding scheme is also discussed in (Zhao et al, 2013). The design of the new potline scheme for ALBA potline 6 is based on connecting the PHF to the regulating transformer tertiary winding as shown in Figure 4.2 which is still not implemented. This configuration was considered to satisfy the IEEE 519 recommended harmonic distortion limits. The same scheme has already been implemented in Ma'aden (Saudi Arabian Mining Company) (A. Collier et al., 2012). This scheme will not prevent the harmonics from flowing in the regulating transformer when the PHF is not connected because characteristic harmonics will flow in the regulating transformer once the PHF is disconnected.

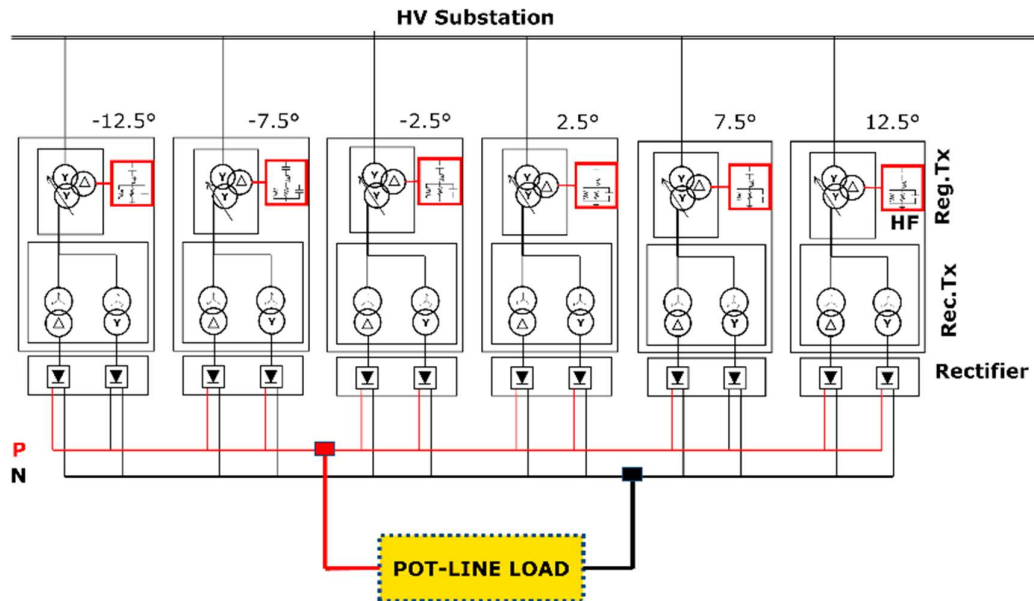


Figure 4.2, Potline Rectifier scheme where PHF connected to the tertiary winding

In this chapter, the proposed potline scheme will be presented and its performance will be compared with both the conventional scheme and the

PHF connected to tertiary winding schemes in terms of harmonic attenuation capability, operational constraints, cost/space requirements. It will be shown that the proposed scheme reduces the distortion at the Rectifier terminal and provide better harmonic attenuation capability at the point of common coupling (PCC) by using the parallel delta connected (PDC) tertiary winding between two adjacent Rectifiers. MATLAB Simulink environment is used to evaluate and compare the performance of the three schemes.

4.2. Proposed Parallel Delta Connection Scheme (PDC)

Figure 4.3 shows the proposed scheme of 24 pulse system. Two Rectifiers with their regulating transformer delta connected tertiary winding is connected in parallel for harmonic filtering. This scheme was initially proposed for HVDC system, where the wiring and tertiary winding design has been evaluated in (C. Liang et al., 2017). Similar approach also presented by Jih-Sheng Lai and Pabbathi Venkatesh (2016).

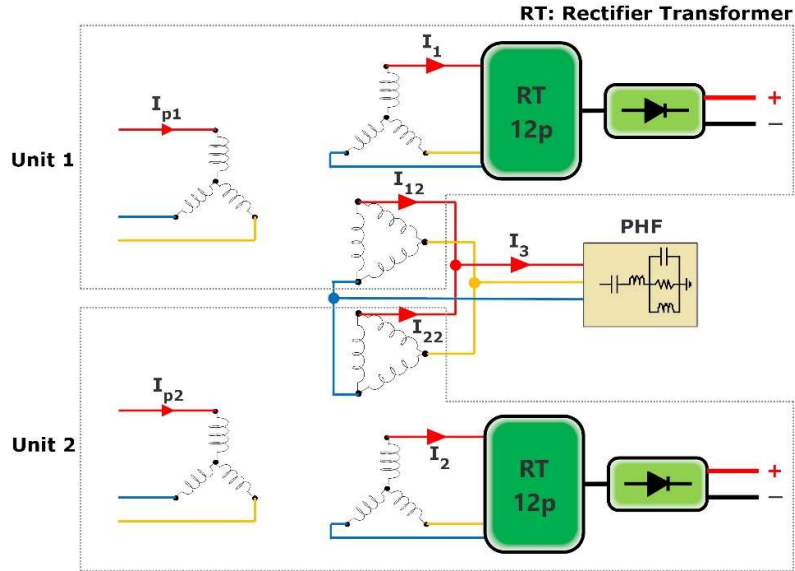


Figure 4.3, PDC 24 pulse system

The harmonics of specific orders are trapped by the shunt connected transformer. This technique can also be used for higher harmonic orders. The tuned PHF with reactive power compensator are connected to the parallel links as shown in Figure 4.3.

In this case it is assumed that the load is pure DC and by using square wave analysis as discussed by C. Liang (2017), Jih-Sheng Lai and Pabbathi Venkatesh (2017) and Paice (1995), the current passing into the regulating transformer secondary of unit 1 and 2 can be expressed as:

$$I_1 = \frac{4\sqrt{3}}{\pi} \left[\cos \omega t - \frac{1}{11} \cos 11\omega t + \frac{1}{13} \cos 13\omega t - \frac{1}{23} \cos 23\omega t + \frac{1}{25} \cos 25\omega t - \dots \right] \quad (4.1)$$

$$I_2 = \frac{4\sqrt{3}}{\pi} \left[\cos \omega t + \frac{1}{11} \cos 11\omega t - \frac{1}{13} \cos 13\omega t - \frac{1}{23} \cos 23\omega t + \frac{1}{25} \cos 25\omega t - \dots \right] \quad (4.2)$$

Consequently the primary current of each unit can be expressed as:

$$I_{p1} = \frac{4\sqrt{3}N}{\pi} \left[\cos \omega t - \frac{1}{11} \cos 11\omega t + \frac{1}{13} \cos 13\omega t - \frac{1}{23} \cos 23\omega t + \frac{1}{25} \cos 25\omega t - \dots \right] \quad (4.3)$$

$$I_{p2} = \frac{4\sqrt{3}N}{\pi} \left[\cos \omega t + \frac{1}{11} \cos 11\omega t - \frac{1}{13} \cos 13\omega t - \frac{1}{23} \cos 23\omega t + \frac{1}{25} \cos 25\omega t - \dots \right] \quad (4.4)$$

Where N is the transformer turn ratio.

The currents passing in the tertiary windings of unit 1 and 2 are respectively expressed as:

$$\begin{aligned}
 I_{12} = \frac{4\sqrt{3}}{\pi} & \left[k_1 \cos\left(\omega t + \frac{\pi}{6}\right) \right. \\
 & - \left\{ -\frac{k_{11}}{11} \cos\left(11\omega t - \frac{\pi}{6}\right) + \frac{k_{13}}{13} \cos\left(13\omega t + \frac{\pi}{6}\right) \right. \\
 & - \frac{k_{23}}{23} \cos\left(23\omega t - \frac{\pi}{6}\right) \\
 & \left. \left. + \frac{k_{25}}{25} \cos\left(25\omega t + \frac{\pi}{6}\right) - \dots \right\} \right] \quad (4.5)
 \end{aligned}$$

$$\begin{aligned}
 I_{22} = \frac{4\sqrt{3}}{\pi} & \left[k_1 \cos\left(\omega t + \frac{\pi}{6}\right) \right. \\
 & - \left\{ \frac{k_{11}}{11} \cos\left(11\omega t - \frac{\pi}{6}\right) - \frac{k_{13}}{13} \cos\left(13\omega t + \frac{\pi}{6}\right) \right. \\
 & - \frac{k_{23}}{23} \cos\left(23\omega t - \frac{\pi}{6}\right) \\
 & \left. \left. + \frac{k_{25}}{25} \cos\left(25\omega t + \frac{\pi}{6}\right) - \dots \right\} \right] \quad (4.6)
 \end{aligned}$$

The current passing in the parallel link is obtained by adding (4.5) and (4.6) which yields to:

$$\begin{aligned}
 I_3 = I_{12} + I_{22} \\
 = \frac{8\sqrt{3}}{\pi} & \left[k_1 \cos\left(\omega t + \frac{\pi}{6}\right) + \frac{k_{23}}{23} \cos\left(23\omega t - \frac{\pi}{6}\right) \right. \\
 & \left. - \frac{k_{25}}{25} \cos\left(25\omega t + \frac{\pi}{6}\right) - \dots \right] \quad (4.7)
 \end{aligned}$$

In the proceeding equations, the coefficients $K_{12n\pm 1}$ ($n = 1, 2, 3, \dots$) can be approximated to unity as discussed by C. Liang et al., (2017).

$$K_{12 \pm 1} \approx 1$$

Therefore, equation (4.7) can be simplified as:

$$\begin{aligned}
 I_3 = & \left[k_1 \cos\left(\omega t + \frac{\pi}{6}\right) + \frac{1}{23} \cos\left(23\omega t - \frac{\pi}{6}\right) \right. \\
 & \left. - \frac{1}{25} \cos\left(25\omega t + \frac{\pi}{6}\right) - \dots \right] \quad (4.8)
 \end{aligned}$$

According to (4.8), the parallel links connecting the tertiary delta windings can eliminate the harmonics of order $12n \pm 1$ ($n=1,3, 5\dots$) which flow out from the tertiary delta windings. Therefore, the harmonic filter should be tuned to target the $24n \pm 1$ orders. When the PHF is disconnected, the harmonics of order $24n \pm 1$ ($n=1,2, 3\dots$) will present in I_{P1} and I_{P2} which means that the dominant characteristic harmonics of the 12-pulse unit (11th and 13th) will not flow into the regulating transformer even when the PHF is not connected.

4.2.1. Simulation of PDC scheme

4.2.1.1. PDC Modeling in Simulation

The modelling of the PDC scheme in Simulink is presented in Figure 4.4. The electrical parameters of the simulated system are provided in Table 4.1, which are obtained from the actual proposed data for ALBA PL6 units. The delta tertiary windings in both units are connected in parallel and the PHF is connected to the parallel link. It is important that the phase shift between the two unit is equal to (Marian P. et al., 2002):

$$\text{Phase shift} = \frac{60^\circ}{\text{Number of converters}} = \frac{360^\circ}{\text{Number of pulses}} = 15^\circ$$

Where, the number of converters are 4 and the number of pulses are 24. The 15° phase shift is implemented using phase shift transformers with $\pm 7.5^\circ$ as shown in Table 4.1.

The PHF tuning frequency was selected base on the discussing presented in section 4.2 and the reactive power value and other parameters were selected based on data obtained from ALBA PL6 specifications.

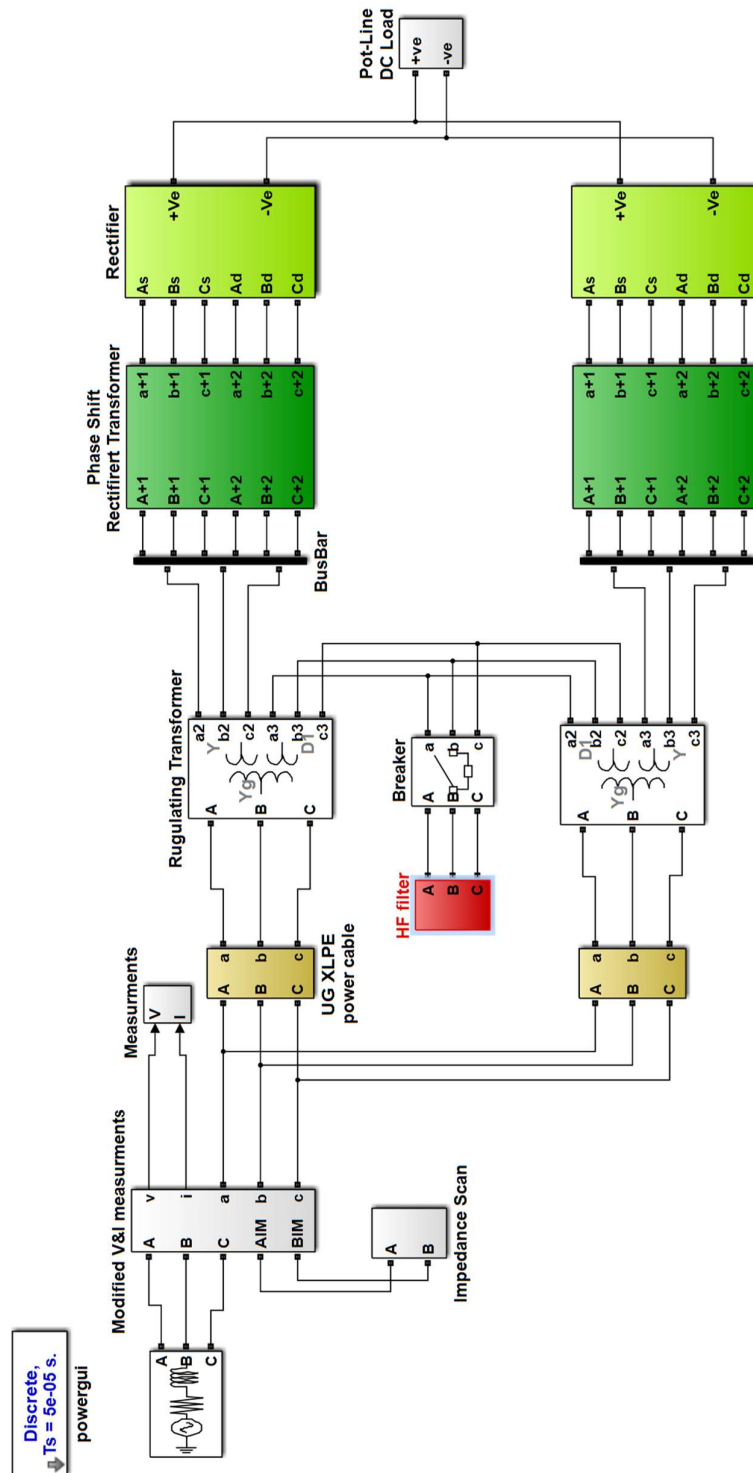


Figure 4.4, Simulink model of PDC block unit

TABLE 4.1
Electrical Parameter of the PDC System

Main Supply Source				
KV=220		Hz = 50	MVAsc = 8000	X/R = 24
Under Ground Cable				
R= 40μΩ/m		L= 636μH/m	C= 0.21μF/m	L= 100m
Regulating Transformer				
YYΔ	MVA = 230	KVs = 95	KVp = 220	KVt = 28
Lp = 47.5mH		Ls = 10.5mH		Lt = 0.56μH
Rectifier Transformer				
ZYΔ	MVA= 2x115	KVp= 95	KVs= 1.39	Phase Shift= ±7.5°
PHF				
MVar= 40		Tuning Hz= 1200	Q= 20	KV= 28

4.2.1.2. Simulation Results of PDC Scheme

Figure 4.5 shows the simulation result of phase A primary current (I_{P1}) of unit 1 while the parallel link left open circuited. In this case, the current THD is 5.7% due to the presence of characteristic harmonics $12n \pm 1$ ($n=1, 2, 3, \dots$). Figure 4.6 shows the same current with parallel link closed. In this case, the current THD is 0.78%, which is greatly reduced as compared to the previous cases because the harmonics of order $12n \pm 1$ ($n=1, 3, 5, \dots$) has been eliminated. The phase A current in the parallel link is shown in Figure 4.7 and it is clearly seen that this current is carrying the harmonics of orders $12n \pm 1$ ($n=1, 3, 5, \dots$) as described in (4.7). With the PHF tuned as per (4.8) and connected as shown in Figure 4.3 to target the 23rd and 25th harmonic orders, the phase A primary current of unit 1 is almost free from harmonics with THD equal to 0.06% as shown in Figure 4.8.

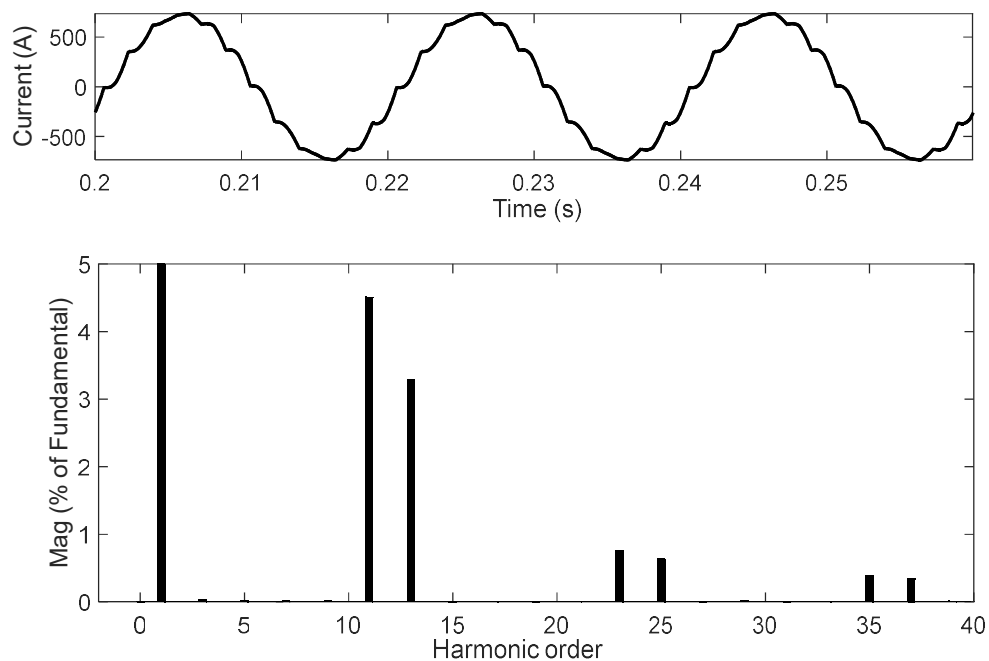


Figure 4.5, Phase A primary current of unit 1 with parallel link open

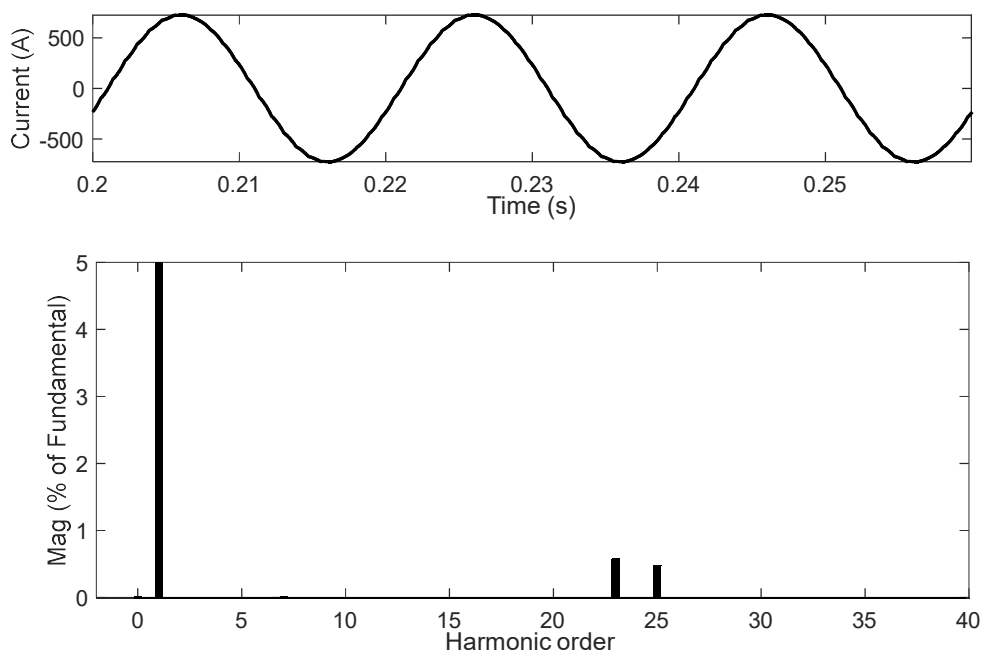


Figure 4.6, Phase A primary current of unit 1 with parallel link closed

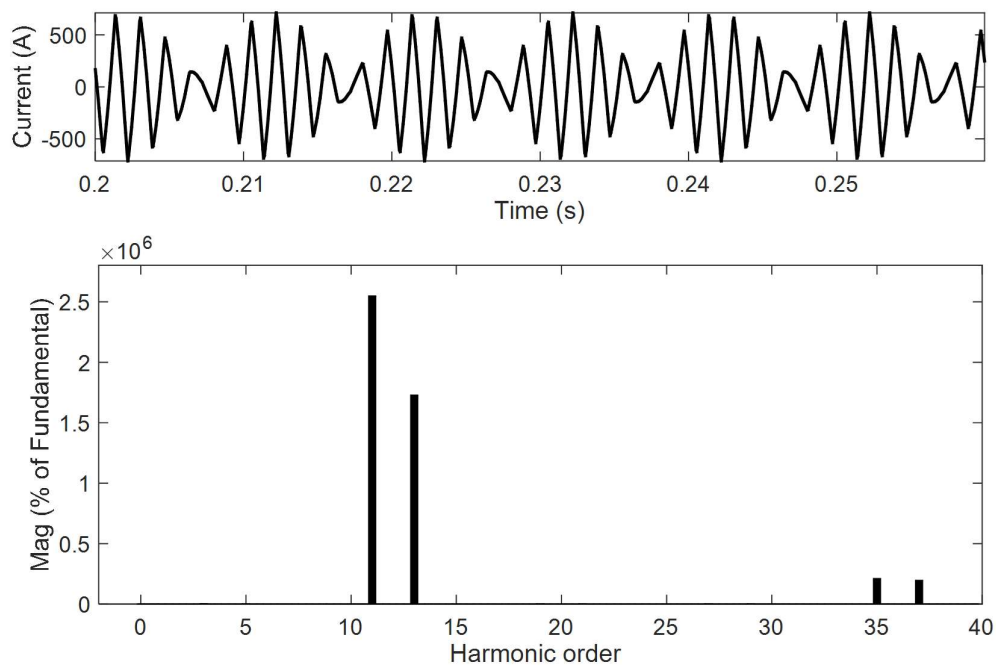


Figure 4.7, Phase A parallel link current

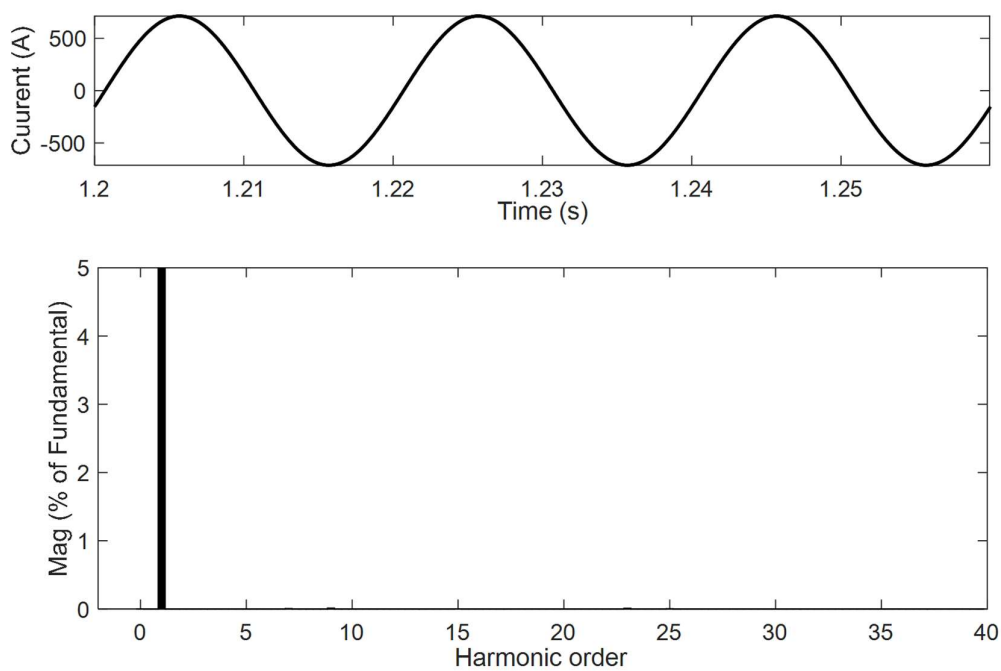


Figure 4.8, Phase A primary current to unit 1 with PHF

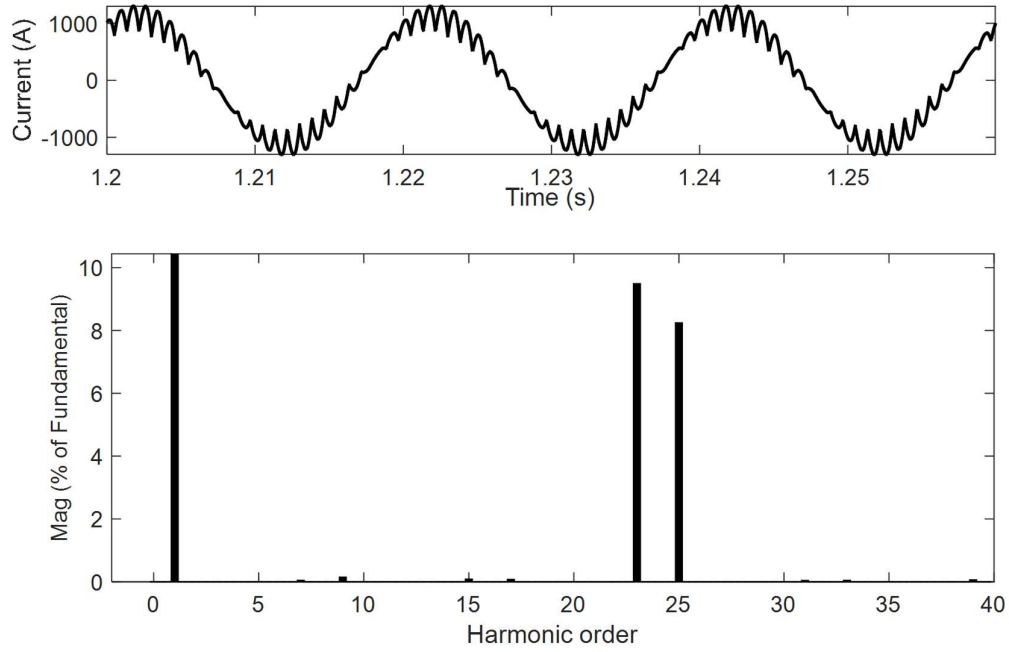


Figure 4.9, PHF Phase A primary current

The phase A PHF current I_3 is carrying the 23rd and 25th harmonic orders as the PHF acting as a low impedance path at these frequencies. The current I_3 is shown in Figure 4.9.

The reactive power supplied by the PHF can be calculated based on the impedance characteristic of the PHF when it is not connected to the system. The impedance characteristic of the PHF alone is shown in Figure 4.10a. The impedance at the fundamental frequency is equal to 19.6 Ω . The reactive power at the fundamental frequency is equal to:

$$Mvar = \frac{V^2}{Z} = \frac{(28k)^2}{19.6} = 40$$

Parallel resonant can be observed at PCC due to source impedance and other apparatus in the system as shown in Figure 4.10b. This is one of the drawback of using PHF. However, due to the absence of harmonic within is the impedance peak region the resonant will not cause harmonics amplification in the study system.

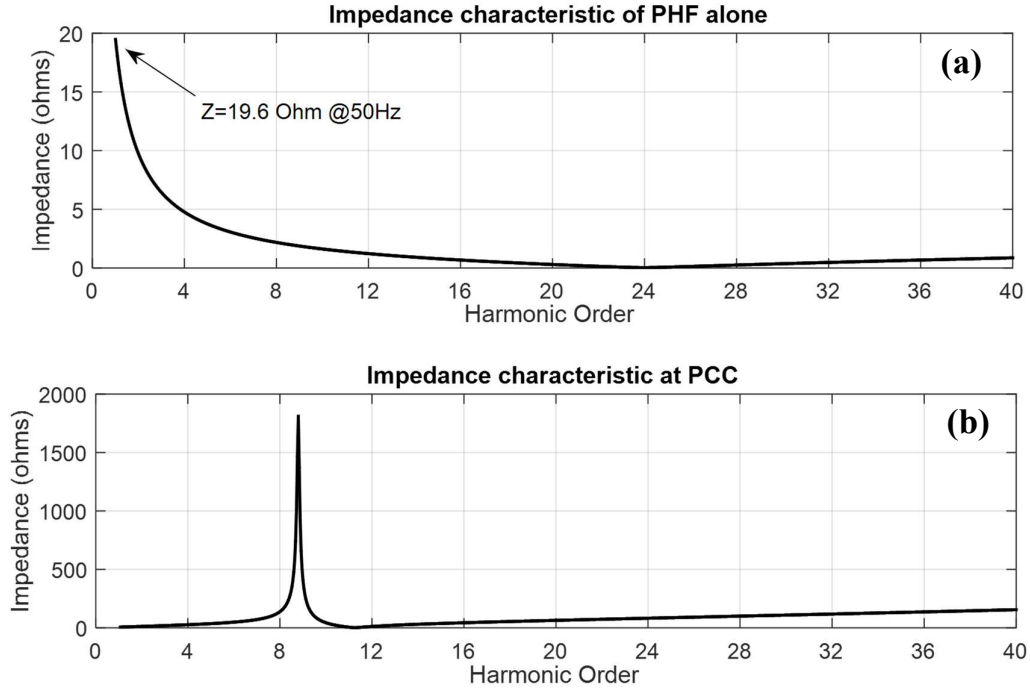


Figure 4.10. PHF Impedance characteristic. (a) PHF impedance characteristic, (b) impedance characteristic at PCC

4.3. Performance Comparison

In this section, a comparison between the conventional scheme, the PHF connected to tertiary winding scheme and the proposed PDC scheme is presented. Figure 4.11 shows the potline Rectifier scheme of the proposed PDC scheme. The PHF tuned to eliminate the 3rd, 5th, 7th and 11th order with total reactive power compensation of 240Mvar for the conventional and PHF connected to the tertiary winding scheme. For the PDC scheme, the PHF tuned at 5th, 12th and 24th with same reactive power compensation capability. ALBA designed their new potline 6 to supply the required DC power at N-2 contingency, where N represent the number of Rectifier units in service. The potline operates at 480KA and 1880VDC.

The three schemes performances are evaluated at three operating conditions with PHF and without PHF.

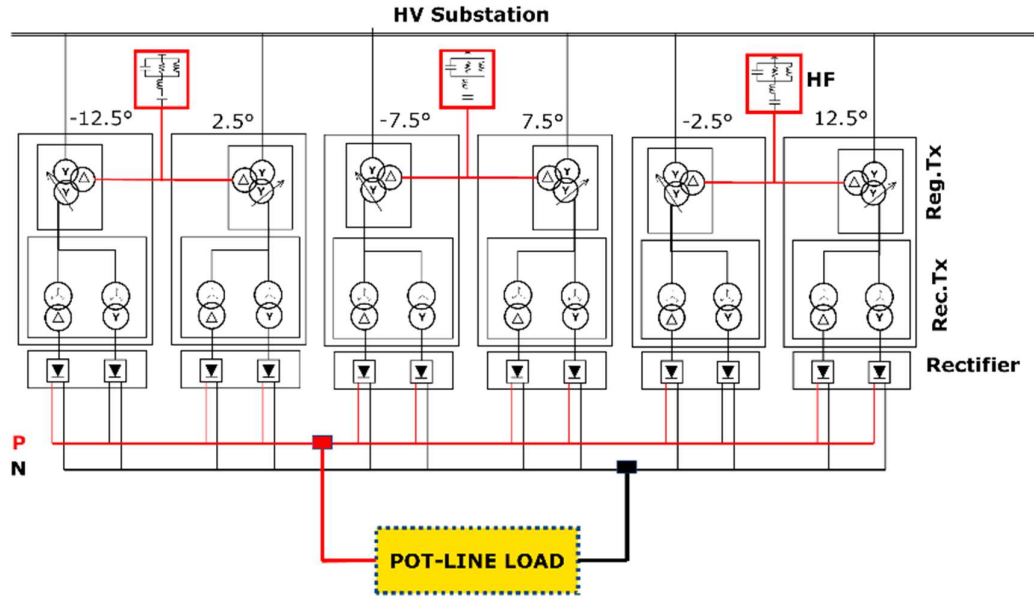


Figure 4.11, Proposed potline PDC scheme

The rectifier transformer no load voltage output is assumed to have 0.3% unbalanced as this unbalance is always there in practice (S.Furuki et al., 2008). The parameters used in both models are shown in Table 4.1. The Rectifier phase shift arrangement in PDC scheme must be connected as shown in Figure 4.11, in order to eliminate the $12n \pm 1$ ($n=1,3, 5...$) harmonic. The simulation results summary for N, N-1, N-2 operating conditions are respectively shown in Figure 4.12, Figure 4.13 and Figure 4.14 for N-2 operating condition. The simulation performed at minimum short circuit power level (worst case scenario) in order to evaluated the current harmonic distortion. Performing the simulation at maximum short circuit level will result in same output however, with lower current harmonic distortions and slightly higher voltage harmonic distortion. The Simulink models of the three schemes are given in appendix B.

At the N operating condition (all units are in service), the conventional scheme has satisfied the IEEE 519 recommended values. However, the unit percentage TDD has exceeded the recommended limit regardless whether the PHF is in service or out of service. At PCC, the percentage THD and TDD is below the IEEE 519 values. The PHF connected to the tertiary winding scheme is satisfying the IEEE 519 when all PHF's are in service. However, when one unit of PHF is taken out of service, the unit percentage TDD is exceeding the IEEE 519 limits. Therefore, the proposed scheme satisfies the IEEE 519 even when the PHF is out of service. It should be highlighted that in the proposed scheme when running with one PHF taken out of service, the THDv slightly exceed the limit by 0.06% which due to disconnecting one PHF from two Rectifier units. Removing one PHF from the potline will reduce the harmonic attenuation capability by 33%.

When the potline running at N-1 (one Rectifier unit is out of service), the conventional scheme harmonic distortion at PCC with PHF in service is still below the limits. However, unit percentage TDD is above the limit. When the PHF is out of service, the percentage THD at PCC and the unit TDD are exceeding the limits. The PHF connected to tertiary winding scheme operating almost similar to the N operating condition. The proposed scheme in this case has slightly lower capability of attenuating the harmonics than the PHF connected to the tertiary winding scheme when the PHF is out of service. This is because the number of PHF's installed in the proposed PDC scheme is lower by 50%.

At N-2 operating condition (two Rectifier units out of service), the overall harmonics distortion is higher than that for the N-1 operating condition with the same harmonic distortion behavior. The comparison between the three conditions should be focused on the normal operating

condition (All Rectifier units are in service) as it represents about 80% of the operating condition in a year.

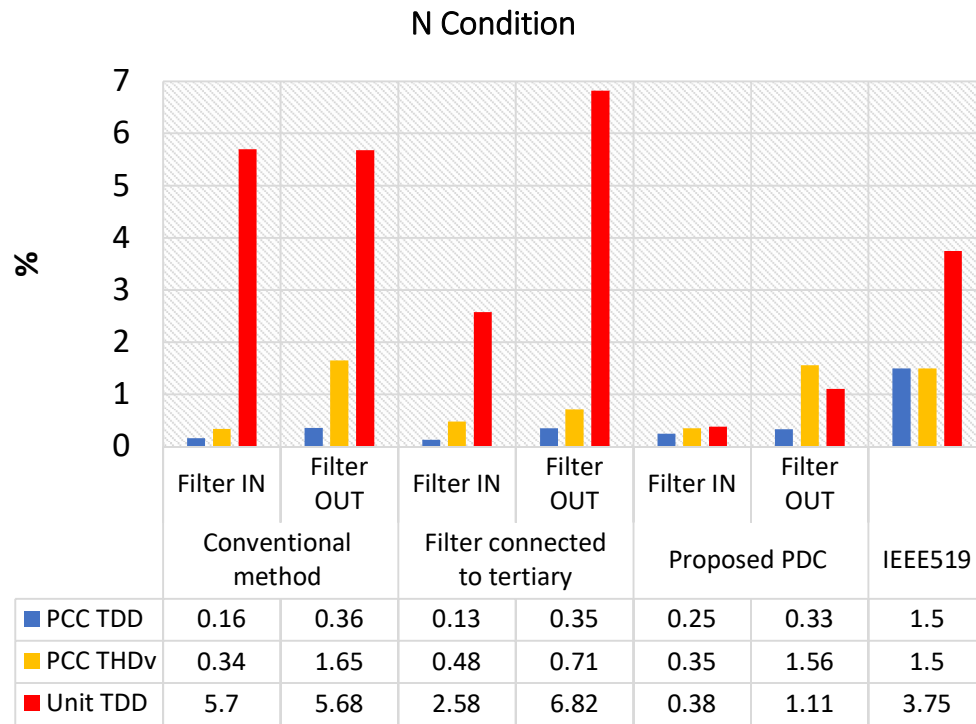


Figure 4.12, Simulation results summary of the N operating condition

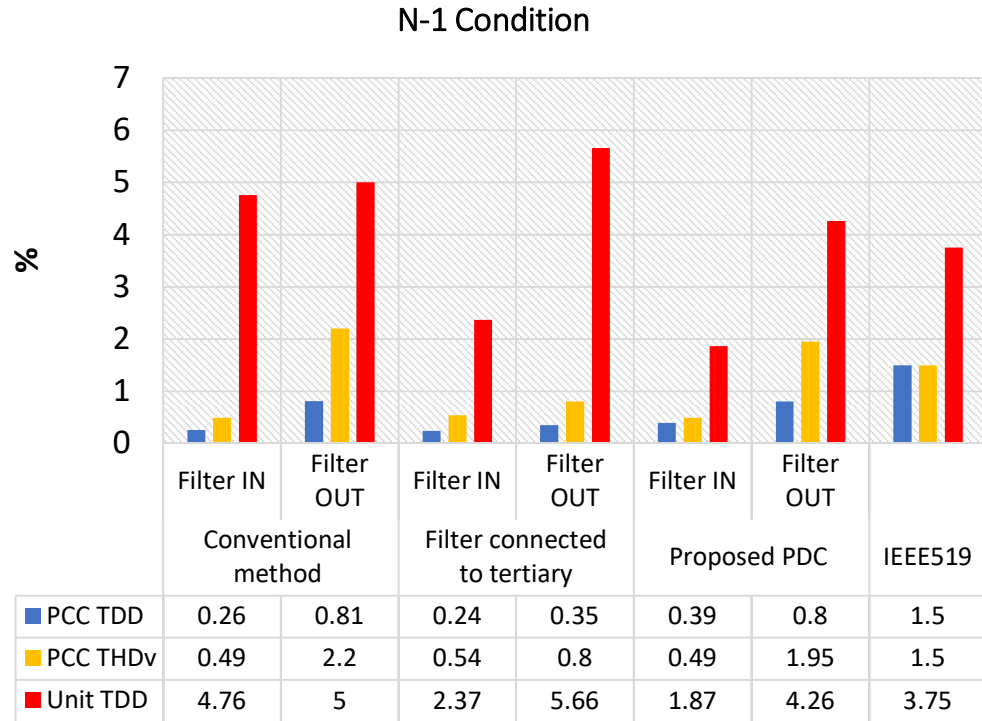


Figure 4.13, Simulation results summary of the N-1 operating condition

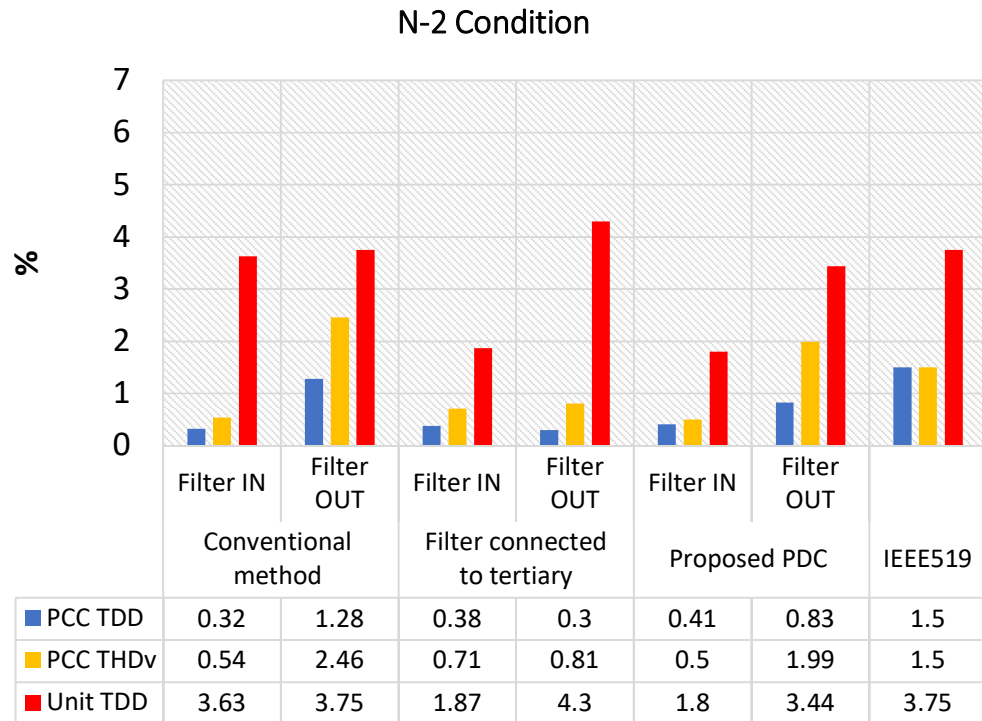


Figure 4.14, Simulation results summary of N-2 operating condition

4.3.1. Discussion

4.3.1.1. Harmonics Attenuation Capability

From the obtained results, it can be seen that the proposed scheme can decrease the overall harmonic distortion, especially in the regulating transformers. On the other hand, ALBA PL6 scheme will not prevent the characteristic harmonics from flowing into the regulating transformer. Looking at the three operating scenarios, the proposed PDC performance is better in attenuating the overall harmonic distortions as compared to the conventional and the ALBA PL6 scheme by improving the harmonic suppression performance which leads to better power quality.

4.3.1.2. Practical Consideration

In the proposed PDC scheme, there will be six planned outages per year for the Rectiformers and three for the block PHF's. Based on my experience as an engineer in ALBA, it is reasonable to expect some 12 days per year to do maintenance for the each Rectiformer and 3 days per year for each block PHF which means that 23% of year the potline is not running under normal operating condition (Rectiformer is out of service or Block PHF is out of service) and 77% of the year the potline will run under normal operating condition (All Rectiformers and Block PHF's are in service). Based on the proposed potline scheme, the maintenance of the block filters shall be done before or after all maintenance activities are completed on the Rectiformer units. This is required to insure minimum distortion by maintaining the parallel link closed on each block. During the 77% of the year, the 12th order branch filter is not required since the parallel links will effectively eliminate the 11th 13th order harmonics. However, this branch

is required to be in service when one Rectifier unit from the same block is out of service as well as to support the reactive power requirements.

4.3.1.3. Cost and Space

In the proposed PDC scheme, there are three PHF units as compared to six required for ALBA PL6 scheme. Consequently, the space requirements will reduce. However, the number of the required circuit breakers for the PHF units will increase in the proposed PDC scheme. The cost of the three PHF units as compared to six circuit breakers shall be evaluated by the owner. The maintenance and spare parts requirements for the PHF is relatively higher than circuit breakers. Indoor type switchgear is reliable with minimal maintenance requirements. Table 4.2 summarize the comparison between the conventional, ALBA PL6 and the proposed PDC potline schemes. In the conventional scheme, the PHF is directly connected to the high voltage feeding bus.

TABLE 4.2
Comparison Summary Between Conventional, ALBA PL6
and PDC Scheme

Criteria	Conventional	PL6	PDC
Harmonic Attenuation	*	**	***
Operational Flexibility	***	**	*
Cost	***	**	**
Space	**	*	***
Number of PHF Units	***	*	**

4.4. Conclusion

The proposed PDC scheme of 24 pulse system has been successfully modeled and simulated in MATLAB Simulink environment. The performance of the scheme is evaluated by showing the harmonic contents of unit 1, parallel link and PHF currents. The parallel link has effectively traps the targeted harmonic orders which result in a primary current with less than 1% THD flowing into the regulating transformer. In addition, the proposed PDC aluminum potline Rectifier scheme then has been modeled and simulated. The proposed scheme shows high capability of reducing the overall harmonic distortion levels at PCC as well as at each unit terminal at normal operating condition which represent almost 80% of the year. Comparison of the proposed PDC scheme with conventional, and ALBA PL6 has been discussed in terms of harmonic attenuation capability, operation flexibility, cost and space requirements.

Only half of the number of the PHF is required in the proposed PDC scheme as compared to the ALBA PL6 scheme. Tuning the PHF to target 11th and 13th harmonic order is not required as shown in Table 4.2 in the proposed scheme when it is running under normal operating condition due to the presence of the parallel links between adjacent Rectifier units. This research could also open the domain for new ideas for optimizing the PHF design (Xin Li, W. Xu, Tianyu Ding, 2017).

Chapter 5

Shunt Active Power Filter for Aluminum Pot Line Rectifiers

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Chapter 5

Shunt active power filter for Aluminum Pot Line Rectifiers

5.1. Introduction

Control of harmonics can be archived mainly by three methods:

1. Passive Filters
2. Phase Multiplication
3. Harmonics compensation or injection (Active Filters)

Passive harmonic filter is affected by the change in the power network which will result in retuning and may increase the harmonic distortions (J.C. DAS, 2015). Smelters are always in continuous improvements for enhancing the efficiency and increasing the production. For this reason, many changes in the network is expected to take place. For example, generators may be added to the power network for obtaining extra megawatts to satisfy the smelter demand. In addition, distribution transformers may be installed to interconnect different substations to have flexible and redundant power sources. These changes can alter the source or network impedance and may lead to undesired effects on the passive harmonic filter.

On the other hand, the second method (phase multiplication) will reduce the AC input line current harmonics and DC output voltage ripple. However, due to the conditions that never fulfilled and other reasons discussed in section 1.2 makes this method alone not sufficient.

In this chapter, the third method will be employed to eliminate the harmonics in a pot line Rectifiers system because it is considered as a modern solution for harmonic distortion problems. L. Gyugyi and E. C. Strycula (1976) introduced the first design of harmonic compensators under the name of “Active AC Power Filters” consisting of PWM inverters using power transistors concept. However, the implementation was not possible due to unavailability of the device with the required power at that time.

H. Akagi, Y. Kanazawa, and A. Nabae (1984) introduced a new control strategy for active filter (AF) based on an instantaneous reactive power compensator (instantaneous $p-q$ theory) and later on, the same control strategy developed to provide more adequate compensation characteristic. The most commonly applied control strategies for AF are the instantaneous active and reactive power theory algorithm (M. Lada et al., 2010), and the Synchronous Reference Frame Method ($d-q$ transformation) (A. K. Al-Othman et al., 2016). There are other time domain methods, such as high pass and low pass filter method have also been used. However, due to their flaws in extracting the magnitudes and phase angle of the harmonics accurately, these methods are not adopted. A review of the control techniques was presented by D. Schwanz et al., (2016).

Frequency domain analysis methods has also been used for extracting the reference current for AF by computing the harmonics using discrete Fourier transform (DFT) technique (M. Karbasforooshan and M. Monfared 2016) and (M. Taleb 2016). This approach is robust, noise tolerant and conducive to remove of the fundamental load current harmonics (M. R. Iravani et al., 2005). Hence, the DFT approach is adopted and will be covered in this research work.

5.2. Parallel Active Filter for Harmonic Current Source

Rectifier is considered as a harmonic current source (nonlinear load) equipment. The principle of a shunt active filter for a harmonic current source is shown in Figure 5.1 (F. Zheng and J. Lai, 1996).

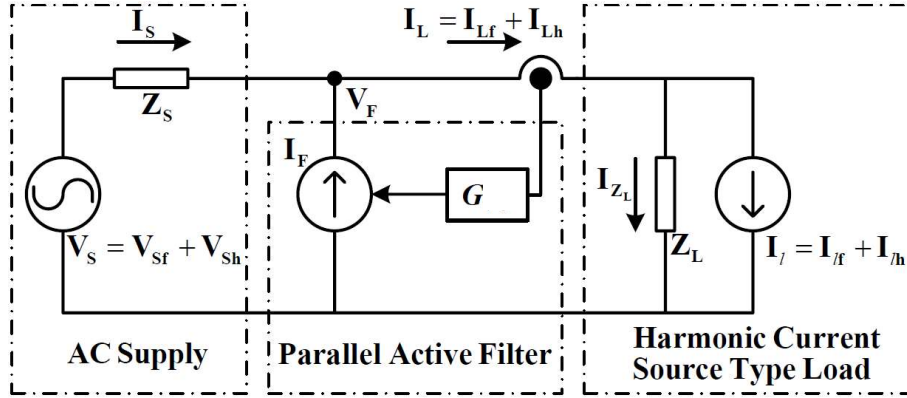


Figure 5.1, Shunt active filter for a harmonic current source

In Figure 5.1, V_S is the source voltage of the AC supply, Z_S is the source impedance and Z_L is the equivalent load impedance. In this case, the rectifier is represented as an equivalent harmonic current source (I_l). The transfer function of the active filter is represented as (G), which includes the control circuit along with its time delay.

The active harmonic filter is represented as a current generator (I_F). I_F is equal to the harmonic current magnitudes but with 180° phase different with respect to the load current (I_L). The filter current is defined by the following equations:

$$I_F = GI_L \quad (5.1)$$

$$I_S = I_L - I_F = (1 - G)I_L \quad (5.2)$$

$$I_L = I_l + I_{ZL} = I_l + \frac{V_S - Z_S I_S}{Z_L} = I_l + \frac{V_S}{Z_L} - \frac{Z_S}{Z_L} I_S \quad (5.3)$$

Substitute equation (5.3) in (5.2), yields:

$$I_S = \left(\frac{Z_L}{\frac{Z_L}{1-G} + Z_S} \right) I_l + \frac{V_S}{\left(\frac{Z_L}{1-G} + Z_S \right)} \quad (5.4)$$

Substitute equation (5.4) in (5.2), yields:

$$I_L = \left(\frac{\frac{Z_L}{1-G}}{\frac{Z_L}{1-G} + Z_S} \right) I_l + \frac{\frac{V_S}{1-G}}{\left(\frac{Z_L}{1-G} + Z_S \right)} \quad (5.5)$$

In an ideal parallel active filter, $G(s)$ is equal to zero at the fundamental frequency ($|G|_f = 0$) and approximately equal to unity at all harmonic frequencies, $|G|_h \approx 1$ (F. Zheng and J. Lai, 1996). Therefore, the following approximation can be considered at the harmonic frequencies.

$$\left| \frac{Z_L}{1-G} \right|_h \gg |Z_S|_h \quad (5.6)$$

If condition in (5.6) satisfied, then equations (5.1), (5.4) & (5.5) can be rewritten as:

$$I_F = I_{Lh} \quad (5.7)$$

$$I_S = 0 \quad (5.8)$$

$$I_{Lh} = I_{lh} + \frac{V_S}{Z_L} \quad (5.9)$$

Where, “h” represent the harmonics components.

Equation (5.8) shows that the supply current (I_s) becomes sinusoidal when (5.6) is fulfilled which is the required condition for parallel active filter operation. Equation (5.6) shows that the power active filter performance is determined by G , Z_s and Z_L . Which mean that the PAF operation is determined by Z_s and Z_L however for pure current source $Z_L \gg Z_s$, PAF cancels the load current harmonics since Z_L goes to infinity. So, equation (5.4) becomes:

$$\frac{I_s}{I_l} = 1 - G \quad (5.10)$$

Equation (5.10) shows that the parallel active filter is not affected by the supply impedance and hence this is considered as a major advantage of parallel active filter over passive filter.

5.3. Shunt Active Power Filter (SAPF)

Active filters can be classified into two configurations; namely shunt and series connected. At present, SAPF are more preferable than series in terms of form and function (H. Akagi, 2006) and it is currently more recognized configuration in the literature. SAPF is connected in parallel to the harmonic source and injecting appropriate harmonics current into the AC system by continuously monitoring the load current. The system configuration of the SAPF is shown in Figure 5.2. The SAPF is connected in parallel with three phase diode rectifier load. The SAPF extracts the fundamental current and its phase angle from load current using DFT algorithm and then convert it to time domain. The reference current (I_h) is calculated by subtracting the fundamental current (I_{Lf}) from the load current (I_L). Finally, the SAPF current (I_A) is subtracted from the reference current (I_h). The result of this subtraction is then send to a hysteresis controller which will generate the switching pattern of the inverter. This switching pattern will force inverter output to follow the harmonics generated by the load.

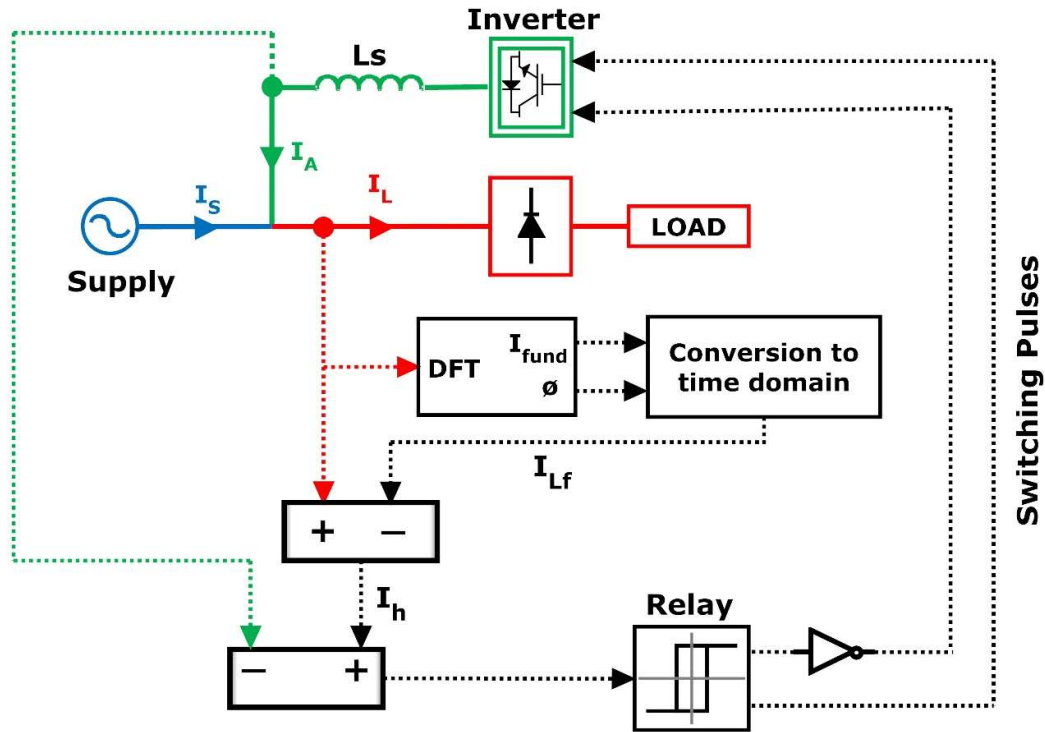


Figure 5.2, Configuration of the SAPF

At steady state condition, the active filter current (I_A) can be found from Figure 5.2 as follow:

$$I_{Aa} = I_{La} - I_{Lfa} = I_{ha} \quad (5.11)$$

$$I_{Ab} = I_{Lb} - I_{Lfb} = I_{hb} \quad (5.12)$$

$$I_{Ac} = I_{Lc} - I_{Lfc} = I_{hc} \quad (5.13)$$

Where:

$I_{A(abc)}$: Active filter currents

$I_{Lf(abc)}$: Fundamental components of the line currents

 $I_{L(abc)}$: Load Currents

$I_{h(abc)}$: Harmonics currents

Applying the Kirchhoff's current law at PCC, yields:

$$I_{sa} = I_{La} - I_{ha} = I_{La} + I_{Lfa} - I_{La} = I_{Lfa} \quad (5.14)$$

$$I_{sb} = I_{Lb} - I_{hb} = I_{Lb} + I_{Lfb} - I_{Lb} = I_{Lfb} \quad (5.15)$$

$$I_{sc} = I_{Lc} - I_{hc} = I_{Lc} + I_{Lfc} - I_{Lc} = I_{Lfc} \quad (5.16)$$

The supply current drawn out from the PCC will be harmonic free as can be seen from equations (5.14) to (5.16).

5.3.1. Discrete Fourier Transform (DFT)

The detailed DFT block diagram is shown in Figure 5.3, which performs a Fourier analysis on the current signal and obtains the fundamental component in terms of their peak magnitude and phase angle over a running window of one cycle. The Clock block provides the current simulation time at each simulation step.

The real and imaginary components of the signal have been calculated using DFT as following (A. Phadke and J. Thorp, 2009):

$$Y_r = Y_p \cos \theta = \frac{2}{N} \sum_{k=0}^{N-1} y_k \sin k\omega\Delta t \quad (5.17)$$

$$Y_i = Y_p \sin \theta = \frac{2}{N} \sum_{k=0}^{N-1} y_k \cos k\omega\Delta t \quad (5.18)$$

Where:

N: the number of samples in a data window

Δt : is sampling interval time and it is equal to $\frac{1}{f_s}$

y_k : value of signal u at sample k .

Based on (5.17) and (5.18), the magnitude and the phase angle of the fundamental components can be calculated as:

$$Y_p = \sqrt{Y_r^2 + Y_i^2} \quad (5.19)$$

$$\theta = \tan^{-1} \left(\frac{Y_i}{Y_r} \right) \quad (5.20)$$

Y_r is real part of phasor.

Y_i is imaginary part of the phasor.

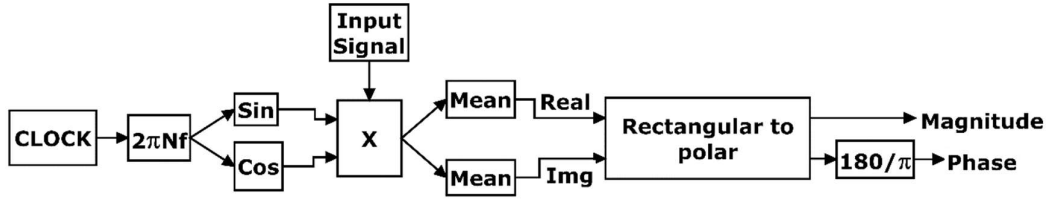


Figure 5.3, DFT block diagram

If a signal with 100A peak fundamental and distorted by a 5th harmonic current with 20A peak is introduced to a DFT algorithm at a sampling rate of 1000 samples per cycle for 5 cycles, the response of the DFT algorithm result is shown in Figure 5.4. Here, the signal magnitude is assumed to be zero for the first cycle. It can be seen that the algorithm need one full cycle to obtain the peak value. The sin and cos factor/coefficient are shown in Figure 5.5. The reference current is calculated after one cycle as shown in Figure 5.5.

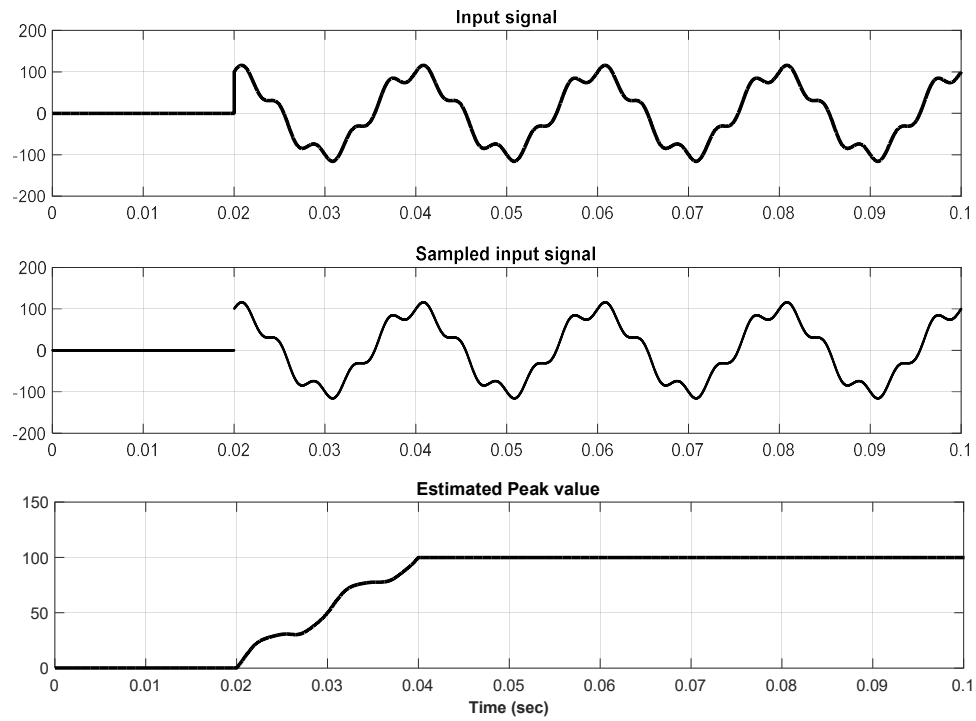


Figure 5.4, Input signal, sampled signal and the estimated peak value.

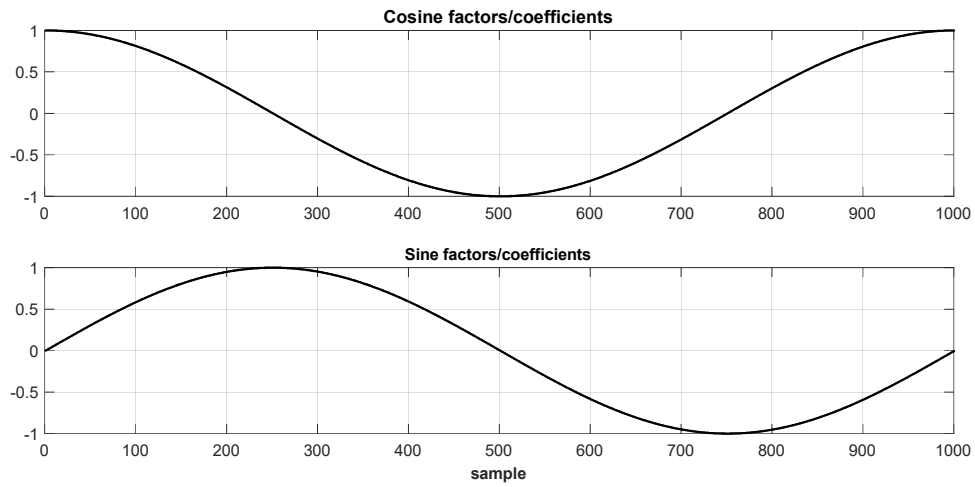


Figure 5.5, Sin and Cos factors

The main advantage of this algorithm is that it can attenuates all harmonics and noise effectively as can be observed from frequency response of the DFT shown in Figure 5.6. When the system has a varying load, this method is impractical because of the time delay introduced by this technique (D. Schwanz et al., 2016). However, the pot line load demand in this case will be stable.

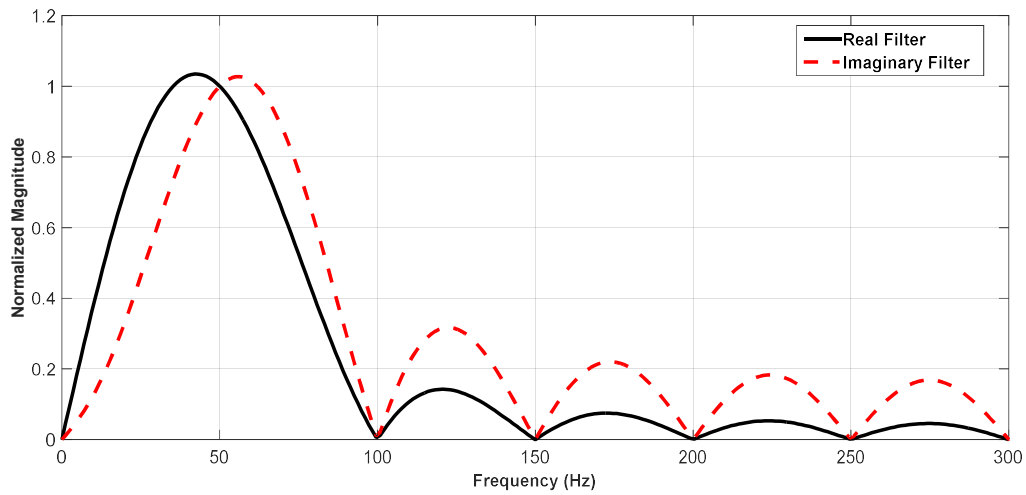


Figure 5.6, Real and imaginary filter frequency response

5.4. SAPF Test model simulation

The test model of the SAPF is shown in Figure 5.7, which consists of two rectifiers with 5000A DC load connected to each rectifier. The SAPF consists of three-phase inverter, line inductance and circuit breaker. The control block subsystem is shown in Figure 5.8. The fundamental current signal is extracted by using the DFT algorithm and then converted from frequency domain to time domain. The Simulink model for extraction the fundamental current signal is shown in Figure 5.9. The reference current (I_h) signal are obtained by subtracting the load current signals from fundamental current signals. The reference current is then fed into a gate control block that will generate the required gate pulses for the three-phase inverter. The gate control block contains hysteresis controllers as shown in Figure 5.10. The gate control philosophy was discussed by M. Taleb (2016).

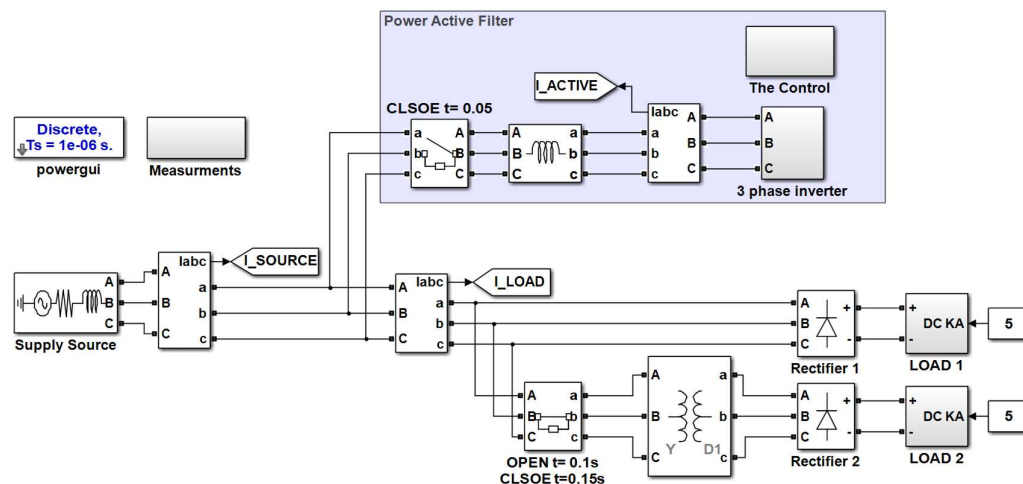


Figure 5.7, SAPF Simulink Test model

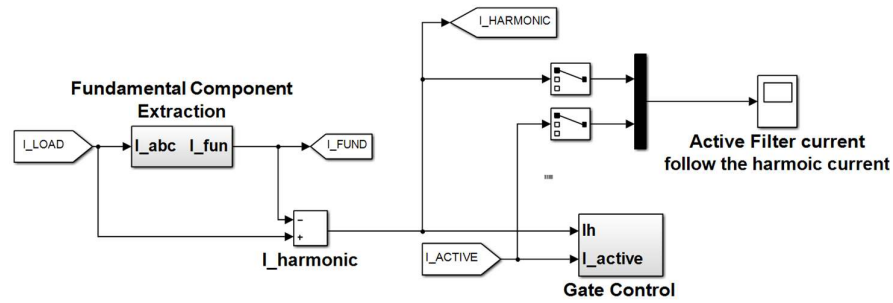


Figure 5.8, Inside the control block

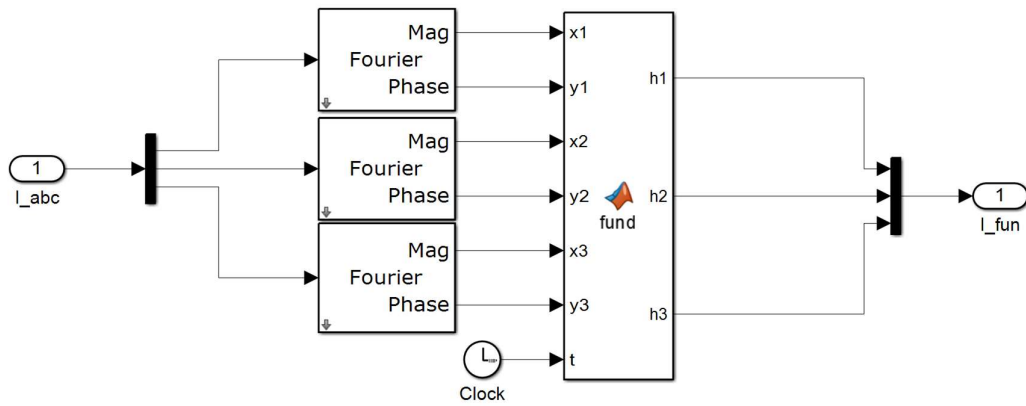


Figure 5.9, Fundamental current signals extraction and time domain conversion

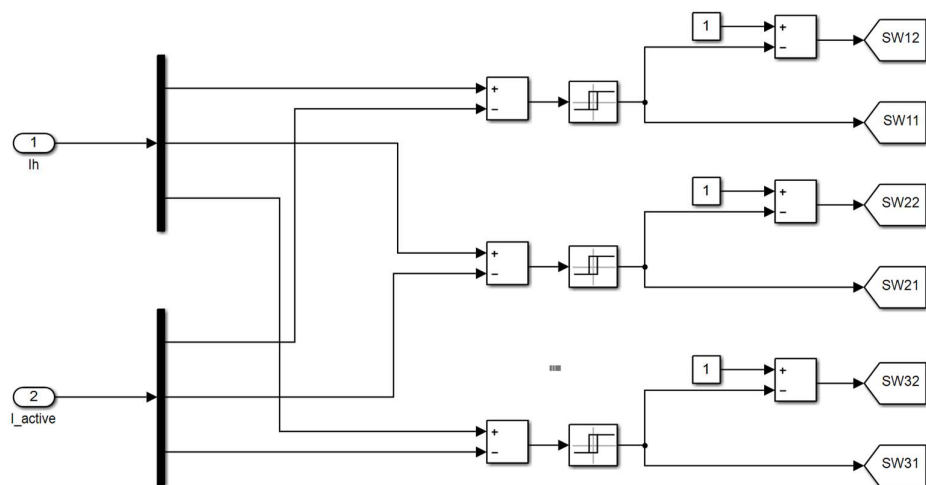


Figure 5.10, Three phase inverter gate control pulses generation

5.4.1. Simulation Results

The SAPF test model is shown in Figure 5.7 is simulated and its performance is shown in Figure 5.11. At $t=0$ sec, rectifier 1 and 2 are in service operating in parallel to create 12 pulse output system with TDD equal to 3.4%. At $t=0.05$ sec, the active filter is connected which reduces the TDD to 0.24%. To examine the response of the SAPF, rectifier 2 is taken out of service at $t=0.1$ sec creating a 6-pulse output system and return back in service at $t=0.15$ sec. It can be seen from Figure 5.11 that the system responded adaptively to this change and maintain the source TDD below 0.3%

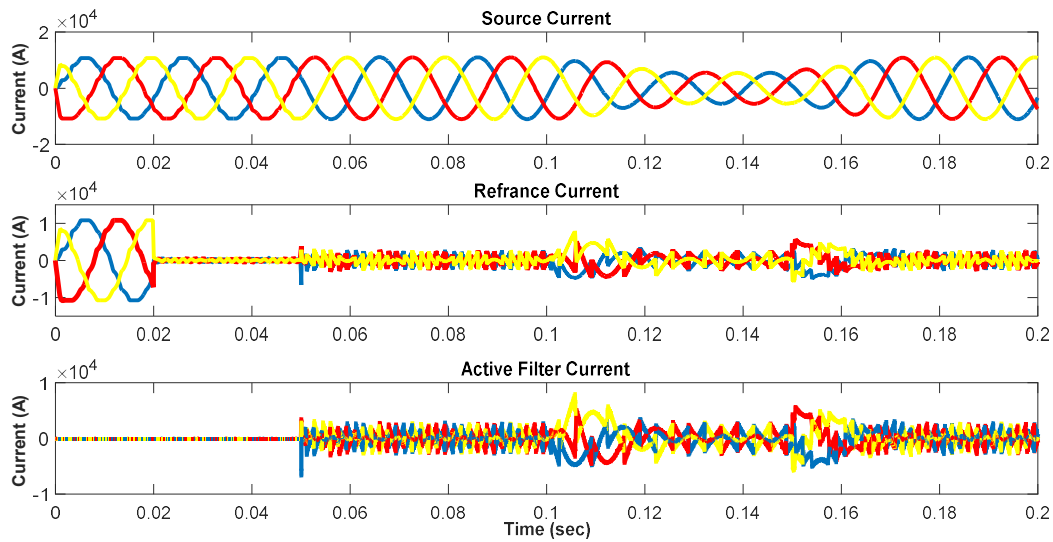


Figure 5.11, Performance of the SAPF results

As the system load by changed from 12-pulse to 6-pulses by disconnecting rectifier 2, the SAPF change its response to maintain the input current at very low TDD. It can be seen from Figure 5.12 that the SAPF current I_F changed as the system load changed. At $t=0.1$ sec, the load current reduced and system configuration changed from 12-pulse to 6-pulse. The SAPF has

reacted to this change and adjust the compensation current I_F to maintain the input current sinusoidal.

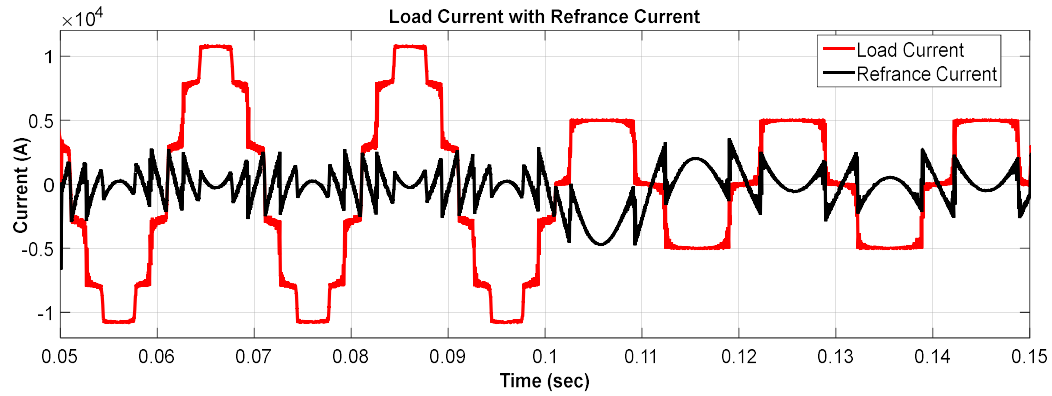


Figure 5.12, Load current with reference current of phase A

The SAPF tracking and switching performance of the hystresis current control (available from MATLAB Simulink components library) is shown in Figure 5.13. The output of the hystresis controller is either 0 or 1, which is fed to the gates of the inverter switches. Under steady state condition, the active filter current will trace the reference current as discussed in section 5.3.

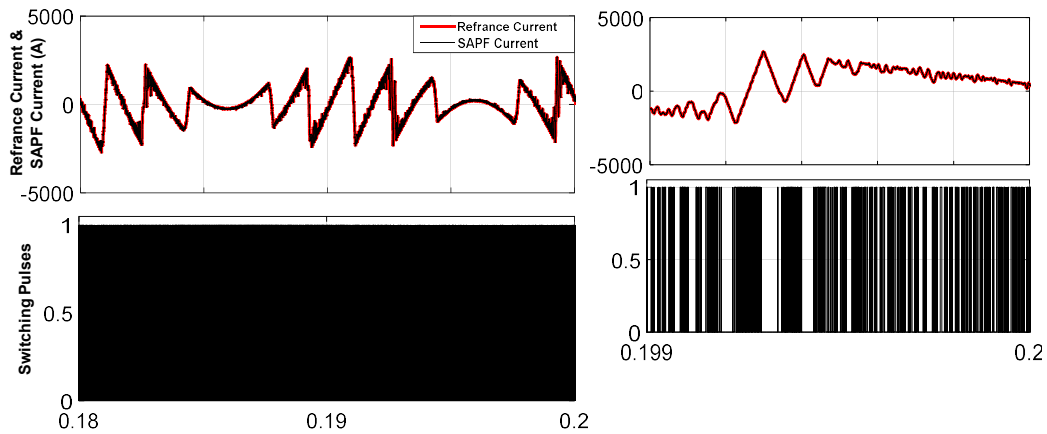


Figure 5.13, SAPF tracking and switching performance of the hysteresis current control

The current source when rectifier 1 is acting alone with SAPF switch on at $t=0.05$ sec is shown in Figure 5.14. The TDD is equal to 18.7% before switching on the SAPF and equal to 0.2% after switching on the SAPF.

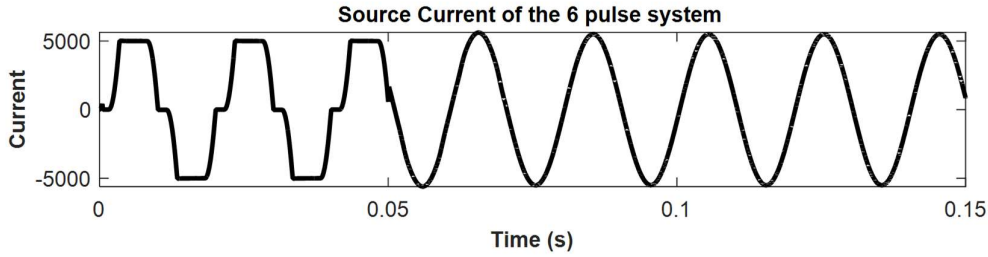


Figure 5.14, Phase A source current waveform before and after switching on the SAPF

5.5. Aluminum Pot Line Scheme with SAPF

Simulation and Results

In this section, an aluminum pot lines Rectifier scheme with SAPF will be presented. With same pot line Rectifiers structure, the SAPF is connected to the primary side of the rectifier transformer as shown in Figure 5.15 in order to ensure harmonics free current is flowing into the regulating transformer and to minimize the harmonic distortion at PCC. The parameters of the system are given in Table 4.1.

The simulation model of the system is shown in Appendix C. The system has been simulated without reactive power compensation because the objective here is to evaluate the harmonic distortions at PCC as well as at unit terminal as has been discussed in Chapter 4 for other pot line schemes.

The results for N operating condition is shown in Figure 5.16. When the poutine is running under normal operating condition which represent 80% of the year, the SAPF scheme shows lower harmonic distortion as

compared to the proposed PDC and PL6 schemes. When the SAPF is taken out of service in SAPF scheme, the behavior is almost similar to PL6 scheme as both are with the same configuration.

In all the operating conditions when the filter is in service, the SAPF scheme is showing superior capability of attenuating the harmonics at PCC and at unit terminal as compared to the proposed PDC and the PL6 schemes as shown in Figure 5.16, 5.17 and 5.18. When the SAPF is out of service in all the operating conditions, the TDD at PCC satisfied the IEEE 519 recommended values. However, the THD_v exceeded the IEEE 519 recommended values due to penetration of the characteristic harmonics component into the PCC. When the SAPF is out in all the cases, the unit TDD has exceeded the limits because the filter is disconnected from the unit which is the same situation for the PL6 scheme.

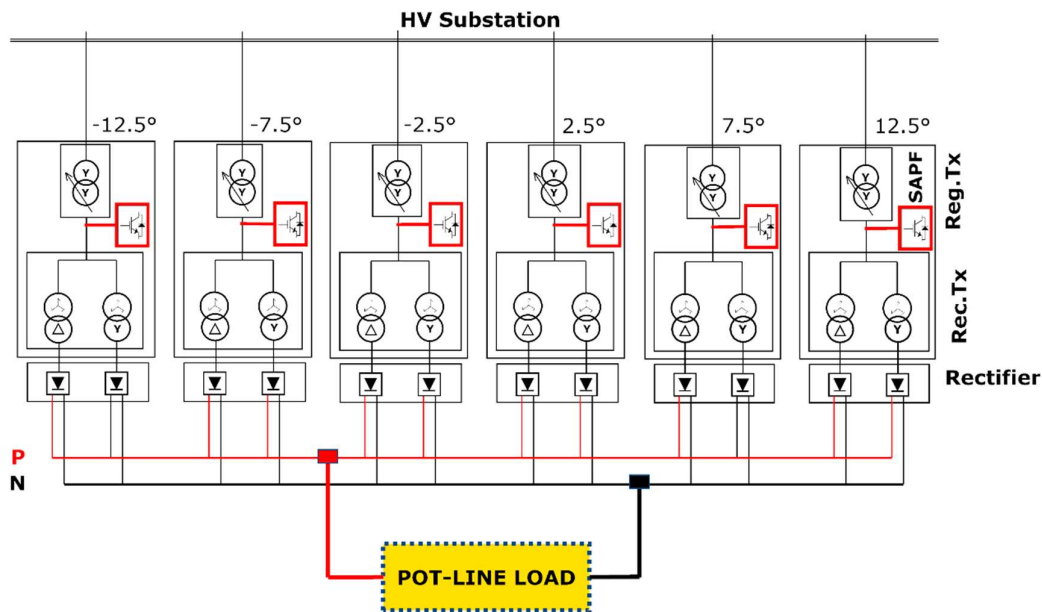


Figure 5.15, Pot line Rectifier scheme with SAPF

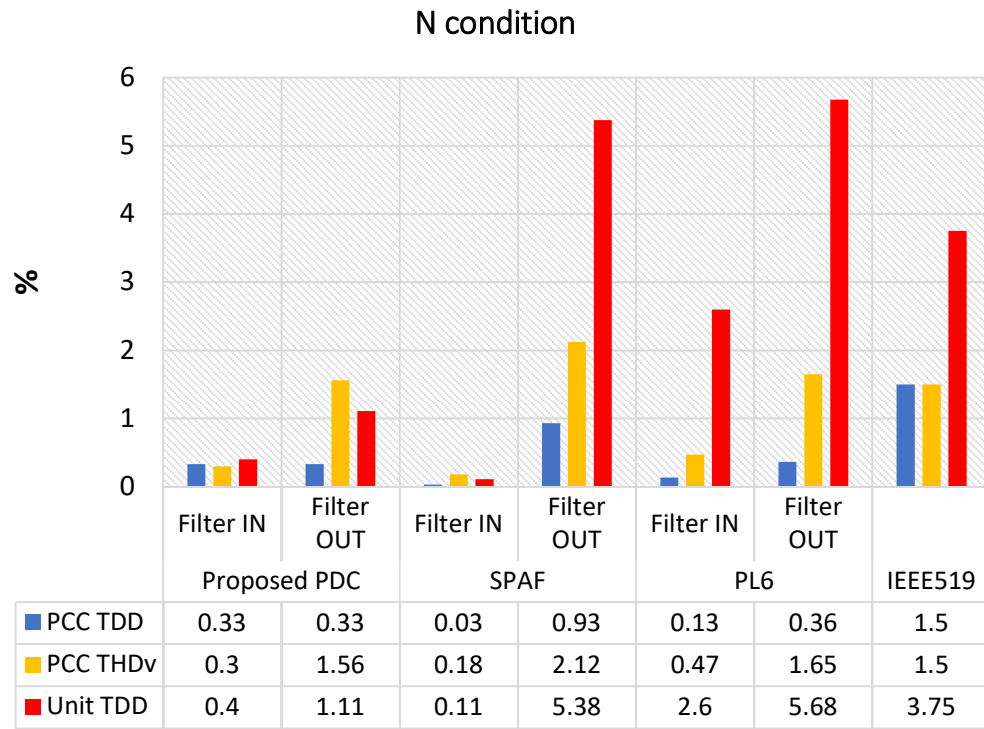


Figure 5.16, Simulation results summary of the N operating condition

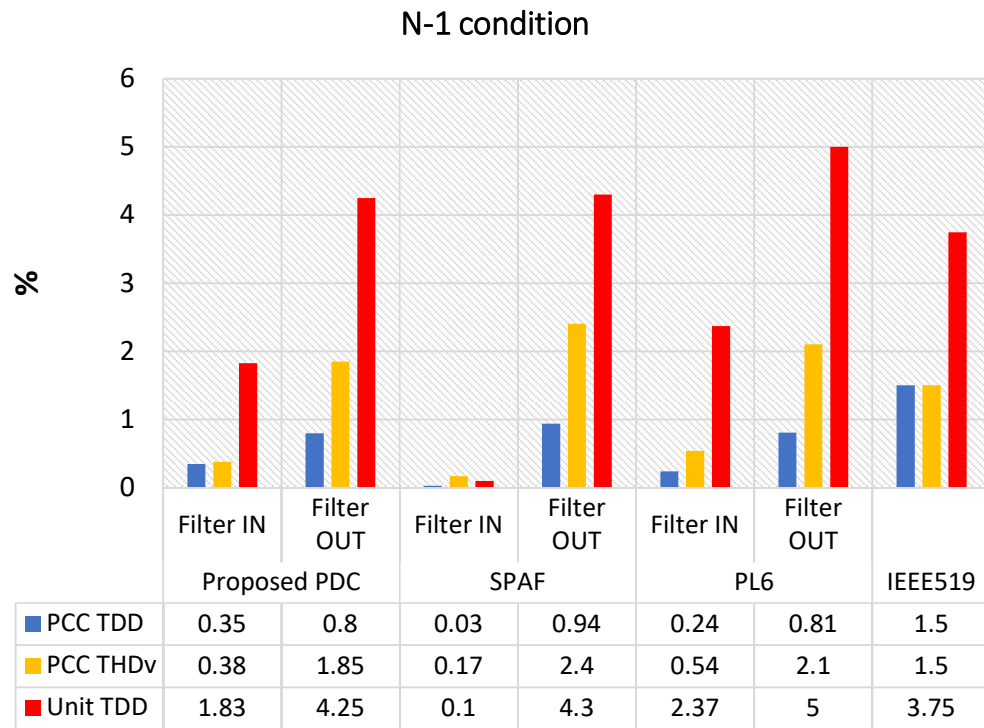


Figure 5.17, Simulation results summary of the N-1 operating condition

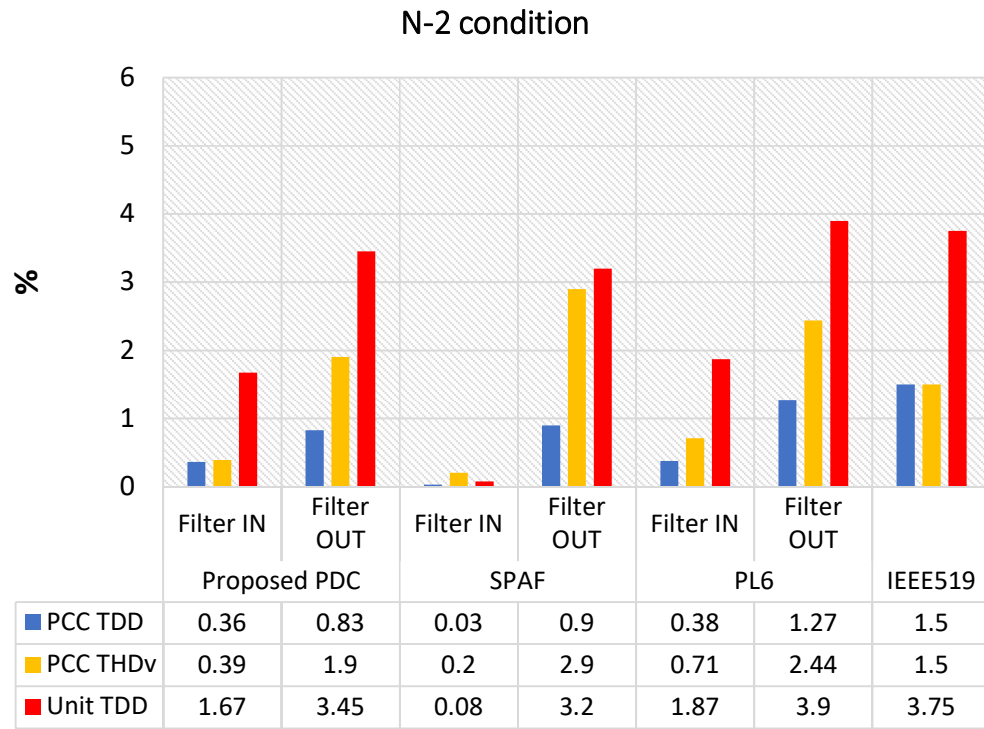


Figure 5.18, Simulation results summary of the N-2 operating condition

5.6. Discussion and Conclusion

Customer needs and requirements will define the potline Rectifiers scheme. Aluminum smelter with their own power generating plant may not focus on harmonics distortion levels in their network but the majority of power consumers will improve the network power factor by reactive power compensation in order to reduce the tension on the generators. Aluminum smelters that purchase the power from other suppliers are required to keep the harmonic distortion levels minimum in order not to affect other consumers and to avoid extra charges from the power supplier. The use of capacitor banks alone for reactive power compensation is possible but with the risk of harmonics amplification. That is why capacitor banks are installed with tuned passive harmonic filters. In chapter 4, two known pot line Rectifier schemes were discussed and compared with the proposed PDC scheme that shows higher capability of attenuating the harmonic distortions. All of the studied schemes in this thesis are equipped with passive harmonic filters and reactive power compensation banks. The resonant risk is always possible whenever passive harmonic filters are used.

Siebert (2002), discussed the future scheme of aluminum smelter pot line Rectifiers. He predicts the future of the rectifier used to be active rectifier type whereas high frequency switching devices will replace the diodes or the thyristors in order to improve the power quality. However, this technology is not available for high current application like Rectifiers due to unavailability of the suitable cost-effective power electronic devices. The same concept can be applied to the passive harmonic filters used in aluminum smelter. Active harmonic filter can be considered as the future to replace the passive harmonic filter in aluminum

smelters. As it can be seen from the results in 5.5, the SAPF scheme has the superior capability of attenuating the harmonics compared to all other schemes discussed in this thesis at normal operating condition.

Some drawbacks of using passive harmonic filter will be revoked as discussed in this chapter. The SAPF used in this chapter is without reactive power compensation elements. In order to compensate the reactive power consumed by the potline, a hybrid SAPF shall be used. The SAPF discussed in this chapter shows good results from the harmonic distortion reduction point of view and it is also suitable for potline load behavior. The SAPF is a good solution as it is self-adaptive and does not involve any risk of resonant with the power network impedance as the SAPF represent a current source independent from the power network impedance. SAPF does not replace the passive filter at this time as it is the most common solution used in aluminum smelter power network. However, hybrid solution can be conceived. The SAPF discussed in this chapter provides an advanced step and proactive action in order to revamp the harmonic distortion equipment.

Chapter 6

Conclusion and Future Work

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Chapter 6

Conclusion and Future Work

6.1. Conclusion

The first objective of this thesis was to study ALBA power network harmonic distortion levels at the main switch houses. Before doing this, a simulation program was selected in order to perform the study. The selection of the simulation program was based on comparing the results of two powerful well-known computer simulation softwares. Based on the obtained result from the test model, MATLAB Simulink was selected to simulated all the models in this thesis. Using Simulink, the IEEE-519 12-pulse model and IEEE-519 72-pulse system model were simulated in order to ensure valid modeling in the simulation. A detailed Rectifier model was simulated to create all the five potlines. All the equipment parameters in the power network were collected from the actual systems data sheets and entered in the Simulink model. The utility supply source is modeled based on the short circuit capacity and the typical reactance to resistance ratio. All the transformers parameters were calculated using the IEEE C37.010 and IEEE C57.12.90-1999 standards. The passive harmonic filter has been also included and verified. The results and the performance of the overall power network has been discussed in Chapter 3.

In Chapter 4, a proposed potline Rectifiers scheme is introduced. A test model for a 24-pulse system has been modeled and simulated in MATLAB/Simulink. The model performance is evaluated by showing the

harmonic contents in the current of unit 1, parallel link and PHF. The parallel link effectively traps the targeted harmonic orders which result to a primary current with less than 1% THD flowing into the regulating transformer. The proposed potline scheme shows high capability of reducing the overall distortion levels at PCC as well as at each unit terminal at N operating condition which represent almost 80% of operating condition in the year. Comparison of the proposed PDC scheme with conventional, and ALBA PL6 has been discussed in Chapter 4. The proposed scheme opens the domain for new ideas for optimizing the PHF design as it can be seen that the number of PHF's as compared to ALBA PL6 scheme has been reduced to half.

In Chapter 5, an investigation study is conducted on the feasibility and performance of using a Shunt Active Power Filter (SAPF) in place of passive harmonic filter (PHF). The structure of the SAPF has been discussed and modeled in Simulink. Frequency domain analysis methods has been used for extracting the reference current for the SAPF by computing the harmonics using discrete Fourier transform (DFT) technique. The performance has been proven using the 12-pulse system model. The SAPF shown good results from harmonic distortion attenuation point of view and it is also suitable for potline load behavior. Unlike PHF, the SAPF solution is adaptive and can run without any risk of resonant when the power network impedance changes as the SAPF represent a current source independent from the power network impedance. The SAPF potline scheme shows superior capability of attenuating the harmonics at PCC and unit terminal compared to proposed PDC and PL6 schemes. The

SAPF discussed in Chapter 5 provides an advanced step and proactive action in order to revamp the harmonic distortion equipment.

6.2. Future Work

The proposed scheme in Chapter 4 open the domain for optimizing the PHF in the PDC scheme. The PHF design can be changed based on recent studies in PHF design and optimization for multipulse rectifiers as discussed by Xin Li et al., (2017). The operation of the overall system and outages can be improved further to include supervisory and synchronizing functions to reduce the man interference. Also, adaptive control for the PHF branch tuned to target 11th and 13th harmonic order can be investigated.

The SAPF has been designed and modeled without reactive power compensation equipment. Since reactive power compensation is mostly required in aluminum smelters, a reactive power compensation bank shall be included to establish a hybrid SAPF. The power rating of the active filter discussed by H. AKAGI (2006). The SAPF topology in this research work intended to be used for high power Rectiformer. The cost discussion of the SAPF used is early to be furnished as this proposed to be the future equipment that replaces the existing mitigation methods that uses passive elements.

Appendix A

Approval emails from ALBA management

The below communications were between the following:

- Mahmood Mohsen: Electrical Engineer in Power Department
- Abdulla Mohd: Power Maintenance Department Superintendent
- Mathew Tharakan: Power Maintenance Department Manager
- Eskander Abdulnabi: Power Operation Department Manager
- Eline Hilal: Public Relations Manager

Please refer to last Email as it is the first.

From: Abdulla Mohd

Sent: Thursday, November 24, 2016 6:20 AM

To: Mahmood Mohsin <Mahmood.Mohsin@alba.com.bh>

Subject: FW: Permission for taking data and parameters form ALBA power network

From: Eline Hilal

Sent: Wednesday, November 23, 2016 5:16 PM

To: Abdulla Mohd <Abdulla.Mohd@alba.com.bh>; Eskander Abdulnabi <Eskander@alba.com.bh>

Cc: Mathew Tharakan <Mathew.T@alba.com.bh>

Subject: RE: Permission for taking data and parameters form ALBA power network

Yes, you may go ahead.

From: Abdulla Mohd

Sent: Monday, November 21, 2016 2:13 PM

To: Eline Hilal <eline.hilal@alba.com.bh>; Eskander Abdulnabi
<Eskander@alba.com.bh>

Cc: Mathew Tharakan <Mathew.T@alba.com.bh>

Subject: RE: Permission for taking data and parameters form ALBA
power network

Good afternoon

Shall we consider this as approval?

Regards

Abdulla

From: Eline Hilal

Sent: Thursday, November 17, 2016 3:15 PM

To: Eskander Abdulnabi <Eskander@alba.com.bh>

Cc: Mathew Tharakan <Mathew.T@alba.com.bh>; Abdulla Mohd
<Abdulla.Mohd@alba.com.bh>

Subject: RE: Permission for taking data and parameters form ALBA
power network

Thanks Eskander for the update.

Regards,

Eline Hilal

Manager - Investor Relations, Public Relations
& Corporate Secretary

Tel: +973 17835100

Tel: +973 17837606

Mob: +973 39907255

Fax: +973 17833822

eline.hilal@alba.com.bh

Aluminium Bahrain

(Alba) B.S.C.

P.O. Box 570,

Manama

Kingdom of Bahrain

www.albasmelter.com

From: Eskander Abdulnabi

Sent: 17 November 2016 15:08

To: Eline Hilal <eline.hilal@alba.com.bh>

Cc: Mathew Tharakan <Mathew.T@alba.com.bh>; Abdulla Mohd
<Abdulla.Mohd@alba.com.bh>

Subject: RE: Permission for taking data and parameters form ALBA
power network

Dear Eline,

The data requested are not confidential and in the same time it is not a
public one. It is a technical data that required & used for any power
system study.

Regards,

Eskander.

From: Eline Hilal

Sent: Sunday, November 13, 2016 1:33 PM

To: Abdulla Mohd

Cc: Mathew Tharakan; Eskander Abdulnabi

Subject: RE: Permission for taking data and parameters form ALBA

power network

Importance: High

Dear Abdulla,

Further to the below correspondence, please consider my email as an official consent, in principle, to access the actual data/parameters of network within Alba provided that Mahmood explicitly states that he has referred to Alba data to generate the analysis and that Alba will be the recipient of the final thesis. Bear in mind too that Eskander needs to confirm that these data which he will make available to the employee is not of confidential nature.

On a separate point, I assume that sharing such data/ stats is not breaching any disclosure the Power Department has and that these data is not considered confidential. If these data is considered public, then the employee should sign on a NDA.

Awaiting Eskander's confirmation on this.

Thanks,

Regards,

Eline Hilal

Manager - Investor Relations, Public Relations
& Corporate Secretary

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Fax: +973 17833822

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Manama

Kingdom of

Bahrain

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From: Abdulla Mohd

Sent: 13 November 2016 12:08

To: Eline Hilal <eline.hilal@alba.com.bh>

Cc: Mathew Tharakan <Mathew.T@alba.com.bh>; Eskander Abdulnabi
<Eskander@alba.com.bh>

Subject: FW: Permission for taking data and parameters form ALBA
power network

Dear Eline

Kind reminder

Regards

Abdulla

From: Abdulla Mohd

Sent: Wednesday, November 02, 2016 8:33 AM

To: Eline Hilal <eline.hilal@alba.com.bh>

Cc: Mathew Tharakan <Mathew.T@alba.com.bh>; Carlos Sanchez
<Carlos.Sanchez@alba.com.bh>; Eskander Abdulnabi
<Eskander@alba.com.bh>

Subject: FW: Permission for taking data and parameters form ALBA power network

Dear Eline, Good morning

Mahmood, our Electrical Engineer is studying MSc degree in Electrical Engineering at University of Bahrain, he is now doing his thesis for the same

The request -as per attached letter from his university advisor- is access to some actual data / parameters of network to asses him to do real case study in designing what we call it “Active Harmonics Filter” – unlike the passive ones we have in SH5 / future of SH1,2 & 3

I believe this study will be a success for the benefit of both Mahmood and Alba

Kindly approve his request in using the parameters requested

Regards

Abdulla Mohd

Act. Superintendent – Power Electrical

From: Mahmood Mohsin

Sent: Thursday, October 27, 2016 1:07 PM

To: Abdulla Mohd

Subject: RE: Permission for taking data and parameters form ALBA power network

Salaam Bu mohd

Please find attached letter form UOB EE department.

Regards

Mahmood Mohsen

Maintenance Electrical Engineer (Power Station)

Aluminium Bahrain B.S.C. | P. O. Box 570, CC 32

Mobile : (+973) 66386555

Office : (+973) 17835468

Mahmood.Mohsin@alba.com.bh

From: Abdulla Mohd

Sent: Tuesday, October 25, 2016 11:01 AM

To: Mahmood Mohsin

Subject: FW: Permission for taking data and parameters form ALBA power network

Salam Mahmood

Please prepare letter from the university and we will sort out with PR

Regards

Abdulla

From: Eskander Abdulnabi

Sent: Tuesday, October 25, 2016 10:54 AM

To: Abdulla Mohd; Carlos Sanchez

Cc: Mathew Tharakan

Subject: RE: Permission for taking data and parameters form ALBA power network

Good Day Abdulla,

I have checked with PR. He needs to go through them.

Regards,

Eskander.

From: Abdulla Mohd

Sent: Tuesday, October 25, 2016 10:46 AM

To: Carlos Sanchez; Eskander Abdulnabi

Cc: Mathew Tharakan

Subject: FW: Permission for taking data and parameters form ALBA power network

Good morning

As you may already aware, Mahmood, our Electrical Engineer is studying MSc degree in Electrical Engineering at University of Bahrain, he is now doing his thesis for the same

The below request is access to some actual data / parameters of network to asses him to do real case study in designing what we call it “Active Harmonics Filter” – unlike the passive ones we have in SH5 / future of SH1,2 & 3

I believe this study will be a success for the benefit of both Mahmood and Alba

Kindly approve his request in using the parameters requested

Regards
Abdulla

From: Mahmood Mohsin

Sent: Tuesday, October 25, 2016 10:41 AM

To: Abdulla Mohd

Subject: Permission for taking data and parameters form ALBA power network

Dear Bu Mohd

As you are aware that I am doing my MSc in UOB since 2014, now I am in the final stage “Thesis”. I have already submitted my thesis proposal

to UOB and got accepted. The proposed thesis is about investigation and mitigation of harmonics in industrial power network of aluminum smelter.

This is required accurate modeling using computer software and in order to create a practical model, data and parameters from actual power network must be used.

I am sending this email to you to obtain a permission from the management for taking data and parameters from ALBA power network to be used in the modeling for my thesis.

ALBA might get benefit from the final results obtained.

Regards

Mahmood Mohsen

Maintenance Electrical Engineer (Power Station)

Aluminium Bahrain B.S.C. | P. O. Box 570, CC 32

Mobile : (+973) 66386555

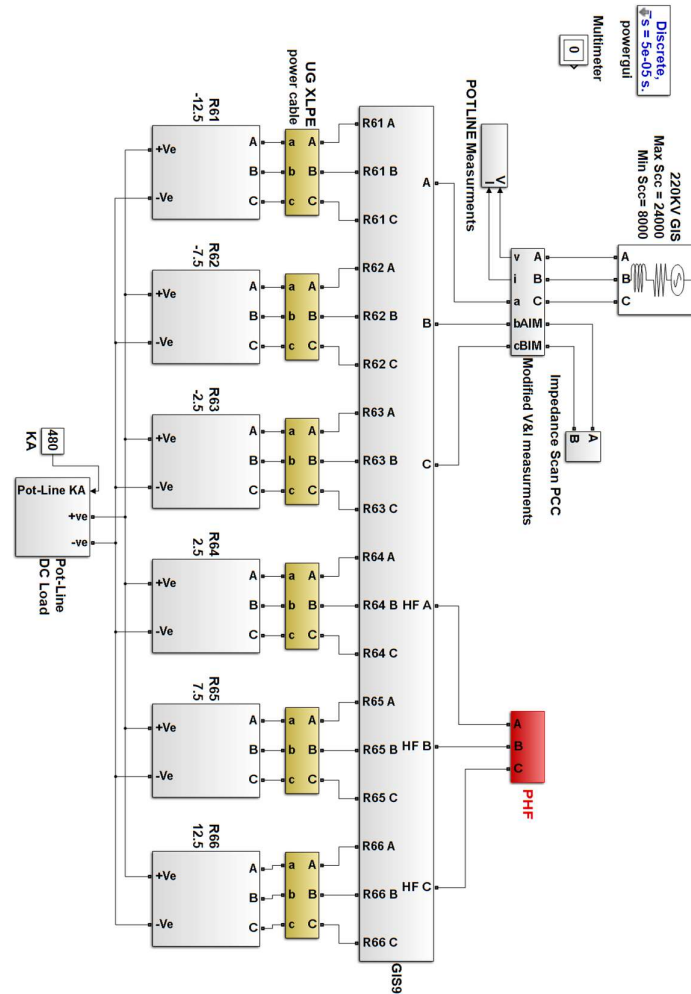
Office : (+973) 17835468

Mahmood.Mohsin@alba.com.bh

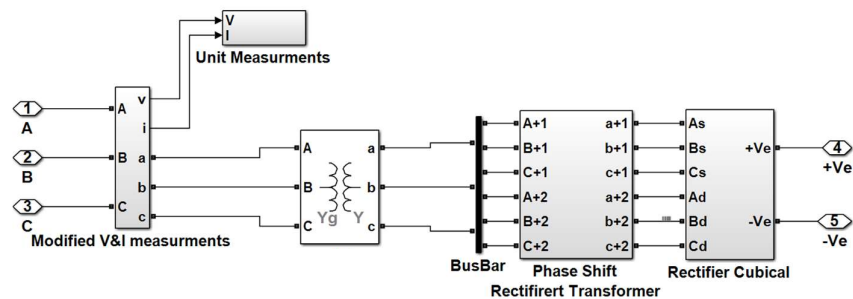
Appendix B

Simulink Models of Rectifier schemes

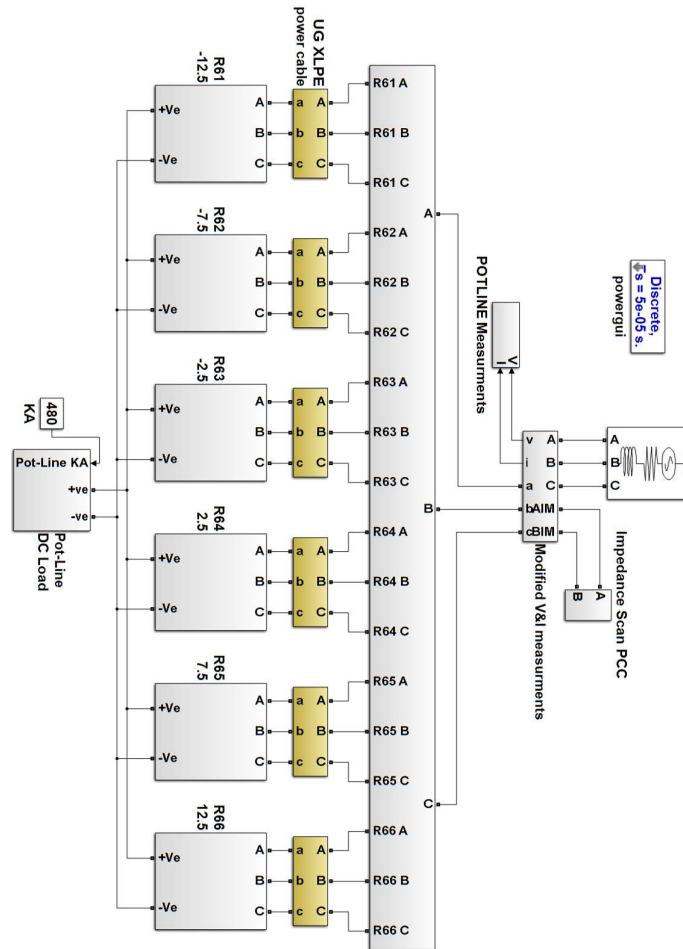
1. Simulink Model of the conventional pot line Rectformer Scheme



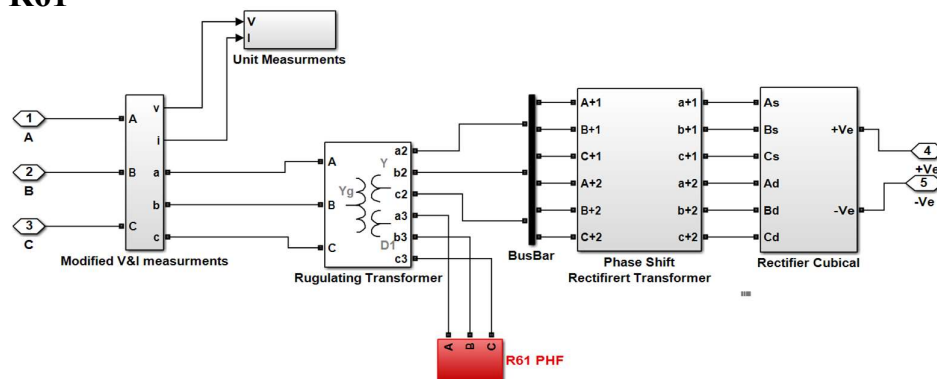
Inside R61



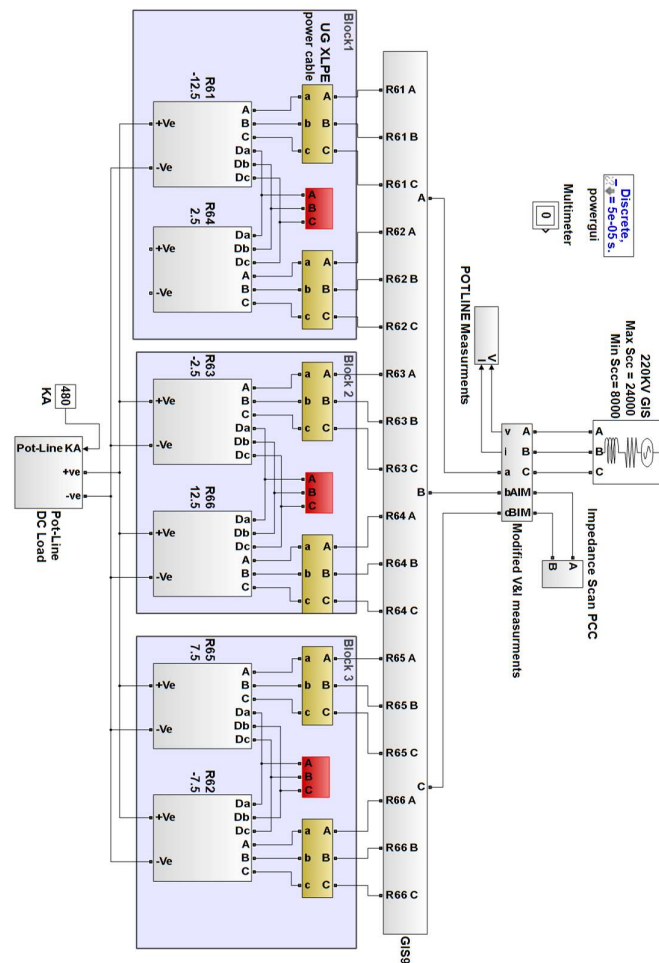
2. Simulink Model of PHF connected to tertiary wining pot line Rectformer Scheme



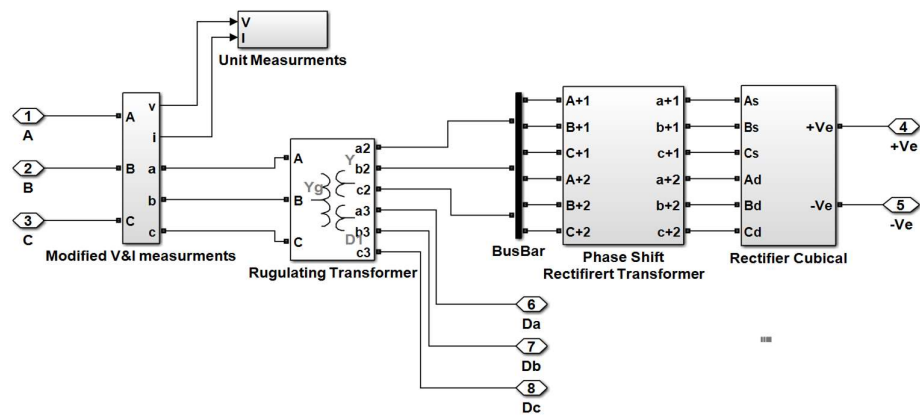
Inside R61



3. Simulink Model of the propped PDC pot line Rectformer Scheme



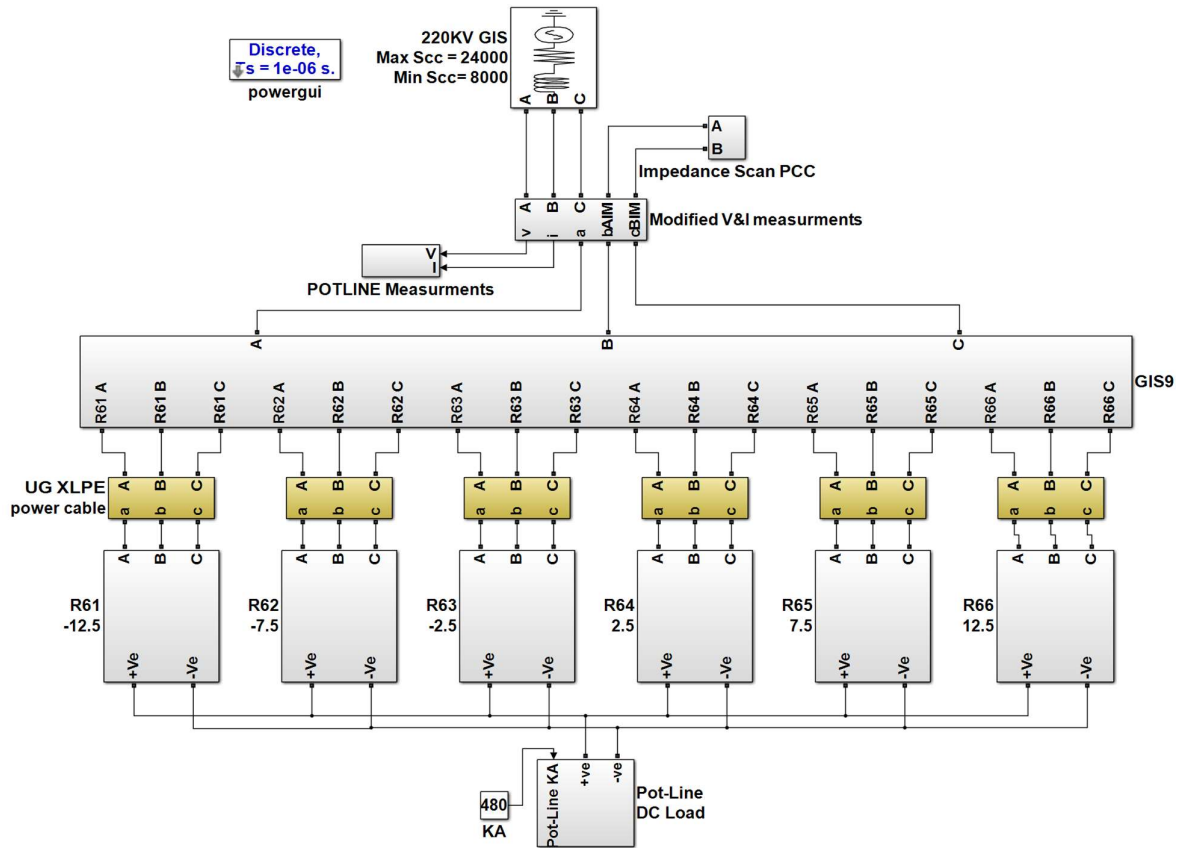
Inside R61



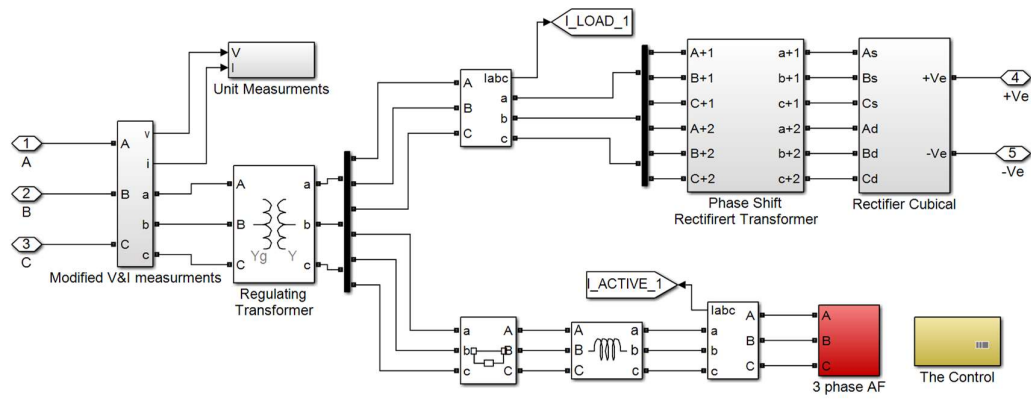
Appendix C

Simulink Model of Rectifier scheme with SAPF

1. Simulink Model of the conventional pot line Rectformer Scheme



Inside R61



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الملخص

مصهر الألمنيوم هو عبارة عن سلسلة متصلة من خلايا التحليل الكهربائي يتم تغذيتها عن طريق أجهزة التيار الكهربائي المستمر والتي تسمى بمحولات التقويم (ركتيفورمر). الركتيفورمر يتكون من محول و مقوم، يستخدم في مصاهر الألمنيوم لتغذية خط الصهر بالتيار الكهربائي المستمر. تستهلك شركة ألومينوم البحرين (ألبا) أكثر من ١,٦ جيجاواط من طاقة التيار المستمر لتغذية خطوطها الخمسة. والتحويل من التيار المتردد الى التيار المستمر يخلق للأسف توافقيات وتسبب مشاكل في جودة الطاقة وخصوصا عندما يتم تحويل كمية كبيرة من الطاقة. تعتمد ألبا ومصاهر الألمنيوم الأخرى في الوقت الحاضر على المرشح السلبي التوافقي لتعويض القدره الحثية و للحد من التأثير الضار للتوافقيات المفروضة على شبكة التيار المتردد.

في هذه الأطروحة، تم محاكاة شبكة الطاقة لشركة ألبا مع أنظمتها الكبيرة المستخدمة في التقويم الكهربائي باستخدام برنامج (ماتلاب / سيمولينك) لتقييم التشوهات التوافقية على أساس سيناريوهات التشغيل العملية المختلفة. وقد تم اقتراح مخططاً جديداً لمغذيات خط الصهر، والذي يقلل من التشوه الكهربائي في أطراف الركتيفورمر ولديه قدرة أفضل على تخفيض التوافقيات عند نقطة التوصيل المشترك، وذلك عن طريق توصيل الملف الثالث (مثلث) على التوازي للمحولات المتجاورة. وقد تم تصميم هذا النموذج المقترح ومحاكاته باستخدام برنامج الماتلاب / سيمولينك وذلك بمقارنة أدائه مع أداء المخططات التقليدية. وأخيراً، تم تقديم مرشح نشط للتوافقيات للركتيفورمر ذات الحجم الكبير في البنية. المرشح النشط هو حل جيد لتخفيض التوافقيات والذي يتميز بالتكيف الذاتي ولا يشكل خطر الرنين مع شبكة الطاقة الكهربائية ، وتقنية التحكم في المرشح النشط تناسب طريقة إستهلاك خط الصهر للطاقة.

جامعة البحرين

قسم الهندسة الكهربائية
و الإلكترونية

كلية الهندسة



التحقيق والتخفيف من التوافقيات في شبكة الطاقة

الصناعية لمصهر الألومنيوم: نهج التكيف

أطروحة مقدمة كجزء من متطلبات الحصول على درجة الماجستير
في الهندسة الكهربائية و الإلكترونية

إعداد

محمود محسن طاهر

٢٠٠٥٢١٠٧

المشرف المشارك

د. فاضل البصري

أستاذ مساعد

إشراف

د. سيد علي الموسوي

أستاذ مشارك

جامعة البحرين

مملكة البحرين

نوفمبر / ٢٠١٧