THE UNIVERSITY OF QUEENSLAND

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# Power Quality and Harmonic Analysis of Multi drive System in Unbalanced Load Conditions in 0-2kHz

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# Abstract

The thesis focuses on Harmonic Analysis for the various mitigation techniques for the Multidrive system under test. This thesis specifically lays focus on passive harmonic mitigation techniques for harmonic mitigation. Various cases of passive filters are considered for harmonic analysis evaluation. MATLAB is used for the simulation of the test cases for analysis of the harmonic performance. The aim of the thesis is to analyse permutations and combinations of passive filters so as to satisfy the IEC Regulations. Post processing of the data is done after simulations of the designs for comparison of the various cases. Various parameters are analysed with respect to the total harmonic distortion like grid impedance, choke values and specific harmonics, analysis of the various parameters and its effects on the harmonic performance. Experimental verification is done on Simulink MATLAB software.

Furthermore, Linear progression is used to analyse and forecast the Total Harmonic Distortion of the Multi-drive System. Forecasting of the harmonic performance can be cost saving in terms of hardware and complications related. Further studies can be done on Linear regression and modelling of the cases for active filter and its performance.

# Acknowledgment

I would like to take the opportunity to thank my Supervisor Dr. Firuz Zare for his immeasurable support and guidance throughout my thesis. Not only did he give me a sense of direction but also gave invaluable feedback about the intricacies involved.

I am grateful to having completed my master's degree from such a prestigious university like The University of Queensland. I would like to thank everyone who directly and indirectly helped me within my time at the University.

Lastly, I would like to thank my Family for standing by my side and giving me emotional support and believing in me when times were tough.

# Contents

# Chapter 1

# Introduction

Stringent harmonic pollution regulations have been placed with the IEC regulations which limit the total harmonic distortion of power system. Non-linear devices cause harmonic pollution.

The thesis is assembled as follows. In chapter two analysis of the literature review existing on the various passive mitigation strategies. Identifying the related literature review needed in the formulation of this thesis. Chapter 3 identifies the passive mitigation strategies used for the simulations and analysis of the research idea. Chapter 4 focuses on the post processing and contemplation of the results obtained by simulations of the circuits on Simulink.

Chapter on begins with the identification of the fact that Multi-pulse SCR rectifiers are the most common choice owing to the low Total Harmonic distortion they are associated with [1]. Further the analysis of the comparison of THD of the six pulse, twelve pulse, eighteen pulse and twenty-four pulse SCR in terms of the total harmonic distortion. The advantages that multi-pulse rectifier is associated with are lower THD, increased DC ripple frequency[1]. There is a regulation in place IEEE Standard 519-1992 defines the limit for harmonic pollution specifically the Total Harmonic Distortion (THD) up to 5%. The regulations also place limit upon the Total Demand Distortion (TDD). The table

Table 1.1: IEEE 519-1992 Regulations

| **Maximum harmonic current distortion of $I_L$ in %** | | | | | | |
|---|---|---|---|---|---|---|
| **Individual Harmonic order (Odd Harmonics)** | | | | | | |
| **$I_{SC}/I_L$** | **$3 \le h < 11$** | **$11 \le h < 17$** | **$17 \le h < 23$** | **$23 \le h < 35$** | **$35 \le h \le 50$** | **TDD** |
| <20 | 4 | 2 | 1.5 | 0.6 | 0.3 | 5 |
| 20 <50 | 7 | 3.5 | 2.5 | 1 | 0.5 | 8 |
| 50 <100 | 10 | 4.5 | 4 | 1.5 | 0.7 | 12 |
| 100 <1000 | 12 | 5.5 | 5 | 2 | 1 | 15 |
| <1000 | 15 | 7 | 6 | 2.5 | 1.4 | 20 |

shows the regulated limitations upon not only the TDD but also upon specific harmonics which must be adhered. The main objective is to meet the limitations specified for curbing the harmonic content.

## 1.1 Comparison of the Total Harmonic Distortion of the Multi-pulse Rectifiers

The AC -DC Converters are important part of power system are a significant contributor of harmonics and analysis of these is an eminent part of harmonic analysis .Thus we try to analyse various Multi-pulse converters to check their harmonic contributions at a system level.

The converters can be classified with respect to the number of pulses and number of diodes which are used for switching. The converters are further classified as : i) 12 -pulse AC-DC Converters ii) 18-pulse AC -DC Converters iii) 24 – Pulse AC-DC Converters iv) Other high-pulse AC-DC Converters The specific harmonics generated by the rectifier in this case are 5th, 7th ,9th , 11th and 13th.The Total harmonic distortion of six pulse rectifier exceeds the requirements of the regulations and thus we need to explore more options of mitigation.

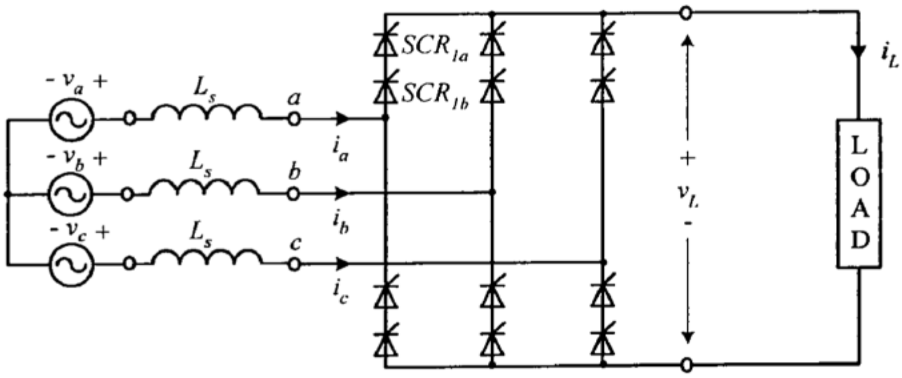



Figure 1.1: Six pulse Rectifier

The diagram below specifies the harmonic spectrum of the six pulse rectifier which indicates the Total harmonic distortion . The performance of the 12-pulse SCR is described below with the

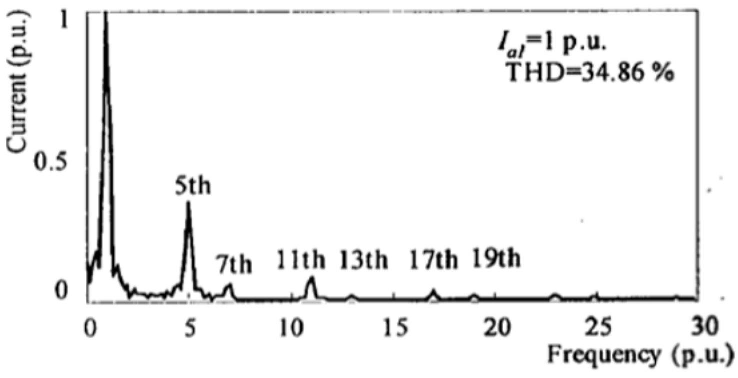



Figure 1.2: Harmonic spectrum of 6 pulse rectifier

line current THD. The frequency spectrum which depicts the Total Harmonic distortion of the 12-

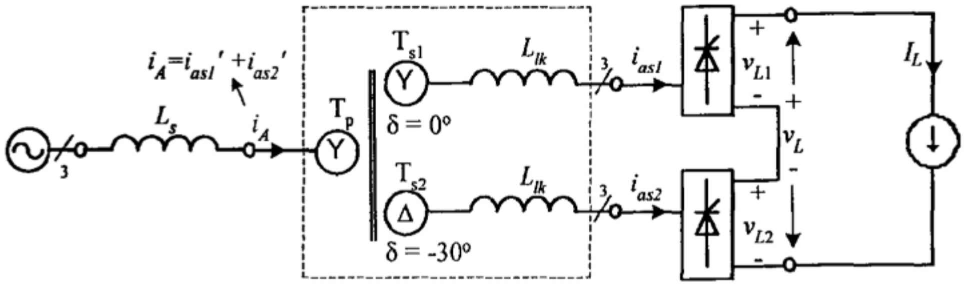


Figure 1.3: Twelve pulse Rectifier

pulse rectifier is depicted below:The input line current THD of the 12-pulse rectifier with either the

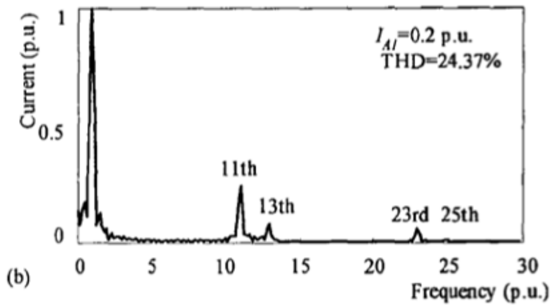



Figure 1.4: Harmonic spectrum of 12 pulse rectifier

capacitive or inductive load fails to meet the IEEE 519-1992 regulations. The input line current THD

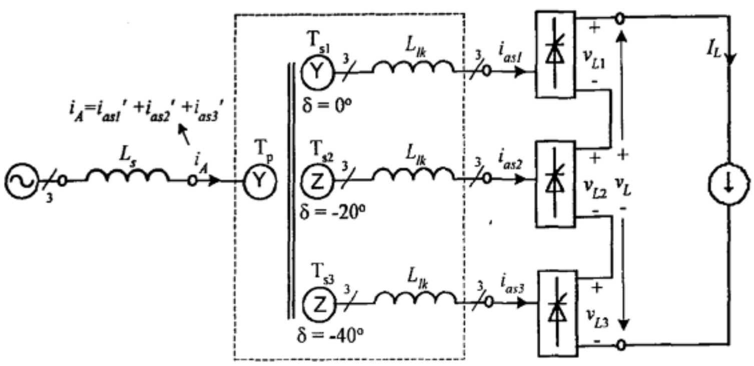


Figure 1.5: Eighteen pulse rectifier

for 24-pulse rectifier is given below : As observed with the increase in the number of pulses the Line current THD decreases. But we don't prefer higher multi-pulse converters as the involve increased complexity[3].

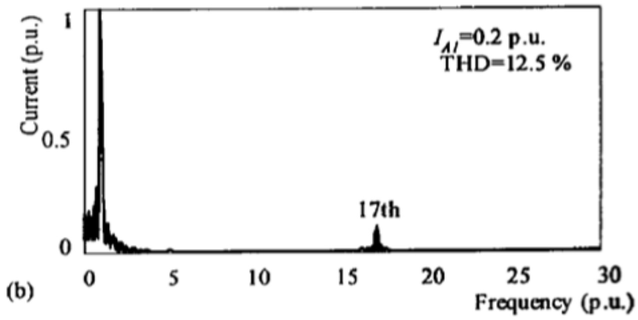



Figure 1.6: Frequency spectrum of 18 pulse rectifier

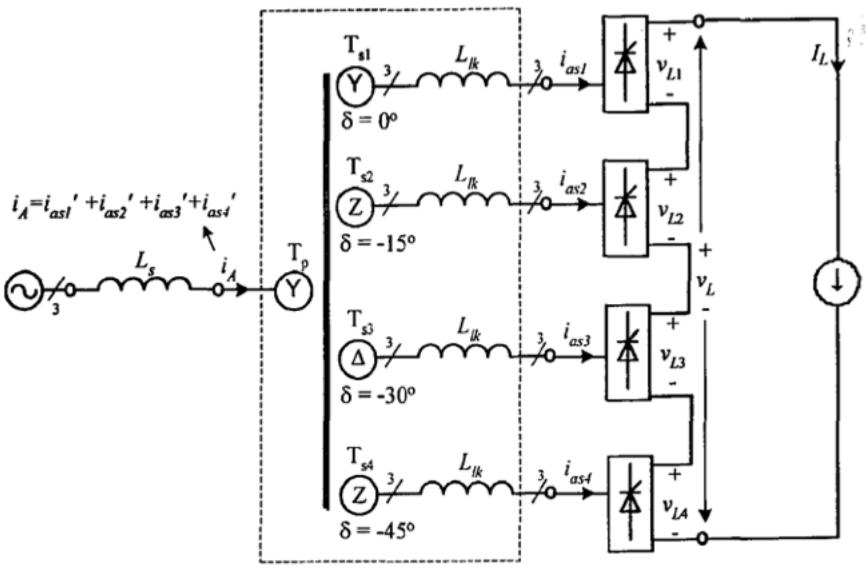



Figure 1.7: Twenty four pulse rectifier

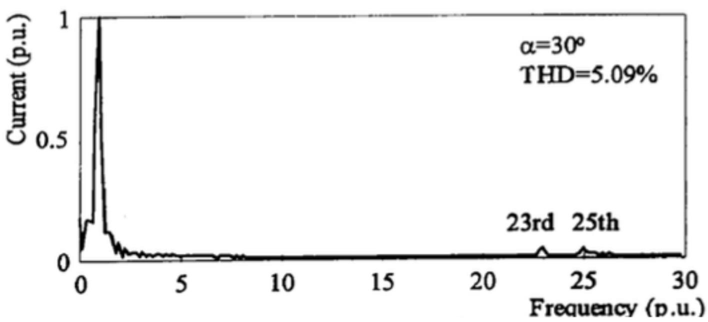



Figure 1.8: Frequency spectrum of 24 pulse rectifier

Table 1.2: Comparison of Multi-pulse Rectifier topologies

| | Harmonic order ($h$) | 5 | 7 | 11 | 13 | 17 | 19 | 23 | 25 | $THD_I$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Typical values of harmonic current (% of fundamental current) of different types of front end configurations (% $I_h/I_1$) | 6-pulse without line reactor (Stiff source) | 80.0% | 58.0% | 18.0% | 10.0% | 7.0% | 6.0% | 5.0% | 2.5% | **101.5%** |
| | 6-pulse with 2-3% line reactor | 40.0% | 15.0% | 5.0% | 4.0% | 4.0% | 3.0% | 2.0% | 2.0% | **43.6%** |
| | 6-pulse with 5% line reactor | 32.0% | 9.0% | 4.0% | 3.0% | 3.0% | 2.0% | 1.5% | 1.0% | **33.9%** |
| | 6-pulse with line harmonic filter (LHF) | 2.5% | 2.5% | 2.0% | 2.0% | 1.5% | 1.0% | 0.5% | 0.5% | **4.9%** |
| | 12-pulse | 3.7% | 1.2% | 6.9% | 3.2% | 0.3% | 0.2% | 1.4% | 1.3% | **8.8%** |
| | 18-pulse | 0.6% | 0.8% | 0.5% | 0.4% | 3.0% | 2.2% | 0.5% | 0.3% | **3.9%** |

## 1.2 Objectives

The objective of this research is to investigate the various passive filter mitigation techniques that can be deployed while trying permutations of the available passive filters .A thorough harmonic analysis of those passive filters so as to compare their relative performance on a standard multidrive system under test. Seeing whether these are compliant with the IEEE 519 1992 regulations . The main aim is to achieve the IEEE Regulations and deliver a filter that is not only has low cost but achieves the IEC regulations.

## 1.3 Scope of Research Work

This research investigates the passive harmonic mitigation strategies ; exploring the various permutations of passive filters.

The existing passive filter harmonic mitigation techniques are:

i) AC Choke

ii) DC Choke

iii) DC Capacitance

iv) Small DC capacitance

The suggested new passive filter harmonic mitigation techniques are : i) DC Choke

ii) AC Choke & DC Choke

iii) AC Choke, DC Choke and DC Capacitance

iv) DC Choke & Dc capacitance

Comparison of the harmonic performance of the 6 pulse, 12-pulse , 18 pulse and 24 -pulse converter topologies. Comparison of the THD of the various Multi-pulse Rectifiers. Finally, doing a regression analysis fir the various passive filter mitigation strategies.

The scope of the research is comparison of the various Passive mitigation strategies : i) DC Choke
ii) AC Choke & DC Choke
iii) AC Choke, DC Choke and DC Capacitance
iv) DC Choke & Dc capacitance
Deriving a comparative analysis of these techniques for the Total Harmonic Distortion limits.

## 1.4 Methodology

The research used Simulink for the simulations of the various passive mitigation strategies. The variable change of parameters considered are as follows: i) Grid impedance
ii) Dc choke values
iii) AC Choke values
iv) DC capacitance values
The effect of the changing parameters on the Total Harmonic distortion is analysed in the various respective cases considered as mentioned above. The effect of change of values of the parameters on the Total Harmonic distortion in each case is analysed.

## 1.5 Breakdown of Chapters

Chapter 2 investigates the already existing literature review on related context so as to identify the research gap and the need for this research. Chapter 3 gives the detailed description of the methodology carried down to do the simulations and results. Chapter 4 gives the observations and results that are noted in after the simulation of the cases. Chapter 5 focuses on results , conclusions and analysis . Appendix chalks down the various programs used in this research and the data generated after simulations (post processing data). References are written at the end.

## 1.6 Novelties of this Thesis

The contributions of this thesis in terms of Novelties are :

1. Providing a theoretical background for the permutations of passive filter techniques
2. Providing a novel design method using the passive filters and linear regression for forecasting the
3. Investigation of the permutations of cases with passive filter mitigation techniques and their performance.

4. Deploying novel filter combinations which satisfies the IEEE regulations for the limitations of Total Harmonic Distortion.

5. Implementing Linear regression on the performance of the

6. Providing a comprehensive qualitative analysis of the various simulation cases.

## 1.7 Limitations of this Thesis

The analysis performed in this thesis is limited to :

1. The frequency range considered is 0 to 2 kHz.
2. Only Voltage and current Total Harmonic Distortion are analysed in this thesis in terms of Power quality and Harmonic analysis.
3. The filters analysed are strictly passive filters mitigation strategies particularly four cases have been considered in this research as mentioned before.
4. Linear regression is conducted for Harmonic pollution prediction.
5. The accuracy of the linear regression is based on the R factor which is around 0.98 for our calculations ; hence the calculations are 98% accurate.

# Chapter 2

# Review on Harmonic Mitigation

## 2.1 Power Quality Categorisation

“Harmonics are signals that are an integer multiple of fundamental frequency[2]”. Harmonics produce unwanted effect on the power system. Harmonic mitigation is necessary for achieving the desired total harmonic distortion. Non-linear loads are loads in which the current is not proportional to the voltage. Power Quality (PQ) is defined as ”Any power problem manifested in voltage,current or frequency deviation which leads to damage,malfunctioning and dis-operation of the consumer equipment[2]”. ”We aim to minimize the probability the occurrence of any disturbance and reducing the effects of the Power Quality Problems.”[2].

There can be varied number of Power Quality problems arising in a power system. The typical power quality problems are outlined in Table 2.1 for reference. The power quality is categorised into the following categories below:

## 2.2 Harmonics

Jean Baptiste Fourier suggested that any periodic signal can be expressed as a addition of sine and cosine terms, which are integer multiple of the fundamental frequency. The periodic function has a period of $T = 2\pi$ , where an and bn are Fourier series constants.

“The non-sinusoidal waveforms produced by non-linear loads which comprises of integer multiple of the fundamental frequency which is known as harmonics.”

$$\begin{aligned} f(t) = a_0/2 + a_1 cos(\omega t) + b_1 sin(\omega t) + \dots \\ + a_2 cos(\omega \times 2t) + b_2 cos(\omega \times 2t) + \dots \\ + a_3 cos(\omega \times 2t) + b_3 cos(\omega \times 2t) + \dots \\ + a_n cos(\omega \times 2t) + b_n cos(\omega \times 2t)] + \dots \end{aligned} \tag{2.1}$$

$$f(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n \cos(n\omega t) + \sum_{n=1}^{\infty} b_n \sin(n\omega t) \tag{2.2}$$

Table 2.1: Power Quality Categorisations[1]

| Categories | Typical spectral content | Typical duration | Typical voltage magnitude |
|---|---|---|---|
| 1.0 Transients | | | |
| 1.1 Impulsive | | | |
| 1.1.1 Nanosecond | 5 ns rise | <50 ns | |
| 1.1.2 Microsecond | 1 µs rise | 50 ns-1 ms | |
| 1.1.3 Millisecond | 0.1 ms rise | >1 ms | |
| 1.2 Oscillatory | | | |
| 1.2.1 Low frequency | <5 kHz | 0.3-50 ms | 0-4 pu |
| 1.2.2 Medium frequency | 5-500 kHz | 20 µs | 0-8 pu |
| 1.2.3 High frequency | 0.5-5 MHz | 5 µs | 0-4 pu |
| 2.0 Short-duration root-mean-square (rms) variation | | | |
| 2.1 Instantaneous | | | |
| 2.1.1 Sag | | 0.5-30 cycles | 0.1-0.9 pu |
| 2.1.2 Swell | | 0.5-30 cycles | 1.1-1.8 pu |
| 2.2 Momentary | | | |
| 2.2.1 Interruption | | 0.5 cycle-3 s | <0.1 pu |
| 2.2.2 Sag | | 30 cycles-3 s | 0.1-0.9 pu |
| 2.2.3 Swell | | 30 cycles-3 s | 1.1-1.4 pu |
| 2.3 Temporary | | | |
| 2.3.1 Interruption | | >3 s-1 min | <0.1 pu |
| 2.3.2 Sag | | >3 s-1 min | 0.1-0.9 pu |
| 2.3.3 Swell | | >3 s-1 min | 1.1-1.2 pu |
| 3.0 Long duration rms variation | | | |
| 3.1 Interruptions, sustained | | >1 min | <0.0 pu |
| 3.2 Undervoltage | | >1 min | 0.1-0.9 pu |
| 3.3 Overvoltage | | >1 min | 1.1-1.2 pu |
| 3.4 Current overload | | >1 min | |
| 4.0 Imbalance | | | |
| 4.1 Voltage | | steady state | 0.5-2% |
| 4.2 Current | | steady state | 1.0-30% |
| 5.0 Waveform Distortion | | | |
| 5.1 DC offset | | steady state | 0-0.1% |
| 5.2 Harmonics | 0-9 kHz | steady state | 0-20% |
| 5.3 Interharmonics | 0-9 kHz | steady state | 0-2% |
| 5.4 Notching | | steady state | |
| 5.5 Noise | broadband | steady state | 0-1% |
| 6.0 Voltage fluctuation | <25 kHz | intermittent | 0.1-7%<br>0.2-2$P_{st}$* |
| 7.0 Power frequency variation | | <10 s | ±0.10Hz |

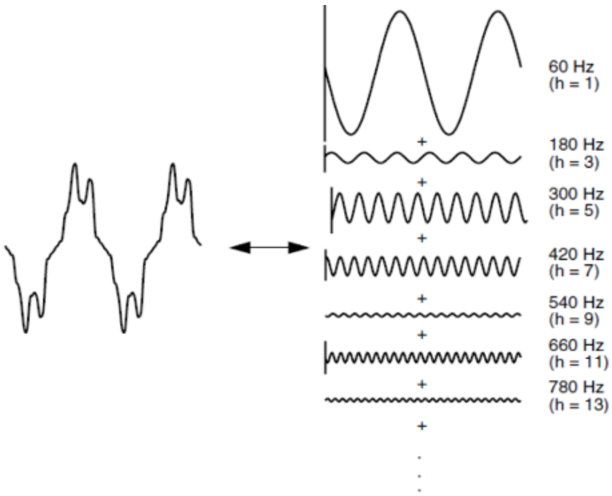



Figure 2.1: Harmonics

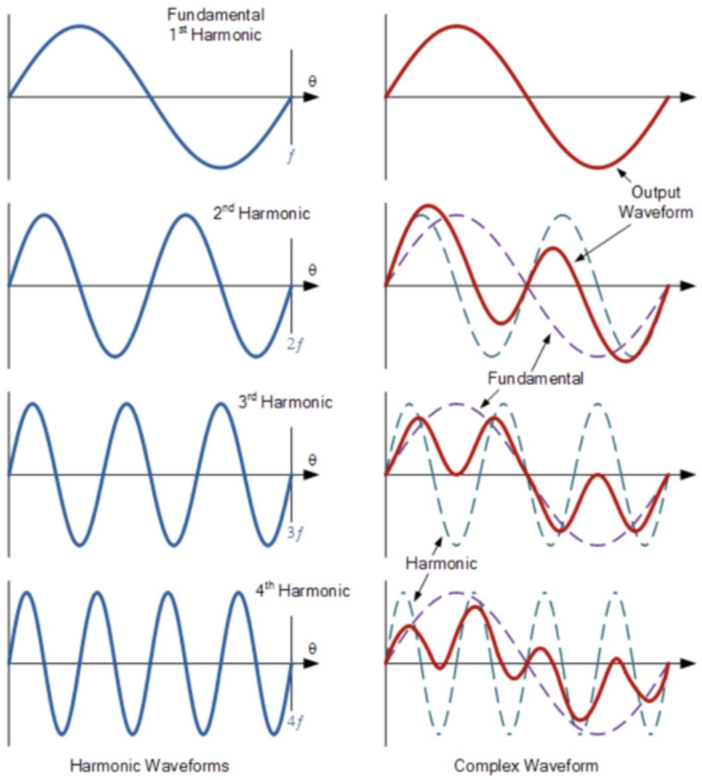
Where,

$$
\begin{aligned}
a_0 &= \frac{\omega}{\pi}\int_0^{2\pi/\omega} f(t)dt & &= \frac{2}{T}\int_0^{T} f(t)dt \\
a_n &= \frac{\omega}{\pi}\int_0^{2\pi/\omega} f(t)\cos(n\omega t)dt & &= \frac{2}{T}\int_0^{T} f(t)\cos\left(\frac{2n\pi t}{T}\right)dt \\
b_n &= \frac{\omega}{\pi}\int_0^{2\pi/\omega} f(t)\sin(n\omega t)dt & &= \frac{2}{T}\int_0^{T} f(t)\sin\left(\frac{2n\pi t}{T}\right)dt \\
c_n &= \sqrt{a_n^2 + b_n^2}
\end{aligned}
$$

The definition of Harmonics is defined by (2.1) and (2.2) which clearly depicts that any function or signal f(t) that is not periodic can be represented as a sum of sine and cosine terms[1]. This

Table 2.2: Effects caused by Harmonics

| **S.NO** | **Equipment Name** | **Complications due to harmonic propagation in power system** |
|---|---|---|
| **1** | Transmission line | Increase in percentage level of THD in receiving end when compared with the sending end. |
| **2** | Electrical Equipment | Poor power quality |
| **3** | Transformers | 1. Excess heat generation due to high load current<br>2. Occurrence of resonance due to interaction between transformer inductance and system capacitance.<br>3. Insulation failures because of vibration and overheating |
| **4** | Rotating Machines | Results in vibrations, Excess heating and abrasive sounds by distorted voltage and current. |
| **5** | Consumer Loads | Experiences potential damage because of distorted parameters. |
| **6** | Capacitor banks | Dielectric breakdown and overloading of reactive power. |
| **7** | Insulated Cables | Over voltage causes dielectric breakdown. |
| **8** | Conductors | Increases skin effect and proximity effect |
| **9** | Fuses and Protecting Devices | 1. Reduces the interruption capability which in turn affects the lifetime of the equipment.<br>2. Malfunction of Relays and Circuit Breakers. |




project focuses primly on Harmonics amongst the various Power Quality issues that present in power systems. We tend to analyse the harmonics and mitigate them in this research project.

## 2.3 Total Harmonic Distortion

Harmonics are generated by Non-linear devices like rectifiers , converters , heaters etc. Harmonic distortion give rise to several troublesome effects like “reduced power factor, deteriorating performance , overheating of equipment , incorrect operation of protection relays , interference with communication devices, circuit resonance etc”[2]. Harmonics causes various troublesome effects which have been outlined in table 2.2.

$$THD = \frac{V_n}{V_1} \tag{2.3}$$

and,

$$V_n = \sqrt{V_2^2 + V_3^2 + V_4^2 + V_5^2 + \dots} = \sqrt{\sum_{h=2}^{h_{max}} V_h^2}$$

The total harmonic distortion should be kept within limits and in compliance to the suggested values of IEEE standards 519 -1992. According to that criteria the Total Harmonic distortion should be less than or equal to 5% and the individual harmonics should be less than 3%. A major number of power systems have Multi-pulse for satisfying the limitations of the harmonic pollution by IEEE regulations[2]. A trend is observed that with increase in the number of pulses the total harmonic distortion decreases.

“Harmonics are known to be the integer multiple of the fundamental component”[2]. For example if the fundamental frequency is 50 Hz then 2nd harmonic component would be 2 times the fundamental frequency i.e. 2 X 50 Hz = 100Hz
3rd Harmonic component is 3 x 50 = 150 Hz 4th Harmonic Component is 4 x 50 = 200Hz . . And so on. . .

It is observed that Half-wave rectifiers contain both even and odd harmonics whereas full-wave rectifier generated just odd harmonics like 3rd, 5th , 7th , 9th and so on. . . A periodic signal can be expressed as a sum of sine and cosine terms as described b the equation below: “Harmonic Distortion refers to the distortion factor of a voltage or current waveform with respect to a pure sine wave”[1]Interharmonics refers to a frequency component of a periodic quantity that is not an integer multiple of the frequency at which the supply system is operating”[1] “Individual Harmonic Distortion (IHDn) is the ratio between the Root Mean Square (RMS) of the individual harmonic current/voltage and the RMS value of the fundamental component of the current/voltage”[1] “Distortion Factor (Harmonic factor) is defined as the ratio of the sum of the root mean square of the harmonic component of the current/voltage to the root mean square of the fundamental component of the current/voltage, expressed as a percentage”[1]
Interharmonics refers to a frequency component of a periodic quantity that is not an integer multiple of the frequency at which the supply system is operating”[1]
“Individual Harmonic Distortion (IHDn) is the ratio between the Root Mean Square (RMS) of the individual harmonic current/voltage and the RMS value of the fundamental component of the current/voltage”[1]
“Distortion Factor (Harmonic factor) is defined as the ratio of the sum of the root mean square of the harmonic component of the current/voltage to the root mean square of the fundamental component of the current/voltage, expressed as a percentage”[1]

## 2.4 Harmonic Mitigation Techniques

The mitigation techniques for harmonics to decrease the Total harmonic distortion within the limits will be discussed more. The mitigation technique depends upon the application and the outcomes that are required[2]. The harmonic mitigation techniques are broadly divided into these major categories:

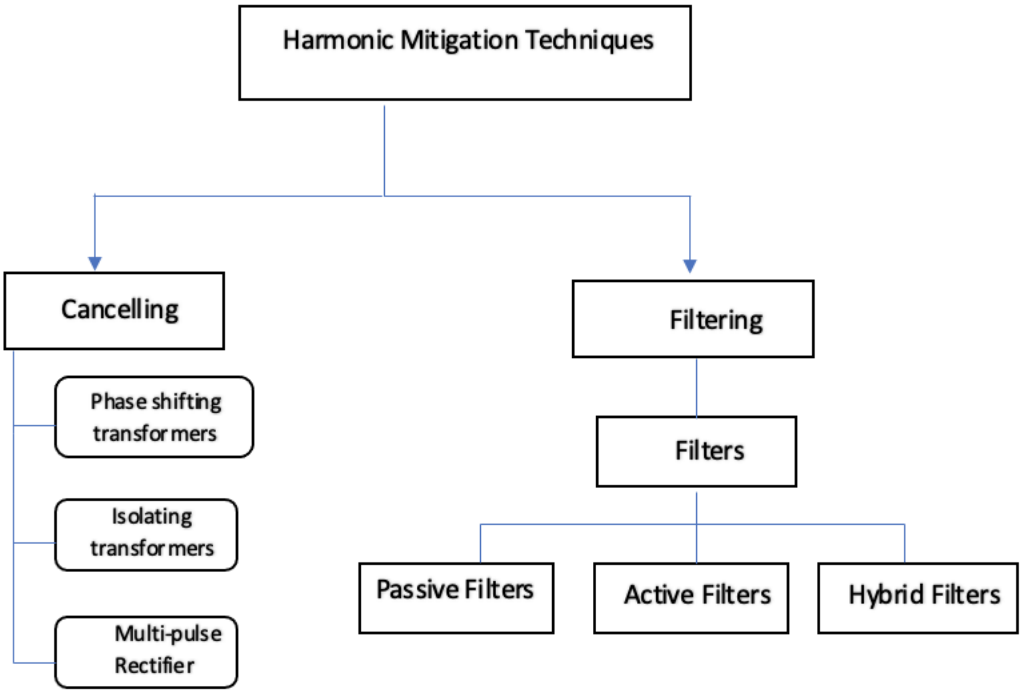
1. Active filters

2. Passive filters

3. Phase shifting transformers

The Total harmonic distortion at the common point of coupling should be less than equal to 5% according to the suggestions of the IEC regulations and the individual harmonics not exceeding 3%[2].

| Type of Harmonic | Sources of Harmonic |
|---|---|
| DC | Electronic switching devices, half-wave rectifiers, arc furnaces (with random arcs), geomagnetic induced currents (GICs) |
| Odd harmonics | Non-linear loads and devices |
| Even harmonics | Half wave rectifiers, geomagnetic induced currents (GICs) |
| Triplen harmonics | Unbalanced three-phase load, electronic switching devices |
| Positive sequence harmonics<br>Negative sequence harmonics<br>Zero sequence harmonics | Operation of power system with non-linear loads<br>Operation of power system with non-linear loads<br>Unbalanced operation of power system or a balanced 3-phase 4-wire system with a single phase non-linear load connected phase to neutral [35] |
| Time harmonics | Voltage and current source inverters, pulse-width modulated rectifiers, switch-mode rectifiers and inverters |
| Spatial harmonics | Induction machines |
| Interharmonics | Static frequency converters, cycloconverters, induction machines, arcing devices, computers |
| Subharmonics | Fast control of power supplies, subsynchronous resonances, large capacitor banks in highly inductive systems, induction machines |



## 2.5 Passive Filters

Passive filters consist of passive elements like he resistor, inductor and capacitors. Their sole harmonic mitigation relies on the principle of resonance. For example :for mitigating 3rd harmonic resonance would occur at that particular frequency. There are various types of passive filters like series passive filter, shunt passive filter , band pass filter etc.

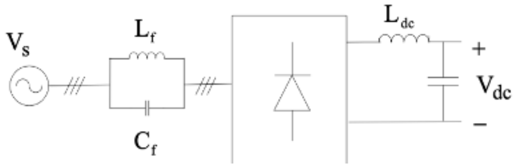



Figure 2.2: Tuned Series passive filter

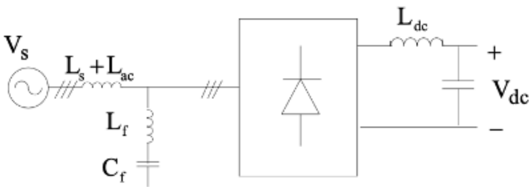
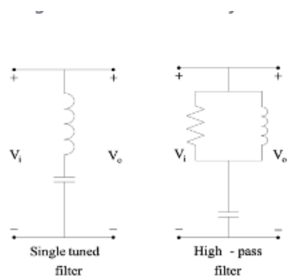



Figure 2.3: Shunt passive filter

Figure 2.4: Shunt filter types



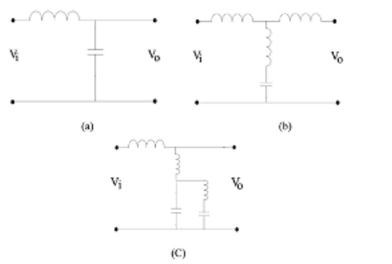




Figure 2.5: Low pass broadband filter a) Basic b) LLCL type c0 modified LLCCL type

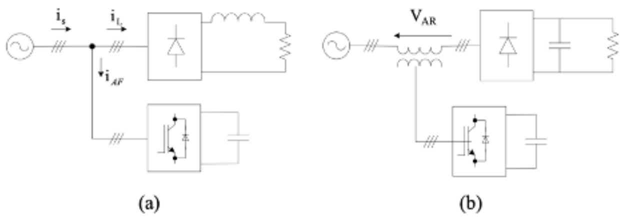



Figure 2.6: Active filter configuration a) Shunt Active Filter b) Series Active Filter

## 2.6 Active Filters

Active filters consist of active elements which are used in four wire systems[2].The sole principle of operation lies on the fact that harmonics injection into the system; 180 degree out of phase harmonic component is injected into the system that lead to harmonic cancellation.

## 2.7 Hybrid Filters

Hybrid filters contain a combination of passive filters and active filters.

# Chapter 3

# Literature Review

## 3.1 Passive Filter Mitigation

There have been several studies about the passive filter mitigation strategies before. Figure 3.1 shows a representation of single line diagram where a Non-Linear load attached at the point of common coupling. Table in figure 3.2 shows the comparative performance of %THD of Multi-pulse Rectifiers.

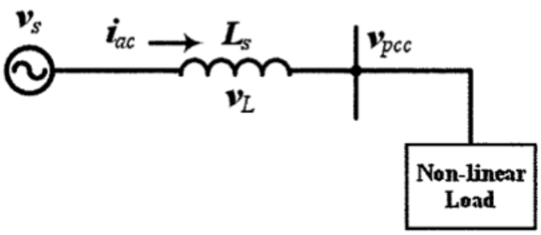



Figure 3.1: Point of common coupling[5]

Figure 3.2: IEEE 519-1992 regulations[5]

| Maximum harmonic current distortation in percent of IL<br>Individual harmonic order (odd harmonics) | | | | | | |
|---|---|---|---|---|---|---|
| $I_{SC}/I_L$ | < 11 | 11≤$h$<17 | 17≤$h$<23 | 23≤$h$<35 | 35≤$h$ | TDD |
| <20* | 4.0 | 2.0 | 1.5 | 0.6 | 0.3 | 5.0 |
| 20<50 | 7.0 | 3.5 | 2.5 | 1.0 | 0.5 | 8.0 |
| 50<100 | 10.0 | 4.5 | 4.0 | 1.5 | 0.7 | 12.0 |
| 100<1000 | 12.0 | 5.5 | 5.0 | 2.0 | 1.0 | 15.0 |
| >1000 | 15.0 | 7.0 | 6.0 | 2.5 | 1.4 | 20.0 |

*Even harmonics are limited to 25% of the odd harmonic limits above. Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed. * All power generation equipment is limited to these values of current distortion, regardless of actual $I_{SC}/I_L$. Where: $I_{SC}$ = maximum short-circuit current at PCC. $I_L$ = maximum demand load current (fundamental frequency component) at PCC.*

Figure 3.3: Voltage distortion limits of IEEE519-1992[5]

| Bus voltage at PCC | Individual voltage distortation (%) | Total voltage distortion THD (%) |
|---|---|---|
| 69 kV and below | 3.0 | 5.0 |
| 69.001 kV through 161 kV | 1.5 | 2.5 |
| 161.001 kV and above | 1.0 | 1.5 |

*Note: High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal that will attenuate by the time it is tapped for a user.*

Research has been done previously in harmonic analysis domain particularly in the frequency range of 9 – 150kHz. Power electronic converters are known for shifting the point of resonance within 0-2kHz which increases the current harmonic emissions[7]. Active front end are known to generate harmonics specifically below 2kHz , hence there is a need to explore the impact of them below 2kHz on a system level[7].
The genetic algorithm fuzzy logic based Shunt Active Power Filter does not meet the IEEE regulations as it has a performance of 6.77% in terms of Total Harmonic distortion[8]. In [9] it has been pointed out by many researchers that reduction the size of DC link capacitor reduces the % THD at PCC .

It has been observed that with constant line inductor a smaller DC link capacitor is associated with higher resonant frequency. Moreover , it is seen that converter is associated with damping problems at partial power levels. With decrease in the DC link capacitor it is observed that resonant frequency gets worse at partial power levels. Moreover, higher order harmonics will be impacted and consequently the THDv increased.

Even though the technology has developed and semiconductors have evolved but transistor costs are extremely high and thus we tr to minimise the costs associated with the increased number of transistors; multipulse rectifiers are associated with increased number of transistors owing to higher cost. In [10] the Active Power Filter designed addresses the limitations of the IEEE to keep THD below 5%. But they are accompanied with high costs of circuits. A profitable relationship between cost and accuracy must be established.

In [11] RBF neural networks has been deployed by bacteria foraging algorithm to obtain a % THD of 7.3%, but it is extremely complicated technique for implementation and is associated with higher costs.[12] presents a comparison of the various Multi-pulse converters for HVDC system and their various of %THD. it is seen that increase in the number of pulse the performance is improved. in [13] the harmonic performance of the various multipulse configurations is analysed with variable and partial loading. [14] does the cost analysis of the various Multi-pulse converters which serves as a point of reference for our research when considering costs.

[15] The unbalanced six pulse & twelve pulse rectifier is analysed with different percentage of unbalanced loading. Also unbalanced system is analysed with balanced system. [17] The harmonic analysis for unbalanced system is done where the variations in bus voltages are analysed with har-

monic current injections. [18] analyses the different Multipulse Rectifier and different phase shifting angles and how they influence the %THD. The unbalanced %THD input line current was simulated with three cases to study the performance of these rectifiers under practical conditions for better anticipation of the Harmonic analysis. The effect of harmonic analysis of large capacitive loads is studied for Multipulse rectifiers like 6 -pulse , 12 -pulse , 18-pulse and 24 pulse in SCR rectifiers[20].

[22] discusses the harmonic cancellation strategy in lower overall harmonics. Autotransformers have the disadvantage of large values of input inductor for being complacent with the IEEE standards.[23] This paper gives comprehensive survey and comparison on the passive Harmonic mitigation strategies of various cases.AC Choke, DC Choke & DC Capacitor are the cases considered for the harmonic analysis. The %THD is compared for the various cases .

[25] Focuses on harmonic passive mitigation technique for the mitigation of harmonics.
The analysis of standalone system is done as well as harmonic analysis of the filter at a system level is done. Six pulse diode rectifier is used with three different topologies of passive filter :
1) Dc choke and large dc link capacitor
2) AC Choke and large dc link capacitor
3) Slim dc link capacitor

The analysis of the harmonic cancellation in a multidrive system is studied when it consists of 1 phase converter and three phase converter. In [26] the selective harmonic elimination technique is used with the help of modified DC link boost converter which controls the shape of the boost current converter. The proposition lies in the fact that where the Fourier series is calculated by the addition of delta starting at 30 degrees or ending at 150 degree. This strategy can be deployed for the elimination of selective harmonics from the grid. [27] provides the comparison of the simulation of system harmonics with reduced and standard DC link capacitor drives. Different load profiles are used for validation of the results.
This paper shows that for multidrive system the % THD of reduced DC link capacitor is worse than standard DC link capacitor. In [28] the frequency range for 0-2 kHz, 2-9kHz , 9-150kHz are considered. The incorporation of the electronic inductor at DC Link stage instead of the bulky DC link capacitor.

The operating mode of the EI is determined with the trade-off of inductor size and the switching frequency of the converter. This paper tasks into consideration LCL filter for the investigation of the scenario.
LCL filters are associated with resonance problem requiring other solutions to tackle the same. The worst case harmonic distortion is associated when the summation of inverters admittance is equal to grid admittance also a phase difference of 180 degree[29]. This paper produces a case of harmonic rejection ability associated with grid connected inverters with the aid of harmonic analysis. The proposition of a new harmonic model for the inverters is done.
It is also depicted that LCL filter when used as a harmonic mitigation technique with inverters are

ineffective, when it comes to filter resonant frequency range[30].Filter series damping resistor is associated with the harmonic rejection ability . [31] deploys current harmonic mitigation strategy based on Active front end given their advantages of being less cost and reliable. A modified current modulation technique deploying electronic inductor (EI) for the harmonic current compensation.

# Chapter 4

# Methodology for Harmonic Analysis

## 4.1 Multidrive system

Passive filters have edge over the other filters being simple and economical to design the are more preferred. We consider various design cases containing permutations of AC Choke , DC Choke and DC capacitance. The diagram below describes a typical power system which consists of industrial drives connected in parallel which is referred to as Multi-drive system. A typical drive consists of AC-DC converter followed by inverter. A typical drive consist of transformer inductance and grid impedance .Six pulse diode bridge rectifier is used for the following configurations of topologies. The Power converter topologies are depicted in the Figures below where three phase converters have

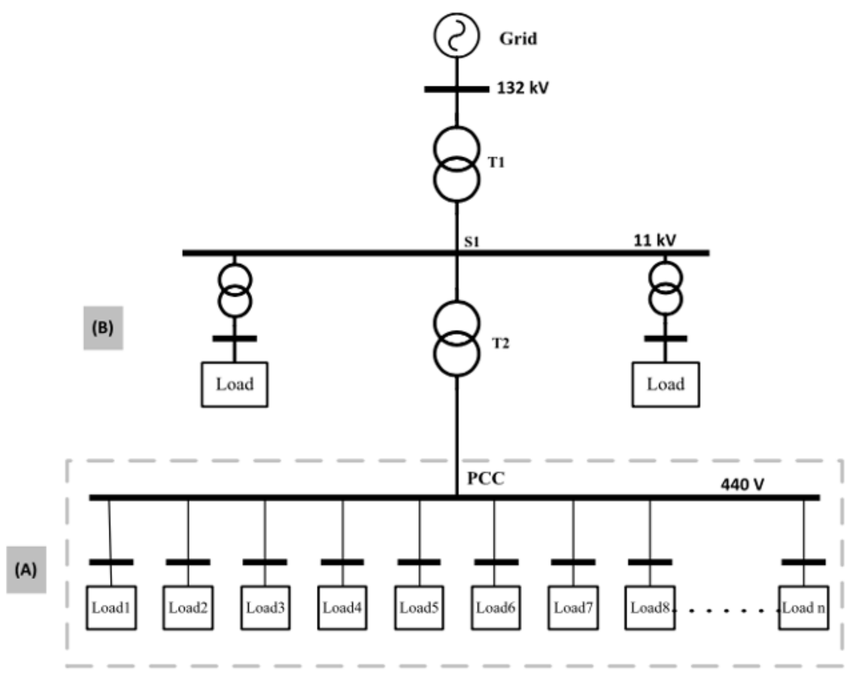



Figure 4.1: Power grid distribution system

been used. The mitigation of harmonics specifically is done with passive filters here.

The main aim of this research is to analyse the effect of grid impedance on the various cases mentioned above. Moreover, to analyse the relative comparison of the Total harmonic Distortion of the various cases. Also to analyse the effect of varying choke values.
The typical circuit of the drive is as follows: It consist of Diode rectifier (six pulse rectifier) followed by intermediate circuit which consist if various cases of novel passive filters further followed by an inverter(DC – AC).The below diagram shows the circuit of the drive .
Multidrive is referred to as the Multipulse drives being connected in parallel configuration.

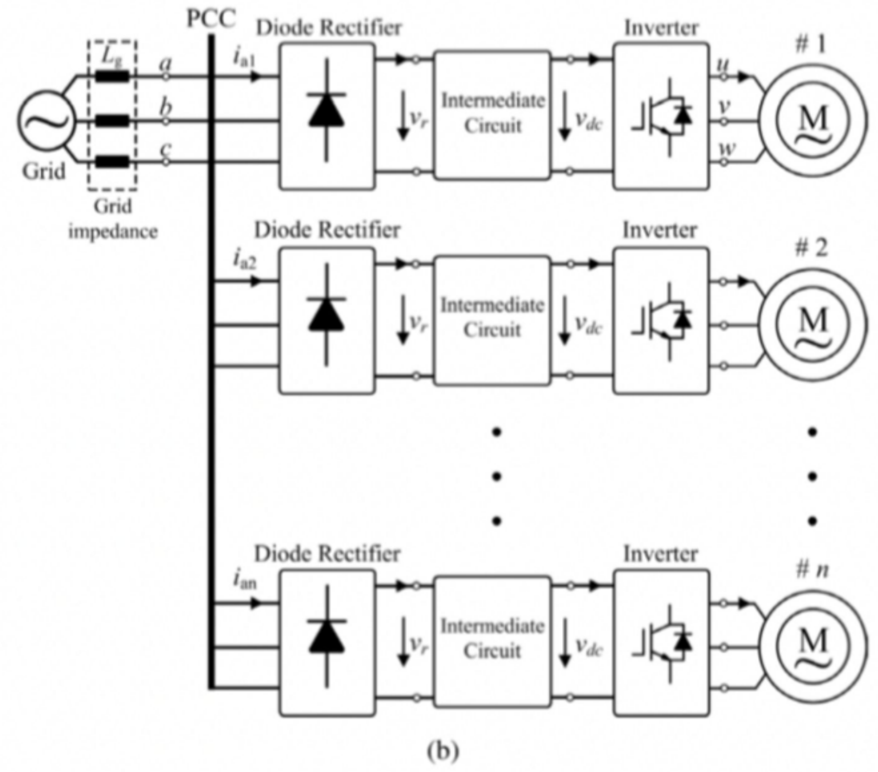



Figure 4.2: Power grid distribution system[7]

The table shows the various values chosen for the research and simulation of the various cases aforementioned . The parameters of the various choke values are mentioned below.

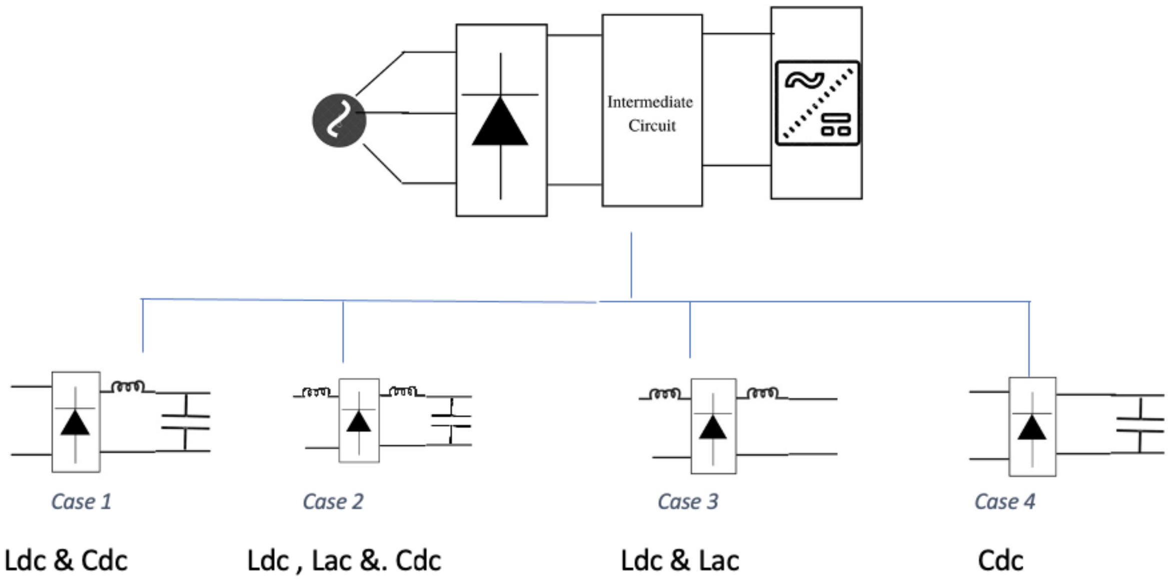



Figure 4.3: Various cases considered

Figure 4.4: Parameters of various cases

| Case | Positive Filters Involved | Parameters |
|---|---|---|
| 1 | DC Choke | 1) 1.5 mH<br>2) 2 mH<br>3) 2.5 mH<br>4) 3 mH |
| 2 | DC Choke and DC Capacitance | 1) DC Choke=1.5 mH,DC Cap = 30$\mu$H<br>2) DC Choke=1.5 mH,DC Cap = 500$\mu$H |
| 3 | AC Choke, DC Choke and DC Capacitance | 1) AC, DC Choke=1.5 mH,DC Cap = 30$\mu$H<br>2) AC, DC Choke=1.5 mH,DC Cap = 500$\mu$H |
| 4 | AC Choke & DC Choke | 1) AC Choke=1.5 mH,DC Choke = 0.5mH<br>2) AC Choke=1.5 mH,DC Choke = 1mH<br>3) AC Choke= 1.5mH,DC Choke = 1.5mH |

## 4.2 Scope of Research

The analysis of this research project focuses on calculating Total Harmonic distortion using MATLAB and Simulink by using the powergui tool for computations. The various circuits are simulated and the powergui tool is used . The rectifiers are first analysed on a unit level for The total harmonic distortion.

The various cases are simulated in a multidrive system setup i.e. on a system level .The total harmonic distortion is analysed for the following parameters:

I) Grid impedance – effect of varying grid impedance

II) DC Choke values – effect of varying DC Choke values

III) DC Capacitance values – effect of varying DC capacitance values

IV) Effect of grid impedance on specific harmonics.

# Chapter 5

# Results

The graphs are obtained after running MATLAB code script. The following Graph depicts Case 4 exclusively where different subparts of Case 4 are plotted on the same graph. The idea is to see the permutations of DC Choke values and how increasing the values of the Choke impact the harmonic performance in a typical multidrive system. Increasing the DC Choke values steadily decreases the harmonic pollution i.e. Total Harmonic Distortion. Increasing the DC Choke values decreased the Harmonic distortion present.

The following results have been analysed in case by case basis.

## 5.1 Case 1

The first case considered was DC Choke variance;where variable DC Choke values are considered at different frequencies. The following parameterrs are analysed as follows:

1. The harmonic performance is analysed with respect to Grid impedance .
2. The harmonic performance i.e. %THD of Case 1 is analysed for Various specific Harmonics.
3. The harmonic performance with respect to variable values of DC Choke impedance.

## 5.2 Case 2

Similar parameters have been analysed for Case 2 as well.

1. The harmonic performance is analysed with respect to Grid impedance .
2. The harmonic performance i.e. %THD of Case 2 is analysed for Various specific Harmonics.
3. The harmonic performance with respect to variable values of DC Choke impedance and DC Impedance.

## 5.3 Case 3

Similar parameters have been analysed for Case 3 as well.

1. The harmonic performance is analysed with respect to Grid impedance .
2. The harmonic performance i.e. %THD of Case 3 is analysed for Various specific Harmonics.
3. The harmonic performance with respect to variable values of DC Choke, AC Choke impedance and DC Impedance.

## 5.4 Case 4

1. The harmonic performance is analysed with respect to Grid impedance .
2. The harmonic performance i.e. %THD of Case 4 is analysed for Various specific Harmonics.
3. The harmonic performance with respect to variable values of DC Choke  AC Choke values.

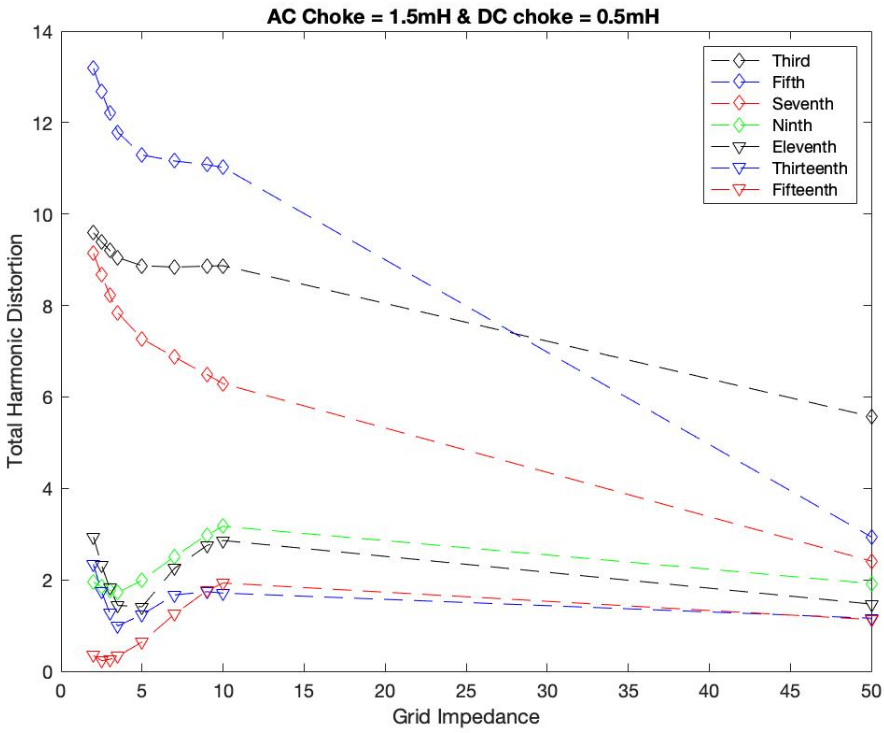



Figure 5.1: Parameters of various cases

The below graph is simulated to see the comparison of the various cases that have been simulated giving us a idea of their performances. Apparently the combination of AC choke  DC Choke gives the best value of harmonic performances.

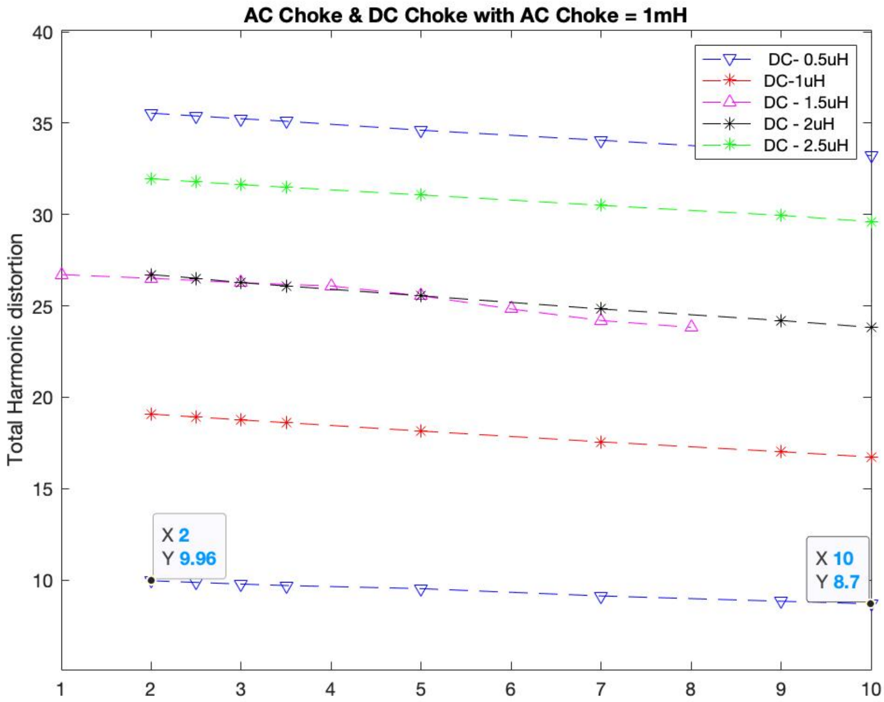



Figure 5.2: Parameters of various cases

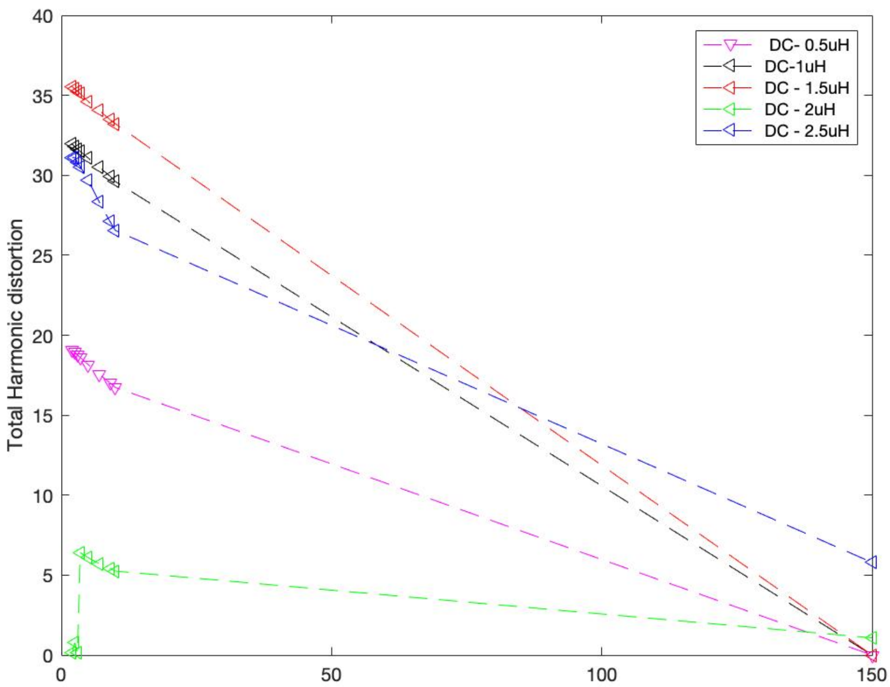



Figure 5.3: Parameters of various cases

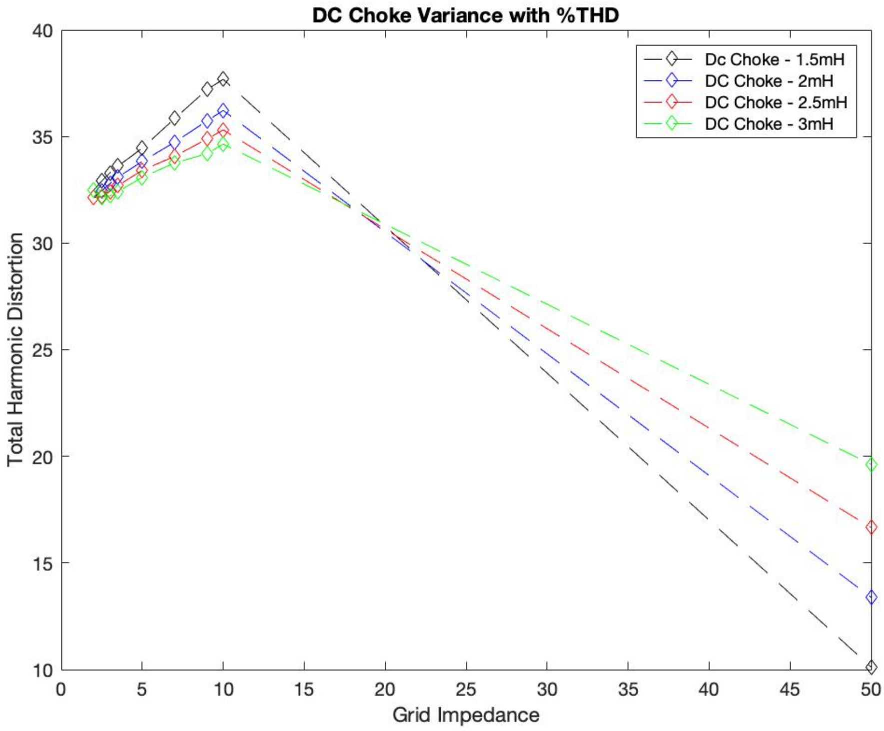



Figure 5.4: Parameters of various cases

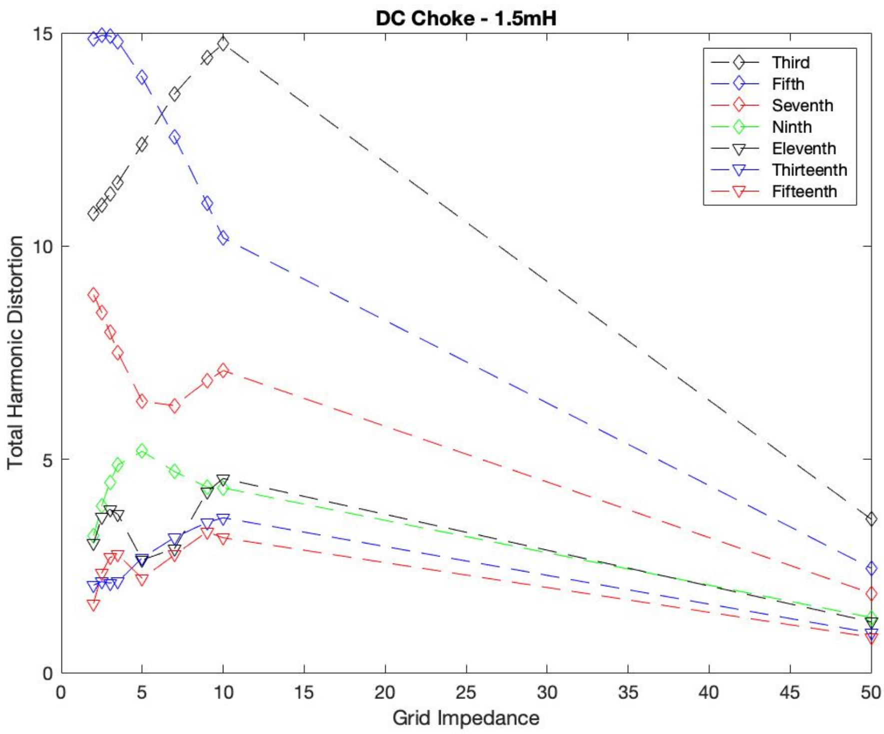



Figure 5.5: Parameters of various cases

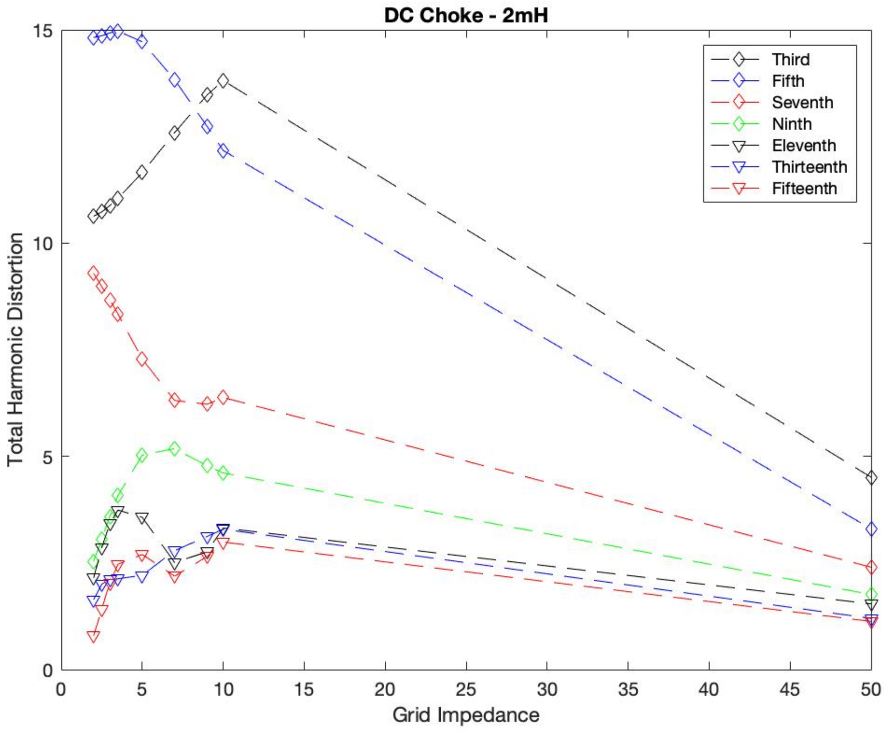



Figure 5.6: Parameters of various cases

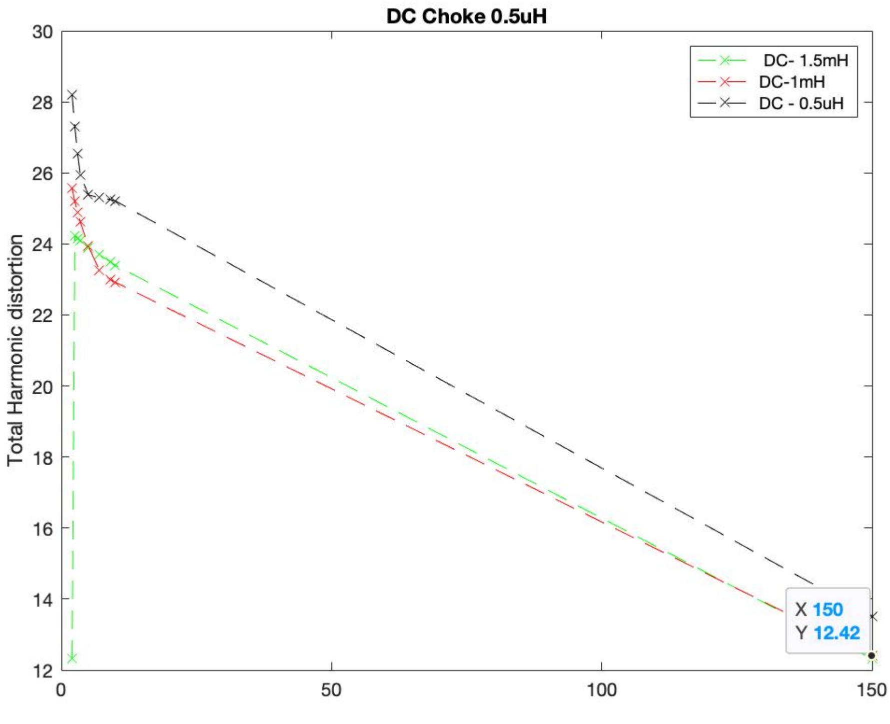



Figure 5.7: Parameters of various cases

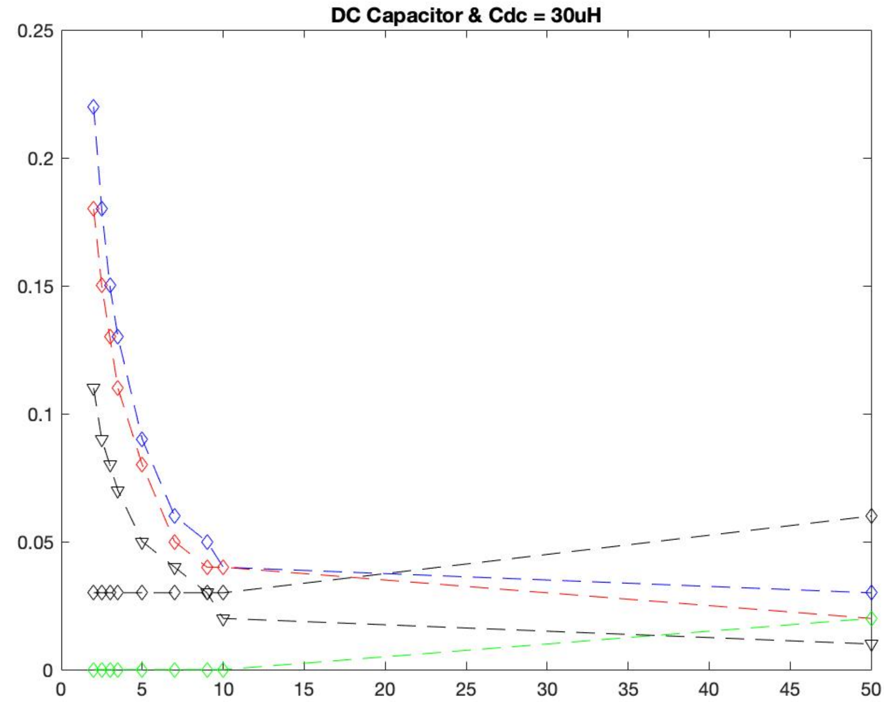



Figure 5.8: Parameters of various cases

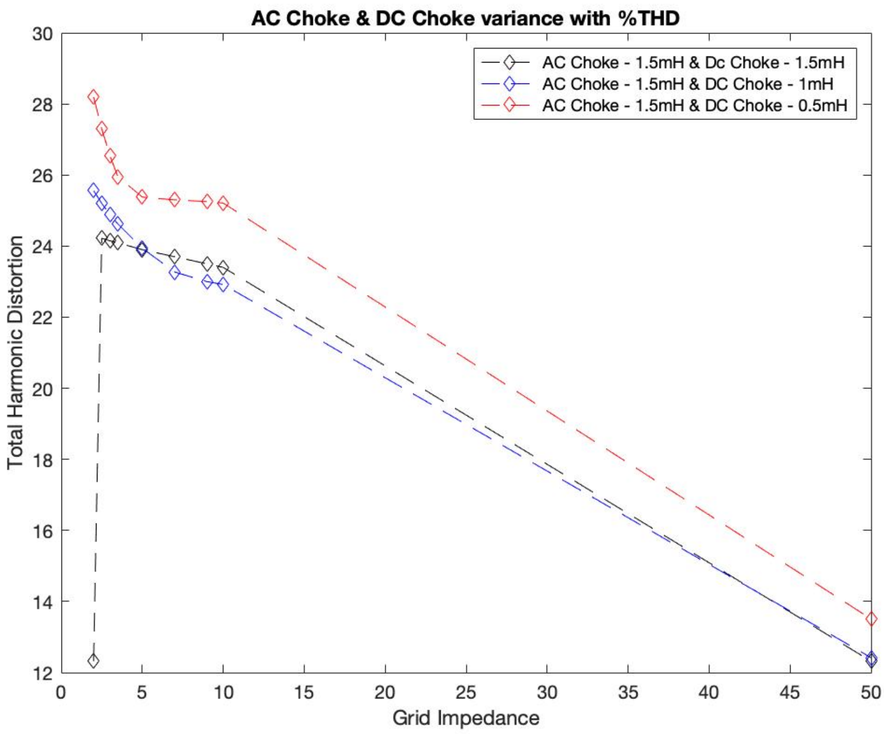



Figure 5.9: Parameters of various cases

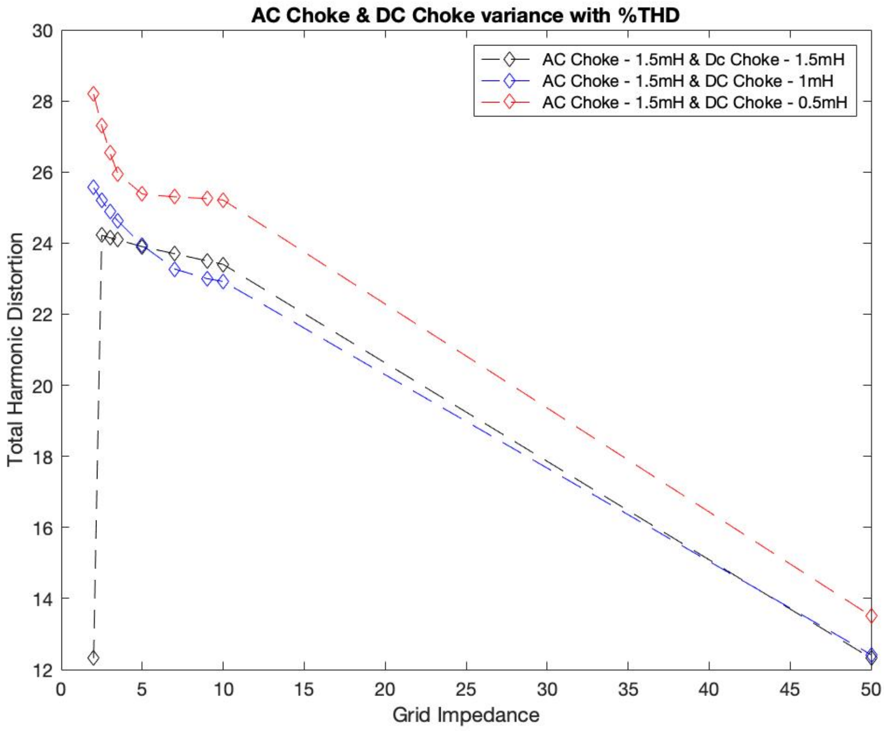



Figure 5.10: Parameters of various cases

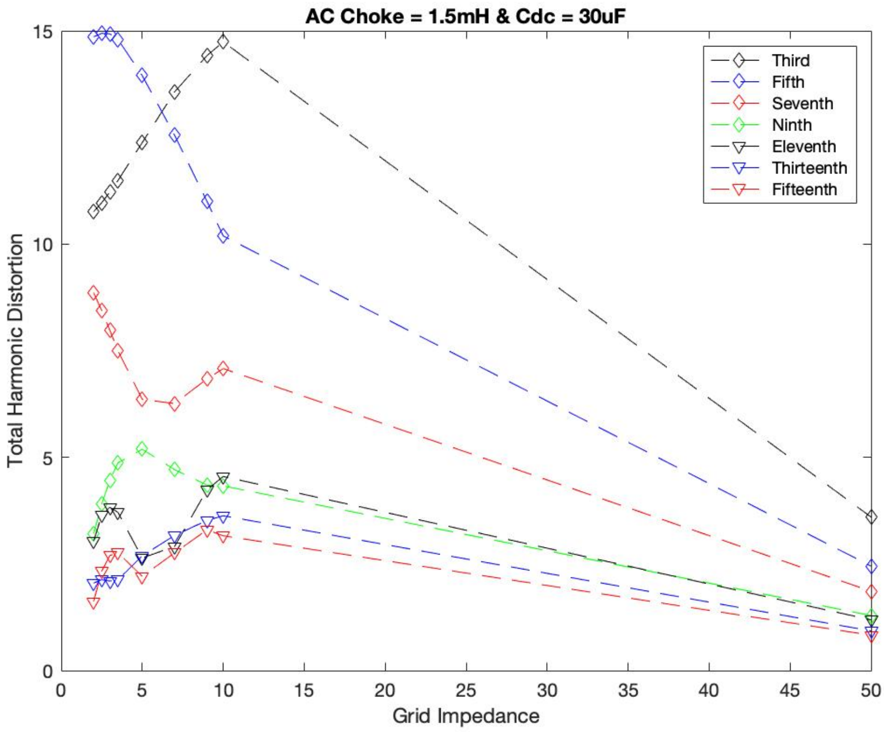



Figure 5.11: Parameters of various cases

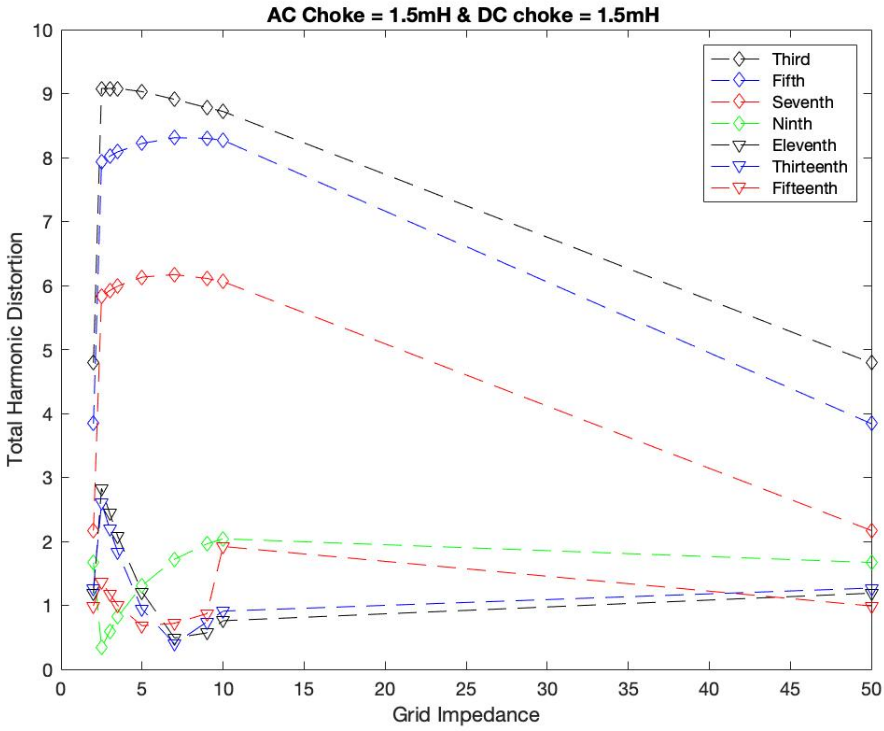



Figure 5.12: Parameters of various cases

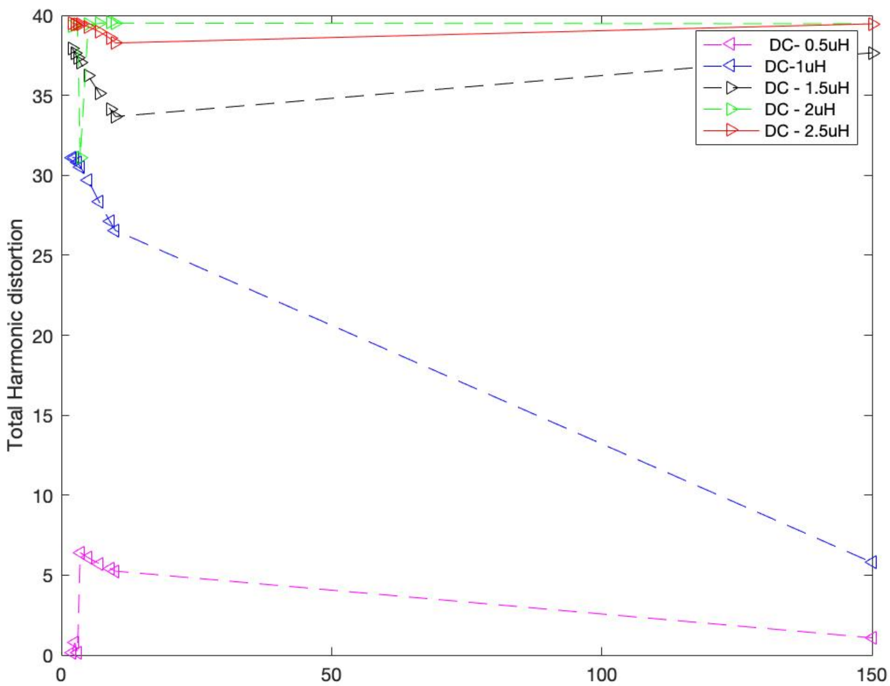



Figure 5.13: Parameters of various cases

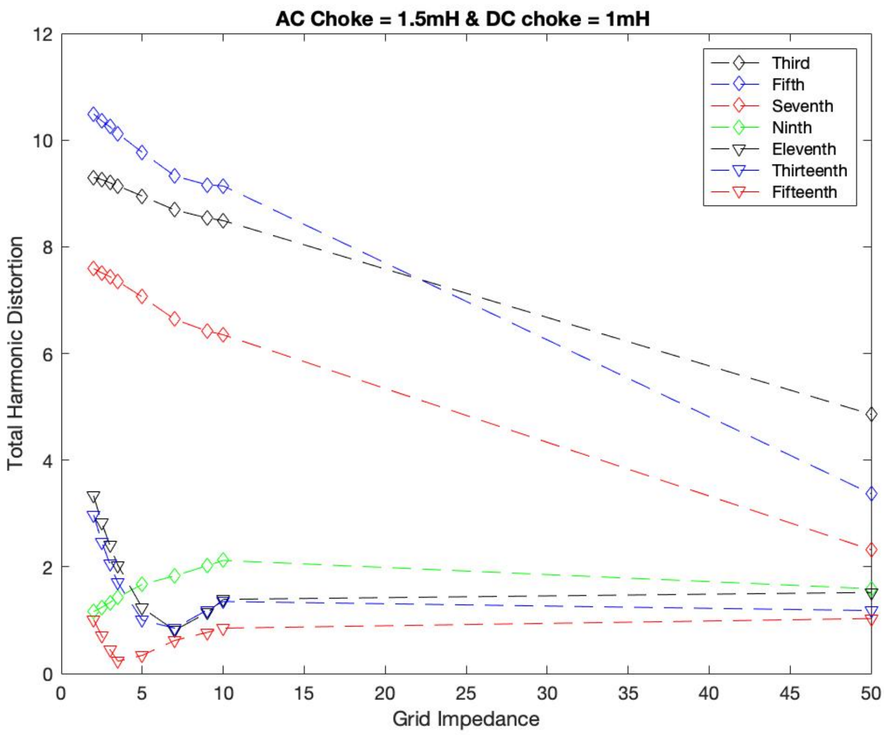



Figure 5.14: Parameters of various cases

# Chapter 6

# Conclusion

Power Quality specifically in terms of Harmonics is analysed , the Harmonics are mitigated with passive mitigation strategies.Various cases are simulated for verification of the hypothesis. Three parameters are analysed with respect to the harmonic performance .The grid impedance , DC Choke values and specific harmonic content is analysed. The data is extracted after simulations are conducted in MATLAB and Simulink and post processing of data is done using MATLAB. MATLAB is used to process data and plot graphs for the harmonic performance with respect to the various parameters.

## 6.1 Linear Regression

The post processing of data is done and linear regression is used for forecasting of the data. Establishing a linear relationship between the variables .

A linear equation in the form of Y = mx + C is obtained. The linear equation derived can be easily used to forecast the future performance. The total harmonic distortion can be predicted well in advance this could prove cost cutting for power systems. Cost is a major parameter while deciding between design of filters. Given that we could predict the performance well ahead of time can be a crucial point of design analysis .The research could be extended to any model with a set of data and simulations conducted for varying values of grid impedance. In the format Y is Total Harmonic Distortion which we are interested in and is the dependent variable where x is the gird impedance , c will be the constant of the equation which would not change. So substituting values for any desired Case for a value of X (grid impedance) would give us the forecasted value of Total Harmonic Distortion.

Various graphs are plotted using Linear fitting with Basic fitting tool in MATLAB after importing the excel file into MATLAB. Further Linear fitting is performed and accuracy is checked with coefficient of correlation.

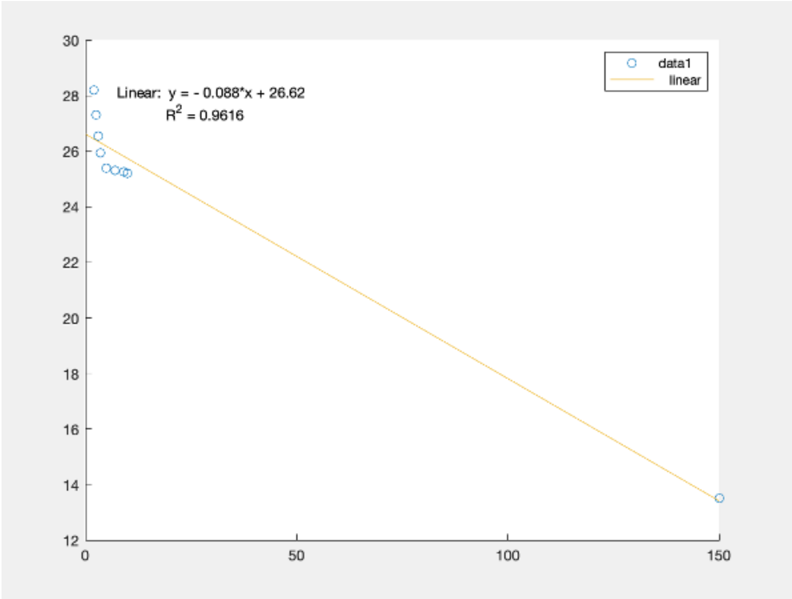



Figure 6.1: Parameters of various cases

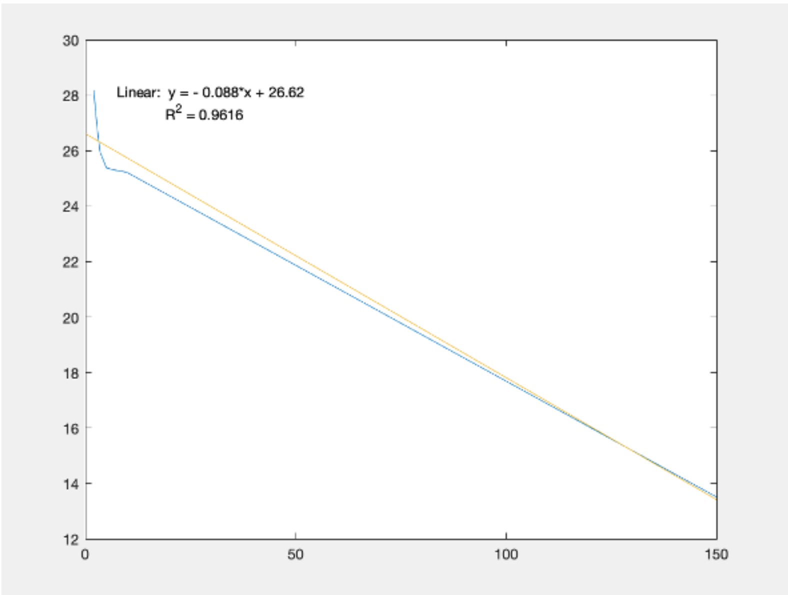



Figure 6.2: DC Choke values variance

# Chapter 7

# Discussion of Results

## 7.1 Discussion of Results and Significance

The effect of varying grid impedance on the Total Harmonic distortion is studied. A general pattern has been seen and an increase in grid impedance tends to decrease the overall THD .

Amongst the four cases AC Choke  DC Choke when implemented together gives the best harmonic performance as compared to others.

A general trend for all the specific harmonics is seen ; specific harmonics decrease with increasing DC Choke values and impedance of the grid. A analysis for the effect of the parameters on Total Harmonic Distortion is studied for Four test Cases .

The other three cases could offer good harmonic performance if the grid impedance is kept high.

Linear Regression offers good potential for research when coupled with Active Filters or Hybrid Filters in Multidrive system.

## 7.2 Future Work

The purpose of this thesis was to establish a methodology for forecasting the total harmonic distortion for any case of simulation before actual design of the power system. This research is specifically constricted to passive filters but can be extended to active filters and hybrid filters.

1. Comparison of the results of simulation to hardware implementations
2. Extrapolating the research for other topologies and rectifier designs
3. Verification of data on actual data set
4. The following research can be further extended for Active filters and Hbrid filter designing.

5. This can be considered as an important aspect of designing for optimisation of the costs and performance.

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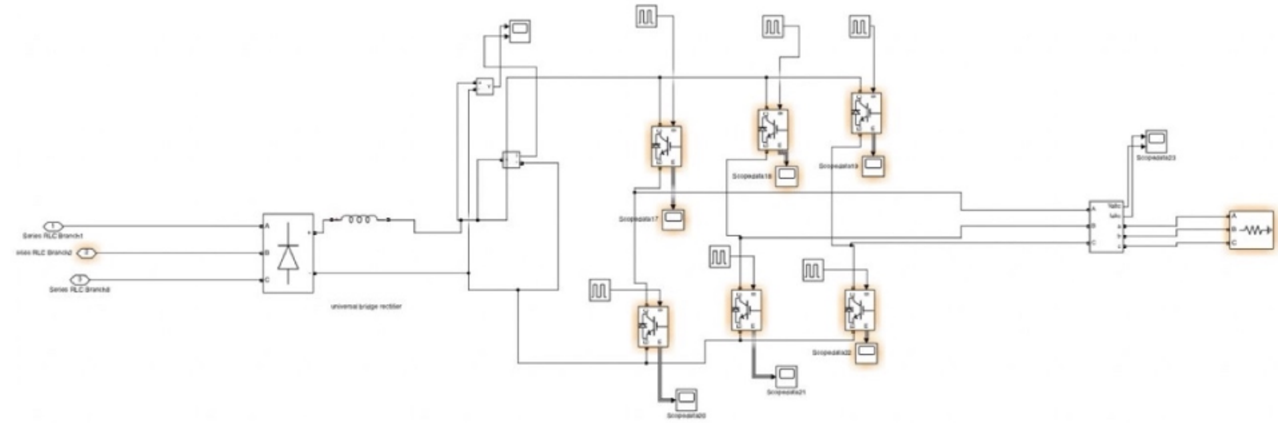
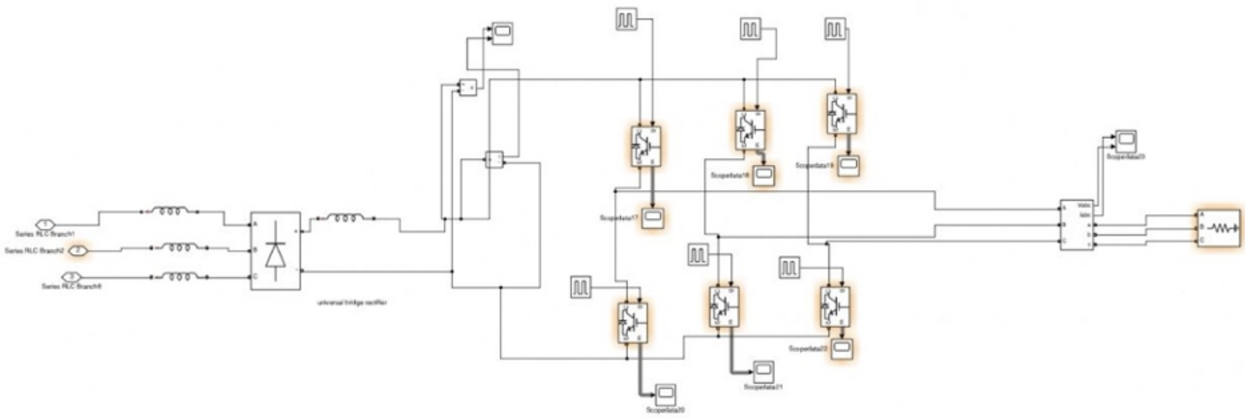
# Chapter 8

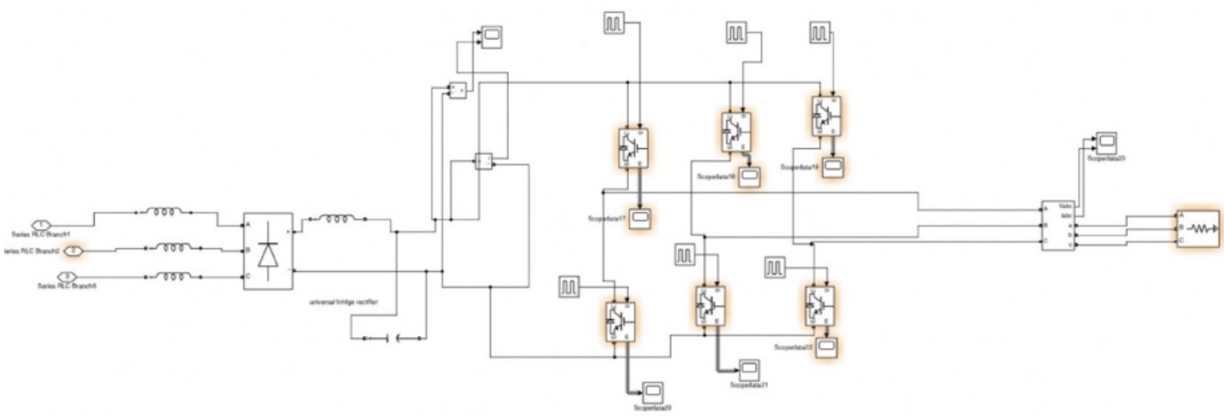
# Appendix

```
%Graph for combining the various cases together
%Graph that plots ac choke + dc choke with ac choke = 1mH and DC Choke 0.5uH
Parameters = TEST(:,1)
Dcchoke_1 = TEST(:,2);
Dcchoke_2 = TEST(:,8);
Dcchoke_3 = TEST(:,10);
Dcchoke_4 = TEST(:,12);
plot (Dcchoke_1,'bv--')
title('Comparison of Various Cases')

hold on

% Graph for AC Choke + Dc choke ( Cdc ac - 1.5mh
dc - 1.5mh  cdc =
% 500uf)
plot (Dcchoke_2,'r*--')
hold on
%graph for DC Choke + DC Capacitance
plot(Dcchoke_3,'m^--')
ylabel('Total Harmonic Distortion')
xlabel('Grid impedance')

%graph for DC Choke = 1.5mH
plot(Dcchoke_4,'ko-')
legend('AC Choke= 1mH & DC Choke = 0.5uH','AC Choke =1.5mH,DC Choke =1.5mH & Cdc = 500uF
'DC Choke = 1.5mH & CdC = 30uF ','DC Choke = 1.5mH')
--------------------------------------------
```

```
% graph for increasing DC Choke values

Dcchoke_1 = DCChange(:,2);
Dcchoke_2 = DCChange(:,3);
Dcchoke_3 = DCChange(:,4);
Dcchoke_4 = DCChange(:,5);
plot(Dcchoke_1,'bv--')
title('Change of DC Choke values')
hold on
plot(Dcchoke_2,'r*--')
hold on
plot(Dcchoke_3,'m^--')
ylabel('Total Harmonic distortion')
xlabel('Grid impedance')
plot(Dcchoke_4,'ko-')
legend('1.5mH','2mH','2.5mH','3mH')
--------------------------------------
%graph of ac choke + DC Choke

Dcchoke_1 = DCChange(:,1);
Dcchoke_2 = DCChange(:,2);
Dcchoke_3 = DCChange(:,3);
plot(Dcchoke_1,'bv--')
title('AC Choke & DC Choke')
hold on
plot(Dcchoke_2,'r*--')
hold on
plot(Dcchoke_3,'m^--')
ylabel('Total Harmonic distortion')

legend('AC -1.5mH, DC- 1.5mH','AC-1.5mH, DC - 1mh','AC - 1.5mH, DC - 0.5mH')
--------------------------------------------------------------------------------------------
```







**Case : AC Choke , DC Choke & Cdc**

i) AC Choke = 1.5mH , DC Choke = 1.5mH & Cdc = 500uF

| Grid Imp | THD |
|---|---|
| 2uh | 24.31 |
| 2.5uh | 24.22 |
| 3uh | 24.15 |
| 3.5uh | 24.09 |
| 5uh | 23.9 |
| 7uh | 23.7 |
| 9uh | 23.5 |
| 10uh | 23.4 |
| 150uh | 12.32 |

ii) AC Choke = 1.5mH , DC Choke = 1.5mH & Cdc = 30uF

| Grid Imp. | THD |
|---|---|
| 2uh | 24.31 |
| 2.5uh | 24.22 |
| 3uh | 24.15 |
| 3.5uh | 24.09 |
| 5uh | 23.9 |
| 7uh | 23.7 |
| 9uh | 23.5 |
| 10uh | 23.4 |
| 150uh | 12.32 |

**Case : AC Choke & DC Choke**

i) AC Choke = 1.5mH & DC Choke = 1.5mH

| Grid Imp. | THD |
|---|---|
| 2uh | 12.32 |
| 2.5uh | 24.22 |
| 3uh | 24.15 |
| 3.5uh | 24.09 |
| 5uh | 23.9 |
| 7uh | 23.7 |
| 9uh | 23.5 |
| 10uh | 23.4 |
| 150uh | 12.32 |

ii) AC Choke = 1.5mH & DC Choke = 1mH

| Grid Imp. | THD |
|---|---|
| 2uh | 25.56 |
| 2.5uh | 25.2 |
| 3uh | 24.89 |
| 3.5uh | 24.62 |
| 5uh | 23.94 |
| 7uh | 23.27 |
| 9uh | 23 |
| 10uh | 22.92 |
| 150uh | 12.42 |

iii) AC Choke = 1.5mH & DC Choke = 0.5mH

| Grid Imp. | THD |
|---|---|
| 2uh | 28.19 |
| 2.5uh | 27.3 |
| 3uh | 26.55 |
| 3.5uh | 25.95 |
| 5uh | 25.38 |
| 7uh | 25.3 |
| 9uh | 25.25 |
| 10uh | 25.21 |
| 150uh | 13.51 |

**Case : DC Choke & DC Capacitance**

i) DC Choke = 1.5mH & DC Capacitance = 30uF

| Grid Imp | THD |
|---|---|
| 2uh | 32.48 |
| 2.5uh | 32.91 |
| 3uh | 33.29 |
| 3.5uh | 33.61 |
| 5uh | 34.45 |
| 7uh | 35.84 |
| 9uh | 37.2 |
| 10uh | 37.68 |
| 150uh | 10.12 |

ii) DC Choke = 1.5mH & DC Capacitance = 500uF

| Grid Imp | THD |
|---|---|
| 2uh | 32.48 |
| 2.5uh | 32.91 |
| 3uh | 33.29 |
| 3.5uh | 33.61 |
| 5uh | 34.45 |
| 7uh | 35.84 |
| 9uh | 37.2 |
| 10uh | 37.68 |
| 150uh | 10.12 |

Case : DC Choke

i) DC Choke = 1.5mH

| Grid Imp. | THD |
|---|---|
| 2uh | 32.48 |
| 2.5uh | 32.91 |
| 3uh | 33.29 |
| 3.5uh | 33.61 |
| 5uh | 34.45 |
| 7uh | 35.84 |
| 9uh | 37.2 |
| 10uh | 37.68 |
| 150uh | 10.12 |

ii) DC Choke = 2mH

| Grid Imp. | THD |
|---|---|
| 2uh | 32.14 |
| 2.5uh | 32.45 |
| 3uh | 32.79 |
| 3.5uh | 33.09 |
| 5uh | 33.83 |
| 7uh | 34.73 |
| 9uh | 35.73 |
| 10uh | 36.22 |
| 150uh | 13.39 |

iii) DC Choke = 2.5mH

| Grid Imp. | THD |
|---|---|
| 2uh | 32.13 |
| 2.5uh | 32.18 |
| 3uh | 32.42 |
| 3.5uh | 32.7 |
| 5uh | 33.41 |
| 7uh | 34.07 |
| 9uh | 34.88 |
| 10uh | 35.31 |
| 150uh | 16.66 |

iv) DC Choke = 3mH

| Grid Imp. | THD |
|---|---|
| 2uh | 32.49 |
| 2.5uh | 32.14 |
| 3uh | 32.21 |
| 3.5uh | 32.42 |
| 5uh | 33.08 |
| 7uh | 33.76 |
| 9uh | 34.19 |
| 10uh | 34.64 |
| 150uh | 19.62 |