EFFECT OF USING PWM RECTIFIERS AND PHASE SHIFTED TRANSFORMER FED RECTIFIERS ON HARMONIC MITIGATION

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By

SALAR AHMED RASOOL

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I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name: Salar Ahmed Rasool

Signature:

Date:

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To my family…

ABSTRACT

Two broad categories of load types exist: linear and non-linear. If the current has the same waveform as the supply voltage (i.e., sine wave) then this is characteristic of a linear load. Examples of linear loads include motors, incandescent lights, heating elements using resistors, capacitors and inductors. Non-linear loads are common in industrial sites and often comprise of equipment such as welding machines, arc and induction furnaces, battery chargers, variable speed drives for AC or DC motors, and uninterruptible power supplies. The currents of non-linear loads deviate from sinusoidal waveforms. They create some harmonic current through the distribution system and, due to the network impedance, cause voltage distortion. Simply stated, power line harmonics flow produce by Non-linear load. Another source of harmonic currents is power electronic converters in power systems.

These undesired currents overburden wiring and transformers, making heat and, in great cases, fire. They are also harmful to equipment. They weaken the reliability and shorten the life expectancy of equipment exposed to the distortion. Therefore, it is extremely critical to mitigate the effects of harmonics.

In this thesis harmonic currents created by variable frequency drives are analyzed. Then, two techniques to reduce the harmonic content are investigated through simulation. These techniques are using a phase shifted transformer connection and using a PWM rectifier at the front end of the drivers. Simulation results obtained in MATLAB R2013a show that phase shifting transformer connection yield slightly better results. However, they are heavier, bulkier and more expensive.

Keywords: Total harmonic distortions (THD); phase shift transformer (PST); variable frequency drive (VFD); insulated gate bipolar transistors (IGBT); PWM rectifier

ÖZET

Enerji sistemlerinin yükleri kabaca iki sınıfa ayrılabilir: Doğrusal yükler ve doğrusal olmayan yükler. Doğrusal yük durumunda yük akımının şekli uygulanan gerilimle aynıdır. Doğrusal yüklere örnek olarak motorlar, akkor lambalar, rezistive ısıtıcılar, kondansatörler ve endüktörler gösterilebilir. Öte yandan, sanayide doğrusal olmayan yük kullanımı da yaygındır. Bunlara örnek olarak da kaynak makineleri, endüksiyon ocakları, ark fırınları, batarya şarj sistemleri, ayarlanabilir hızlı sürücüler ve kesintisiz güç kaynakları sayılabilir. Doğrusal olmayan yüklerin akımları bozulmuş sinüs şeklindedir. Bu akımlar dağıtım sistemine harmonik akımlar enjekte ederler ve şebekenin empedansı nedeniyle gerilim bozuntusuna da yol açarlar. Basitçe, doğrusal olmayan yüklerin güç sistemlerinde harmonik akım akışına neden olduğu söylenebilir. Harmonik akımların bir diğer kaynağı da güç elektroniği devreleridir.

Bu istenmeyen akımlar iletim hatlarının ve transformatörlerin aşırı yüklenmesine neden olurlar ve ısınmaya, bazı durumlarda da yangına neden olurlar. Ayrıca donanıma da zarar verebilirler. Bozunum maruz kalan donanımın ömrü kısalır ve güvenilirliği azalır. Bu nedenle, harmoniklerin etkilerinin azaltılması yaşamsaldır.

Bu tez çalışmasında değişken frekanslı sürücülerin yarattığı harmonikler incelenmekte ve analiz edilmektedir. Sonra, harmonikleri azaltmak için kullanılan iki yöntem benzetim yoluyla incelenmektedir. Bu yöntemler faz kaydırıcı transformatör kullanımı ve sürücünün ön katında PWM doğrultucu kullanımıdır. MATLAB R2013a ile elde edilen benzetim sonuçları faz kaydırıcı transformatör kullanımının biraz daha iyi sonuç verdiğini göstermektedir. Ancak, bu sistemler daha ağır, daha hantal ve daha pahalıdır.

Anahtar Kelimeler: Toplam harmonik bozunum; faz kaydırıcı transformatörler; değişken frekanslı sürücüler; PWM doğrultucu

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i'_{ap}:	i_a referred to Primary side
i'_{bp}:	i_b referred to Primary side
i'_{cp}:	i_c referred to Primary side
$\bar{V}_{AB}$:	Line-to-Line Primary phasor
$\bar{V}_{ab}$:	Line-to-Line Secondary phasor
$i_{\tilde{a}}$:	Line current in secondary delta transformer
$i'_{\tilde{a}}$:	Line current in secondary delta transformer referred to primary
δ:	Phase angle
$\hat{I}_n$:	Peak value of the n^{th} order harmonic current
N1:	Primary winding number turns
$\angle i'_{an}$:	Phase angles of n^{th} order harmonic i'_{an}
$\angle i_{an}$:	Phase angles of n^{th} order harmonic i_{an}
V_{AB}:	Primary Line voltage
N2:	Secondary winding number turns
V_{ab}:	Secondary Line voltage
i_a, i_b, i_c:	Secondary Line current

LIST OF ABBREVIATIONS

AC : Alternative current

ASD : Adjustable speed drive

P : Active power

S : Apparent power

CSO : Current source output

CSI : Current source inverter

CFI : Current fed inverter

DC : Direct current

EMI : Electromagnetic Interference

fs Source frequency

GTO : Gate turn-off thyristor

I/P : Input voltage

IEEE : Institute of Electrical and Electronics Engineers

IEC : International Electro technical Commission

IGBT : Insulated gate bipolar transistor

M_i: Modulation index

PWM : Pulse width modulation

PCR : Phase controlled rectifier

PF : Power factor

Q : Reactive power

O/P : Output voltage

RMS : Root Mean Square

SMPS : Switch Mode Power Supply

THD : Total Harmonic Distortion

UPS : Uninterruptable power supply

VFD : Variable frequency drive

VSD : Variable speed drive

VSO : Voltage source output

VSI : Voltage source inverter

VFI : Voltage fed inverter

CHAPTER 1

INTRODUCTION

This document has been created to give general information of power system harmonics, their causes, effects and methods to control them especially when these harmonics are related to variable frequency drives (or adjustable speed drives). Some of the subjects covered are definition of harmonic, generation of harmonics, effects of harmonics and control of harmonics. As the sin wave voltage is given to the load (linear), Furthermore, The load current is directly proportional to the voltage, and impedance, as a result voltage waveform. Most common linear-loads are resistive heaters, incandescent lamps and induction or synchronous motors operating in the unsaturated region.

For some loads current and voltage are not proportional to each other. These loads are classified as nonlinear loads. In this case current and voltage waveforms are non-sinusoidal and contain distortions. The 50-Hz waveform has numerous additional waveforms superimposed upon it creating multiple frequencies within the normal 50-Hz sine wave period. The fundamental frequency multipliers are harmonics. Normally, harmonic current distortions create harmonic voltage distortions. When the applied voltage source is stiff, meaning that no matter how much current is drawn from it, its voltage will remain constant, and this will not be a concern. Variable frequency motor drives (VFD), switch mode power supplies and battery charges can be shown as the most prominent examples of nonlinear loads.

Power electronic devices are used in VFDs to adjust the amplitude and the frequency of the voltage that is applied to the load. Pulse Width Modulation (PWM) is the most widespread technique to obtain near sinusoidal currents for the motor windings. However, the dc bus voltage needed by the inverter is typically obtained by a diode rectifier which draws non-sinusoidal currents from the line, creating harmonic distortion in the line voltage. Harmonic magnitudes should be limited to be able to have a clean and efficient power. Voltage and current waveforms rich in harmonics may lead to following abnormal operations and conditions in power systems (Svensson, 1999):

- Due to voltage harmonics, it produces heating in induction, and synchronous motors along with generators at all.
- By the effect of voltage harmonics, the higher values can cause the reduction of insulation levels results weaken insulation in winding as well as in capacitors.
- Voltage distortions cause the malfunction of different electrical components.
- Due to current harmonics, while winding of the motor, results EMI (Electro-magnetic interference).
- Current harmonics in motor windings can create electromagnetic interference (EMI).
- Current distortion flowing through transformers& cables produce higher heating additional with the heating that is produced by the fundamental signal.
- Heat losses are increasing, as the current harmonics passes from circuit breakers, and switch-gears.
- In power system, different filtering topologies are used, create failure of capacitors or in other equipment, all these issues are regarding to current harmonics produce resonant currents.
- Finally, harmonics results false tripping of circuit breakers, and relays failure which used for protection of power systems.

1.1 Objective

Objective of the thesis is to investigate the effects of driving techniques of variable speed motors on harmonic generation. In this context, simulations have been performed for an induction motor driven by an inverter with two different front-end rectifiers. First a 24-pulse rectifier obtained by phase shift transformers has been designed and tested by simulation. Then a buck-type PWM rectifier has been designed and tested. Simulations have been carried out for a 4 kW induction motor operating at different conditions. Results for each case has been obtained and compared. It is concluded that both techniques can be effectively used to keep the harmonics in related standards but the PWM rectifier is preferred since it is simpler, cheaper and more compact.

1.2 Thesis Structure

In Chapter 1 general information of power system harmonics and objective of this thesis are explained. In Chapter 2 harmonic issues in power systems are discussed. In Chapter 3 the techniques used in this thesis are explained. Phase shift transformer structure is discussed and its turns-ratios are calculated. Simulation results are given in Chapter 4. Chapter 5 gives the conclusions.

CHAPTER 2

HARMONIC PROBLEMS IN POWER SYSTEMS

In this chapter, harmonic issues in power systems are discussed. Sources of harmonics are explained and mitigation techniques are summarized. The two techniques that are used in this thesis, multi-pulse rectifiers and PWM rectifiers are explained in more detail.

2.1 Electrical Load Classification

Electrical loads can be classified as linear and non-linear depending on their voltage-current relationships.

2.1.1 Linear electrical loads

Linear loads obey the Ohm's Law and therefore the wave shape of their steady state current will follow the wave shape of the applied voltage. Some examples of linear loads are given in Table 2.1.

Table 2.1: Some examples of linear-loads

Resistive	Inductive	Capacitive
Incandescent Lamps	Induction motors	Capacitor banks used for power factor correction
Electric heaters	Current limiting reactors	Capacitors used in harmonic filters
	Induction generators (Wind mills)	Underground cables
	Harmonic damping reactors	Insulated cables
	Tuning reactors in harmonic filters	

2.1.1.1 Properties of linear loads

- In AC circuits, voltage and current waveforms of linear loads are sinusoidal. There may be a phase shift between the voltage and the current waveforms but their amplitudes are proportional as shown in Figure 2.1.
- Impedance of a linear load does not change with the amplitude of the applied voltage. The fixed impedance means that the current drawn by the linear load will be sinusoidal just like the voltage.
- Linear loads do not produce any new frequency (harmonics) or change the applied frequency.

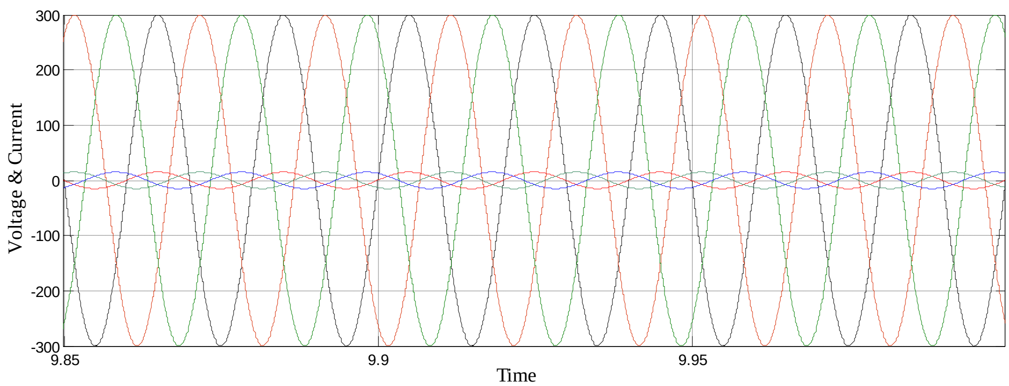


Figure 2.1: Characteristics of electrical linear loads

2.1.2 Non-linear electrical loads

Non-linear electrical loads do not obey the Ohm's Law. Their voltage-current relationship is nonlinear. As a result, even if the applied voltage is sinusoidal, the current may be distorted. Distorted waveforms include components in different frequencies called harmonics. Some examples of non-linear loads are given in Table 2.2.

Table 2.2: Some examples of non- linear loads

Power electronics	Arc devices
Variable frequency drives	Fluorescent lighting
DC motor controllers	Arc furnaces
Cycloconverters	Welding machines
Cranes	
Elevators	
Steel mills	
Power supplies	
UPS	
Battery chargers	

2.1.2.1 Properties of non-linear loads

- Non-linear loads change the shape of the current waveform from a sine wave to some other form as shown in Figure 2.2.
- Non-linear loads create harmonic currents in addition to the original (fundamental frequency) AC current. Under these conditions, the voltage waveform is no longer proportional to the current.
- Impedance of non-linear loads changes with the amplitude of the applied voltage. The changing impedance means that the current drawn by the non-linear load will not be sinusoidal even when it is connected to a sinusoidal voltage. These non-sinusoidal currents contain harmonic currents that interact with the impedance of the power distribution system to create voltage distortion that can affect both the distribution system equipment and the loads connected to it.

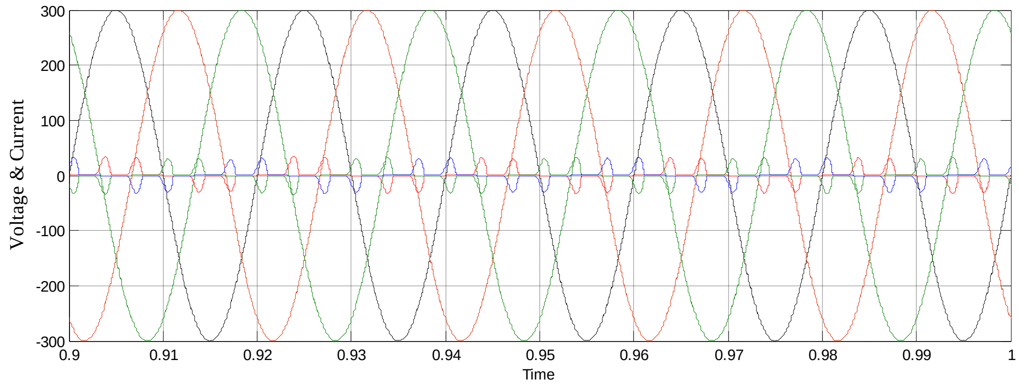


Figure 2.2: Characteristics of non-linear load

2.2 Power Factor in Electrical Power Systems

Power factor is an important parameter for the loads of distribution systems. Industrial consumers are required to use power factor correction (PFC) systems to keep the power factor in certain limits to reduce the amount of reactive power drawn from the line. Traditional PFC methods typically focus on displacement power factor and therefore do not achieve the total energy savings available in facilities having both linear and non–linear loads. Only a through Total Power Factor Correction can the savings and power quality be maximized (Sandoval, 2014).

2.2.1 Power factor with linear loads

When the loads connected to the system are linear and the voltage is sinusoidal, the power factor is calculated with the following equation:

$$\mathrm{Pf} = \mathrm{COS}(\varphi) \tag{2.1}$$

It can also be defined as the ratio of active power to apparent.

$$\mathrm{Pf} = \frac{\mathrm{P}}{\mathrm{S}} \tag{2.2}$$

When the loads are linear and the voltage is sinusoidal, the active, reactive and apparent powers are calculated mathematically with the following equations:

$$P = VI\cos(\varphi) \tag{2.3}$$

$$Q = VI\sin(\varphi) \tag{2.4}$$

$$S = VI \tag{2.5}$$

Figure 2.3 shows these relationships in phasor forms.

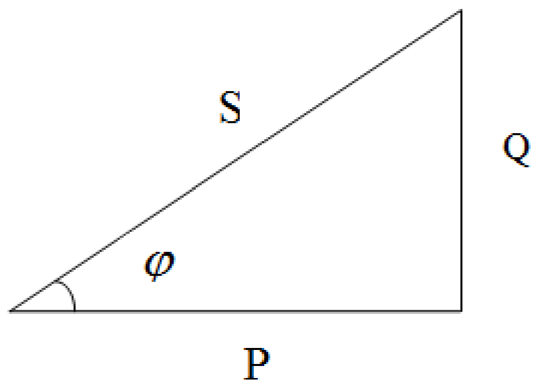


Figure 2.3: Power triangle

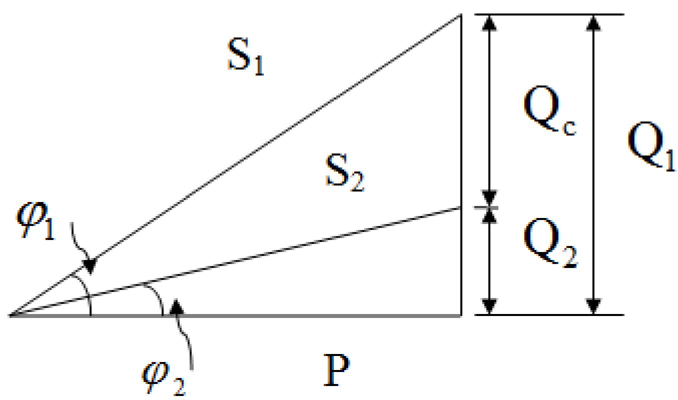


Figure 2.4: Power triangle with capacitor bank

If the power factor is low, a smaller portion of the total power is used to create work, which is called active power (P), and the rest is known as reactive power (Q). Power factor can be improved by power factor correction systems to minimize the reactive power and maximize the active power. The most common technique used in power factor correction is connecting a capacitor bank in parallel with the load (Sandoval, 2014). This is called compensation. Effect of compensation is shown in Figure 2.4. When a capacitor is added the phase angle is reduced and thus $\cos\varphi_2 > \cos\varphi_1$.

2.2.2 Power factor for non–linear loads under sinusoidal voltage

When the loads are non–linear but the applied voltage is sinusoidal, the current has harmonics and the active, reactive and apparent power should not be calculated using traditional methods. In this case, only the fundamental harmonic of the load current contributes to the active power generation. Therefore active power is defined as

$$\mathrm{P} = \mathrm{VI}_1 \cos(\varphi_1) \tag{2.6}$$

Where I_1 is the fundamental current and φ_1 is the phase angle between the voltage and fundamental current.

Total Harmonic Distortion (THD) is an important power quality parameter and shows how distorted a waveform is. THD of the current signal is defined as

$$(\mathrm{THD})_i = \frac{\sqrt{\sum_{n=2}^{\infty} \mathrm{I}_n^2}}{\mathrm{I}_1} \tag{2.7}$$

Where I_n is the rms value of the n^{th} harmonic since

$$\mathrm{I} = \sqrt{\sum_{n=2}^{\infty} \mathrm{I}_n^2} \tag{2.8}$$

THD can be rewritten as

$$(\mathrm{THD})_i = \frac{\sqrt{\mathrm{I}_n^2 - \mathrm{I}_1^2}}{\mathrm{I}_1} = \sqrt{\left(\frac{\mathrm{I}_n}{\mathrm{I}_1}\right)^2 - 1} \tag{2.9}$$

Therefore, the RMS value of current can also be expressed as a function of THD, as well as fundamental current value is mentioned in Equation.(2.10).

$$I = I_1 \sqrt{1 + THD_1^2} \tag{2.10}$$

By using the equations (2.5), (2.6) and (2.10), total power factor can be calculated in Equation.(2.11)

$$pf = \cos(\varphi_1) \frac{1}{\sqrt{1 + THD_1^2}} \tag{2.11}$$

There are two terms involved in the calculation of the power factor: $(\cos \varphi_1)$ and $1 / \sqrt{1 + THD_1^2}$. The term $(\cos \varphi_1)$ is called the displacement power factor pf_{disp} since it is the cosine of the phase angle between the voltage and the fundamental component of the current, similar to the power factor calculated with linear loads under sinusoidal voltage. The term $1 / \sqrt{1 + THD_1^2}$ is called distortion power factor pf_{dist}. Total Power Factor pf_T obtained mathematically as in Equation. (2.12):

$$pf_T = pf_{disp} \times pf_{dist} \tag{2.12}$$

Total power factor decreases if and only if the angle between the voltage and fundamental current grows due to increase in the reactive power. Similarly if the $(THD)_i$ increases the total power factor decreases. Because of distortion, total power factor is always lower than the displacement power factor.

Total power factor correction can only be achieved when both displacement power factor and distortion power factor are corrected. Therefore, the displacement angle between voltage and current should be reduced and the total harmonic current distortion should be minimized. If both of these measures are not taken together, the total power factor may still be improved but it may not be enough to meet the demands of the utility.

Power triangle for nonlinear loads under sinusoidal voltage is shown in Figure 2.5. The triangle is built by using the fundamental components. Relationship between the active power (P), the fundamental reactive power (Q_{1F}) and the fundamental apparent power (S_{1F}) can be obtained by using this triangle. Effect of connecting a capacitor bank is shown in Figure 2.6.

Reactive power supplied by the capacitor (Q_{CF}) reduces the reactive power supplied by the line. However, there is always the risk of resonance between the capacitor bank and the inductive transformer winding.

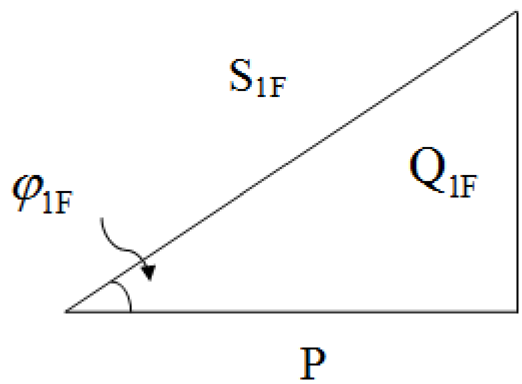


Figure 2.5: Power triangle in non-linear load and sinusoidal voltage

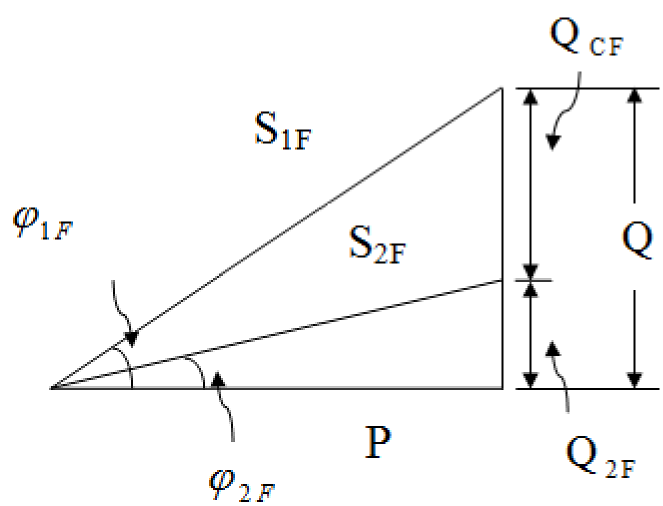


Figure 2.6: Power triangle in non-linear load and sinusoidal voltage with capacitor bank

2.2.3 Power factor for non-linear loads under distorted supply voltage

When the loads are non–linear and the voltage is distorted, the active, reactive and apparent power cannot be calculated by using the previous equations. Now, each harmonic component of the voltage and current can contribute to the total active power. Therefore, voltage and current components at each harmonic frequency should be included in the summing equation. As the phase angles of the voltage harmonics can be neglected, total active power equation can be expressed as follows:

$$P = \sum_{n=1}^{N} V_n I_n \cos(\varphi_n) \tag{2.13}$$

Mathematically Power factor calculated by

$$pf = \frac{\sum_{n=1}^{N} V_n I_n \cos(\varphi_n)}{VI} \tag{2.14}$$

However, the voltage rms value is a function of the total harmonic voltage distortion and the rms value of the fundamental component of voltage:

$$V = V_1 \sqrt{1 + THD_V^2} \tag{2.15}$$

By applying equations (2.10),(2.14) and (2.15), the power factor can be obtained as:

$$pf = \frac{P}{S_1} * \frac{1}{\sqrt{1 + THD_I^2} * \sqrt{1 + THD_V^2}} \tag{2.16}$$

$1 \Big/ \left(\sqrt{1 + THD_I^2} * \sqrt{1 + THD_V^2} \right)$ is the distortion power factor. Its value depends on both the voltage distortion and the current distortion. So,

$$pf_T = \frac{P}{S_1} pf_{dist} \tag{2.17}$$

The term P/S_1 can be written as:

$$\frac{P}{S_1} = \frac{V_1 I_1 \cos(\varphi_1)}{S_1} + \frac{\sum_{n=2}^{N} V_n I_n \cos(\varphi_n)}{S_1} \tag{2.18}$$

Where $V_1 I_1 \cos(\varphi) / S_1$ is the displacement power factor. So,

$$pf_T = \left(pf_{disp} + \frac{\sum_{n=2}^{N} V_n I_n \cos(\varphi_n)}{S_1} \right) pf_{dist} \tag{2.19}$$

Power triangle for nonlinear loads under distorted sinusoidal voltage is shown in Figure 2.7. Again the reactive power supplied by the capacitor (Q_{CF}) reduces the reactive power supplied by the line, and there is still the risk of resonance between the capacitor bank and the inductive transformer winding. The total power factor can be improved by decreasing the harmonic current distortion by using a harmonic filter. The capacitive part of the filter improves the displacement power factor while the combination of the reactor and the capacitor bank decreases the total harmonic distortion of the current, thus improving the distortion power factor, as well as the total power factor (Sandoval, 2014).

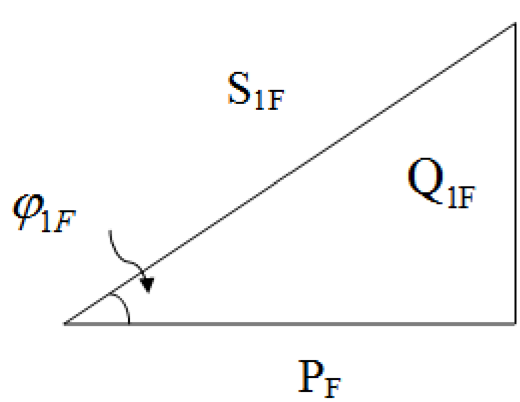


Figure 2.7: Power triangle in non-linear load and voltage distortion

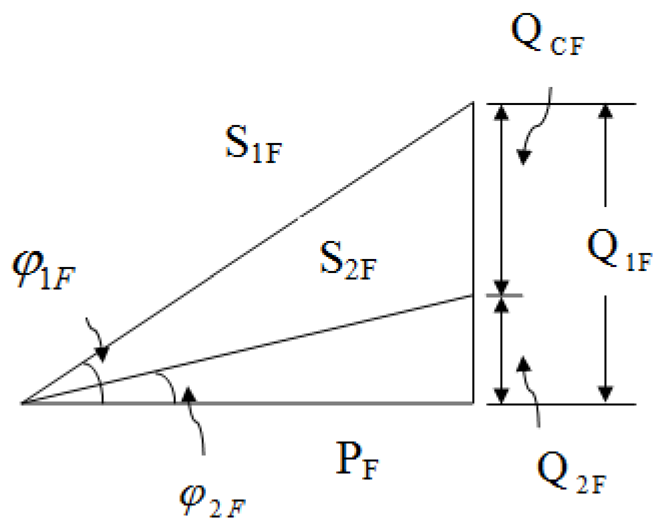


Figure 2.8: Power triangle in non-linear load and voltage distortion with capacitor bank

2.3 Variable Frequency Drives

Variable frequency drives (VFD) utilize power electronic switches to adjust the amplitude and the frequency of the voltage applied to motor windings. VFDs are also called Variable Speed Drives (VSD) and Adjustable Speed Drives (ASD). VFDs typically consist of an inverter to supply the motor with adjustable frequency and magnitude, and a rectifier stage to obtain the dc link required by the inverter. A typical system is shown in Figure 2.9, which includes a three-phase diode rectifier.

The dc bus typically employs a large capacitor to store energy. The dc voltage across the capacitor is switched by the inverter which generally consists of IGBTs or power MOSFETs, depending on the voltage and power levels of the load. Most popular switching algorithm is PWM (BalaRaju et al., 2012).

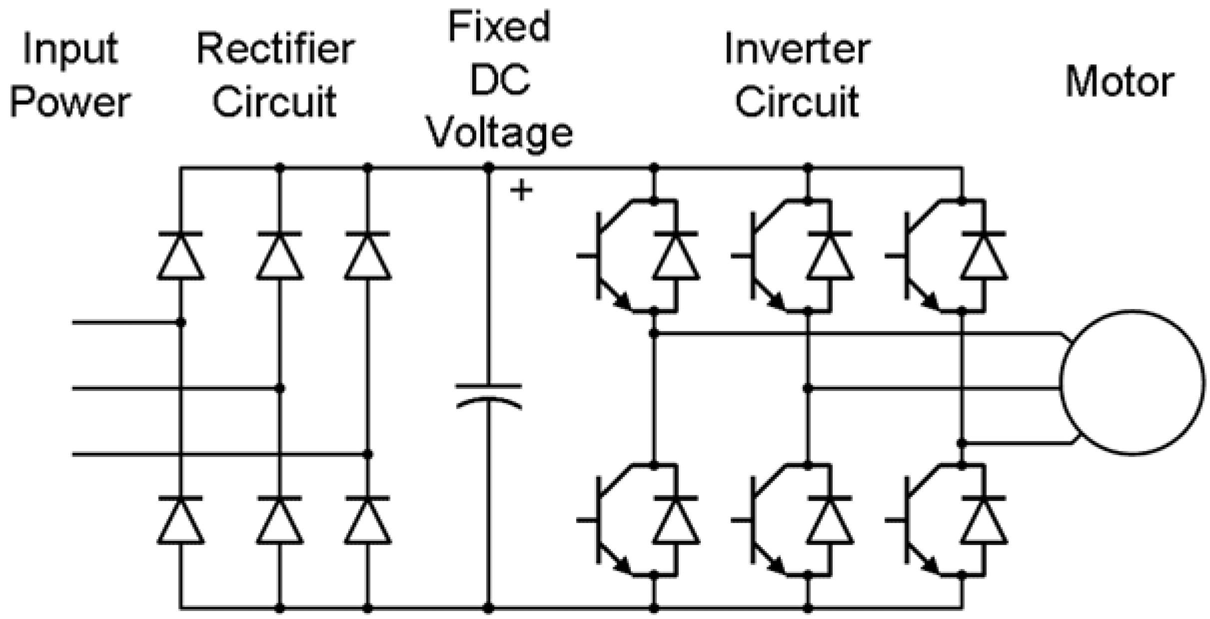


Figure 2.9: VFD system (BalaRaju et al., 2012)

2.4 Harmonics Mitigation

There are many techniques to mitigate the effects of harmonics. Before applying those techniques, one should know which harmonic frequencies are more effective and which ones are not. Typically the lowest harmonic is the third one since mostly three-phase loads are used. The exception is highly nonlinear loads such as arc furnaces. Arc furnaces create second order harmonics too. The impact and elimination of these harmonics are out of the scope of this thesis.

In three-phase system harmonics of the 3rd order and its multiples (3rd, 6th, 9th etc.) cancel each other because there are 120° phase shifts between the voltages. Remaining harmonics are the 5th, 7th, 11th, 13th… harmonics. Naturally, amplitudes of the first few harmonics are greater, and the magnitude rolls down as the harmonic order increases. Typically, 5th, 7th, and 11th harmonics are the most important ones (BalaRaju et al., 2012).

Nonlinear loads and distorted currents produce distorted voltage drops across the line impedances. As a result, non-sinusoidal voltages appear across the other loads which are connected to the same line. Extra losses in the lines and windings of the transformers and generators, and extra iron losses in the transformer and generator cores are generated as a result of these non-sinusoidal currents and voltages. Therefore, it is required to reduce the harmonics under certain levels set forth by standards such as IEEE 519-1992 in the USA and IEC 61000-3-2/IEC 61000-3-4 in Europe (Manlinowski, 2001).

There are several techniques to mitigate the effects of harmonics. These are categorized as the following:

1- Reduction of harmonics for existing non-linear loads.
2- Reduction of harmonics through linear power electronics load installation.

These techniques which are based on passive components, mixing single and three-phase diode rectifiers, and power electronics techniques as multi- pulse rectifiers, active filters and PWM rectifiers are shown Figure 2.10.

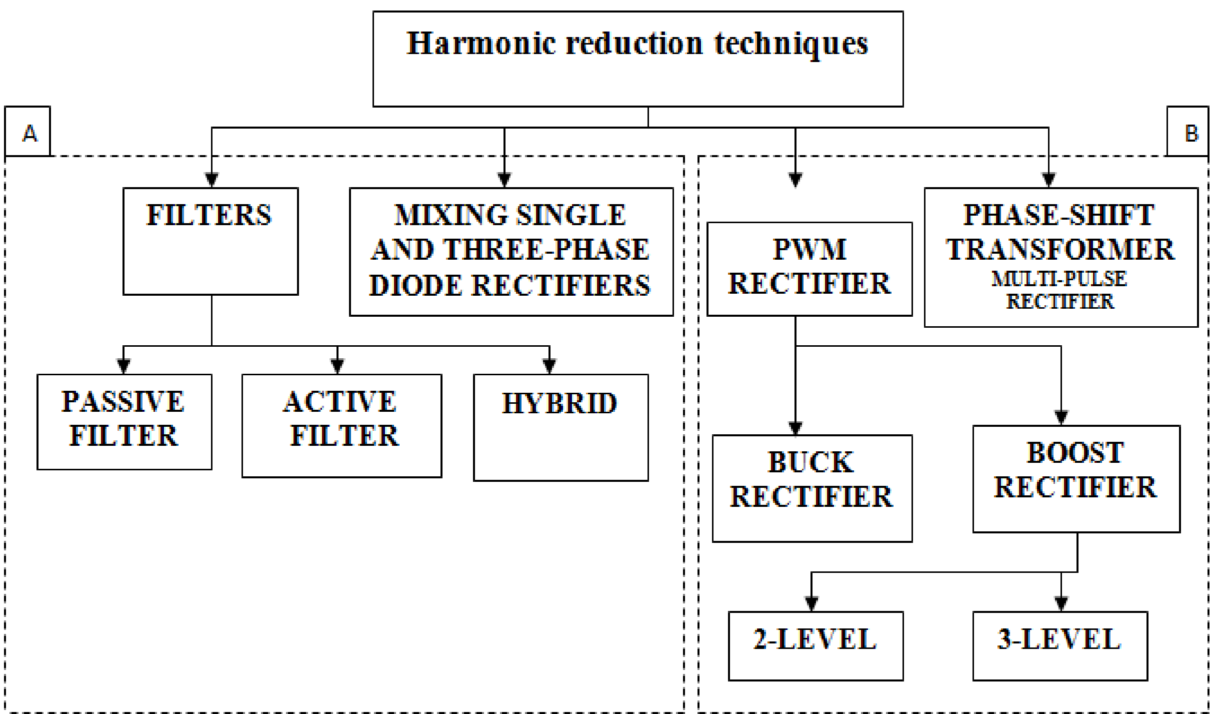


Figure 2.10: Most popular three-phase harmonic reduction techniques for currents

Passive LC filters in parallel with the line are generally used to reduce the current harmonics. They include series-connected legs of capacitors and inductors. A filter leg is used for each harmonic to be filtered. Typically, a leg is used for the fifth, another one for the seventh and another one to reduce the 11th and 13th harmonics together. Passive filters are cheap and simple (Manlinowski, 2001). However, they also have some disadvantages such as below:

1- Separate filters should be designed for each installation and application.
2- High fundamental current result in extra power losses.
3- Filters are heavy and bulky.

Harmonics can be reduced by using multi-pulse transformers too. It is well known that certain harmonics can be cancelled with the proper phase-shifting angle on the secondary side of the transformers. This way, harmonics generated by one of the converters are cancelled with harmonics generated by another converter. There are several line frequency phase shifting transformer connections to reduce harmonics generated by nonlinear loads in electric power distribution system.

Figure 2.11 shows the phase shifted phasors for a 24-pulse rectifier.

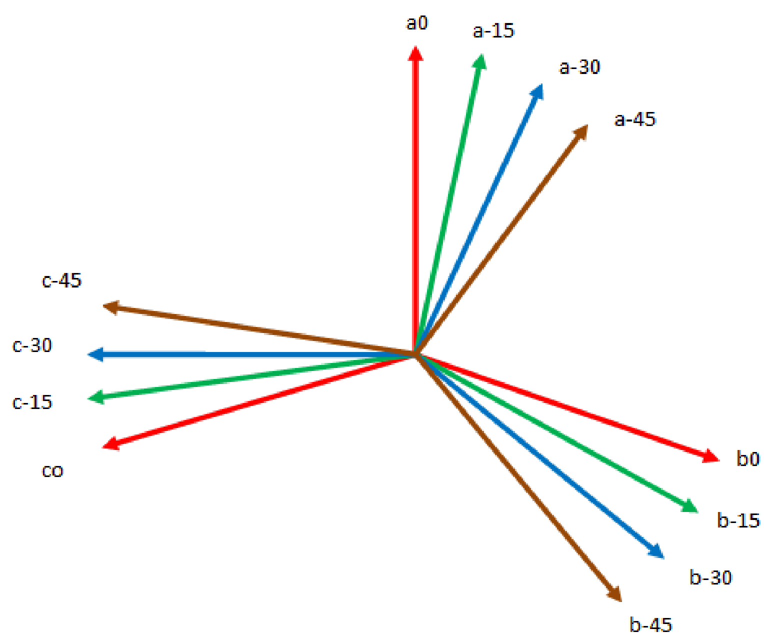


Figure 2.11: Phase shifting transformer voltage phasors

The phase shifting transformer reduction method, possesses several drawbacks like bulky and heavy transformer, excessive voltage drop, and increased harmonic currents at non-symmetrical load.

PWM rectifiers are also used for harmonic mitigation. These rectifiers replace the uncontrolled diode rectifier. The input current for these rectifiers can be made near sinusoidal with zero phase shift. They can provide constant output voltage or current. They can also boost the input voltage (boost type PWM rectifier) or reduce it (buck type PWM rectifier) (Manlinowski, 2001).

Main properties of PWM-rectifiers are as follows:

1- Power can flow in both directions.
2- Input current is nearly sinusoidal.
3- Unity input power factor is possible.
4- Input current total harmonic distortion is very low (under 5%).
5- Adjustment and stabilization of DC-link voltage or current is possible.
6- Capacitor or inductor size is lowered due to the continuous current.

2.4.1 Phase displacement of harmonic currents

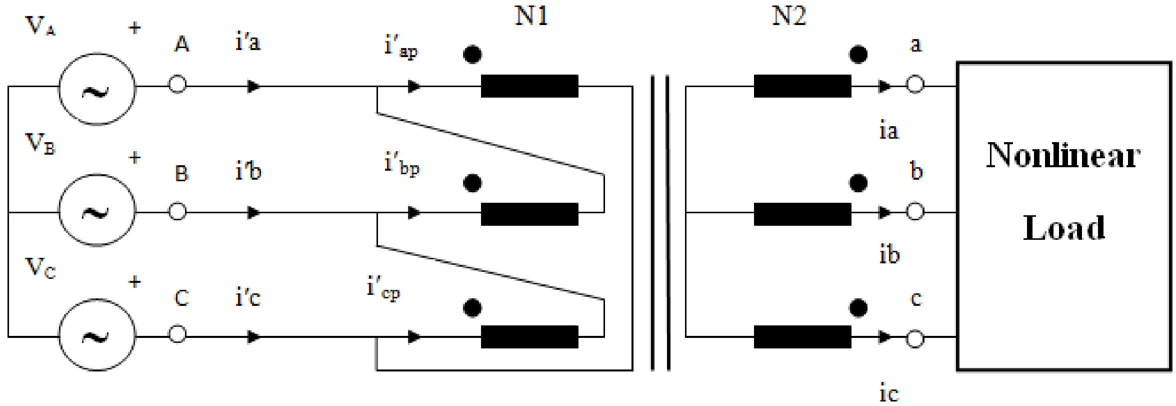
The phases of the harmonic currents are shifted when they are reflected from the secondary to the primary of a phase-shifting transformer. This makes it possible to cancel certain harmonic currents generated by a non-linear load (Wu, 2006). A Δ-Y connected transformer supplying a non-linear load is shown in Figure 2.12.

Assuming that the ratio of the line-to-line voltages is unity, the turn ratio is found as

$$N_1 / N_2 = \sqrt{3}$$

The phase difference between the "line-to-line" voltage of the primary and secondary of the transformer is

$$\delta = \angle\bar{V}_{ab} - \angle\bar{V}_{AB} = -30°$$



$$\delta = \angle\overline{V}_{ab} - \angle\overline{V}_{AB} = -30^\circ$$

Figure 2.12: Investigation of harmonic currents in the primary and secondary windings

In balanced 3-phase system, line currents of the non-linear load are expressed as follows:

$$\left.\begin{aligned} i_a &= \sum_{n=1,5,7,11,....}^{\infty} \hat{I}_n \sin(n\omega t) \\ i_b &= \sum_{n=1,5,7,11,....}^{\infty} \hat{I}_n \sin(n(\omega t - 120^\circ)) \\ i_c &= \sum_{n=1,5,7,11,....}^{\infty} \hat{I}_n \sin(n(\omega t - 240^\circ)) \end{aligned}\right\} \quad (2.20)$$

Where $\hat{I}_n$ is the peak value of the nth order harmonic current.

The referred current in the primary windings can be defined as follows:

$$i'_{ap} = i_a \frac{N2}{N1} = \frac{1}{\sqrt{3}} (\hat{I}_1 \sin(\omega t) + \hat{I}_5 \sin(5\omega t) + \hat{I}_7 \sin(7\omega t) + \hat{I}_{11} \sin(11\omega t) + ...) \quad (2.21)$$

$$i'_{bp} = i_b \frac{N2}{N1} = \frac{1}{\sqrt{3}} (\hat{I}_1 \sin(\omega t - 120^\circ) + \hat{I}_5 \sin(5\omega t - 240^\circ) + \hat{I}_7 \sin(7\omega t - 120^\circ)$$

$$+\hat{I}_{11} \sin(11\omega t - 240^\circ) + ...) \quad (2.22)$$

Line current in the primary can be now calculated:

$$i'_a = i'_{ap} - i'_{bp} = \hat{I}_1 \sin(\omega t + 30°) + \hat{I}_5 \sin(5\omega t - 30°) + \hat{I}_7 \sin(7\omega t + 30°)$$

$$+\hat{I}_{11} \sin(11\omega t - 30°) + ... \tag{2.23}$$

$$= \sum_{n=1,7,13,...}^{\infty} \hat{I}_n \sin(n\omega t - \delta) + \sum_{n=5,11,17,...}^{\infty} \hat{I}_n \sin(n\omega t + \delta) \tag{2.24}$$

In the right side of this equation the first term sums all the positive sequence harmonic currents (n = 1, 7, 13, etc.) while the second term sums the negative sequence harmonics (n = 5, 11, 17, etc.).

When the harmonic components of the reflected line currents in Equation (2.23) are compared to those of the secondary expressed in Equations (2.20), it is seen that the phase is shifted backward for the positive sequence harmonics, and forward for the negative sequence ones:

$$\left.\begin{array}{ll} \angle i'_{an} = \angle i_{an} - \delta \text{ for n=1, 7, 13, 19,…} & \text{Positive sequence} \\ \angle i'_{an} = \angle i_{an} + \delta \text{ for n=5, 11, 17, 23,…} & \text{Negative sequence} \end{array}\right\} \tag{2.25}$$

Here $\angle i'_{an}$ and $\angle i_{an}$ are the phase angles of harmonic currents for the primary and secondary. This equation is valid for any phase angle (Wu, 2006).

2.4.2 Harmonic Cancellation

Harmonic current cancellation using a phase shifting transformer connection is shown in this section for a 12-pulse system, shown in Figure 2.13. The phase shifting angle δ is 0° for the Y connected secondary, and 30° for the Δ connected secondary windings (Wu, 2006).

Let’s the ratio of the line-to-line voltages be $V_{AB}/V_{ab} = V_{AB}/V_{\tilde{a}\tilde{b}} = 2$.The line currents in the secondary windings then can be expressed as follows:

$$i_a = \sum_{n=1,5,7,11,13,...}^{\infty} \hat{I}_n \sin(n\omega t)...$$

$$i_{\tilde{a}} = \sum_{n=1,5,7,11,13,\ldots}^{\infty} \hat{I}_n \sin(n(\omega t + \delta)) \tag{2.26}$$

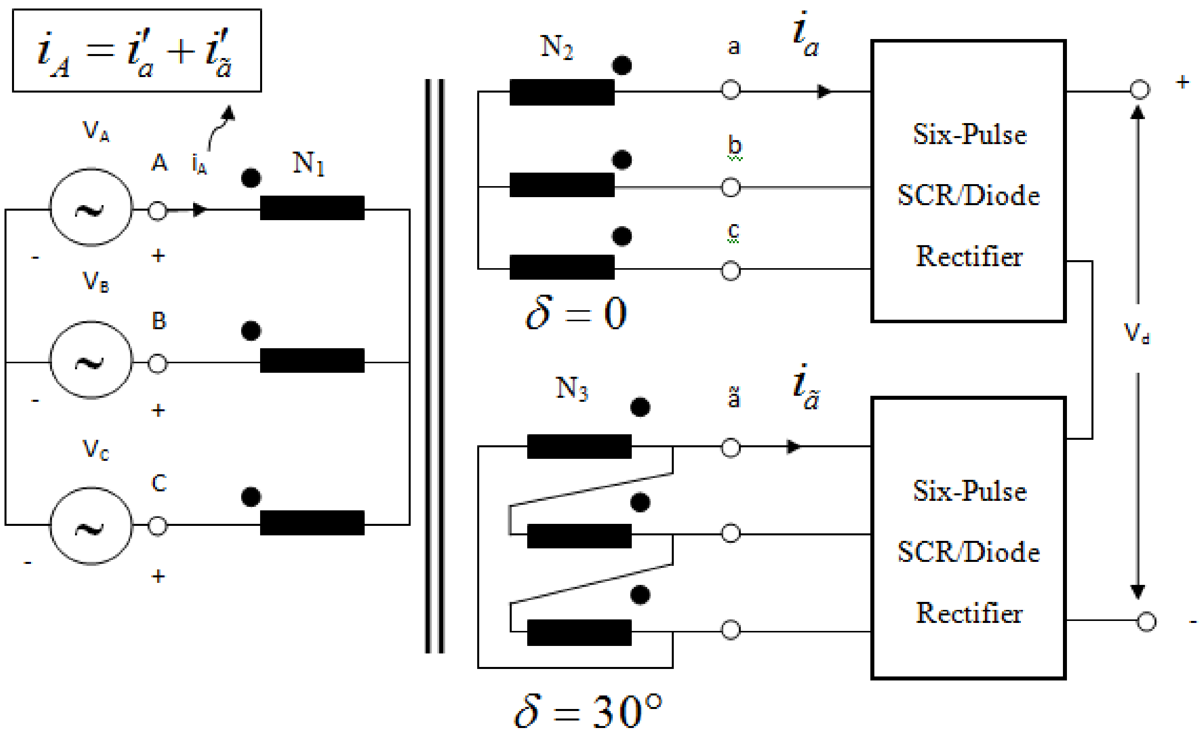


Figure 2.13: An example of harmonic current cancellation

When i_a is referred to the primary side, the phase angle of all the harmonic currents remains the same since the connection type is Y-Y. The reflected current i'_a is expressed as

$$i'_a = \frac{1}{2}(\hat{I}_1\sin(\omega t) + \hat{I}_5\sin(5\omega t) + \hat{I}_7\sin(7\omega t) + \hat{I}_{11}\sin(11\omega t) + \hat{I}_{13}\sin(13\omega t) + \ldots) \tag{2.27}$$

These terms can be grouped together as

$$i'_{\tilde{a}} = \frac{1}{2}\left(\sum_{n=1,7,13,\ldots}^{\infty} \hat{I}_n \sin(n(\omega t + \delta) - \delta) + \sum_{n=5,11,17,\ldots}^{\infty} \hat{I}_n \sin(n(\omega t + \delta) + \delta)\right)$$

$$= \frac{1}{2}(\hat{I}_1\sin(\omega t) - \hat{I}_5\sin(5\omega t) + \hat{I}_{11}\sin(11\omega t) + \hat{I}_{13}\sin(13\omega t) \tag{2. 28}$$

For $\delta = 30°$ the total primary line current i_A is

$$i_A = i'_a + i'_{\tilde{a}} = \hat{I}_1 \sin\omega t + \hat{I}_{11} \sin 11\omega t + \hat{I}_{13} \sin 13\omega t + \hat{I}_{23} \sin 23\omega t + \ldots \tag{2.29}$$

In this equation the 5^{th}, 7^{th}, 17^{th}, and 19^{th} harmonic currents in i_a and i'_a are 180° out of phase. Therefore these harmonics cancel each other (Wu, 2006).

2.5 PWM Rectifier

The disadvantages of diode rectifiers and advantages obtained by using PWM rectifiers have been explained earlier. A simple representation of a PWM rectifier-load connection as in Figure 2.14.

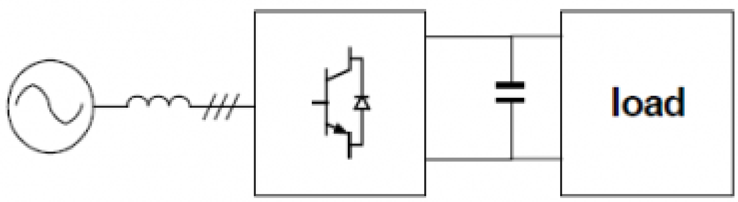


Figure 2.14: PWM rectifier

2.5.1 PWM boost type rectifier

Three phase PWM boost rectifier is shown in Figure 2.15. In these rectifiers the output voltage is always higher than the highest line voltage. It operates in all four quadrants and therefore bidirectional power flow is possible. Operation of this rectifier is similar to boost SMPS. When the SW_{R2} is turned on, the inductor stores energy. This stored energy is transferred to the capacitor when the switch is turned off. Unity power factor is achieved by controlling the current in the inductor (Khan et al., 2013).

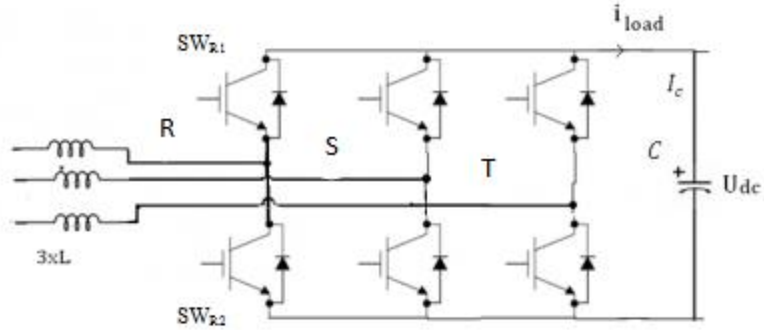


Figure 2.15: Boost type PWM rectifier

2.5.2 PWM buck type rectifier

The Figure (2.16) shows the buck type PWM rectifier. The highest possible output voltage is 26% more than the line-to-line rms voltage. Therefore the power flow is unidirectional. Power flow and input displacement factor can be controlled by modulation index and delay angle. Lagging power factor can be obtained by changing the delay angle to compensate the leading power factor. This technique can be used to obtain unity input power factor. If the capacitor current is greater than rectifier current unity displacement factor is not obtained (Khan et al., 2013).

Buck type rectifiers are used in UPS battery chargers and DC motor speed control applications.

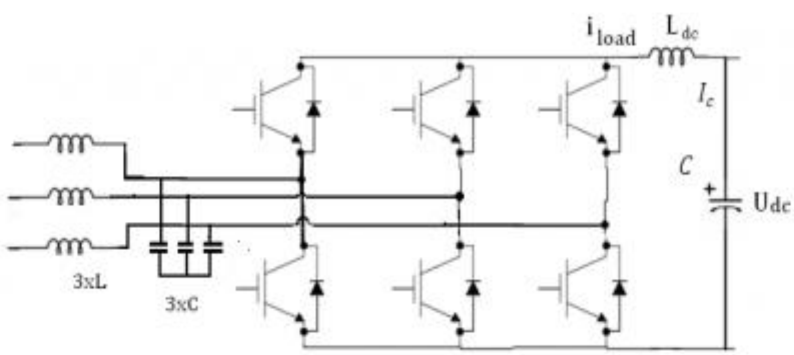


Figure 2.16: Buck type PWM rectifier

CHAPTER 3

PHASE SHIFT TRANSFORMER AND BUCK TYPE PWM RECTIFIER

Variable Frequency Drives (VFD) utilizes a frond end rectifier to obtain the required DC bus voltage for the inverter. This rectifier could be a diode rectifier (uncontrolled) or PWM rectifier (controlled). Diode rectifiers have the worst harmonic distortion due to the large capacitor connected at its output. PWM rectifiers use high frequency switching to synthesize near sinusoidal input currents. Another technique that can be used at high power levels is to include a phase-shifting transformer at the input to have multi-pulse rectified voltage causing a better harmonic content.

In this chapter, these three structures are explained in more detail.

3.1 Phase Shift Transformer

A 24-pulse rectifier topology based on phase shifting by conventional magnetic, is used at high power levels. Four 3-phase systems can be obtained from a single 3-phase source using single-phase and 3-phase transformers (Wu, 2006). As shown in Figure 3.1.Two seriously connected six-pulse rectifiers in the upper side are fed from the 30º displaced secondary windings of a three phase transformer, yielding 12-pulse rectified output. One of the two seriously connected diode rectifiers at the bottom is fed from the secondary windings of Y-Δ connected single-phase transformer while the other one is fed from the secondary windings of another three phase transformer. The phase-shift of the voltages applied to all rectifiers are 15º yielding a 24-pulse rectified output voltage (Arvindan, 2010).

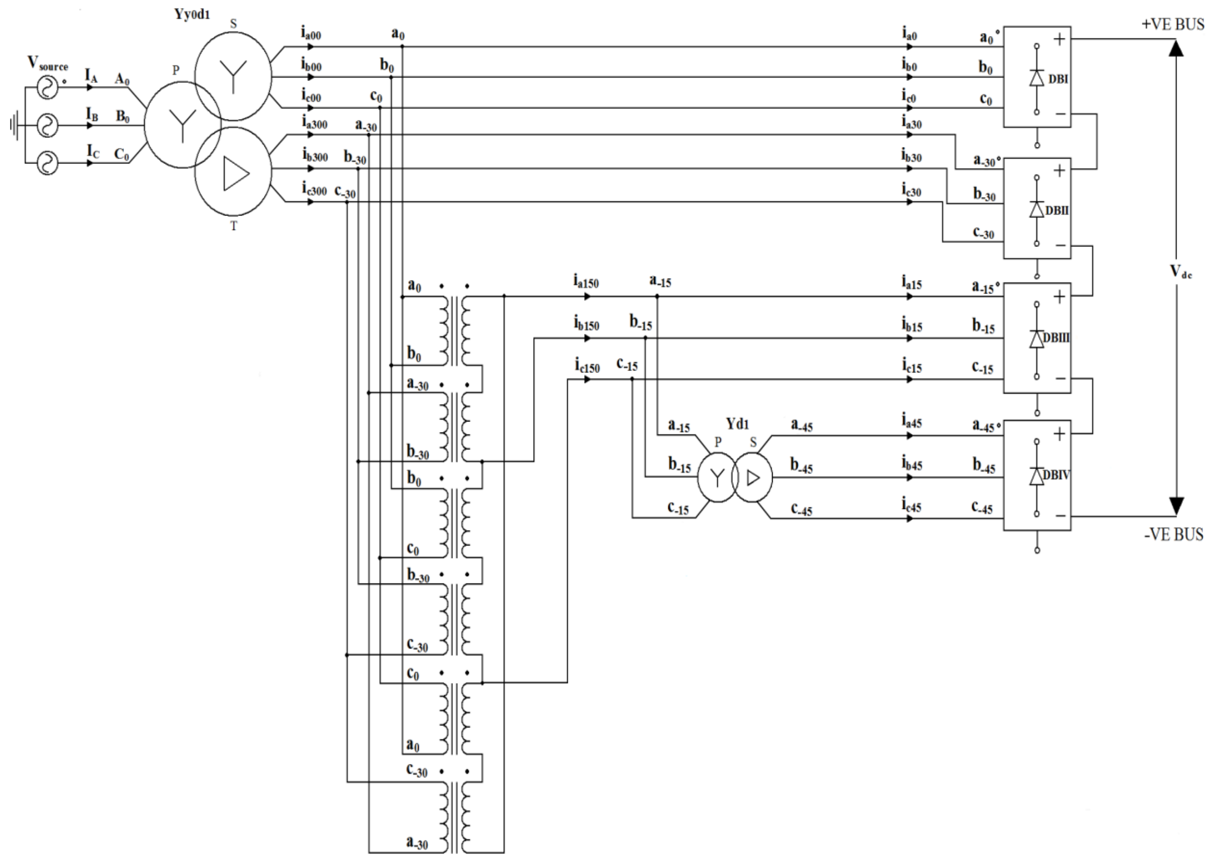


Figure 3.1: 24-Pulse rectifiers (Arvindan, 2010)

3.2 Multi-Pulse Converters

High transfer applications, and multi-pulses converters depends on multi-pulse, (for Vdc_{out}) within period of (ac source voltage). Application related to high power, multi-pulse (12, 18, 24, ..), pulses are used to decrease(ac current harmonics). As in table 3.1.

Pulse number is the number of pulses in the Vdc_{out} within one full period of the ac source voltage. In high-power applications higher number of pulses is preferred. As three-phase rectifiers generate six pulses per one full period, rectifiers obtained by combining three-phase rectifiers generate pulse numbers that are multiples of six, such as 12, 18, 24, 36 and 48. As the number of pulses increase, the lowest order of harmonic that exist is also increases. Table 3.1 shows the order of harmonics, ripple frequency and ripple factor of the output voltage for various converters.

Table 3.1: Harmonics and ripple variation with pulse number (Arvindan, 2010)

No. of Pulses	Harmonic numbers	Frequency	Ripple factor (%)
1	1,2,3,…	1*fs	121
2	1,3,5,…	2*fs	48.2
3	2,4,5,…	3*fs	18.2
6	5,7,11,…	6*fs	4.2
12	11,13,23,…	12*fs	1
18	17,19,35,…	18*fs	0.64
24	23,25,47,…	24*fs	0.22

3.2.1 Bidirectional multi-pulse rectifier

These thyristorized converters provide harmonic reduction through pulse multiplication with the aid of magnetics. Bidirectional power flow and adjustable output dc voltage are obtained by utilizing fully controlled thyristor bridge converters. A multiple winding transformer is used at the input to allow multi pulse rectification. Pulse multiplication is made possible by using tapped reactors. Input current THD and output voltage ripple are low. These converters are especially useful for dc motor drives operating at high powers and HVDC transmission systems. Autotransformers can help reduce the "cost" and "weight" of input transformers in low- and medium-voltage applications (Arvindan, 2010).

3.2.2 Unidirectional multi-pulse converters

By using similar magnetic structures to Bidirectional Multi-pulse Rectifiers, unidirectional converters can be obtained for high pulse numbers all the way from 12 to 48. Autotransformers can be used for this purpose with phase splitting (Arvindan, 2010).

3.3 Design of 24-Pulse Rectifier

Figure 3.1 represents the investigated 24-pulse rectifier topology. The whole system is supplied by one three-phase transformers with Y-Δ secondary. Phase shifted outputs of this secondary is used at the input of two other three-phase transformers, constructed by using six single-phase transformer. There is another three-phase with Y-Δ secondary supplied by the output of these single-phase transformers. Overall there are four individual 3-phase systems.

The phase shift for a topology with a certain number rectifiers is given as follows:

Phase shift = 60°/No. of bridge

Harmonics that are created by these transformers are at the following frequencies:

Harmonics = nk ± 1

Where n is the number of bridges used in the system and k = 1, 2, 3,…

So, as the numbers of bridges go up, so does the minimum order of harmonic (Arvindan, 2010).

3.3.1 One to four, 3-phase system

In Figure 3.1, the source lines $A_{0,}B_{0,}C_0$ feeds the Yy0d1, 3-ph., 3-winding, step down transformer and two 3-ph. systems, one (represented as a_0, b_0 and c_0) with line voltages ($\mathbf{V}_{a0,b0}$, $\mathbf{V}_{b0,c0}$, $\mathbf{V}_{c0,a0}$) in phase with the source line voltages and the other (represented as a-30, b-30 and c-30) with line voltages ($\mathbf{V}_{a-30,b-30}$, $\mathbf{V}_{b-30,c-30}$, $\mathbf{V}_{c-30,a-30}$) lagging the source line voltages by 30º are obtained from the secondary Y (y0) and Δ (d1) windings respectively. The line voltages $\mathbf{V}_{a0,b0}$, $\mathbf{V}_{b0,c0}$, $\mathbf{V}_{c0,a0}$ and $\mathbf{V}_{a-30,b-30}$, $\mathbf{V}_{b-30,c-30}$, $\mathbf{V}_{c-30,a-30}$ are shown in Figures 3.2 and 3.3 respectively. It should be noted that only the phase angles of the six line voltages of the 3-phase systems are different. Voltages of these lines have the same magnitude. The six line voltages $\mathbf{V}_{a0,b0}$, $\mathbf{V}_{b0,c0}$, $\mathbf{V}_{c0,a0}$, $\mathbf{V}_{a-30,b-30}$, $\mathbf{V}_{b-30,c-30}$, $\mathbf{V}_{c-30,a-30}$ are isolated using 6 single-phase transformers with appropriate turns ratio. The secondary voltages of the 1- phase transformers corresponding to $\mathbf{V}_{a0,b0}$ and $\mathbf{V}_{a-30,b-30}$ are connected in series in order to yield $\mathbf{V}_{a-15,b-15}$, a voltage equal in magnitude to the six line voltages but lagging $\mathbf{V}_{a0,b0}$ by 15º. This 15º phase shift is by phasor sum of appropriate line voltages (Arvindan, 2010).

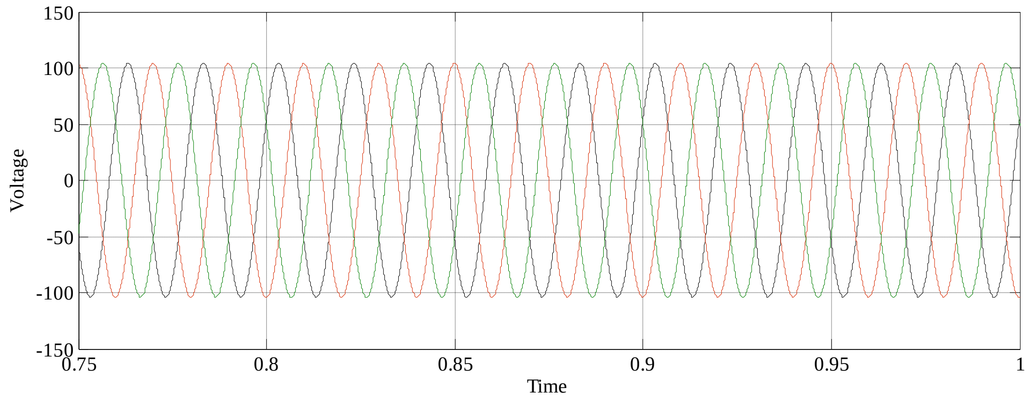


Figure 3.2: Input line $V_{a0,b0}$, $V_{b0,c0}$ and $V_{c0,a0}$ at DBI

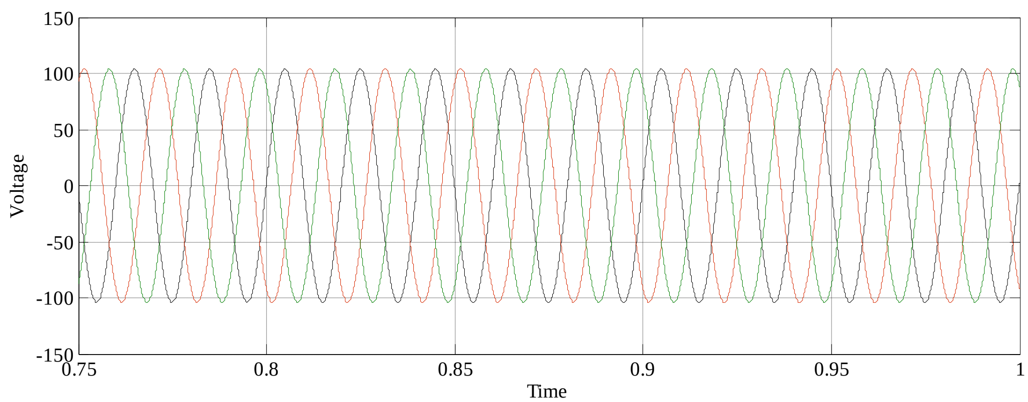


Figure 3.3: Input line $V_{a30,b30}$, $V_{b30,c30}$ and $V_{c30,a30}$ at DBII

The line voltage $V_{a0,b0}$ is 30º ahead of the phase voltage V_{a0} and the line voltage $V_{a-30,b-30}$ is 30º ahead of the phase voltage V_{a-30}. However, since V_{a0} is 30º ahead of V_{a-30}, $V_{a-30,b-30}$ is in phase with V_{a0}. This implies that $V_{a0,b0}$ leads $V_{a-30,b-30}$ by 30º. The phasor addition of these two line voltages that are equal in magnitude gives the resultant $V_{a-15,b-15}$ as follows:

$$V_{a-15b-15} = \left(V^2_{a0b0} + V^2_{a-30b-30} + 2V_{a0b0}V_{a-30b-30}\text{Cos}30\right)^{1/2} \quad (3.1)$$

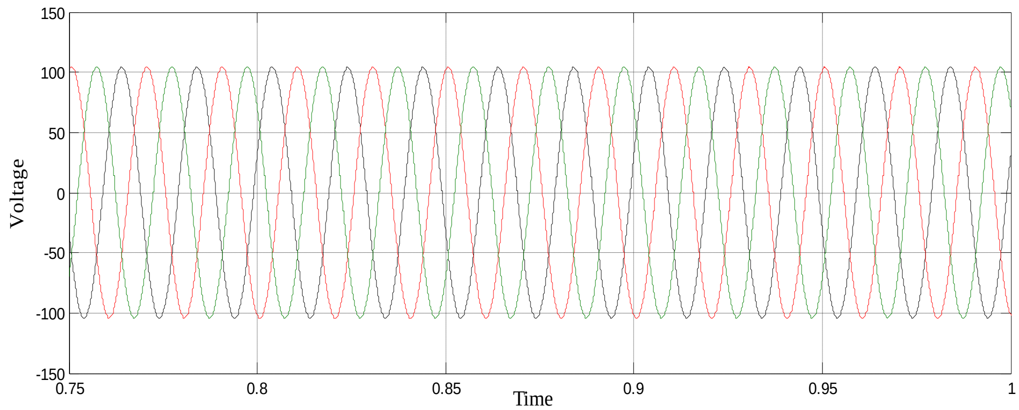


Figure 3.4: Input line $V_{a15,b15}$, $V_{b15,c15}$ and $V_{c15,a15}$ at DBIII

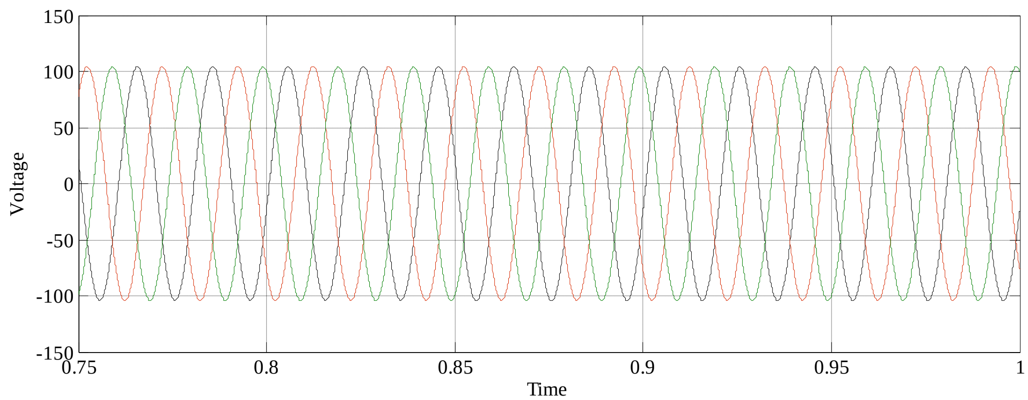


Figure 3.5: Input line $V_{a45,b45}$, $V_{b45,c45}$ and $V_{c45,a45}$ at DBIV

Since V_{a0b0} and $V_{a-30,b-30}$ have the same magnitude, the resultant $V_{a-15,b-15}$ bisects the 30° between $V_{a0,b0}$ and $V_{a-30,b-30}$. Thus the line voltage $V_{a-15,b-15}$ is 15° behind $V_{a0,b0}$. Similarly, the line voltages $V_{b-15,c-15}$ and $V_{c-15,a-15}$ are obtained by the phasor additions via the secondary windings of the one-phase transformers corresponding to the line voltages $V_{b0,c0}$ and $V_{b-30,c-30}$; and $V_{c0,a0}$ and $V_{c-30,a-30}$ respectively. The line voltages $V_{a-15,b-15}$, $V_{b-15,c-15}$ and $V_{c-15,a-15}$have the same magnitude but there is a phase shift of 120 ° between them. Therefore, a balanced 3-ph. system is obtained by connecting these windings in delta. Figure 3.4 shows the voltages V_{a-}

$_{15,b-15}$, $V_{b-15,c-15}$ and $V_{c-15,a-15}$. Hence, in Figure 3.1 the (phasors) lines a-15, b-15 and c-15 are obtained and are fed to a 3-phase. transformer of the Yd1 configuration which provides a phase shift of -30º i.e. 30º laggingº and hence, yields the (phasors) lines a45, b45 and c45 respectively. The corresponding line voltages $V_{a-45,b-45}$, $V_{b-45,c-45}$ and $V_{c-45,a-45}$ that lag by 30º the voltages $V_{a-15,b-15}$, $V_{b-15,c-15}$ and $V_{c-15,a-15}$ respectively are shown in Figure 3.5. Thus, four 3-ph. systems with successive 3-phase. systems displaced by 15º are realized (Arvindan, 2010).

3.3.2 Implementation of rectifier topology

The 24-pulse rectifier seen in Figure 3.1 has four 6-pulse diode bridges connected in series. If an output voltage of 400 V is required each bridge should generate 400/4 = 100V. Since the output DC voltage for a bridge is given by the

$$V_{dc} = \frac{3\sqrt{3}}{\pi} V_m \tag{3.2}$$

The peak voltage for the input voltage is obtained as follows.

$$100 = 1.6539V_m$$

$$V_m = \frac{100}{1.6539} = 60.463V$$

The peak line-to line voltage then

$$\sqrt{3}V_m = \sqrt{3} * 60.463 = 104.725V_{Peak} \tag{3.3}$$

RMS value is given as

$$\sqrt{\frac{3}{2}}V_m = 74.051V_{rms} \tag{3.4}$$

3.3.3 Transformers turns ratio

The main transformer in the system is a 3-phase, 3-winding transformer with Yyod1 vector configuration. The primary Y winding is connected to the 3- phase 268.7V utility.

Main transformer Yyod1: The two upper diode bridges are supplied from the y0 and d1 secondary windings. The winding turn's ratio for the Yyo mathematically obtained as follows:

Y-primary $V_{line\ (rms)}$=268.7V

V_o secondary desired line voltage = 74.05V

N2/N1 = 74.05/268.7= 0.275

Similarly the winding turns ratio for the Yd1 mathematically obtained as follows:

Y-primary $V_{line\ (rms)}$= 268.7V

d1 secondary desired line voltage = 74.05V

N2/N1 =(74.05* $\sqrt{3}$)/268.7= 0.477

Single-phase transformers

Primary windings of the six single-phase transformers are used to isolate the Y (y0) and Δ (d1) secondary windings of the main transformer. The six secondary windings of the single-phase transformers are divided into three pairs, with each pair containing two relevant secondary windings corresponding to the voltage combinations $\mathbf{V}_{a0,b0}$ and $\mathbf{V}_{a-30,b-30}$, $\mathbf{V}_{b0,c0}$ and $\mathbf{V}_{b-30,c-30}$ and $\mathbf{V}_{c0,a0}$ and $\mathbf{V}_{c-30,a-30}$ that are synthesized by series cascade connection to obtain the line voltages $\mathbf{V}_{a-15,b-15}$, $\mathbf{V}_{b-15,c-15}$ and $\mathbf{V}_{c-15,a-15}$ respectively. The synthesis of the voltage combinations is as per Equation (3.1) yields $\mathbf{V}_{a-15,b-15}$ as follows:

$$V_{a0,b0} = 74.05\angle 30^\circ \text{ V}$$

$$V_{a-30,b-30} = 74.05\angle 0^\circ \text{ V}$$

$$V_{a-15,b-15} = \sqrt{74.05^2 + 74.05^2 + 2 * 74.05 * 74.05 * \cos 30^\circ} \text{ V}$$

$$V_{a-15,b-15} = 143.05\angle 15^\circ \text{ V}$$

Similarly, the line voltages $V_{b-15,c-15}$ and $V_{c-15,a-15}$ are obtained by the synthesis of the relevant voltage combinations. The synthesis yields magnitudes as follows:

$$\left|V_{a-15b-15}\right| = \left|V_{b-15c-15}\right| = \left|V_{c-15a-15}\right| = 143.05\,V$$

The three secondary pairs are connected in Δ to form a 3- phase winding. The Δ winding feeds the third diode bridge and the desired magnitudes of the line voltages have to be as follows:

$$\left|V_{a-15b-15}\right| = \left|V_{b-15c-15}\right| = \left|V_{c-15a-15}\right| = 74.05V$$

Turns ratio of each single-phase transformers is

N2/N1 = 74.05/143.05 = 0.5176 $\approx$0.52

3-phase Y/d1 transformer

The voltages $V_{a-15,b-15}$, $V_{b-15,c-15,}$ and $V_{c-15,a-15}$ are fed to a Yd1 transformer to obtain line voltages $V_{a-45,b-45}$, $V_{b-45,c-45}$ and $V_{c-45,a-45}$ that are 30^0 behind the input Y voltages and supply the fourth diode bridge. The magnitudes of the line voltages on Y and delta sides must be equal.

$$\left|V_{a-15b-15}\right| = \left|V_{b-15c-15}\right| = \left|V_{c-15a-15}\right| = \left|V_{a-45b-45}\right| = \left|V_{b-45c-45}\right| = \left|V_{c-45a-45}\right| = 74.05\,V$$

Thus, the turns is given by

N2/N1 = $\sqrt{3}$ =1.732

3.4 Inverter

The dc bus voltage is switched at high frequency to obtain the adjustable frequency, adjustable magnitude voltage necessary for the motor. Figure 3.6 shows the structure for the phase-shifting transformer case (Bhattacharya, 2014).

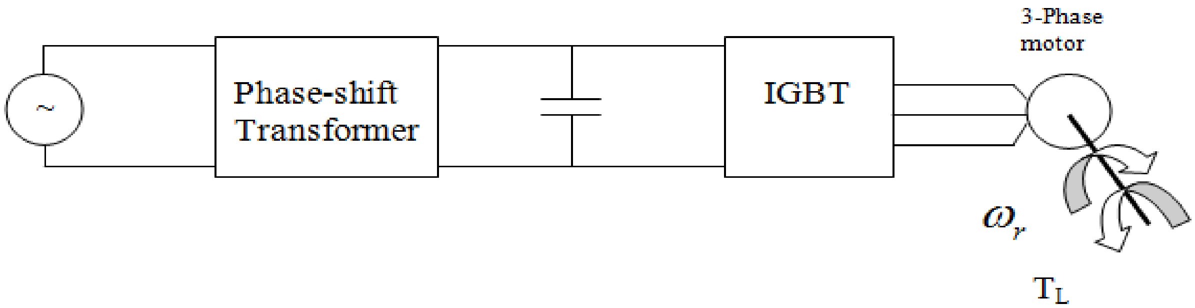


Figure 3.6: Schematic diagram of the phase shifting transformer fed drive

An LC filter is connected at the output to remove high switching frequency components from output current of inverter. The structure of the LC filter is shown in Figure 3.7.

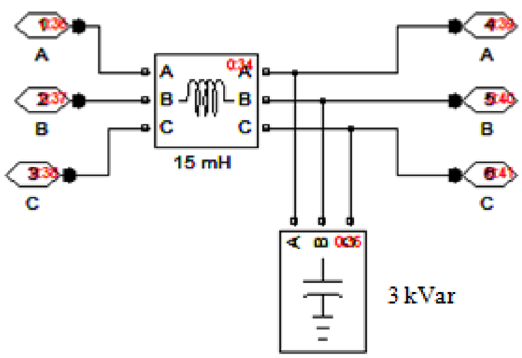


Figure 3.7: LC output filter

3.5 PWM Buck Rectifier

Figure 3.8 shows the structure for the case buck type PWM rectifier is used at the input. IGBTs with the same rating as those of the inverter can be used in the rectifier too (Manlinowski, 2001).

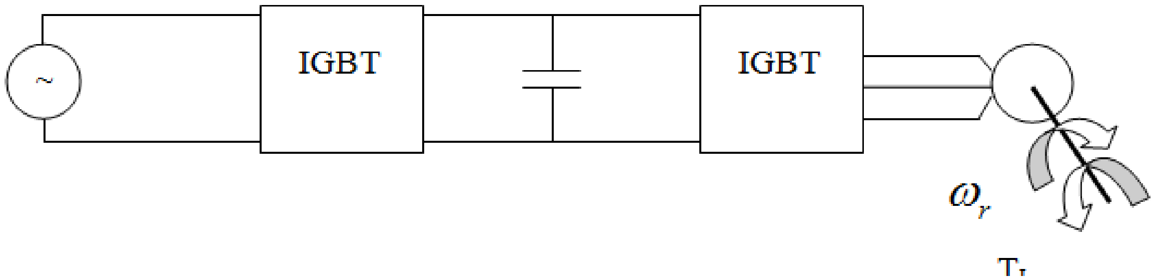


Figure 3.8: Schematic diagram of the PWM rectifier fed drive

CHAPTER 4

SIMULATION, RESULTS AND DISCUSSIONS

In this chapter, simulation results are presented for the variable frequency drive. Simulations were performed for three cases: 1) DC bus obtained with simple diode rectifier, 2) DC bus is obtained with PWM rectifier and 3) DC bus is obtained with phase shifting transformers (24-pulse rectifier). Simulations were performed in Matlab R2013a Simulink program with a 4 kW induction motor with the following parameters:

5.4 HP, 400 Volts, 50 Hz, 4-pole, 1430 rpm Induction motor.

For each type of rectifier simulation has been run for the following cases:

A. Rated load and rated speed
B. Rated load and 50% of rated speed
C. Rated load and 10% of rated speed
D. 50% of the rated load and rated speed
E. 10% of the rated load and rated speed

The devices suitable for a 4 kW system at 400 dc bus voltage have an on-state resistance of 0.001Ω. PWM gate pulses are applied to the switches of the converter. The control signal frequency (fc) is taken as 50 Hz and the carrier frequency as 1000 Hz. Modulation index is 1. LC filter connected to the output has the following parameters: L= 15mH, C= 66μF. Also, a 1 mH line inductance was used for each source line to represent the leakage effects.

4.1 Loading and Driving Motor

Rated power (P_R) of the Variable Frequency Drive is equal to 4 kW and rated speed (n_R) of the motor is equal to 1430 rpm. The rated torque (T_R) can be found as

$$T_R = \frac{P_R}{\omega_r} = \frac{4000}{n_R * \frac{\pi}{30}} = 26.71Nm$$

4.2 Simulation Model and Results of the Drive with Phase Shift Transformer

Figures 4.1 and 4.2 shows the 24-pulse rectifier that involves obtaining four individual 3-phase systems with 15° phase shift between each output line.

The simulation results are shown between Figure 4.3 and 4.12. Results include transformer output voltages, rectifier output voltage, total dc link voltage, and input line voltage and current. Power values, power factors and THD values were calculated in the simulation and the results were summarized in Table 4.1.

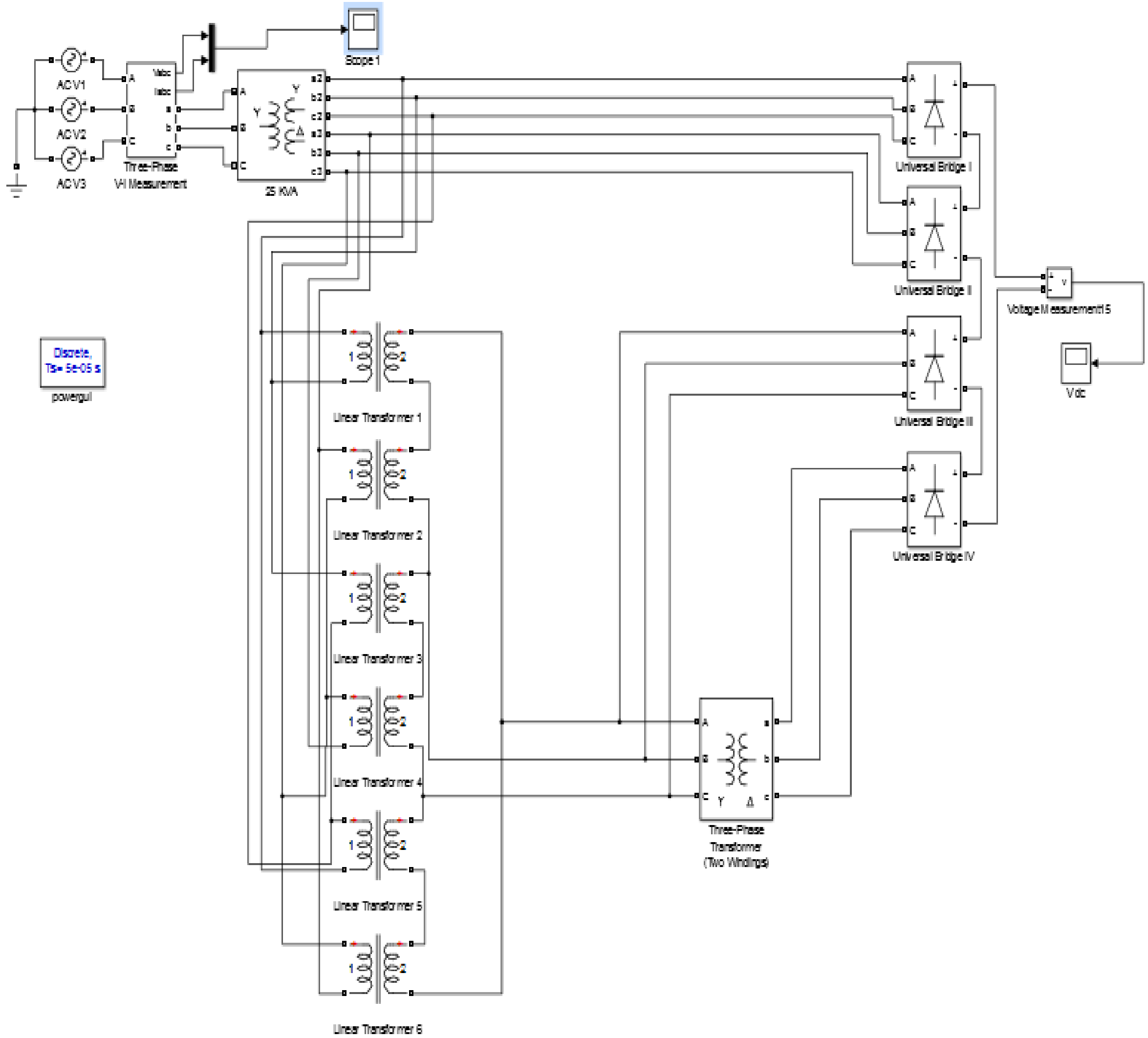


Figure 4.1: Simulation model of phase shift transformer connection

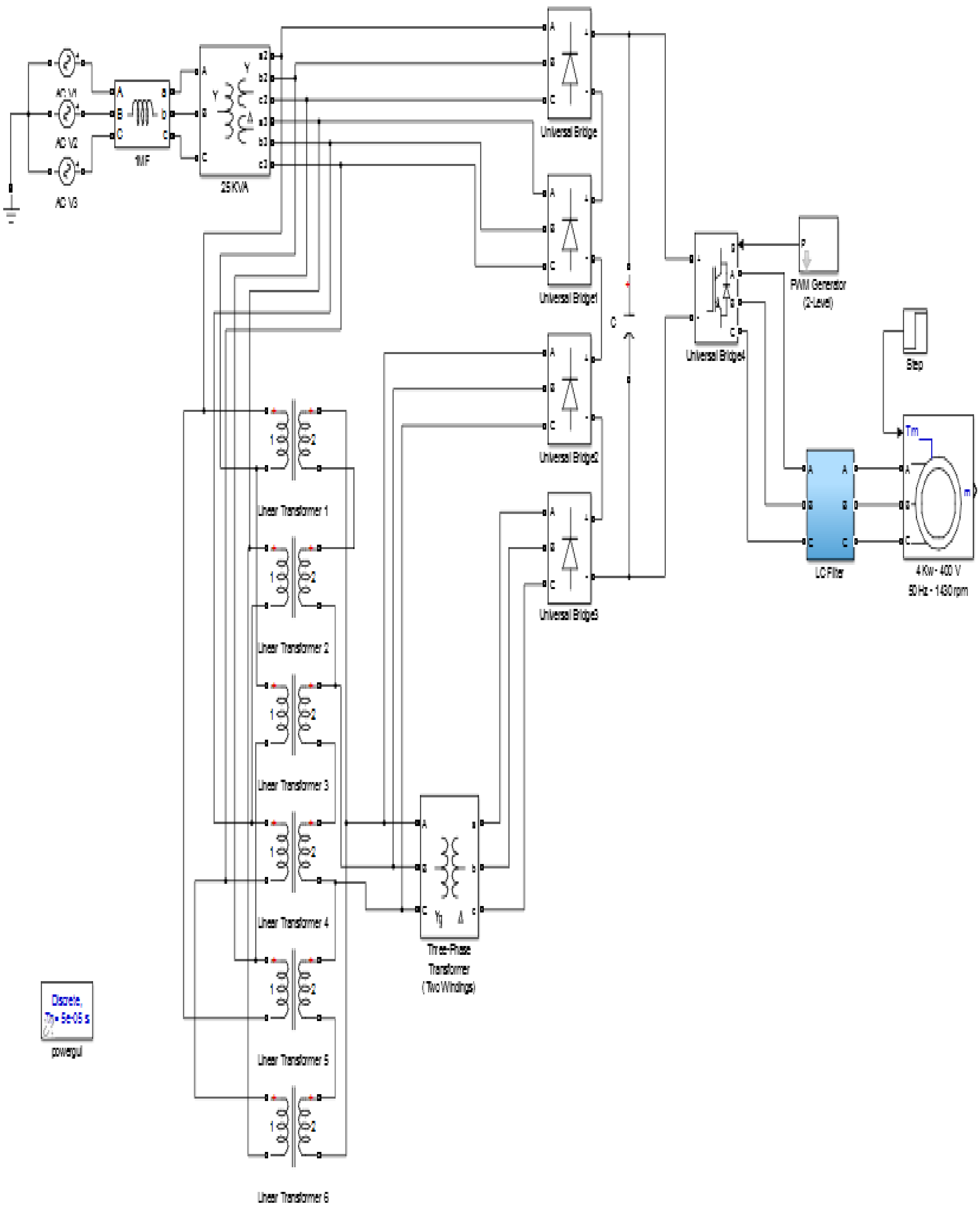


Figure 4.2: Simulation model of phase shift transformer fed drive system

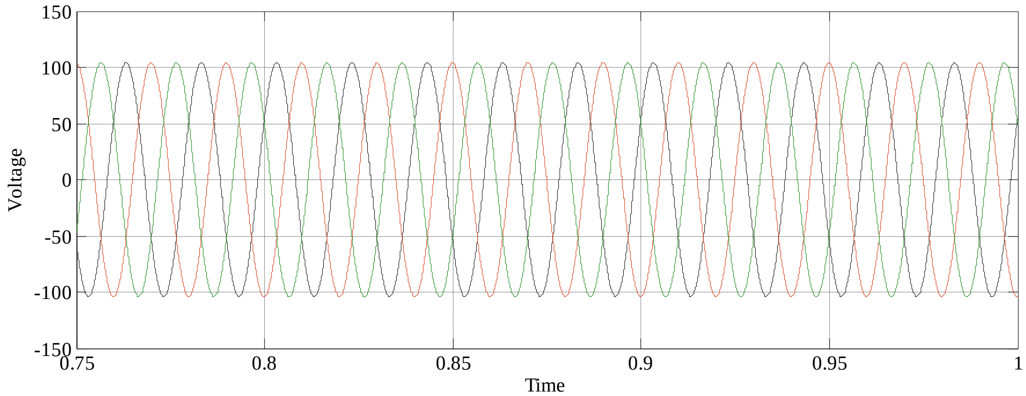


Figure 4.3: Voltage input to bridge I

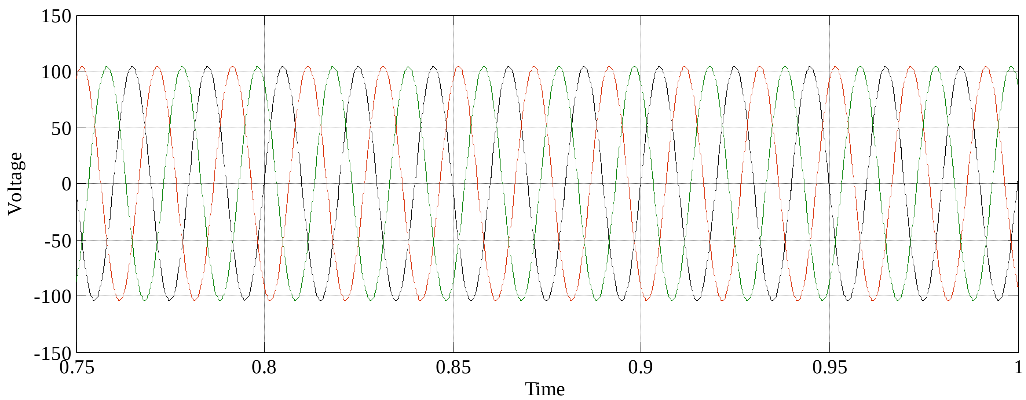


Figure 4.4: Voltage input to bridge II

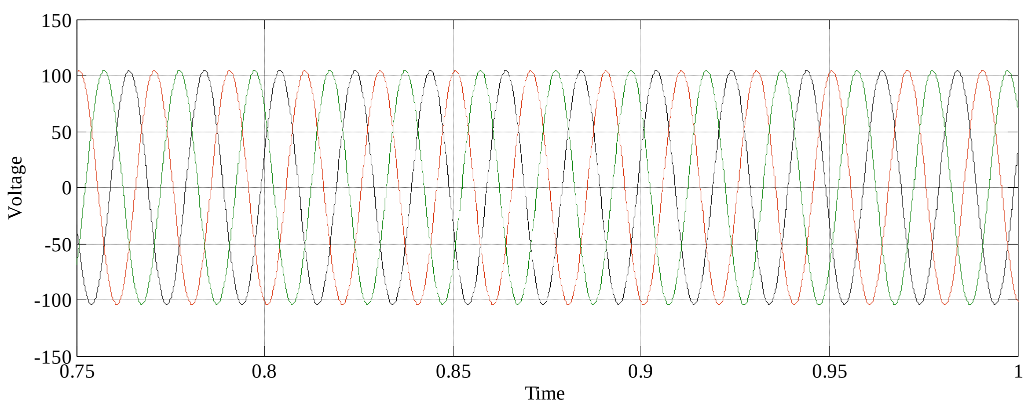


Figure 4.5: Voltage input to bridge III

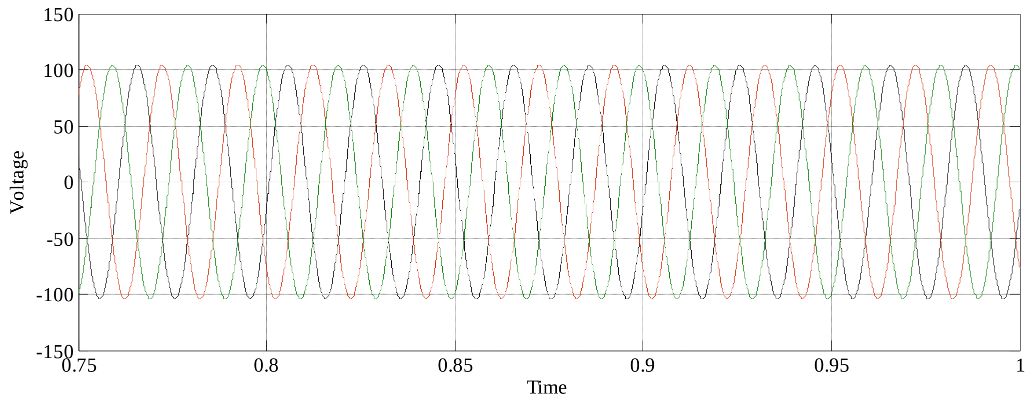


Figure 4.6: Voltage input to bridge IV

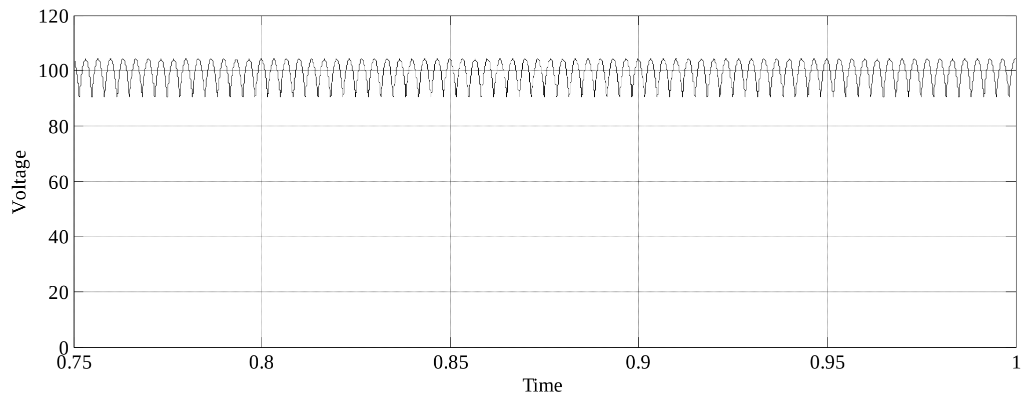


Figure 4.7: Output dc voltage in bridge I

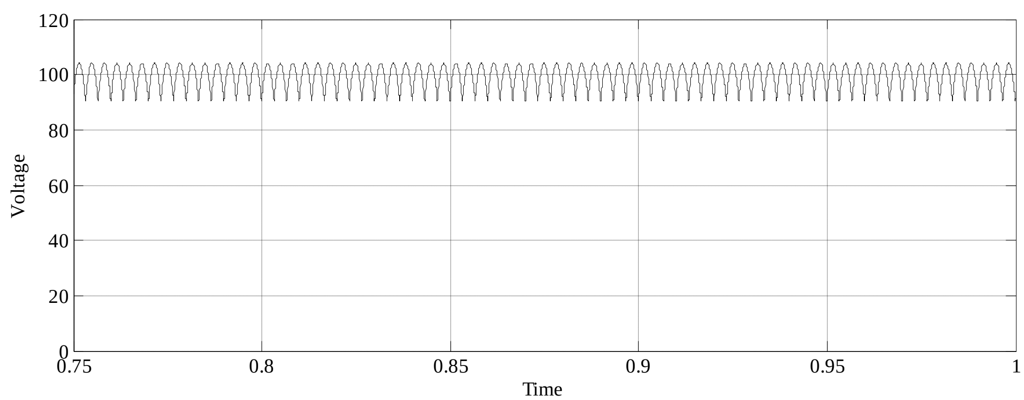


Figure 4.8: Output dc voltage in bridge II

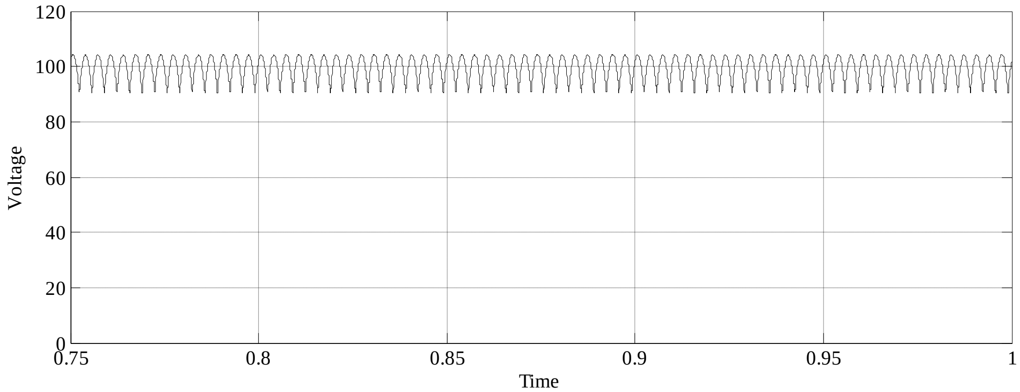


Figure 4.9: Output dc voltage in bridge III

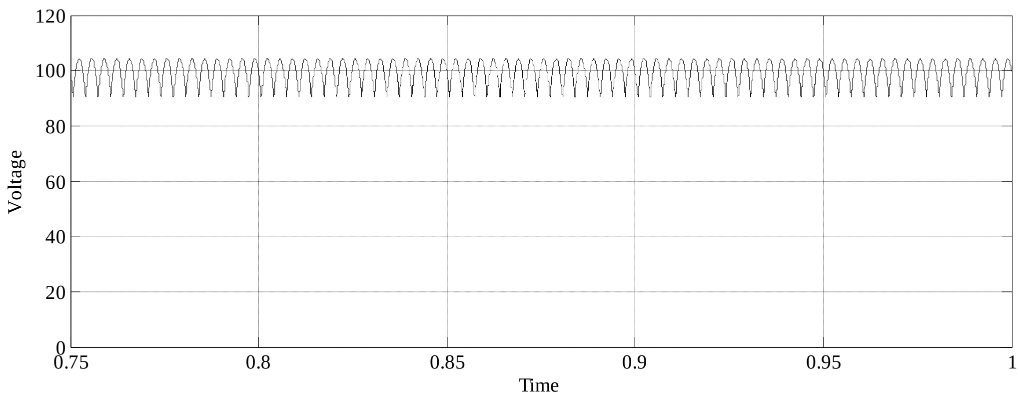


Figure 4.10: Output dc voltage in bridge IV

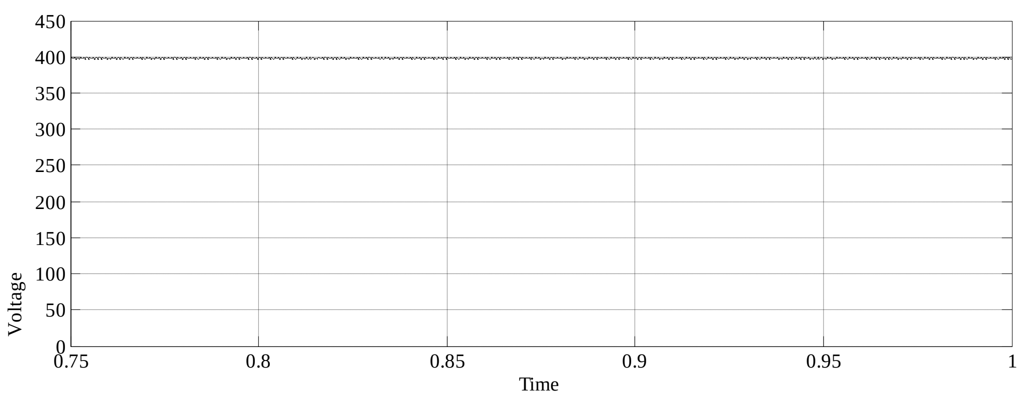


Figure 4.11: DC output voltage with series cascaded bridges (I,II,III,IV)

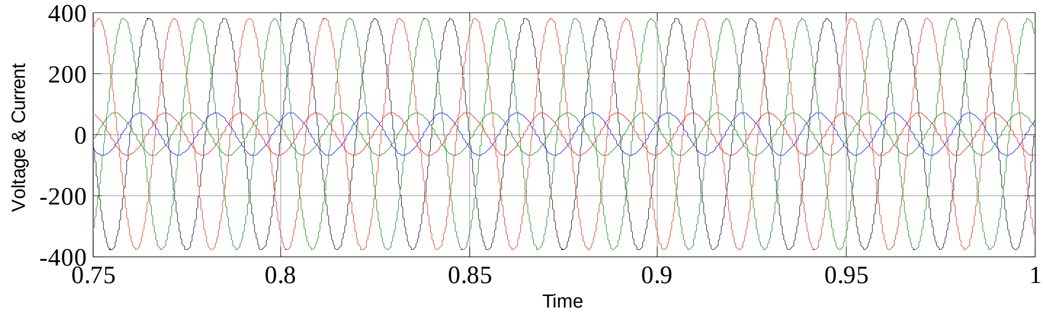


Figure 4.12: 3-Phase line voltage & line current in Y winding of Yy0d1 main transformer

Table 4.1: THD_I, Pf results with various cases by using phase shift transformer technique

		VFD = 4 kW (5.4HP), 400V, 50Hz, 1430RPM		
Case	$\mathbf{T_R}$	$\mathbf{n_R}$	$\mathbf{THD_I}$	**pf**
A	(T_R) = 26.71 Nm	(n_R) = 1430 rpm	THD_I = 2.464%	pf = pf $_{(disp)}$pf $_{(dist)}$ = 0.965*0.999=0.96
B	(T_R) = 26.71 Nm	$(n_R)/2$ = 715 rpm	THD_I = 2.387%	pf = pf $_{(disp)}$pf $_{(dist)}$ = 0.97*0.99=0.97
C	(T_R) = 26.71 Nm	$(n_R)/10$ = 143 rpm	THD_I = 2.154%	pf = pf $_{(disp)}$pf $_{(dist)}$ = 0.97*0.99=0.97
D	$(T_R)/2$ = 13.355 Nm	(n_R) = 1430 rpm	THD_I = 2.29%	pf = pf $_{(disp)}$pf $_{(dist)}$ = 0.97*0.99=0.97
E	$(T_R)/10$ = 2.671 Nm	(n_R) = 1430 rpm	THD_I = 1.4%	pf = pf $_{(disp)}$pf $_{(dist)}$ = 0.98*0.99=0.98

4.3 Advantages of 24-Pulse Phase Shift Transformer

- Virtually guarantees compliance with IEEE 519-1992.
- Harmonic cancellation from the 5th to 19th harmonics.
- High power factor (0.96 -0.98).

4.4 Disadvantages of 24-Pulse Phase Shift Transformer

- Can be more expensive than other methods (for up to three times the harmonic reduction of buck type PWM rectifier methods).
- Larger and heavier magnetic than some other methods.
- Highly complicated in design and connection.
- Loss in efficiency.

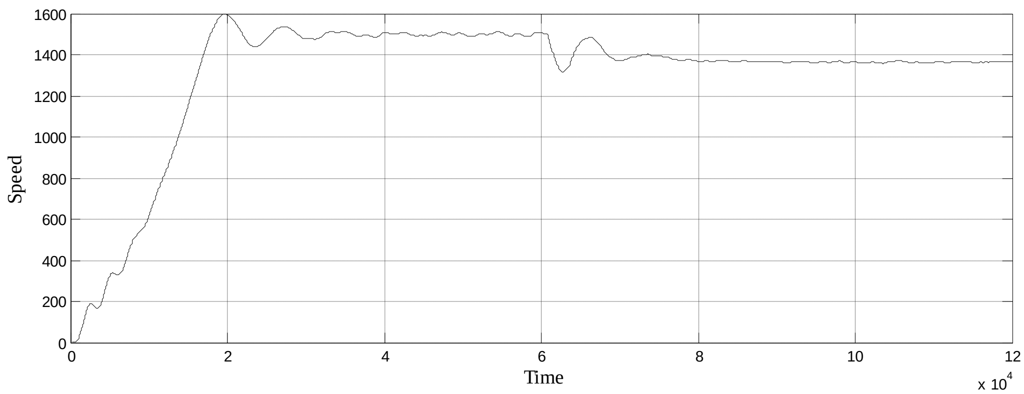


Figure 4.13: Rotor speed in case (A), at (Tr) = 26.71Nm & (nr) =1430 rpm

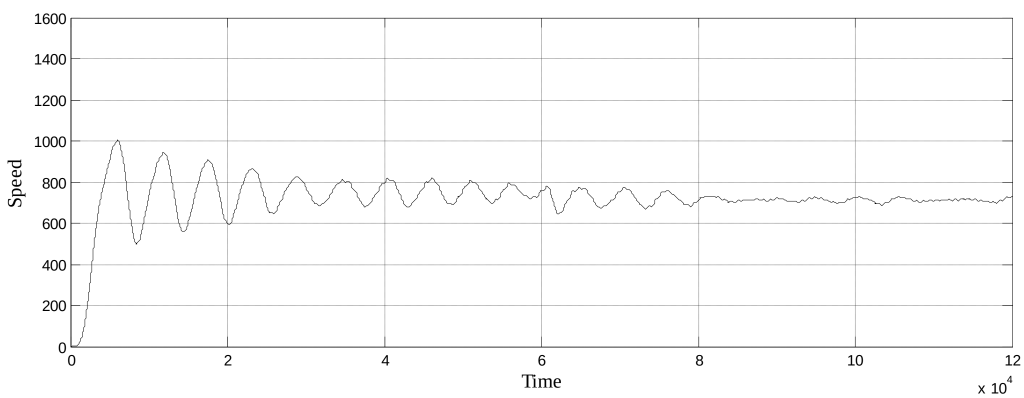


Figure 4.14: Rotor speed in case (B), at (Tr) = 26.71Nm & (nr) =715 rpm

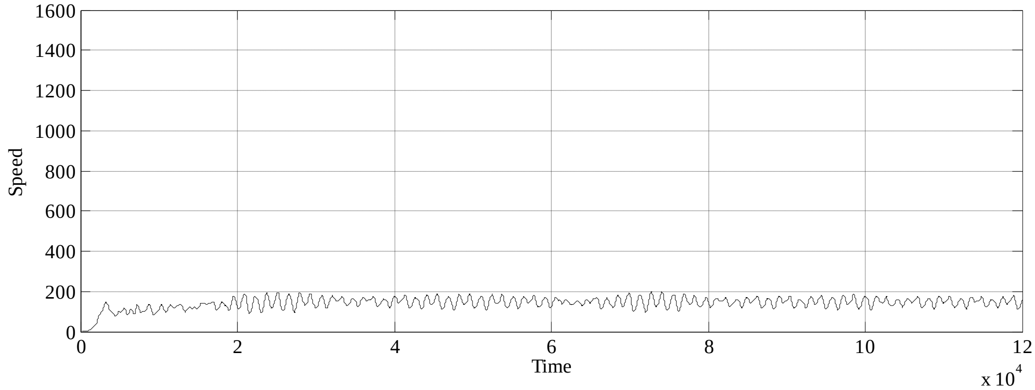


Figure 4.15: Rotor speed in case (C), at (Tr) = 26.71Nm & (nr) =143 rpm

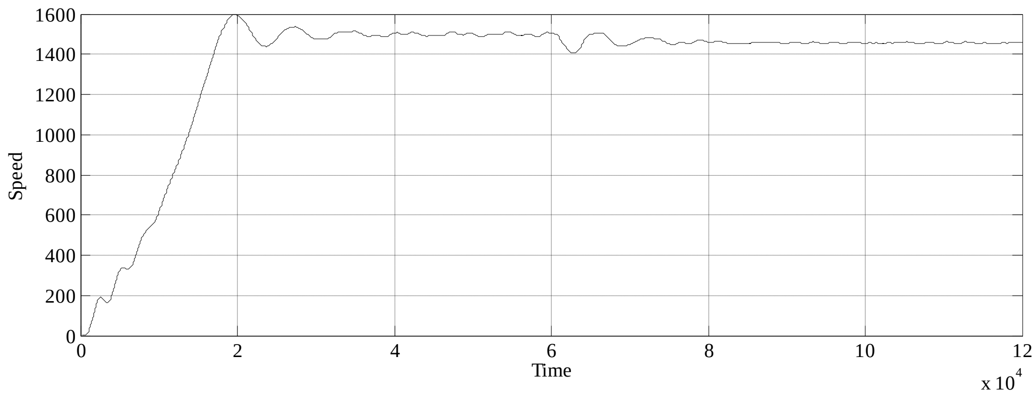


Figure 4.16: Rotor speed in case (D), at (Tr) = 13.355Nm & (nr) =1430 rpm

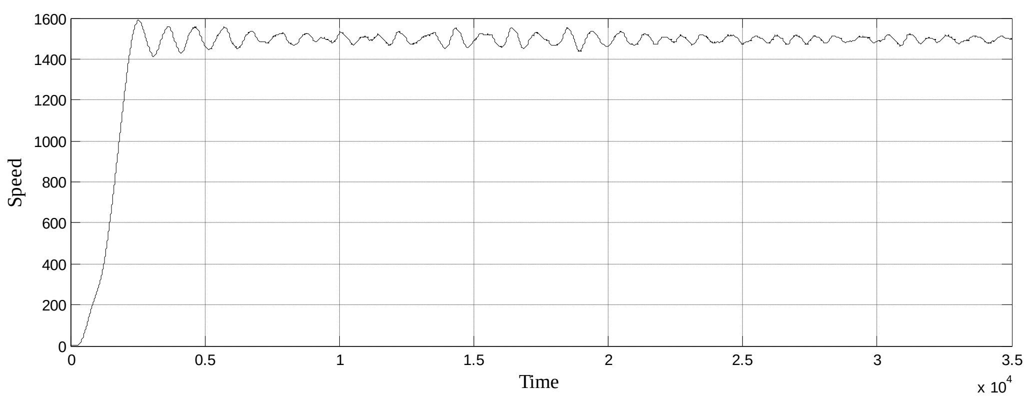


Figure 4.17: Rotor speed in case (E), at (Tr) = 2.671Nm &(nr) =1430 rpm

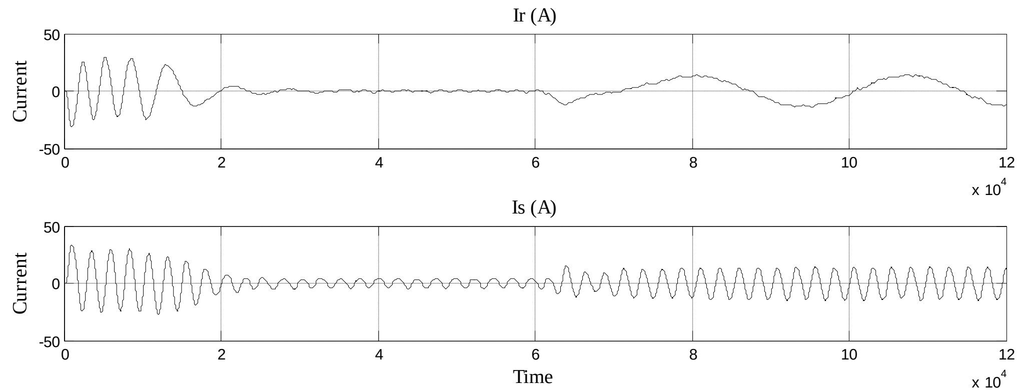


Figure 4.18: Rotor & stator current in cases (A), at (Tr) = 26.71Nm & (nr) = 1430 rpm

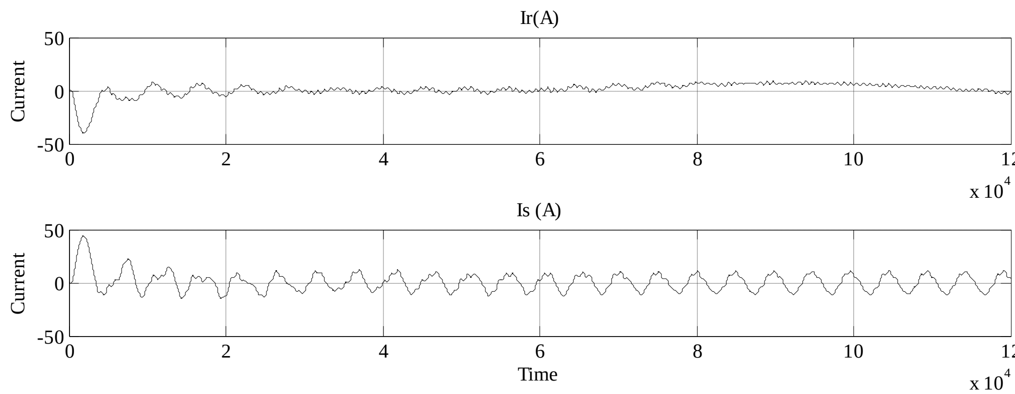


Figure 4.19: Rotor & stator current in cases (B), at (Tr) = 26.71Nm & (nr) = 715 rpm

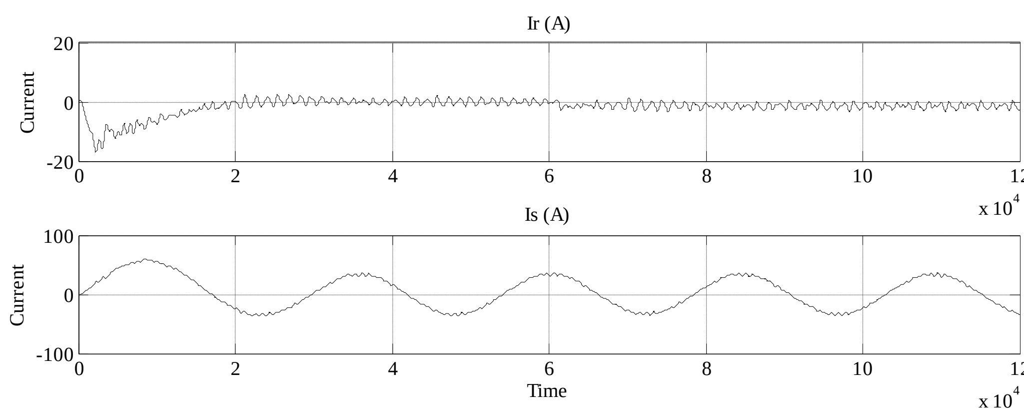


Figure 4.20: Rotor & stator current in cases (C), at (Tr) = 26.71Nm & (nr) = 143 rpm

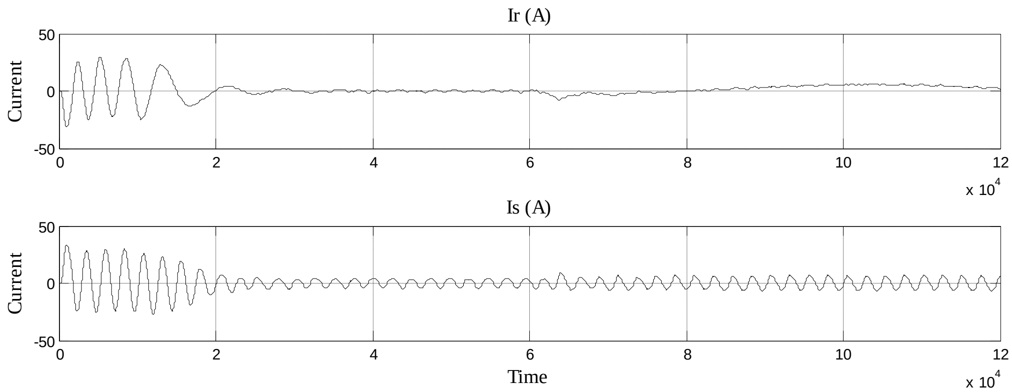


Figure 4.21: Rotor & stator current in cases (D), at (Tr) = 13.355Nm & (nr) = 1430 rpm

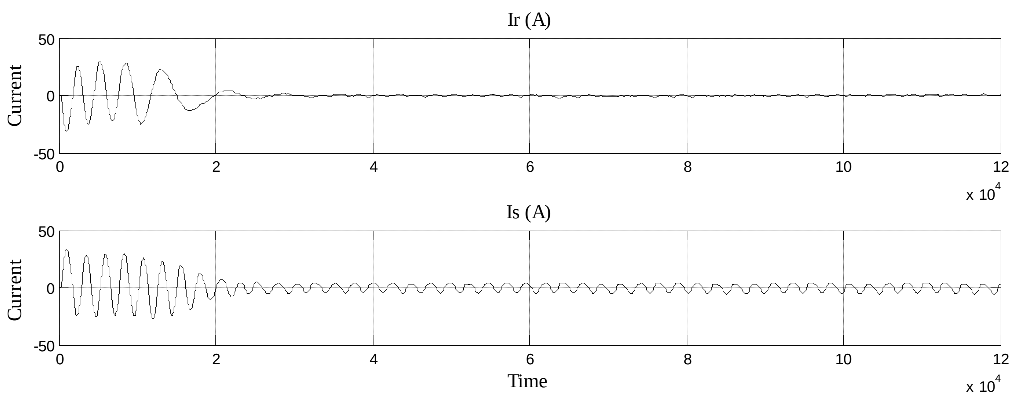


Figure 4.22: Rotor & stator current in cases (E), At (Tr) = 2.671Nm & (nr) = 1430 rpm

4.5 Simulation Results with Buck Type PWM Rectifier

The MATLAB simulation model is shown in Figure 4.8. In this model sinusoidal Pulse Width Modulation is using to mitigate the harmonics. 340 volts, 3- phase source is used for supply source. The buck type PWM rectifier is used to convert AC to DC and inverter is used for DC to AC.

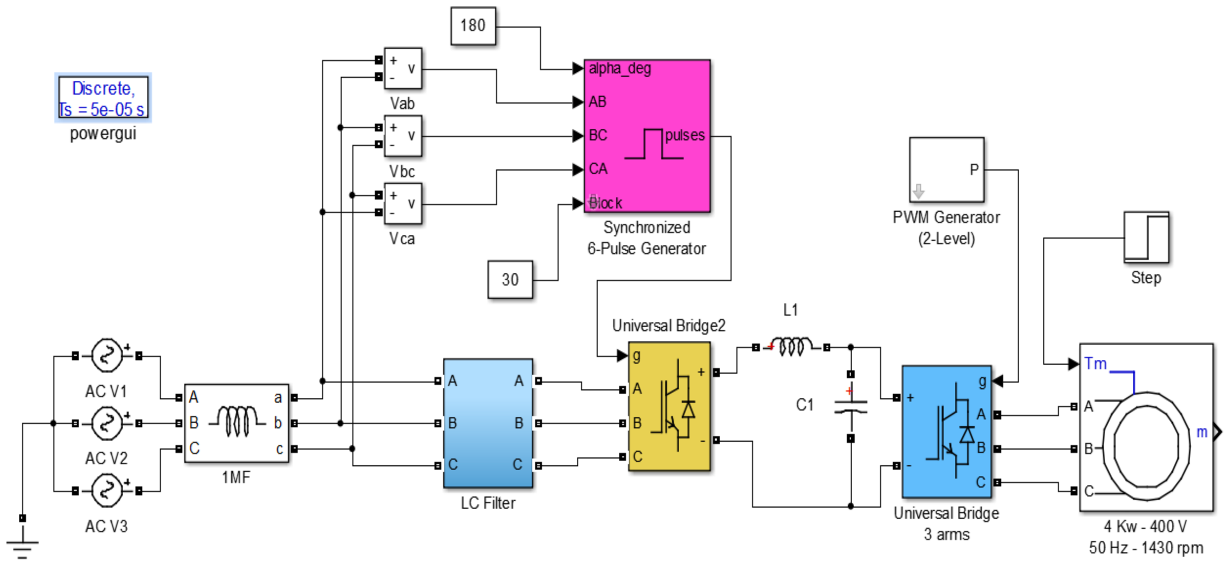


Figure 4.23: Simulation circuit diagram of buck type PWM rectifier harmonic mitigation technique

Simulation results are summarized in Table 4.2 for different operation conditions. Figures 4.24 through 4.33 show the simulation results in plots.

Table 4.2: THD_I, pf results with varies cases by using buck type PWM rectifier technique

VFD = 4 kW (5.4HP), 400V, 50Hz, 1430RPM				
Case	**T_R**	**n_R**	**THD_I**	**pf**
A	(T_R) = 26.71 Nm	(n_R) = 1430 rpm	THD_I = 2.262%	pf = pf $_{(disp)}$pf $_{(dist)}$ = 0.96*0.99=0.96
B	(T_R) = 26.71 Nm	$(n_R)/2$ = 715 rpm	THD_I = 1.699%	pf = pf $_{(disp)}$pf $_{(dist)}$ = 0.93*0.99=0.93
C	(T_R) = 26.71 Nm	$(n_R)/10$ = 143 rpm	THD_I =3.11%	pf = pf $_{(disp)}$pf $_{(dist)}$ = 0.99*0.99=0.99
D	$(T_R)/2$ = 13.355 Nm	(n_R) = 1430 rpm	THD_I = 1.47%	pf = pf $_{(disp)}$pf $_{(dist)}$ = 0.92*0.99=0.92
E	$(T_R)/10$ = 2.671 Nm	(n_R) = 1430 rpm	THD_I = 3..6%	pf = pf $_{(disp)}$pf $_{(dist)}$ = 0.86*0.99=0.86

4.7 Properties and Performance of Buck Type PWM Rectifier

- Virtually guarantees compliance with IEEE 519-1992.
- Low THD_I between 1.47% - 3.6%.
- High power factor (0.86 - 0.99).
- Easy design & connection.
- Fast switching.
- High voltage and high current IGBTs.

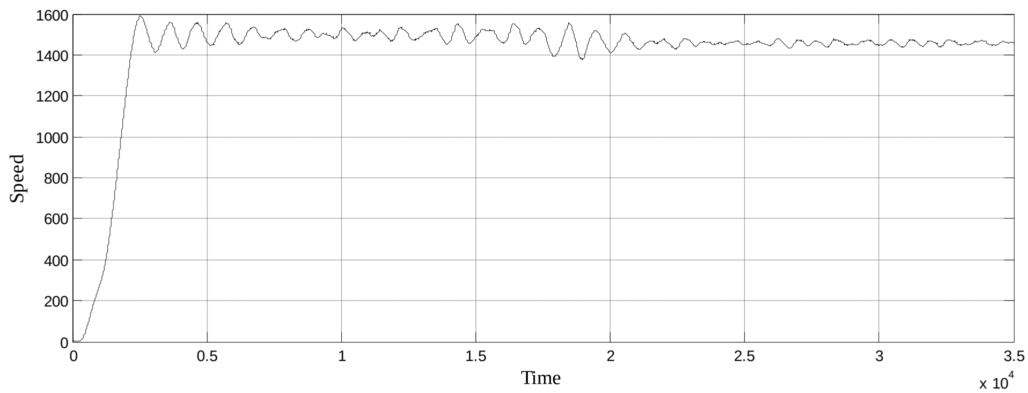


Figure 4.24: Rotor speed in case (A), At (Tr) = 26.71Nm &(nr) =1430 rpm

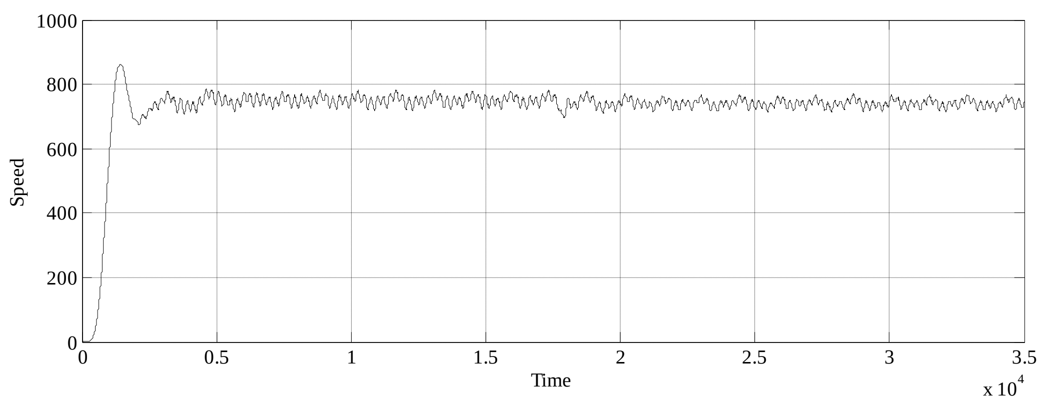


Figure 4.25: Rotor speed in case (B), at (Tr) = 26.71Nm &(nr) =715 rpm

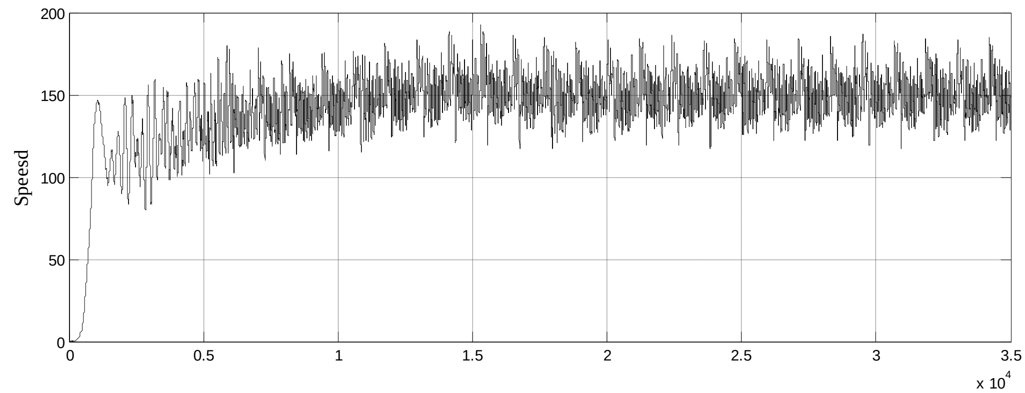


Figure 4.26: Rotor speed in case (C), At (Tr) = 26.71Nm & (nr) =143 rpm

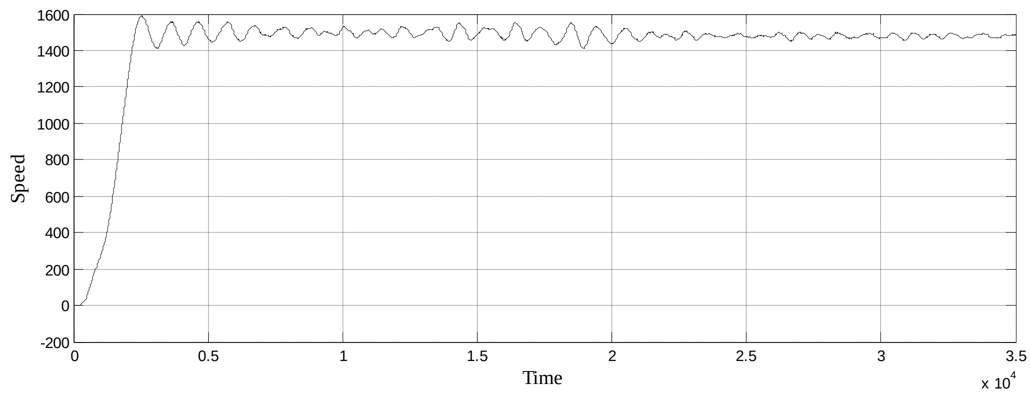


Figure 4.27: Rotor speed in case (D), at (Tr) = 13.355Nm & (nr) =1430 rpm

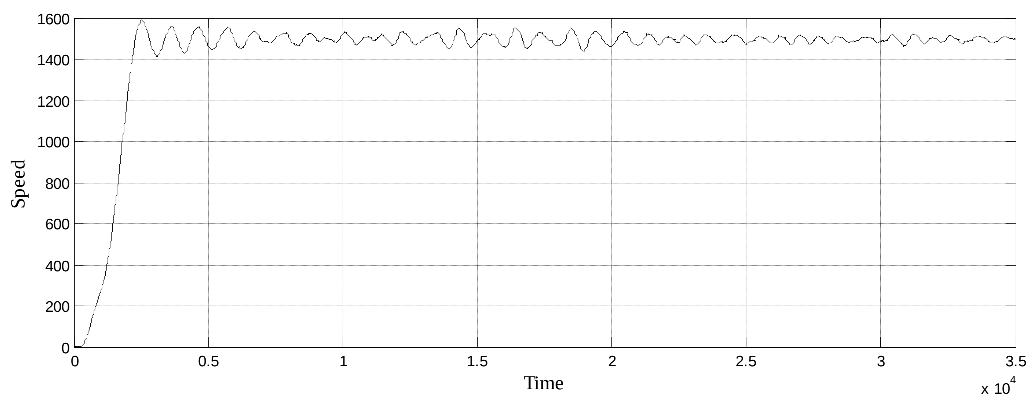


Figure 4.28: Rotor speed in case (E), at (Tr) = 2.671Nm & (nr) =1430 rpm

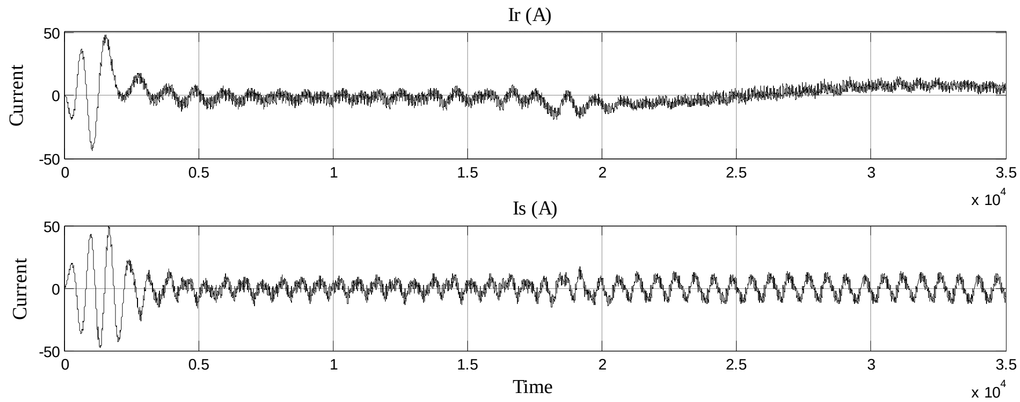


Figure 4.29: Rotor & stator current in cases (A), At (Tr) = 26.71Nm & (nr) = 1430 rpm

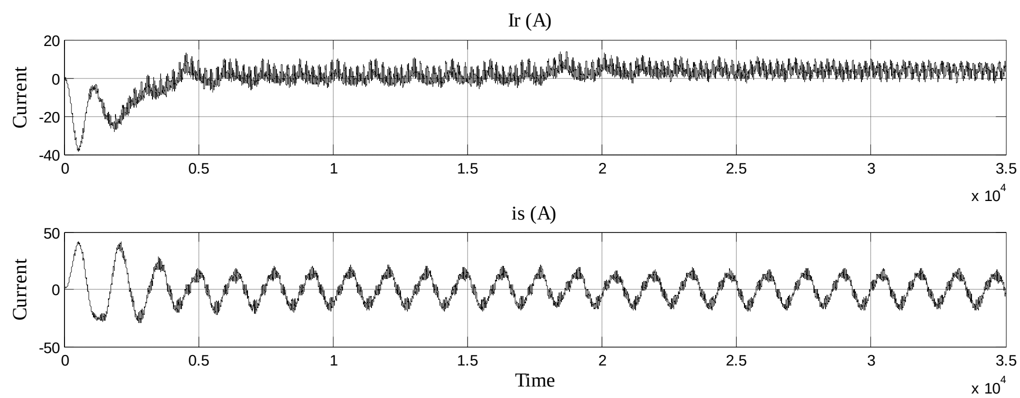


Figure 4.30: Rotor & stator current in cases (B), At (Tr) = 26.71Nm & (nr) = 715 rpm

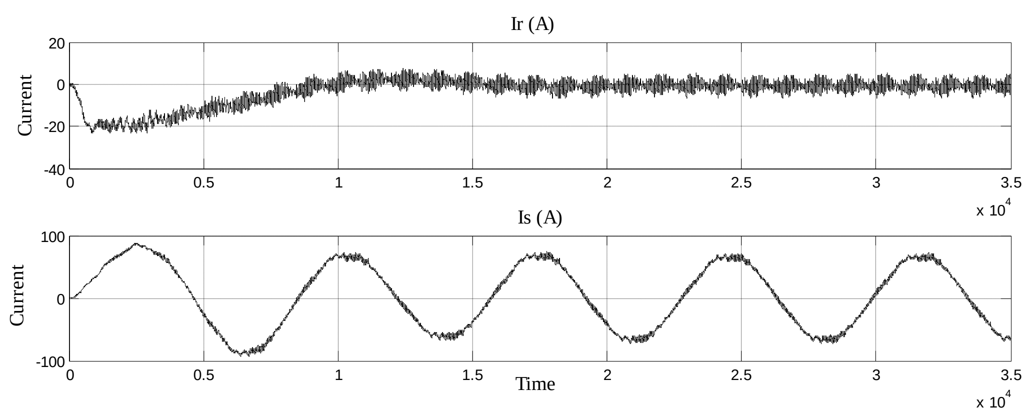


Figure 4.31: Rotor & stator current in cases (C), At (Tr) = 26.71Nm & (nr) = 143 rpm

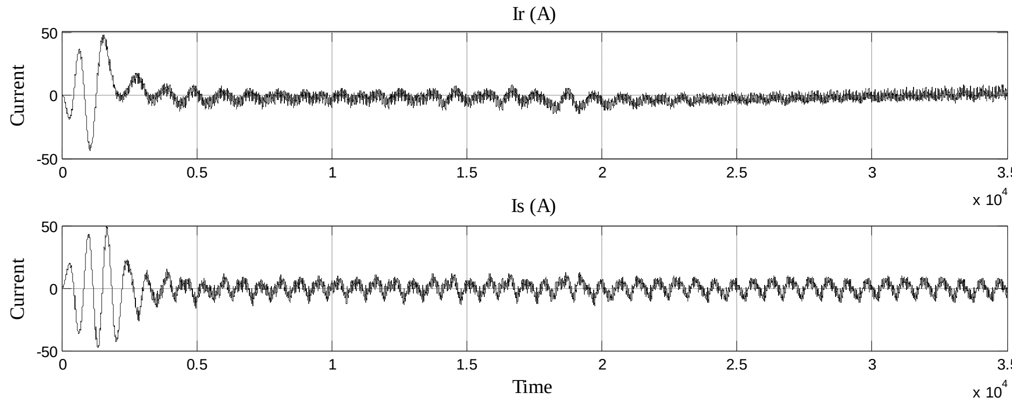


Figure 4.32: Rotor & stator current in cases (D), At (Tr) = 13.355 Nm & (nr) = 1430 rpm

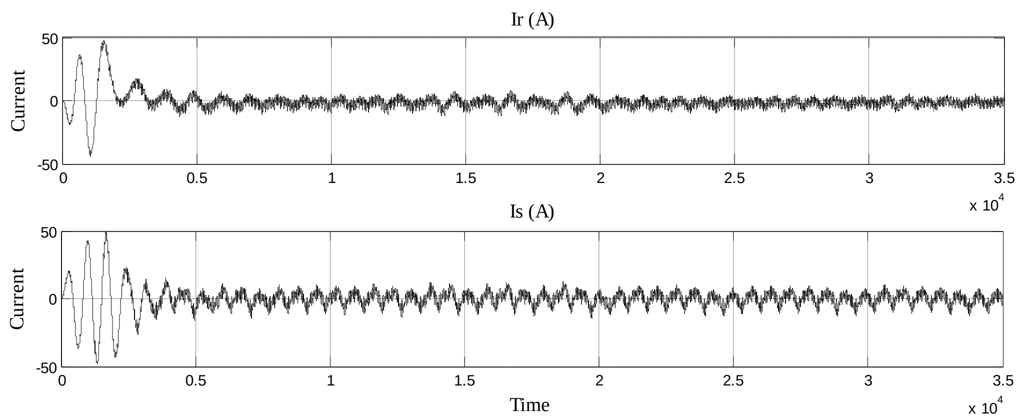


Figure 4.33: Rotor & stator current in cases (E), At (Tr) = 2.671 Nm & (nr) = 1430 rpm

Table 4.3 gives a comparison of the two systems in terms of THD, pf, efficiency, overall system size, overall system weight, simplicity and cost for a 4 kW system. A grade is assigned for each criteria between 1 and 5, 5 being the best.

Table 4.3: Comparison of harmonic mitigation methods

	24-pulse phase shift transformer	**Buck type PWM rectifier**
Harmonic mitigation (THD_I)	%1.4 - %2.46 Rating = 5	%1.47 -%3.6 Rating = 4
Power factor	0.96 – 0.98 Rating = 5	0.86 -0.99 Rating = 4
Power Efficiency	69% Rating = 3	95% Rating = 5
Overall space required	100*80*50 cm Rating = 1	50*50*25 cm Rating = 3
Overall weight	95 kg Rating = 1	15 kg Rating = 5
Overall simplicity	Rating = 3	Rating = 3
Overall price	6000$ Rating = 1	2000$ Rating = 3

Harmonic elimination performance is shown in Figure 4.34 and Table 4.4 also.

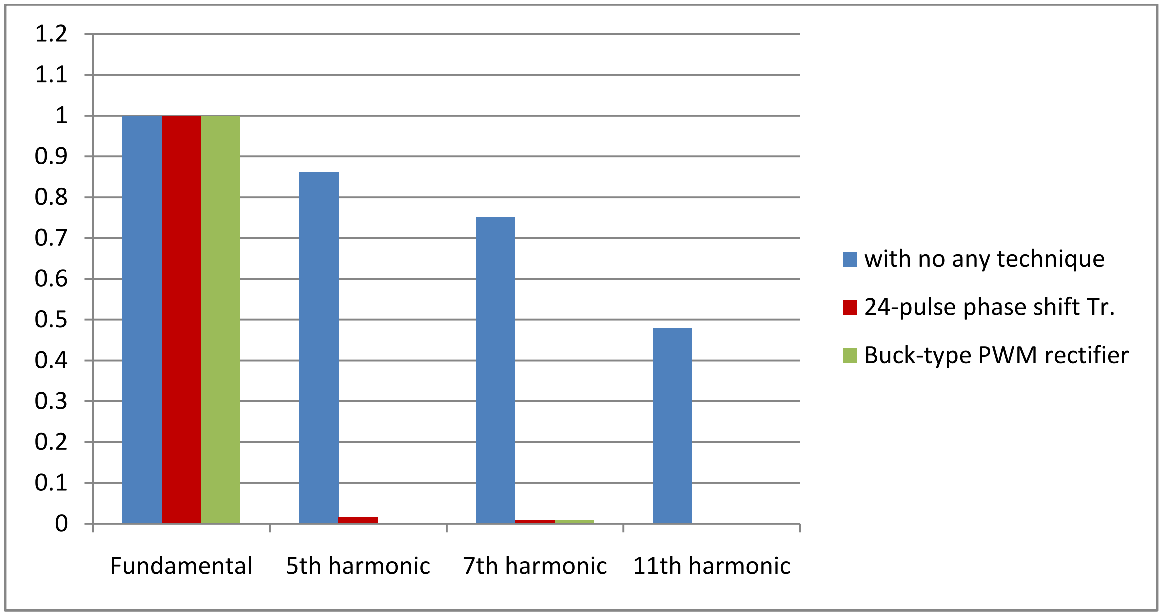


Figure 4.34: Harmonics chart graph

Table 4.4: Percentage of harmonics to fundamental

	with no any technique	24-pulse phase shift Tr.	Buck-type PWM rectifier
Fundamental	1	1	1
5^{th} harmonic	0.86	0.015	0.0022
7^{th} harmonic	0.75	0.0081	0.0079
11^{th} harmonic	0.48	0.0027	0.002

Simulation results show that both techniques yield comparable results. However, using multi-pulse rectifiers is a costly and low efficiency system with a big size and weight. Therefore PWM rectifier should be the choice for this application.

CHAPTER 5

CONCLUSION AND SUGGESTIONS FOR FUTURE WORK

5.1 Conclusion

The front end rectifier used in VFDs is a big source of harmonics. In this thesis, two different front-end rectifier topologies have been used and compared through simulations under various operation conditions.

One of the techniques is using a multi-pulse rectifier. A 24-pulse rectifier has been designed and tested by simulation. The turns ratios and connection diagrams of the phase shift transformers are given.

The second technique used in this thesis is PWM rectifier. This rectifier has also been simulated under the same conditions.

Simulations have been carried out in MATLAB Simulink R2013a. The following points are observed:

- Nowadays, harmonic distortions and low Power Factor (pf) are serious problems that gained more importance in VFD as a power electronics area. Harmonic mitigation and power factor correction can be achieved by using a 24-pulse phase shift transformer and buck type PWM rectifier.
- Harmonic mitigation and power factor correction can be achieved by using a 24-pulse phase shift transformer and buck type PWM rectifier.
- A 24-pulse phase shift transformer rectifier achieved by conversion of a 3-phase voltage source power supply to four individual 3-phase isolated systems by utilized a novel interconnection of conventional 3-phase, and single phase transformer. The transformers are used for creating the relevant phase shifting (15°). The 24-pulse output dc voltage results by cascading of four six-pulse diode bridges that are sustained by the four individual isolated 3-phase voltage.

- Mitigation harmonic circuit with 24-pulse phase shift transformer topology controls the THD and input power factor correction very much better than the circuit buck type PWM rectifier technique. The THD_I reduced to 2.73% and the power factor improved to a value 0.965. So 24-pulse phase shift transformer technique topology can be considered as a good choice for harmonic mitigation and improving of power factor.
- Pulse Width Modulation (PWM) rectifier in distribution systems represents the best solution if compared the results of both techniques as a base of cost & size. The simulation and the results based on PWM rectifier AC-DC converter has improved efficiency and, high dynamic performance and has distortion well under (5%) which is quite acceptable in IEEE 519-1992 recommended.

5.2 Future Work

Further research can be done in the following areas:

- Study of (delta-polygon) connected transformer-based 36-pulse (ac to dc) converter for improvement power quality.
- Comparative analysis of 36, 48, 60 pulse AC-DC controlled multi-pulse converters for Harmonic Mitigation.
- Advanced control techniques on PWM rectifiers to improve the THD.

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APPENDECES

APPENDIX (1)

Overall Circuit Diagram of Simulation of 24-Pulse Phase Shift Transformer System

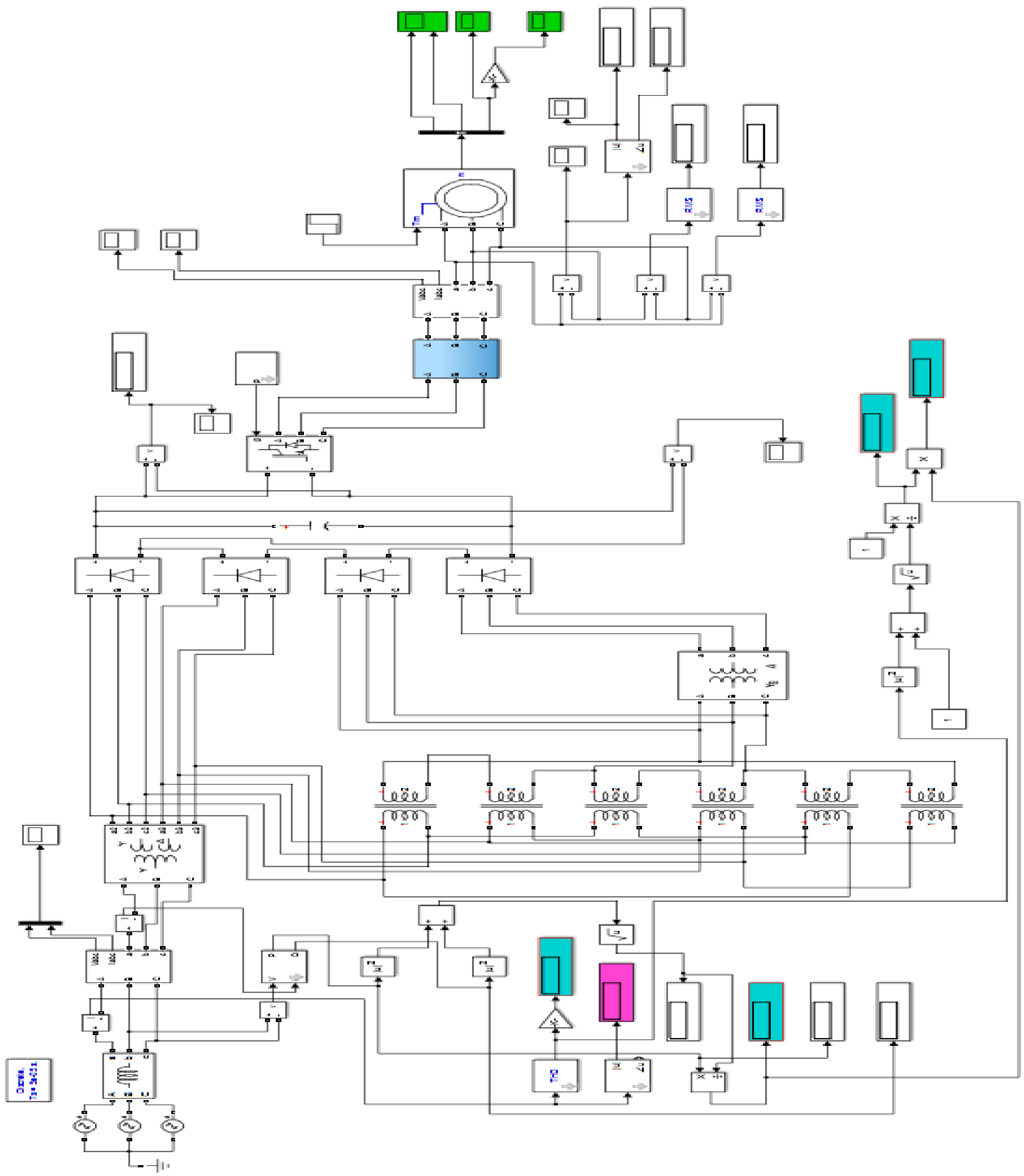

Figure A: Overall circuit diagram of simulation of 24-pulse Phase shift transformer system under non-linear load (VFD)

APPENDIX (2)

Overall Circuit Diagram of Simulation Model of VFD with Using PWM

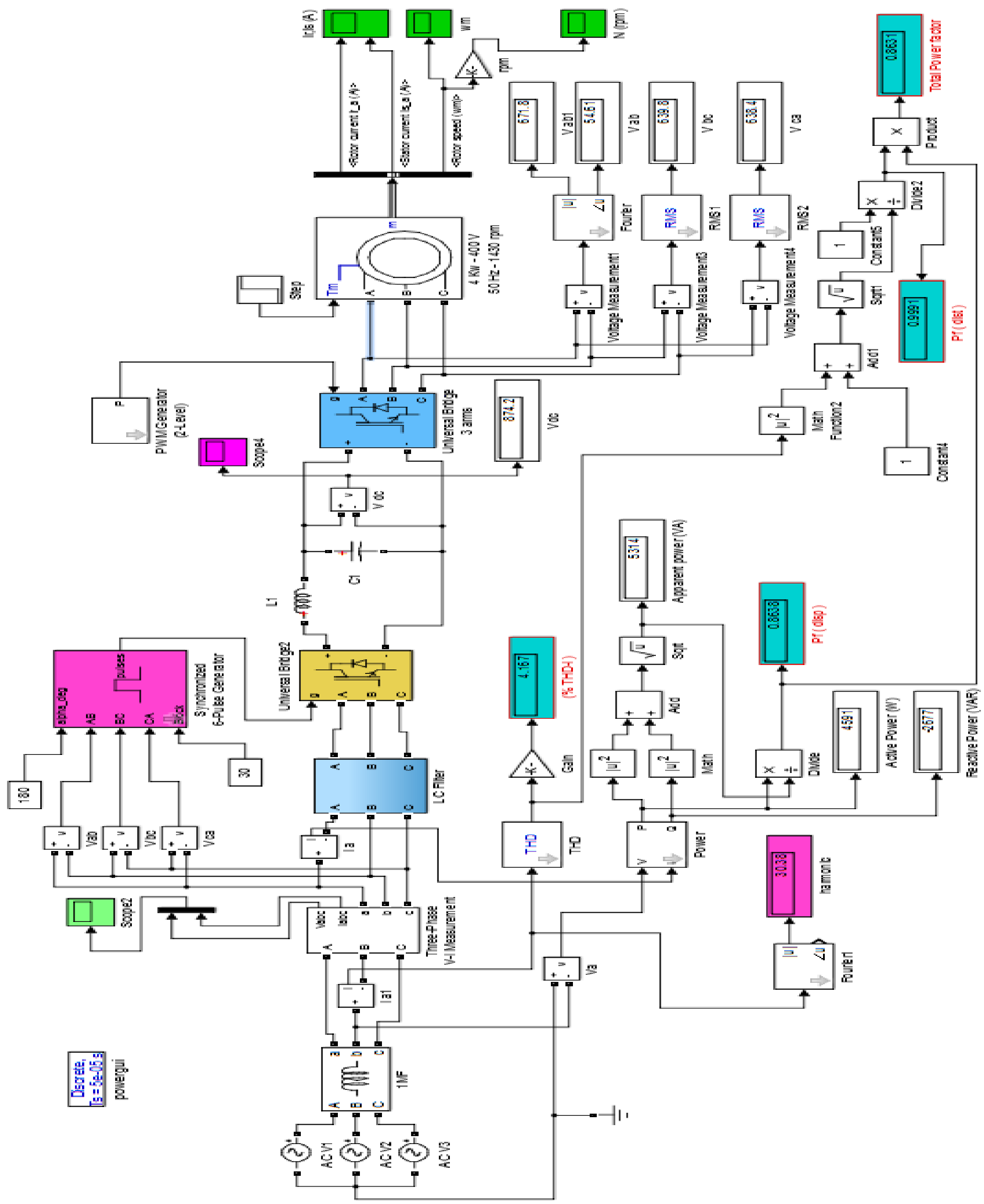

Figure B: Overall circuit diagram of simulation model of VFD with using PWM of system under non-linear load (VFD)

APPENDIX (3)

Table 1: IEEE std 519-1992 Harmonic Voltage Limits

Table 1—Voltage distortion limits

Bus voltage V at PCC	Individual harmonic (%)	Total harmonic distortion THD (%)
$V \leq 1.0$ kV	5.0	8.0
1 kV < $V \leq 69$ kV	3.0	5.0
69 kV < $V \leq 161$ kV	1.5	2.5
161 kV < V	1.0	1.5[a]

[a]High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal whose effects will have attenuated at points in the network where future users may be connected.

Table 2: IEEE std 519-1992 Harmonic Current Limits

Maximum Harmonic Current Distortion in % of I_L

Individual Harmonic Order (Odd Harmonics)

I_{sc}/I_L	< 11	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h$	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. TDD refers to Total Demand Distortion and is based on the average maximum demand current at the fundamental frequency, taken at the PCC.

* All power generation equipment is limited to these values of current distortion regardless of I_{sc} I_L.

I_{sc} = Maximum short circuit current at the PCC
I_L = Maximum demand load current (fundamental) at the PCC
h = Harmonic number

Table 3: IEEE std 519-1992, listing recommended harmonic voltage limits

Harmonic Voltage Limits	
(low-voltage system)	
Application	**Maximum THD (%)**
Special applications ----- Hospitals and airports	3.0
General system	5.0
Dedicated system ----- exclusively converter load	10.0

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Approval of Director of Graduate School of Applied Sciences

Prof. Dr. İlkay SALİHOĞLU

We certify this thesis is satisfactory for the award of the degree of Masters of Science in Electrical and Electronic Engineering

Examining Committee in Charge:

M. aydemir

Assoc. Prof. Dr. Timur Aydemir	**Electrical & Electronic Engineering Department, NEU**
Assist. Prof. Dr. Samet Biricik	**Electrical & Electronic Engineering Department, EUL**
Assist. Prof. Dr. Ali Serener	**Electrical & Electronic Engineering Department, NEU**
Assoc. Prof. Dr. Timur Aydemir	**Electrical & Electronic Engineering Department, NEU**

Ali Serener

M. aydemir