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College of Engineering

Analysis of Three Phase Inverter Fed from a Multiphase Rectifier for Power Processing Applications

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Submitted to the College of Engineering/University of Babylon as Partial Fulfillment of the Requirements for the Degree of Higher Diploma in Engineering / Electrical Engineering.

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بسم الله الرحمن الرحيم

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Dedication

To my mother ... source of my courage and inspiration.

To my family . . . who always give me support and love .

To my friends... who share my sadness before my joy.

To my professors . . . who gave me knowledge.

To the students of science ... in all parts of the world.

To all those ,I dedicate this work.

Salwan
2022

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Salwan

2022

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Abstract

Power electronics converters are considered one of the biggest factors that contributed in the development of the energy field. This contribution became more pronounced after the massive application of renewable energy sources worldwide. To achieve the setout objectives, interfacing and conditioning of the power from these renewable sources requires the use of one or more converters .

This study aims to build a power processing unit, which is comprised from two converters. The first operates as an AC/DC converter, whereas the second is employed as a DC/AC converter. In this work, the first converter is built from a twenty four pulse output rectifier. Using MATLAB/Simulink platform, this rectifier is built and simulated. Initially, the task is to examine the rectifiers' performance under different load conditions. Then, the work is extended such that the above rectifier is loaded by a three phase pulse width modulated inverter. The latter converter is simulated under different loading conditions. Results confirm the feasibility of the multiphase rectifier in providing a DC voltage that approximately mimics that of a battery pack. Which in turn provides a very satisfactory inverter operation, not to mention the quality of the current at the rectifier input terminals. The performance of the inverter in this work is evaluated based on the quality of the output voltage and its response in attaining a zero mean. Furthermore, results reported in this work document that the size of the transformer, which provides the necessary phase shift between the building block rectifiers, can be considerably reduced by changing the phase shift pattern.

The work also presents a comparison between a power processing unit with a multiphase and pulse width modulated rectifier. Herein , the DC/AC converter is analyzed under the same conditions as those in the multiphase rectifier

based unit. It is concluded from the comparison that several advantages are obtained from the power processing unit with the multiphase rectifier.

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List of Symbols

Symbol	Definition
v_{ab}, v_{bc}, v_{ca}	line to line voltage at the inputs
V_m	Maximum value of the voltage at the fundamental frequency.
$v_d(t)$	Time function output from the rectifier.
V_{dc}	DC content in $v_d(t)$.
I_{dc}	Average current
$F(t)$	Fourier series function
ω	Angular frequency
t	Time
f	Frequency
$v_S(\omega t)$	Alternating Voltage Source
p	Number of pules in the output of the rectifier
V_n	Amplitude of the nth harmonic content in $v_d(t)$
θ_n	Phase shift angle of the n^{th}order harmonic voltage.
$r.m.s$	Root mean square
$p.f$	Power factor
$V_{Xn}(\omega t)$	phase voltage
Z	Impedance
R_L	load resistance
t_r:	Rise time of the response
ΔV	Amount of ripple specified in the output voltage

List of Abbreviations

Symbol	Description
AC	Alternating Current
DC	Direct Current
HVDC	High Voltage Dc Transmission
SVPWM	Space Vector Pulse Width Modulation
PWM	Pulse Width Modulation
B2B	Back To Back
MPPT	Maximum Power Point Tracking
NPC	Neutral Point Clamped
IGBTs	Insulated Gate Bipolar Transistor
PID	Proportional Integral Derivative
VFDs	Variable Frequency Drives
MVDC	Medium Voltage Dc Transmission
SOP	Soft Opening Points
THD	Total Harmonic Distortion
CSI	Current Source Inverter
VSI	Voltage Source Inverters
MMC	Multilevel Modular Converter

Chapter One: Introduction

1.1 Introduction to Power Processing Units

Electric power needs to be conditioned and processed by single or multi stage converters. In many applications, such as the integration of renewable energy sources ,electrical power needs to be converted to unidirectional form stored and then converted back to ac at the utility frequency. Such a process calls for two power converters that operate back to back. It is standard in the literature to call such a system, a power processing unit. This calls for a study of the power converters that comprise the power processing unit.

1.2 Literature Surveying

Power processing units play an important role in many practical applications. This unit uses two power electronic converter in back-2-back formation. Previous work has concentrated on four main fields;

1. Renewable energy integration and power conditioning.
2. High voltage dc transmission (HVDC)
3. Drives operation and control.
4. Soft opening points.

As mentioned above, many applications exit for power processing units. One of the most pronounced applications is the integration of renewable energy sources into existing distribution grids **[1-8]**.

In **[1]**, a processing unit composed of two back to back converters are used to interface a wind energy source. The two converters are controlled by space vector pulse width modulation (SVPWM). The authors used a PWM based AC/DC converter to obtain a controlled voltage. Through MATLAB/SIMULINK simulations authors concluded that the SVPWM

produced an out voltage and current waveforms with higher quality in terms of the quanitity of distortion.

In **[2]**, a processing unit is also composed from two back to back converters (B2B converter).In order to obtain alternating current, the two converters were used to interface and condition power from a DC-renewable energy sources. Using the MATLAB / SIMULINK platform, and by means of the DSPACE DS1104 board, the prototype was implemented and the focus of the work was on the control algorithm of the DC-link voltage of the B2B converter. Thus, according to what the simulation results showed for the power rectifier circuit, the output voltage and waveforms became less distorted than the input, and the DC-link voltage was controlled as required by changing the width of the space vector pulse corresponding to each variation of the load current. In addition to what was mentioned, it was noticed in the experimental results an improvement in the alternating current voltage, as 200 volts were entered, in return, a direct constant voltage of 364 volts was obtained.

The processing unit consists of two back to back converter (B2B converter) to condition and interface a wind power source**[3,4]**. In **[3]**, the authors approach is based on viewing the two converters as two generators synchronized with the utility grid. The DC link voltage is controlled through the rotor side of one of the converters. Due to the variable nature of the renewable source, energy is first stored in the DC link capacitor .The converter near to the utility grid is responsible for Maximum Power Point Tracking (MPPT). Through the use of MATLAB/SIMULINK simulations, the results extraction found that the proposed method gives correct results, in terms of the injected power following the reference setting and the fast response of the system to varying power conditions as a result of wind speed changes.

Work in **[4]**, Investigated the operation of a DC/AC converter with an LC filter and step up transformer near to the grid. The aim is to evaluate the efficiency of the overall interfacing components which in turn determines the efficiency of the whole system. The latter is implemented by calculating the losses for all the influential components of the system.

Authors in **[5]**, studied the behavior of the two back to back converters with a wind turbine as the primary energy source. Two topologies were investigated in the work. The first is a processing unit which consisted of two converters; AC/DC connected to the wind generator and DC/AC connected to the grid. The second topology consists of a three level converter, AC/DC connected to the wind generator, DC/DC to store energy and DC/AC near the grid for interfacing the power at grid frequency. Simulations for two systems concluded that any impact or variable component of the structure will result in certain losses. Whereas the first topology is suitable if the wind speed is stable and the second is suitable if there is a large fluctuation in wind speed which alters the power extracted.

In**[6]**, the processing unit consists also of two back to back converter (B2B converter), where the rectifier is a PWM converter built from IGBTs. A five level neutral clamped converter is used in the inversion side with five level outputs to achieve high voltage grid integration. Since one of the big problems that must be treated is the balancing of the DC link capacitor in the installed neutral point (NPC) of the converters, which may cause stress on the semiconductors and a large distortion was investigated. The work in this research focused on employing two different control strategy for each converter. In the first converter, which represents AC to DC conversion, a hysteresis based algorithm is used, whereas in the second stage, which represents a DC to AC conversion, the vector control is used to generate the

switching pulses. The work was implemented on MATLAB/SIMULINK simulation. Results indicated the effectiveness and validity of the proposed algorithms.

The two stage power processing unit was implemented to integrate a wind power system into an existing utility network in the city of Derna in Libya**[7]**. The authors in **[7]** used a rectifier circuit followed by an inverter stage with a DC link at the input terminals. The control algorithm for both converters is designed in the DQ reference frame. This enables the use of conventional PID controllers to control the injected real and reactive power to the utility grid. The rectifier circuit used is a PWM controlled IGBT converter.

Due to the importance of wind sources, researchers presented different methods of utilizing and controlling converters in renewable energy applications. In **[8]**, the authors designed a back-to-back converter based on a step-by-step method, which is considered an ideal method. The processing unit consists of AC/DC converter connected to a wind turbine and DC/AC converter connected near the grid, while DC link capacitor connected between them for storage. The controlled system is implemented using proportional-integral (PI) controllers. The value of the generation from the wind turbine was assumed equal to 2 MW. The system was simulated in MATLAB/ SIMULINK and the performance of the wind generator evaluated even at low voltage and during a sudden change in wind speed .

In power conditioning applications, the power processing unit with its two conversion processes implements several objectives. These include the conversion of power into unidirectional form which can be easily controlled and/or stored. Also, through switching techniques, the shape of the input current can be modified to provide a more sinusoidal shape. Here, harmonic content can be mitigated, which can result in a better power factor at the

nominal frequency of the system. Authors in **[9]**, presented a two stage power conditioning system. The first stage is composed of a controlled rectifier through PWM. The second stage is responsible for inverting the power back to AC form at the nominal frequency of the grid where power is to be injected. The authors used MATLAB/SIMULINK to achieve simulations under different operating conditions.

Sometimes the supply voltage source is unbalanced due to certain conditions. This imbalance causes a problem in the drive of the motors. Therefore, among the most important applications of back-to-back converters is the control of the end front rectifier drive in motors. Therefore, researches focused on studying the use of back-to-back converter and improved performance in this field **[10-13]**.

In **[10]**, the processing unit consists of a rectifier that is near to the grid side that converts the alternating voltage to a continuous voltage (AC/DC) and the energy is temporarily stored in the DC link capacitor in addition to filtering unwanted harmonics. Then power is transmitted to the inverter, which is near to the motor drive. Here, the constant voltage is re-converted to alternating current, at a frequency as required by the motor drive. Results show the a positive impact on the motors work even when the utility grid suffers from unbalancing conditions.

In **[11]**, a multi motor system is presented with a power processing unit for each motor drive. The rectifier circuit consisted of two rectifier circuits controlled and uncontrolled. The rectifier used is the three phase full wave. The authors pointed that the proposed method has an operating performance that is free from load variations. Simulation results with experimental validation confirmed the feasibility of the proposed method in producing an input current quality that outweighs the conventional rectifier circuit.

Over time, the industry and technology in the field of energy developed to reach the highest quality of production, lowest cost ,and the largest amount of production. Variable frequency drives (VFDs) were considered the low quality which led to some motor drives not finding applications. However, with the presence of back-to-back converters (power processing unit), it became the focus of studies for the purpose of improving the quality of performance. In **[12]**, the processing unit for the back-to-back converter consists of a rectifier connected to the source, which converts the AC voltage into a DC voltage, with a DC link capacitor that stores energy and filters out ripple. The DC/AC stage converts the DC power to AC at a constant frequency which significantly improves the performance of the drive.

In **[13]**, the study focused on induction motors, where the system consists of a back-to-back converter of two parts, the first part is the AC / DC rectifier line which consists of IGBTs transistors, and the control of the output voltage is made through PWM. The induction drive is fed from the PWM converter, which supplies AC power at the desired frequency. The system was simulated in MATLAB/ SIMULINK under different mechanical loading.

Back-to-back converter applications are not limited to what was previously mentioned but were used within the processes of energy transmission, where the rectifier is used to convert energy from alternating to continuous and transmitted in a continuous form to long distances and then it is re-converted to alternating and at frequency corresponding to rate grid value **[14-15]**.

In **[14]**, the processing unit consists of a back-to-back converter system within the electric power transmission system. A study of the system was carried out in the city of Tomsk for the purpose of finding solutions to the problems facing the transmission of energy between the southern and northern

parts. Since the distance is too long, approximately 800 km, the load increases with time, as well as the complexity of the network, since the transmission capacity becomes low and a reliable connection of these parts cannot be established. Therefore, the HVDC series back-to-back converter system was applied, after determining the required size and the appropriate place for installation, as it is characterized by the possibility of asynchronous connection for the work of these parts. The results of the study indicated the great benefit of applying the HVDC back-to-back converters system, as its effectiveness was very clear in reducing the level of short-circuit current and the possibilities of controlling frequencies in the power system and thus increasing the possibility of stabilizing the loading process, especially motors the load.

In addition to the back-to-back converter studies in power transmissions, the unidirectional rectifier is also one of the technologies used in MVDC and HVDC power transmission. Much research has dealt with the behavior of a multi-pulse rectifier, but its behavior has not been adequately described when the power source is balanced by three-phase sinusoidal waves. In **[15]**, the behavior of the 12-pulse rectifier diode was studied in MVDC and HVDC transmission lines, and through the MATLAB /SIMULINK platform. Results were obtained showing the multiplicity of the output voltage wave, which contributes to eliminating several orders of harmonics, thus reducing the size of the insulators and reducing the losses in the windings transformers.

A more recent application of a two converter power processing unit is the Soft Opening Points (SOP) in distribution networks **[16-18]**. Usually, the distribution system is mostly of a radial structure. Although this structure is simple in-terms of protection strategy, however the main drawback is the case when a fault occurs in a feeder, no support can be given from other feeders.

On the other hand meshed topologies, have the ability to supply feeders in case of emergency conditions. However, meshed distribution systems suffer from complex protection schemes and increased short circuit MVA levels. Hence, SOPs, which are composed from two power electronics converters (AC/DC & DC/AC) that are located in points on the distribution system that are normally left open (NOP), mimicking a meshed topology but with none of the above mentioned disadvantages **[16]**.

Authors in **[16]**, presented the principles of SOPs in a distribution system and investigated their operation during usual and none usual conditions. The authors developed a control algorithm that controls active and reactive power flow, before, at and after fault conditions with two types of transitions methods. The rectifier used is an IGBT PWM topology with a two-level inverter.

Work presented in **[17]**, dealt with an optimization method to generate the reference points of active and reactive power for the SOP. Here, an optimization function is setup to reduce losses, enhance voltage balancing and to modify voltage values . The work didn't mention the topology of the power electronics converters.

Authors in **[18]**, presented a method based on a nonlinear optimization problem to find the required settings for the SOP converters. The SOP considered in this work is a two IGBT rectifier and inverter converters.

1.3 Objectives of Current Work

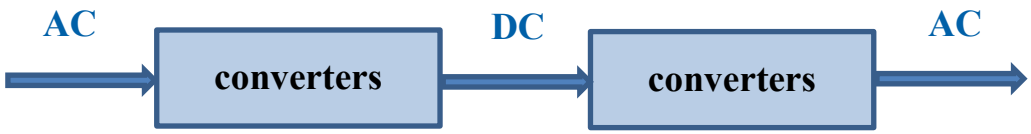
Based on the presented literature survey above, the following points present the objectives of the work presented in this project:-

1. Investigate multiphase rectifier topologies; this includes six, twelve, eighteen and twenty four pulse output rectifiers.
2. Select the multiphase rectifier circuit based on the above investigation to act as a substitute for the IGBT PWM rectifier circuit. Using multiphase rectifiers can produce output voltage with a rich DC content, yet with less complicity.
3. Investigate the multiphase rectifier performance, under various loading conditions. The aim here is to examine voltage/current waveform shapes at input and output terminals.
4. Design and simulate the power processing unit with two back to back converters, using the selected rectifier topology.
5. Evaluate the performance of the three phase inverter with various load and response of this converter in providing symmetrical output with a zero mean.
6. Compare the performance of the multiphase AC/DC with a the DC/AC power processing unit with the conventional unit that employs the two IGBT PWM circuits. Here, simulations are made under the same loading condition to provide a fair comparison.

Chapter Two: Theoretical Work

2.1 Introduction

Power processing unit consist of one or more converters



2.2 The AC/DC Converter

There are several types of AC/ DC converters or rectifier circuits, whether they are single phase or three phase, with half wave or full wave rectifiers. Rectifiers may be classified as controlled, uncontrolled and semi- or half-controlled **[19]**. Figure (2.1) provides a diagram of rectifier topologies

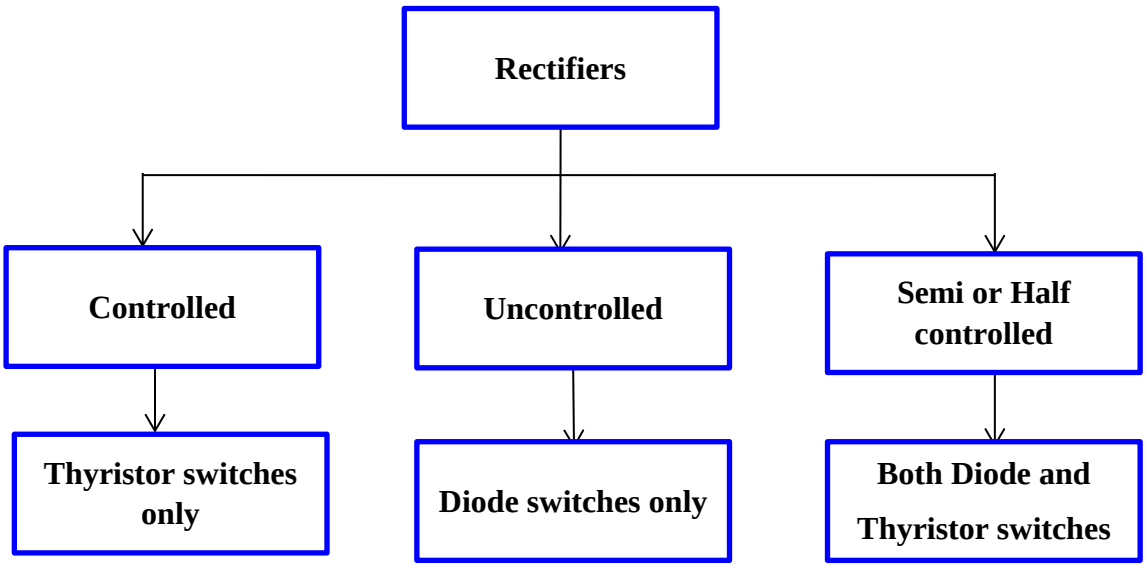


Figure (2.1) Classification of rectifier topologies

2.2.1 Conventional Three Phase Uncontrolled Rectifier Circuit

In general, three-phase rectifiers are widely used in industrial applications because the outputs are smoother and are of less ripple than the corresponding single-phase rectifiers **[20]**. Uncontrolled rectifier, only diodes are used and they behave like power switches.

2.2.1.1 Three Phase Half – Wave Uncontrolled Rectifier

The circuit of this type is very simple. When the load is pure resistance, the voltage and current are in the same phase at the input, the circuit shown in figure (2.2). Sometimes, a delta/star transformer is used to control the amount of input AC voltage to the rectifier.

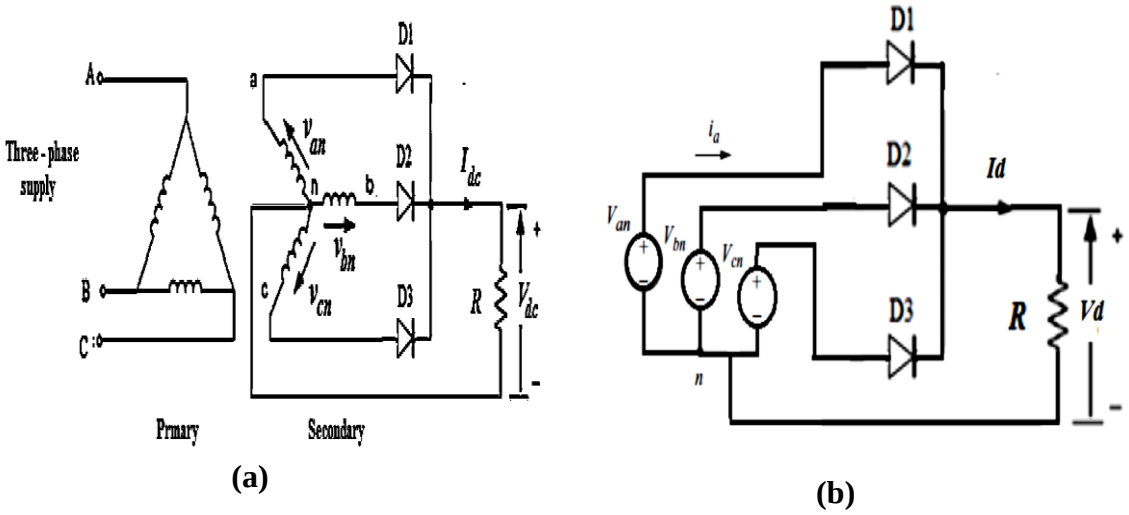


Figure (2.2) Three phase half wave rectifier[19] (a) With transformer and (b) Without transformer.

The line to line voltage for uncontrolled three phase half-wave rectifier is defined as;

$$v_{ab}(\omega t) = \sqrt{3}V_m \sin(\omega t + \pi/6) \quad (2.1)$$

$$v_{bc}(\omega t) = \sqrt{3}V_m \, sin(\omega t - \pi/2) \tag{2.2}$$

$$v_{ca}(\omega t) = \sqrt{3}V_m \, sin(\omega t - 7\pi/6) \tag{2.3}$$

Where V_m and ω are the peak voltage per phase and angular frequency respectively. The mean voltage content in the output voltage is given by;

$$v_{dc}(\omega t) = \frac{1}{2\pi/3} \int_{\frac{\pi}{6}}^{\frac{5\pi}{6}} v_{ab}(\omega t).d\omega t \tag{2.4}$$

The v_{dc} for uncontrolled three phase half-wave rectifier equal:

$$V_{dc} = \frac{3\sqrt{3}}{2\pi} \, Vm \tag{2.5}$$

The average current I_{dc} is given by,

$$I_{dc} = \frac{3\sqrt{3}v_m}{2\pi R} \tag{2.6}$$

2.2.1.2 Three Phase Full – Wave Uncontrolled Rectifier

In usual cases the three phase full-wave uncontrolled rectifier is supplied through a delta- star transformer. The latter is fed from a three phase balanced supply with zero internal impedance, as shown in the circuit of the figure (2.3) ,input and output waveforms are shown in figure (2.4) .

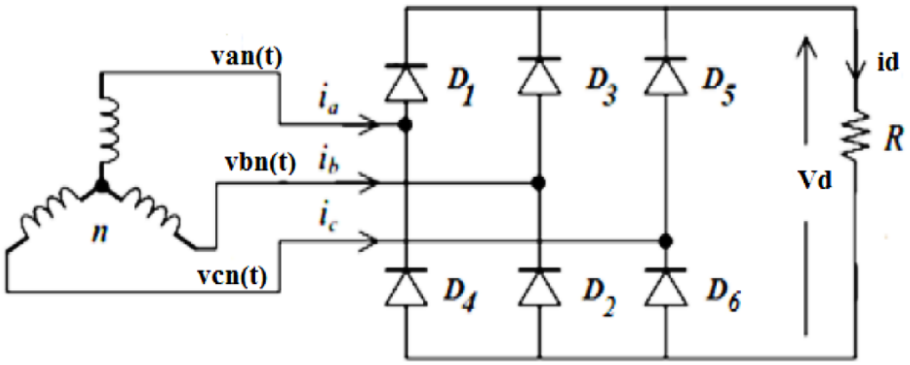


Figure (2.3) Three phase full – wave uncontrolled rectifier[19].

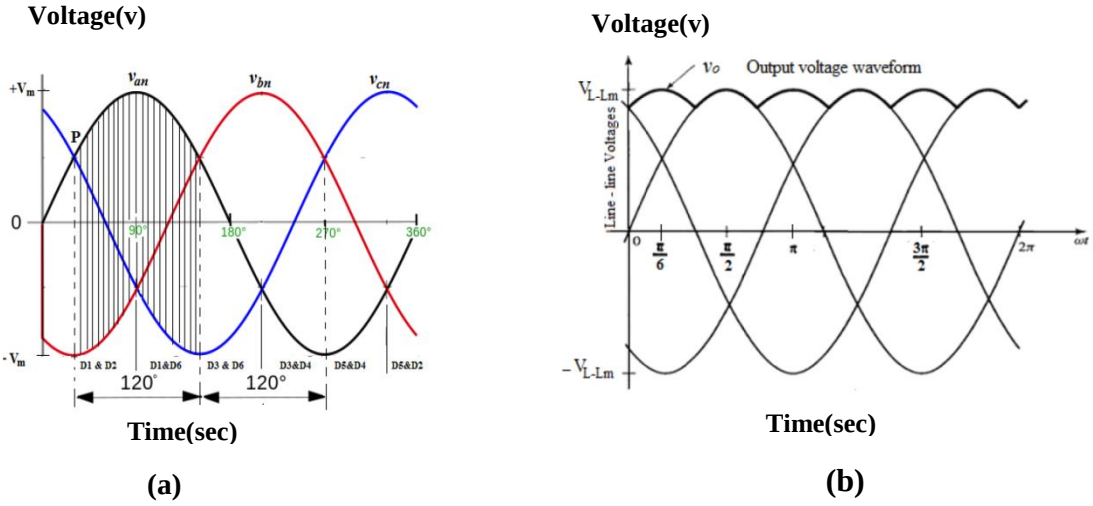


Figure (2.4) (a) Input and (b) Output voltages for three phase full – wave uncontrolled rectifier[19].

The v_{dc} and I_{dc} for uncontrolled three phase full-wave rectifier equal:

$$v_{dc} = \frac{3\sqrt{3}}{\pi} \int_{\frac{\pi}{6}}^{\frac{\pi}{2}} v_{ab}(\omega t).d\omega t = \frac{3\sqrt{3}}{\pi} V_m \tag{2.7}$$

And the average current is,

$$I_{dc} = \frac{3\sqrt{3}v_m}{\pi R} \tag{2.8}$$

2.2.2 Multi- Pulse Three Phase Uncontrolled Rectifier Circuit

The main purpose of using a multi-pulse rectifier is to obtain a wave with a highly attenuated ripple and smoother shape, as well as to reduce harmonic distortions of current at the AC input. When the harmonics at the input decrease, this leads to a decrease in the total harmonic distortion (THD). Therefore, we resort to increasing the number of pulses by connecting the bridge rectifiers appropriately to provide multi-phase power sources that are controlled through the use of a suitable transformer. The transformer provides phase shifts between groups of the three phase bridges, as a result, a portion of the low-order harmonic currents generated by the pulse rectifiers are canceled. In general, the more pulses of the rectifier, the less distorted line current will be obtained and the more smother is the dc voltage**[21]**.

2.2.2.1 Six Pulse Three Phase Uncontrolled Rectifier Circuit

The six-pulse rectifier is also considered a three-phase rectifier. Diodes are used in circuit design for the purpose of converting alternating current into direct current, where six diodes are used. Diodes are arranged in three legs .Each leg has two pairs attached to the chain and in the following order**[21]**,

1- D1, D3, and D5 are the upper diodes representing the positive group of diodes and they work when they encounter the highest positive voltage
2- D2, D4 and D6 are the lower diodes and represent the negative group of diodes and they work when they encounter the highest negative voltage.

Three-phase transformers connected in a star-delta manner feed the bridge, as shown in figure (2.5). Here at the side of the diodes, the input is six phases which are displaced by 60^{o}.

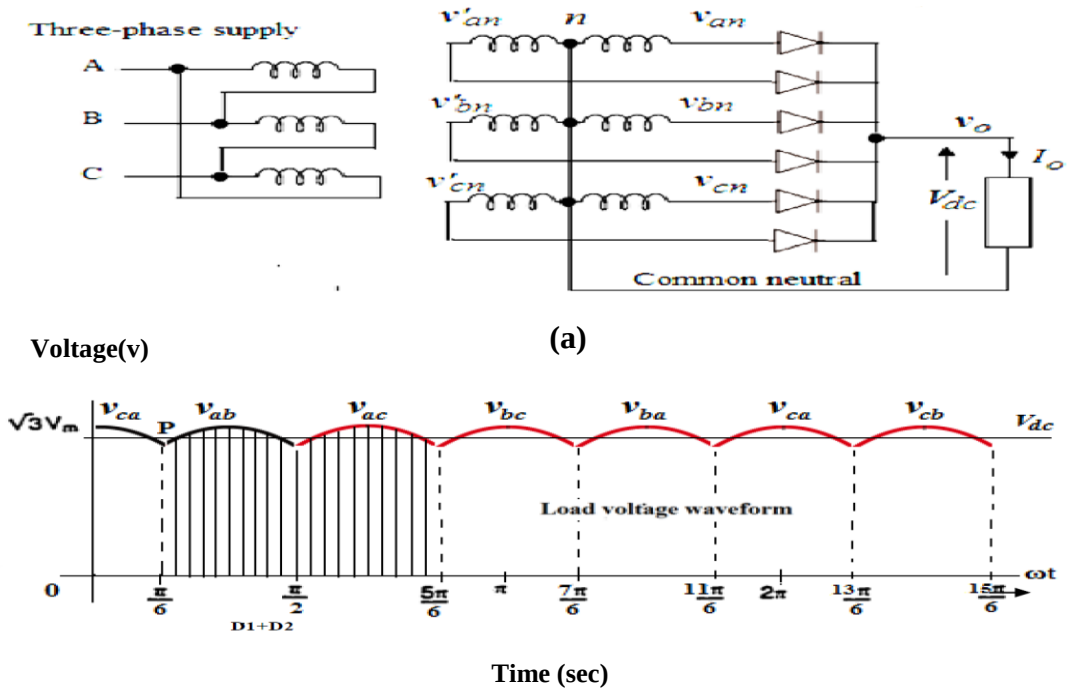
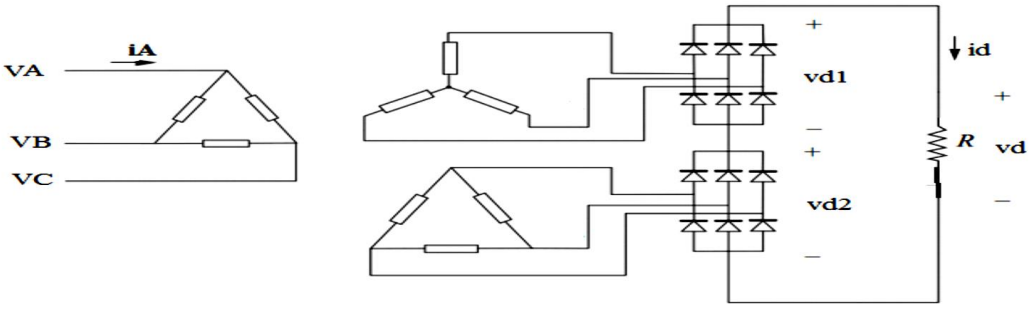


Figure (2.5) (a) Six pulse three phase uncontrolled rectifier circuit and (b) Output voltage waveforms[19].

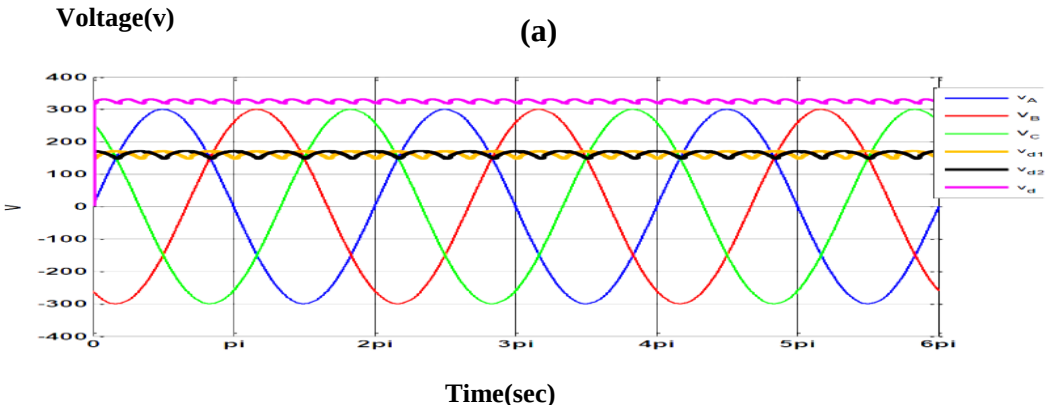
Here, this converter is equivalent to two half –wave rectifiers that produce six pulses of voltage at the output.

2.2.2.2 Twelve Pulse Three Phase Uncontrolled Rectifier Circuit

The twelve-pulse rectifier is also a three-phase pulse rectifier that converts alternating current to direct current . As there are twelve pulses per cycle, the quality of the resulting waveform will be improved as for as the ripple content is concerned. A total of twelve diodes are used, each bridge rectifier uses six diodes .The two bridges are connected in series so that the net output voltage is equal to output voltage of the upper rectifier plus the output voltage of the lower rectifier **[21]**. The circuit and waveform are shown in figure(2.6). To generate the 12 pulse output a phase shift is mandatory between the two bridges. In figure (2.6) this phase shift is provided through a delta/star/delta transformer.



(a)



(b)

Figure (2.6) (a) Twelve pulse three phase uncontrolled rectifier circuit[19] and (b) Wave form for Twelve pulse 3φ uncontrolled rectifier [20].

2.2.2.3 Eighteen Pulse Three Phase Uncontrolled Rectifier Circuit

An eighteen-pulse diode rectifier circuit can be easily built by connecting in series three six-pulse rectifier bridges, we need to provide six phase shifts to power the three-pulse bridge rectifier. In the previous rectifier circuits, such as the 12 pulse, the phase shift could be easily achieved by a simple delta/star transformer with double winding. However, for the 18 pulse circuit, the required phase shift is 20^{o} and this calls for the use of a zigzag transformer. The latter could provide arbitrary a phase shift as needed. The transformer consists of three secondary windings. The first is wrapped in a star shape while the second and third winding is structured in a zigzag formation **[21]**.The circuit is shown in figure (2.7) and the waveform for output voltage is shown in figure (2.8).

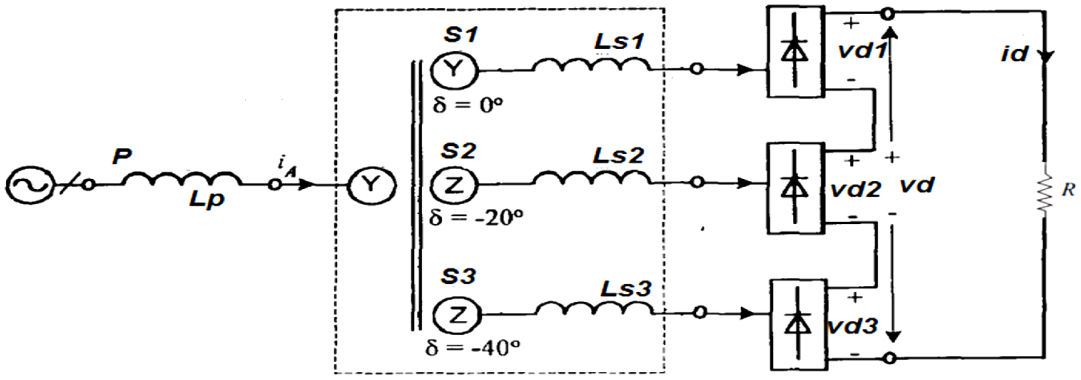


Figure (2.7) Eighteen pulse three phase uncontrolled rectifier circuit [22].

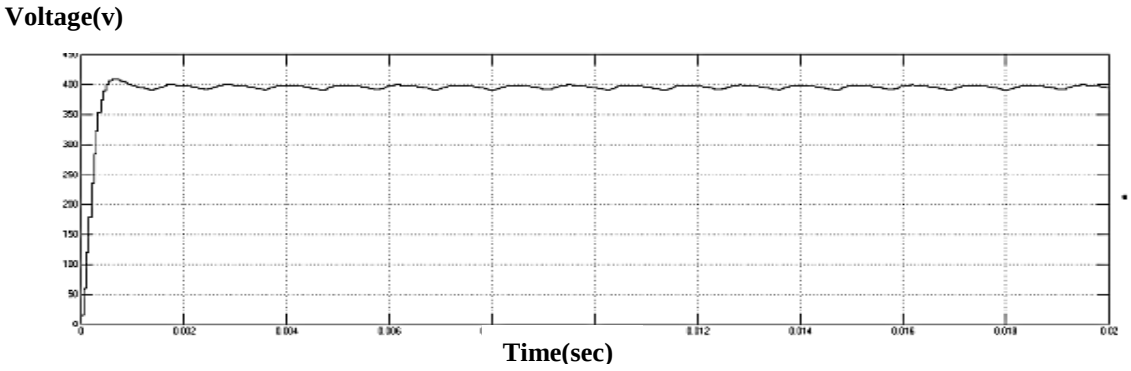


Figure (2.8) The waveform for output voltage for 18 pulse three phase uncontrolled rectifier [21].

2.2.2.4 Twenty Four Pulse Three Phase Uncontrolled Rectifier Circuit

The 24-pulse rate is obtained by connecting four bridges in series. Here the phase shift is 15 degrees, which again calls for the use of a multi-winding transformer. One possible combination is to use one primary winding, which is a star or delta with four windings on the secondary. The four windings can be one star or delta with three other zigzag windings, as shown in figure (2.9). Here it is noticed that the waveform output voltage is of little ripple and THD than the previous multi-pulse rectifier circuits. Hence, the DC output of 24-pulse is nearly a DC voltage. There is also a 36-pulses multi-rectifier type

which is slightly different from a 24-pulses in terms of output waveforms **[22]**.

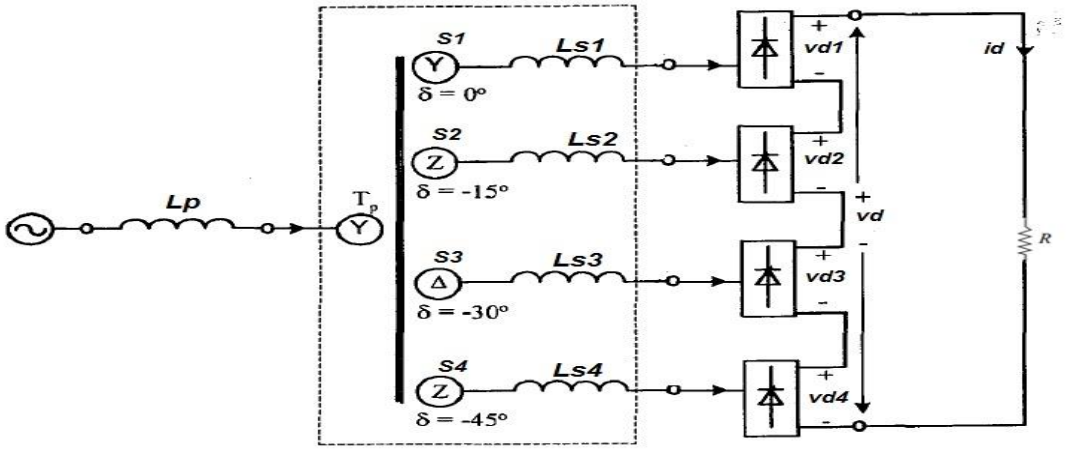


Figure (2.9) Twenty four pulse three phase uncontrolled rectifier circuit [22].

2.3 The DC / AC Converter

DC/AC converters or commonly called inverters provide an opposite job compared to rectifiers. These inverters are used in many important applications including unite power supply(UPS)units, AC motors, aircraft power supplies, and High Voltage DC (HVDC) transmission. These converters, whether single-phase or three-phase, are fed from a DC voltage source and the output is AC. Below, the two main types of inverters are presented **[20]**,

2.3.1 Current Source Inverter (CSI)

The input to this type is direct current (DC) and is converted into alternating current (AC) in the form of a square wave as shown in figure (2.10), for the purpose of obtaining a fixed input current an inductor is used at the input, usually this type of inverters is used in applications that require high power. The output current shown corresponds to an inductive load**[20]**.

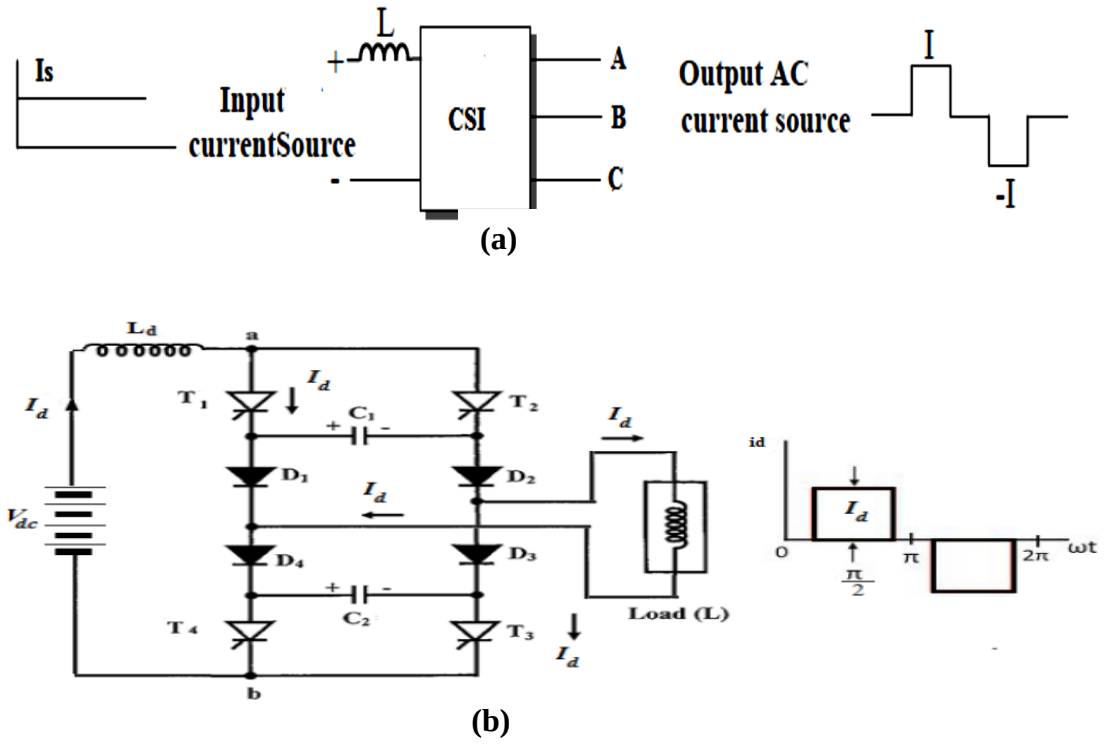


Figure (2.10) Current source inverter (CSI), (a)Block diagram and (b)Circuit [19].

2.3.2 Voltage Source inverters (VSI)

The input in this type is a DC voltage and it is converted into an alternating voltage, the output is also in a square shape, as shown in figure (2.11). This type of converter usually has a capacitor at its input terminals to provide a nearly fixed voltage. The battery or rectifier can be used as an input to this type. Applications of this converter include low and medium power **[20,23]**.

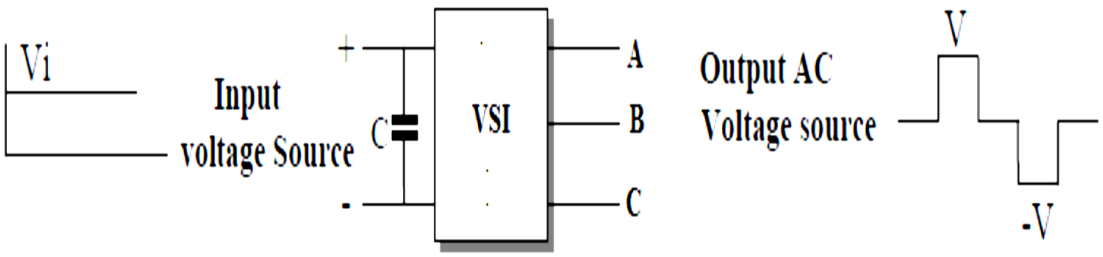


Figure (2.11) Voltage source inverter (VSI) [1].

2.3.2.1 Three Phase Inverter

Through the use of a voltage inverter, a three-phase alternating voltage can be produced. Figure(2.12) shows a three phase voltage source inverter, in each cycle, a switch conducts for 60^{o} ,here the name six step inverter. One of the most important applications in which this inverter is used is to control the speed of the three-phase induction motor, where we can through this converter control voltage and frequency. One of the most important considerations when designing the switching pulses of this inverter is that the two transistors in one leg operate in a complementary manner**[20,23]**. For example, (S1 & S4) cannot be turned on at the same time, otherwise a short circuit will occur across the supply.

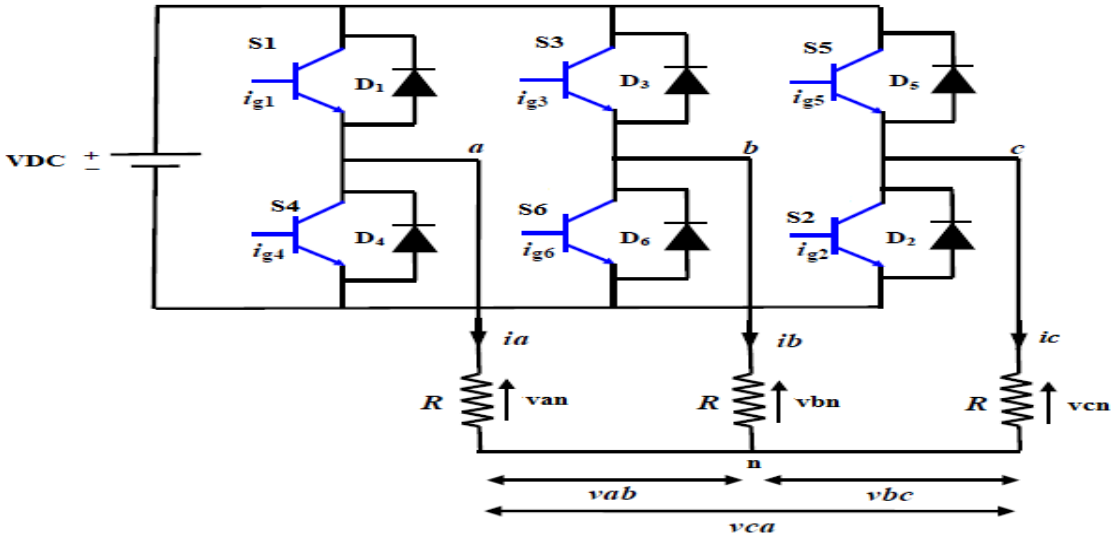


Figure (2.12) Three phase inverter circuit [19].

There are two approaches that can be used to generate switching pulses

1- Switching pulses based on 180^{o} connection mode.
2- Switching pulses based on 120^{o} connection mode.

In both modes, the state of the switch changes every 60^{o} degrees. In mode180 degrees each switch works for 180°. Reference to figure (2.13), which shows the switching periods for the 180^{o} conduction mode, for example S_1 is

triggered at $\omega t = 0$ and continuous till $\omega t = \pi$. However, the tripartite switching pattern changes every $\omega t = {}^{\pi}/_{3}$. If the period $0 \leq \omega t \leq \pi$ is considered a switching pattern of S_1 S_6 S_5 is conducting the current. That changes at $\omega t = {}^{\pi}/_{3}$ to S_1 S_6 S_2 and so on. In the 120°, any switch in the converter conducts for a period of 120°, with a change of status every 60° as in the 180° conduction mode. At any instant of time, only two switches are conducting**[20]**. Switching waveforms for this mode are depicted in figure(2.14)

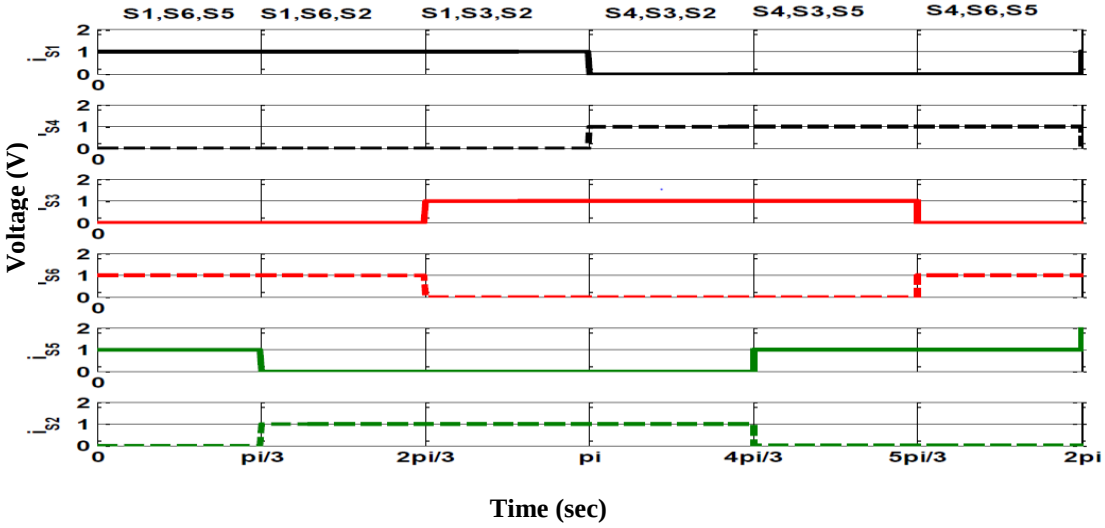


Figure (2.13) The waveform for three phase inverter mode 180° [20].

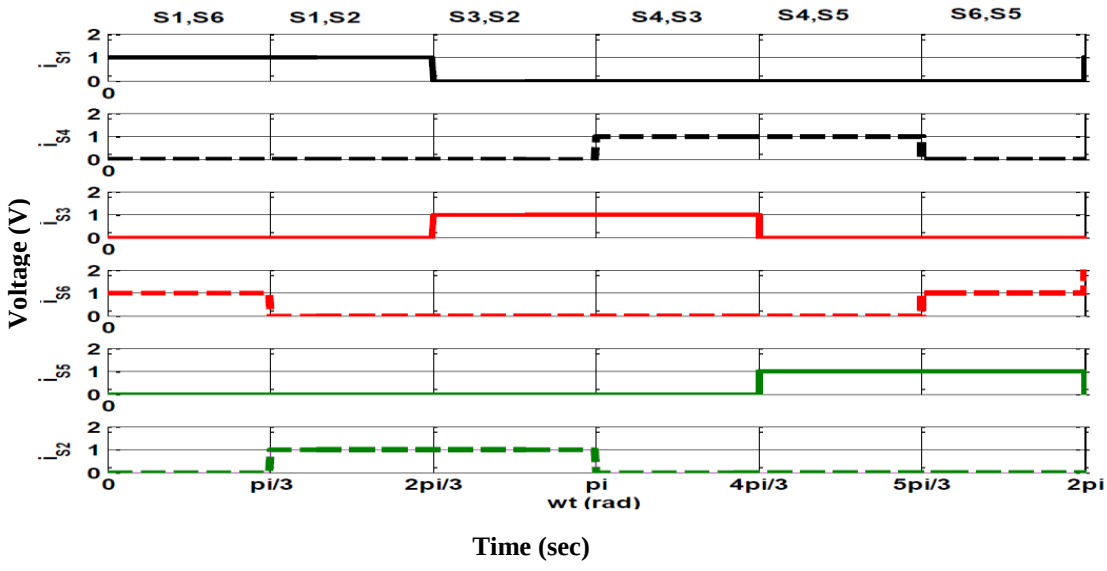


Figure (2.14) The waveform for three phase inverter mode 120°[20].

2.3.3 Pulse Width Modulation in Inverters

The voltage inverter always generates fixed values of output voltages. However, these outputs may not be compatible with loads fed by the inverter. Therefore, some sort of control is required to drive the output voltage and frequency to the desired values. Accordingly, different methods are used to control the output values from the inverter, the most important of which is the pulse width modulation (PWM) control method. Since the working principle of this method is based on the fixed amplitude, the duty cycles differ by adjusting the time period. A carrier wave is used, which may be a triangle wave and a fundamental wave which is the reference wave, which can be sinusoidal or square **[24]**. Hence, in a PWM scheme the design deals with two frequencies; the high carrier frequency and the low modulating wave frequency. These two signals are compared. The principle of comparison is adopted in the construction of the output wave. One of the most important advantages of this method is that without the use of additional components, the output voltage can be controlled, and the order of harmonics is higher which can be easily filtered by using high pass filters and high amplitudes of harmonic voltages **[23,24]**. On the other hand, there are drawbacks to this method, including the high cost. The PWM method has several techniques, including; Single-pulse modulation, Multiple pulse modulation, and Sinusoidal pulse width modulation carrier based Pulse Width Modulation Technique. A PWM scheme can either produce a bipolar or unipolar output. These techniques are explained below.

2.3.3.1 Bipolar Pulse Width Modulation in Inverters

In this type, the output voltage alternates between $+V_{DC}$ and $-V_{DC}$, hence the name bipolar. Implementation of this type is based on comparing a saw tooth with a sine wave. The switching alternates between an upper and a

lower switch producing $+V_{DC}$ and $-V_{DC}$ respectively. The waveforms for bipolar PWM are show in figure (2.15) for single phase inverters and in figure (2.16), for three phase **[25]**. It is worth mentioning here that for three phase, a PWM scheme is used for each leg (phase), where the carrier is the same but the low frequency modulating wave is phase shifted by 120^{o}.

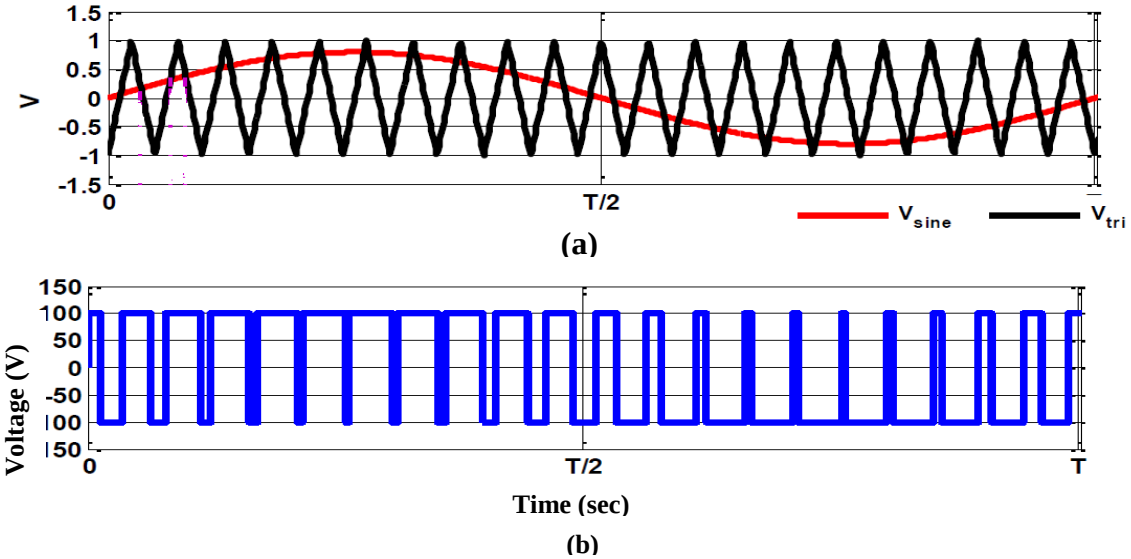


Figure (2.15) (a) Input waves and (b) Output waves for bipolar pulse with modulation in single phase inverters [20].

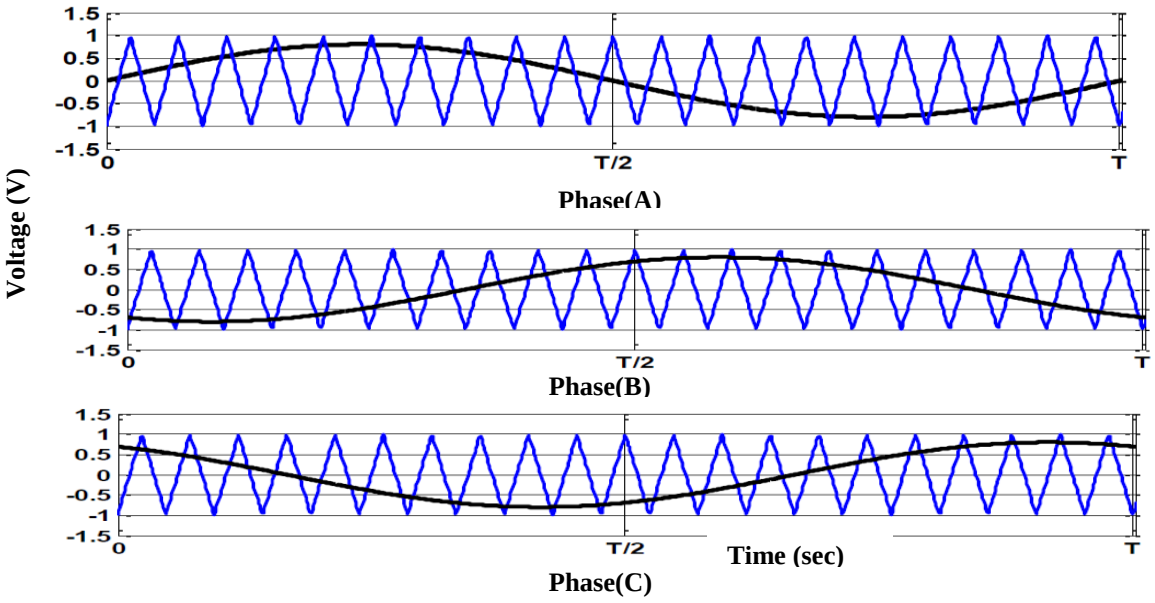
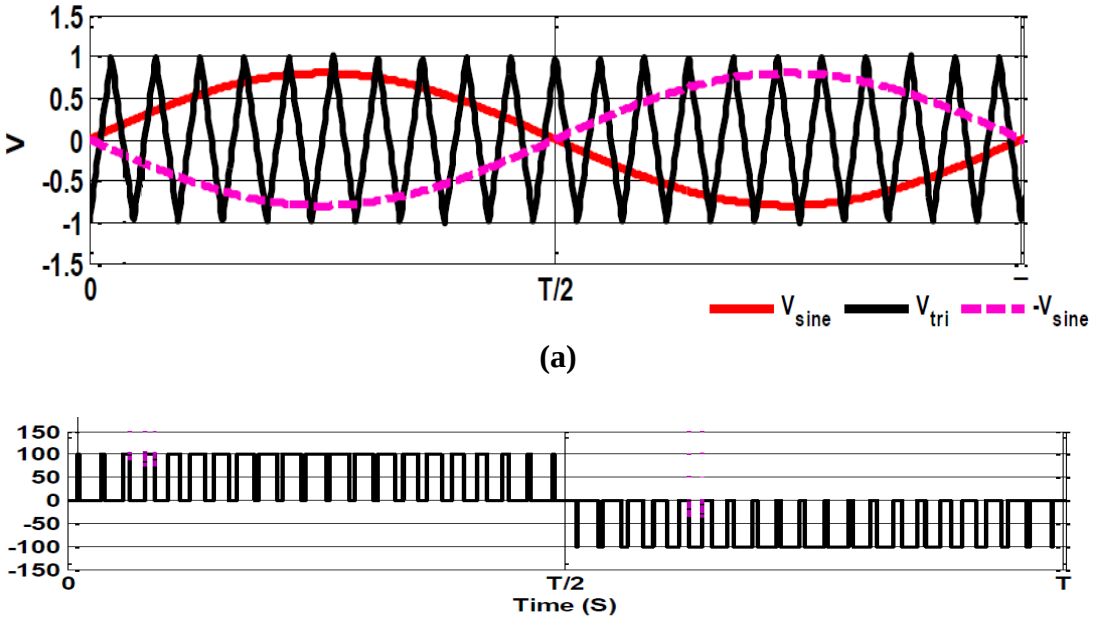


Figure (2.16) Input waves for bipolar PWM in three phase inverter [20].

2.3.3.2 Unipolar Pulse Width Modulation in Inverters

In this scheme, the output voltage from the converter alternates between $+V_{DC}$ and 0 or 0 and $-V_{DC}$. This scheme is generated by inter seeing the carrier with a low frequency sine wave and its complement. Figure (2.17) shows the unipolar switching and output for a single phase inverter. This scheme has less harmonic effect than the bipolar PWM scheme**[24,25]**.



(a)

(b)

Figure (2.17) (a) Input waves and (b) Output waves for unipolar pulse with modulation inverters [20].

2.4 MATLAB / SIMULINK of 24-Pulse Rectifier

At the beginning of the simulation, the work was done to connect the rectifier circuit which is a three-phase rectifier consisting of four bridges connected in series. A rectifier of the uncontrolled type was used, i.e. a diode is used in the construction of the circuit. Here the phase shift is 15 degrees, and therefore it cannot be achieved using ordinary transformers, so the use of winding transformers is reconstructed to obtain the required phase shift. Using a transformer with four secondary windings, the first winding is a star, the third is a delta, and the second and fourth windings are wound to achieve a phase shift of 15^o and 45^o. The work of the circuit components will be explained in detail as follows :

2.4.1 Circuit of Twenty Four Pulse Rectifier

The rectifier circuit is fed from a three-phase sinusoidal AC voltage source. Voltage is introduced into the transformer winding such that the required phase shift of 15° between one rectifier and another is obtained. Each bridge rectifier circuit works on the same principle. The rectifier converts the voltage from AC to DC Of course, the output voltage and current of the rectifier will not be perfectly continuous, but will rather contains harmonics of high order. To study the harmonic content of the rectifier output voltage. The Fourier analyses is used as shown below, in general by the Fourier series**[19,24]**;

$$F(t) = a_o + \sum_{n=1}^{\infty} a_n \cos n\,\omega t + \sum_{n=1}^{\infty} b_n \sin n\,\omega t \qquad (2.9)$$

Where: $\omega = 2\,\pi f$

For an electrical waveform the Fourier series is defined as;

$$v_d(t) = V_{dc} + \sum_{n=2,4,6\ldots,24}^{\infty} V_n(\,cos\, n\, 2\pi f_o t + \theta_n) \tag{2.10}$$

$$v_S(\omega t) = v_m sin(\omega t) \tag{2.11}$$

$$V_{dc} = \frac{1}{T}\int_0^T v_s(\omega t).\, d\omega t \;=\; \frac{1}{T}\int_0^T v_m sin(\omega t).\, d\omega t \tag{2.12}$$

In general for a converter that produces p pulse in the output $V_{dc}$is **[19]**:

$$V_{dc} = \frac{1}{\frac{2\pi}{p}} \int_{-\frac{\pi}{p}}^{+\frac{\pi}{p}} v_m\, cos(\omega t)\,.\, d\omega t$$

$$V_{dc} = \frac{p}{2\pi} v_m\, [sin\left(\frac{\pi}{p}\right) - sin(-\frac{\pi}{p})] = \frac{p}{2\pi} v_m\;\, [2sin(\frac{\pi}{p})]$$

$$V_{dc} = \frac{p}{\pi} v_m\;\, [sin(\frac{\pi}{p})] \tag{2.13}$$

Where,

$v_d(t)$ is the time function output from the rectifier.

V_{dc} is the DC content in $v_d(t)$.

V_n is the amplitude of the nth harmonic content in $v_d(t)$

V_m is the maximum value of the voltage at the fundamental frequency.

p is the number of pules in the output of the rectifier.

θ_n is the phase shift angle of the n^{th}order harmonic voltage.

As an example , for a three phase , half wave rectifier with $p = 3$,

$$V_{dc} = \frac{3}{\pi} v_m \sin\frac{\pi}{3} = \frac{3\sqrt{3}}{2\pi} v_m \frac{\pi}{3} \tag{2.14}$$

The line to line voltage at the inputs, for uncontrolled three phase full-wave 24 pulse rectifier equal,

$$v_{ab}(\omega t) = \sqrt{3}\, v_m \sin(\omega t + \frac{\pi}{6}) \tag{2.15}$$

$$v_{bc}(\omega t) = \sqrt{3}\, v_m \sin(\omega t - \frac{\pi}{2}) \tag{2.16}$$

$$v_{ca}(\omega t) = \sqrt{3}\, v_m \sin(\omega t - \frac{7\pi}{6}) \tag{2.17}$$

The v_{dc} for three phase-24 pulses rectifier the is ,

$$v_{dc} = \frac{1}{2\pi/24} \int_{\frac{\pi}{6}}^{\frac{\pi}{4}} v_{ab}(\omega t).\, d\omega t$$

$$v_{dc} = \frac{1}{2\pi/24} \int_{\frac{\pi}{6}}^{\frac{\pi}{4}} \sqrt{3} v_m \sin(\omega t + \frac{\pi}{6}).\, d\omega t$$

$$v_{dc} = \frac{1}{12/\pi}\int_{\frac{\pi}{6}}^{\frac{\pi}{4}} \sqrt{3}v_m(sin\omega t cos\frac{\pi}{6} - cos\omega t sin\frac{\pi}{6}).d\omega t$$

$$v_{dc} = \frac{1}{12/\pi}\sqrt{3}v_m[-cos\left(\frac{\pi}{4}\right) + cos\left(\frac{\pi}{6}\right)\frac{\sqrt{3}}{2} + sin\left(\frac{\pi}{4}\right) - sin\left(\frac{\pi}{6}\right)\frac{1}{2}]$$

$$V_{dc} = \frac{12\sqrt{3}v_m}{\pi} \quad (2.18)$$

$$v_{rms=}\sqrt{\frac{1}{2\pi/24}\int_{\frac{\pi}{6}}^{\frac{\pi}{4}} \sqrt{3}\,(v_m sin(\omega t + \frac{\pi}{6}))^2.d\omega t} = \frac{v_m}{\sqrt{2}} \quad (2.19)$$

The average current**[1]**:

$$I_{dc} = \frac{12\sqrt{3}v_m}{\pi R} \quad (2.20)$$

The $r.m.s$ current**[1]**,

$$I_{rms=}\sqrt{\frac{1}{\pi}\int_{\frac{\pi}{6}}^{\frac{\pi}{4}} {I_{dc}}^2.d\omega t} = \frac{I_{dc}}{\sqrt{24}} \quad (2.21)$$

Power factor for 24 pulse 3-phase rectifier**[19]**,

$$p.f = \frac{v_{dc}\ I_{dc}}{v_{rms} I_{rms}} \tag{2.22}$$

To find the Fourier coefficient for this rectifier p pulse is evaluated as follows**[19]**,

$$a_o = V_{dc} = \frac{p}{\pi} v_m\ [sin(\frac{\pi}{p})] \tag{2.23}$$

As for a_n and b_n , the general equation for a P pulse output rectifier is expressed as,

$$a_n = \frac{2}{2\pi/p} \int_{-\frac{p}{2}}^{\frac{p}{2}} v(\omega t)\, cos(\omega t)\, .\, d\omega t$$

$$a_n = \frac{v_m p}{\pi(n^2 - 1)} [-sin\left(\frac{\pi}{p}\right) cos\ (n\left(\frac{\pi}{p}\right) - sin\left(\frac{\pi}{p}\right) cos\ (n\left(\frac{\pi}{p}\right)]$$

$$a_n = -\frac{p}{\pi} v_m sin\left(\frac{\pi}{p}\right) \frac{2\, cos(\frac{\pi n}{p})}{(n^2 - 1)} \tag{2.24}$$

The b_n coefficients are evaluated as,

$$b_n = \frac{2}{2\pi/p} \int_{-\frac{p}{2}}^{\frac{p}{2}} v(\omega t)\, sin(\omega t)\, .\, d\omega t = 0 \tag{2.25}$$

The amplitude V_n of the n^{th} order harmonic is,

$$V_n = \sqrt{an^2 + bn^2} = \sqrt{an^2 + 0} = a_n \tag{2.26}$$

The phase angle θ_n of the n^{th} order harmonic is,

$$\theta_n = tan^{-1}\frac{a_n}{b_n} = tan^{-1}\frac{a_n}{0} = \infty \quad , \therefore \theta_n = 90^o \tag{2.27}$$

2.4.2 Zigzag Transformer

A zigzag transformer is an auxiliary transformer that is very similar to the main transformer, except that its voltage and power are less, so its size is smaller. And this depends on the amount of phase shift required. These transformers consist of one coil connected by the interconnected star method, or what is called zigzag. Here, one phase is divided into two parts, a section that overlaps with the neighboring phase. In this work the zigzag transformer is used for the purpose of providing the respective phase shift of 15 degrees for the rectifiers. For the zigzag transformer, the voltage at each secondary is defined as,

$V_{a1} = V\angle 30^o, V_{a2} = V\angle 20^o, V_{a3} = V\angle 40^o$

$V_{b1} = V\angle -90^o, V_{b2} = V\angle -100^o, V_{b3} = V\angle -80^o$

$V_{c1} = V\llcorner -210^o, \ V_{c2} = V\llcorner -220^o, \quad V_{c3} = V\llcorner -200^o$

And finally , the 4^{th} output ,is:

$V_{a4} = V\llcorner 60^o, V_{b4} = V\llcorner -60^o, V_{c4} = V\llcorner -180^o$

Here, one of the merits of a zigzag transformer ,the power rating is a function of the required phase shift **[26]**.The relationship between the apparent power required for the zigzag transformer and phase shift is given by**[26]**,

$$S_{zigzag} = 0.025\, S_{load} a_{max} \tag{2.28}$$

Here, S_{load} is the load apparent power and a_{max} is the required phase shift between the respective rectifiers. It is worth mentioning that the relationship in (2.28) holds for phase shift angles below 20^{o}**[26]**.

2.4.3 DC Link Capacitor

Often in the processes of converting energy from one form to another, or conditioning energy of the same form but at a different frequency, is accompanied by energy loss and distortion. The use of DC link capacitor has been employed as a means of addressing these problems to mitigate or reduce their effects**[27]** . In this work, a small value of capacitor is used, since the output voltage contains ripples that oscillate at high frequencies. In addition to the capacitor, a small resistance is added in series to compensate for the dielectric losses.

2.4.4 The DC/AC Converter

The main national grid has its output alternating, so most electrical devices are designed to operate on alternating voltage. Sometimes power is generated from DC sources such as photovoltaics and fuel cells. Hence when integrating such sources, a DC/AC converter is required to condition the power at the grid frequency. Inverters are commonly controlled by the PWM technique which provides an output voltage with very high frequency oscillations which make the filtering process trivial. In this work Fourier analysis is employed to study the harmonic content of the inverter. The phase voltages are expressed as,

$$V_{orms(an)} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} v^2 dt} = \sqrt{(\frac{4}{2\pi}\int_0^{\frac{\pi}{3}}(\frac{1}{3}V_{DC})^2 dt + \frac{2}{2\pi}\int_{\frac{\pi}{3}}^{\frac{2\pi}{3}}(\frac{2}{3}V_{DC})^2 dt} = \frac{\sqrt{2}}{3}V_{DC} \quad (2.29)$$

$$V_{orms(L-L)}\ \frac{\sqrt{3}\sqrt{2}}{3}V_{DC} = \sqrt{\frac{2}{3}}V_{DC} \quad (2.30)$$

The amplitude of the n^{th} harmonic phase of the inverter voltage is given,

$$V_{n(xn)} = \sum_{n=1,5,7,9,\ldots}^{\infty} \frac{4V_{DC}}{\sqrt{3}n\pi} sin\left(\frac{n\pi}{2}\right) sin\left(\frac{n\pi}{3}\right) \quad (2.31)$$

Where: x is a, b, or c.

The phase (a) instantaneous expression is obtained by**[19]**,

$$V_{an(\omega t)} = V_{n(an)}\, sin[n(\omega t + \theta_n) - \frac{\pi}{6}]$$

Since at $n = 1$, the fundamental frequency is of positive sequence orientation, then θ_n must be equal to $\pi/6$ so that phase a remains the reference phase. Hence, the negative sign is taken for all positive sequence harmonics and positive sign is reserved for negative sequence harmonics**[19]**.The phase a voltage is expressed as **[19]**,

$$V_{an}(\omega t) = \sum_{n=1,5,7,9,\ldots}^{\infty} \frac{4V_{DC}}{\sqrt{3}n\pi} sin\left(\frac{n\pi}{2}\right) sin\left(\frac{n\pi}{3}\right) sin[n\left(\omega t + \frac{\pi}{6}\right) \pm \frac{\pi}{6}] \quad (2.32)$$

In a similar way, phase b and c are considered. Therefore, the expressions for $v_{bn}(\omega t)$ and $v_{cn}(\omega t)$ are **[1]**,

$$V_{bn}(\omega t) = \sum_{n=1,5,7,9,\dots}^{\infty} \frac{4V_{DC}}{\sqrt{3}n\pi} sin\left(\frac{n\pi}{2}\right) sin\left(\frac{n\pi}{3}\right) sin[n\left(\omega t - \frac{\pi}{2}\right) \pm \frac{\pi}{6}] \qquad (2.33)$$

$$V_{cn}(\omega t) = \sum_{n=1,5,7,9,\dots}^{\infty} \frac{4V_{DC}}{\sqrt{3}n\pi} sin\left(\frac{n\pi}{2}\right) sin\left(\frac{n\pi}{3}\right) sin[n\left(\omega t - \frac{7\pi}{6}\right) \pm \frac{\pi}{6}] \qquad (2.34)$$

As for line- line expressions, the amplitude can be found by simply multiplying eq.(2.31) by $\sqrt{3}$. Hence,

$$V_{ab}(\omega t) = \sum_{n=1,5,7,9,\dots}^{\infty} \frac{4V_{DC}}{n\pi} sin\left(\frac{n\pi}{2}\right) sin\left(\frac{n\pi}{3}\right) sin[n\left(\omega t + \frac{\pi}{6}\right) \pm \frac{\pi}{6}] \qquad (2.35)$$

$$V_{bc}(\omega t) = \sum_{n=1,5,7,9,\dots}^{\infty} \frac{4V_{DC}}{n\pi} sin\left(\frac{n\pi}{2}\right) sin\left(\frac{n\pi}{3}\right) sin[n\left(\omega t - \frac{\pi}{2}\right) \pm \frac{\pi}{6}] \qquad (2.36)$$

$$V_{ca}(\omega t) = \sum_{n=1,5,7,9,\dots}^{\infty} \frac{4V_{DC}}{n\pi} sin\left(\frac{n\pi}{2}\right) sin\left(\frac{n\pi}{3}\right) sin[n\left(\omega t - \frac{7\pi}{6}\right) \pm \frac{\pi}{6}] \qquad (2.37)$$

Chapter Three: Simulation of a Power Processing Unit with Multi-Phase Rectifier

3.1 Introduction

In this chapter, the main objective is to simulate the power processing unit with a multiphase rectifier at the inputs. Here, a rectifier with 24 pulse output is used. The power processing unit is simulated under different load conditions. The simulation is carried out using the Simulink platform.

3.2 Simulations of a Power Processing Unit with Multi-Phase Rectifier

In this section, the power unit is simulated with the two converters. One of the converters, which is operated as a AC/DC rectifier, is implemented using the 24 pulse output multiphase circuit. The objective is to analyzes the performance of the unit in terms of the quality of output voltage and current. Also, the quality of the input current at the utility AC source is also investigated. Then the 24 pulse rectifier is connected with a three-phase inverter circuit to converted DC/AC voltage. Where, the performance at the inverter output terminals is also analyzed. Simulations are run for 30 cycles to observe the results. Parameters that are used in the simulations are shown in **table (3.1)**.

Table (3.1) Parameters of The Simulations Employed for Two Converters

Description	Value
Peak AC input voltage, V_m	1000 V
Nominal frequency, f_0	50 Hz
Amplitude modulation index, m_a	0.8
Frequency modulation index, m_f	20
Maximum allowable load current, I_p	150 A
Load phase shift angle, θ_1	45^o
DC link capacitor, CL	0.0001 µF
Mean output of rectifier voltage	1322 V

3.2.1 Simulation of 24 Pulse Rectifier Circuit

The simulations was carried out on a three-phase rectifier with 24 pulse output using a zigzag transformer in order to provide a phase difference of 15^o, 30^o, 45^o , and 60^o, under different loading conditions. Figure (3.1) shows the built simulation circuit of a 24 pulse rectifier .

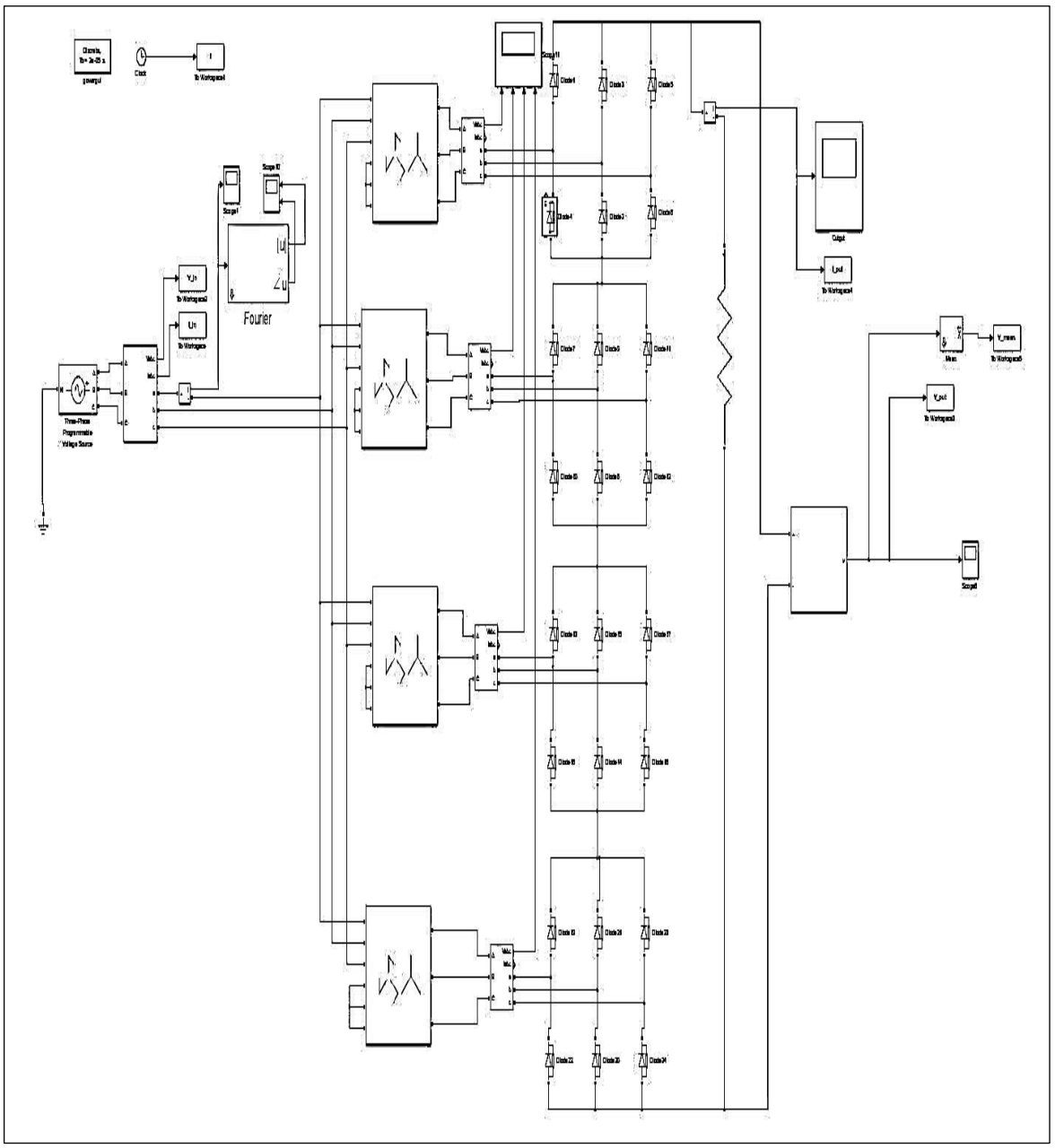


Figure (3.1) Simulation circuit of a 24 pulse rectifier with R load.

Case (1): Simulation of 24 Pulse Rectifier Circuit with Resistance loading

A resistance load of 20 Ω is used, the current and voltage are in the same phase as shown in the figure (3.2).

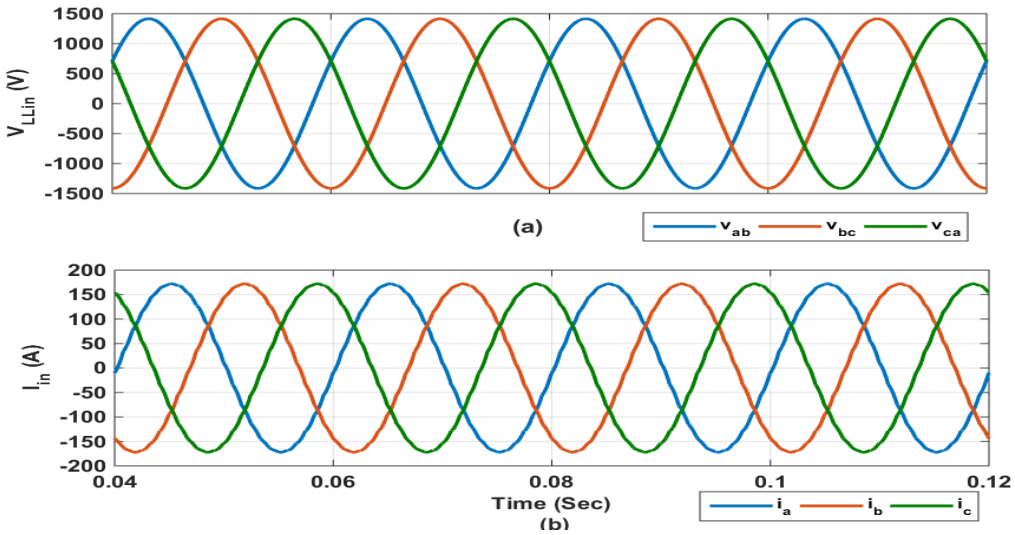


Figure (3.2) (a) Input voltage and (b) Input current, of the 24-pulse multiphase rectifier with R load.

Voltage, mean voltage, and load current waveforms at the output of converters are shown in figure (3.3).

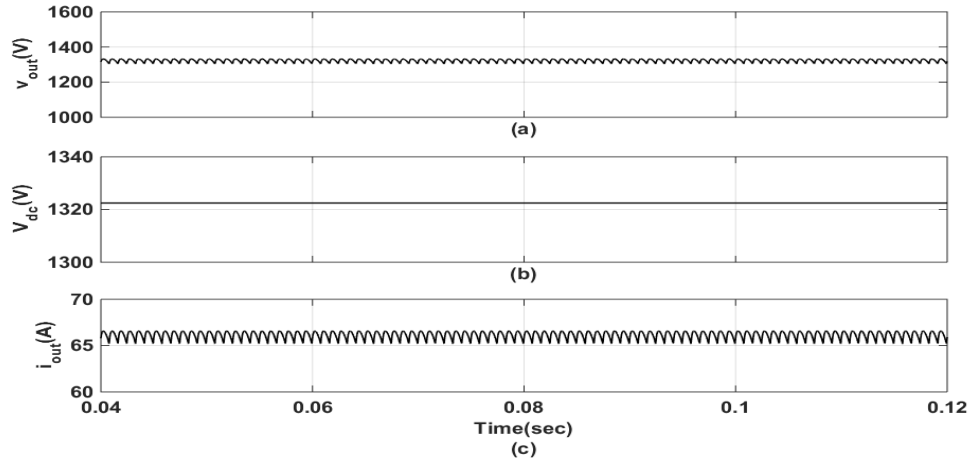


Figure (3.3) (a) Output voltage, (b) Mean voltage, and (c) Load current of the 24-pulse multiphase rectifier with R load.

Case (2) : Simulation of 24 Pulse Rectifier Circuit by using RL load

A resistive load of 20 Ω and an inductance of 60mH were used in this case, the current here lags behind the voltage at the input, as shown in figure(3.4).

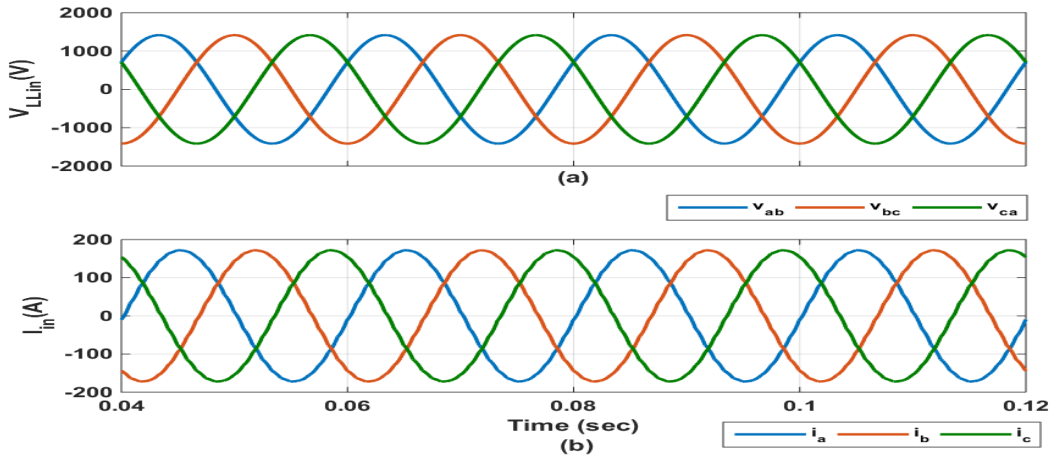


Figure (3.4) (a) Input voltage, and (b) Input current of the 24-pulse multiphase rectifier with RL load.

At the rectifier out, the voltage, mean voltage, and current across the load are shown in figure (3.5) below. It is clear that both loads produces the same mean voltage. Since the inductance at steady state has no effect.

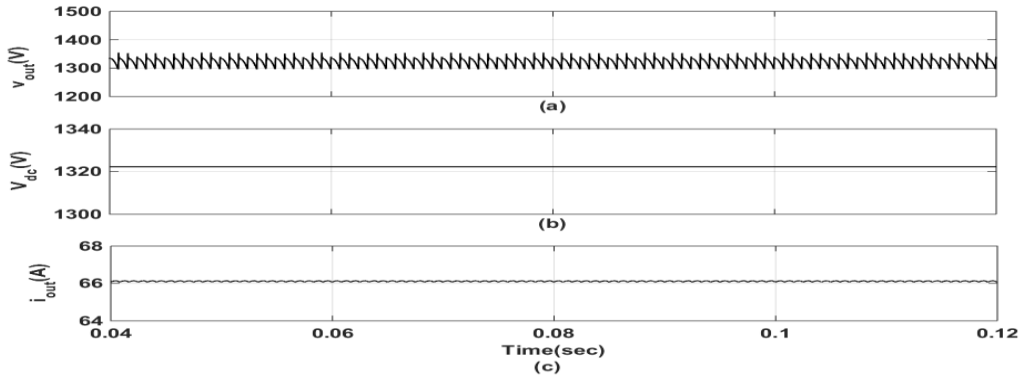


Figure (3.5) (a) Output voltage, (b) Mean voltage and (c) Load current of the 24-pulse multiphase rectifier with RL load.

Case (3): Simulation of 24 Pulse Rectifier Circuit by using RC Load

In the case of a capacitive load, the current will be a lead of the voltage by an angle. A capacitive load with a capacity of 10 µF and resistance of 20 Ω were connected and simulated. Input/output voltage and current are shown in figure (3.6) and figure (3.7) respectively.

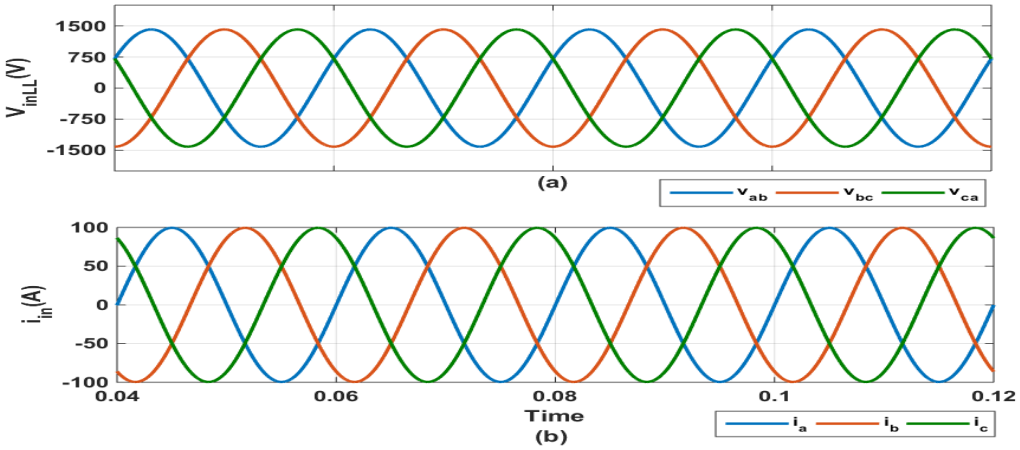


Figure (3.6) (a) Input voltage and (b) Input current for a 24-pulse multiphase rectifier with RC load

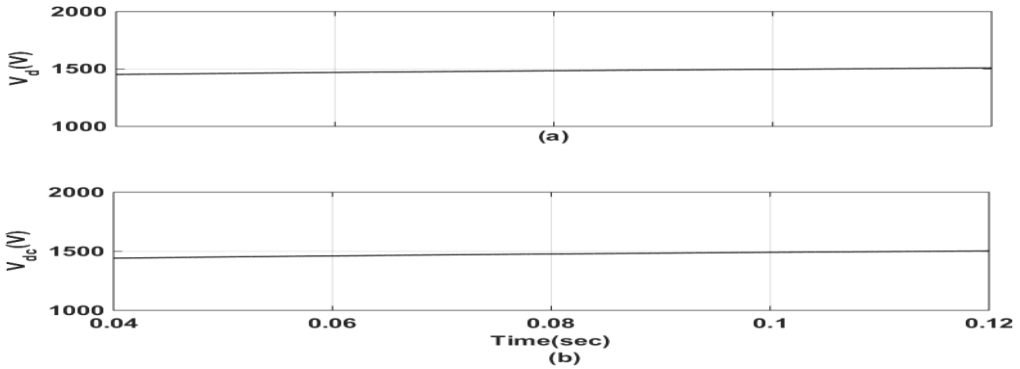


Figure (3.7) (a) Output voltage and (b) Mean voltage for a 24-pulse multiphase rectifier with RC load.

Inspection of the output voltage shows no ripple content since the load capacitance acts as a ripple filter. Also, an increase in the mean voltage is evident.

3.3 Simulation of Power Processing Unit under Various Loads

After the simulation was carried out on the multiphase rectifier circuit (24pulse), the back-to-back connection of the two converters are performed to construct. The power unit is simulated with a PWM controlled inverter. Also, the unit feeds different loads with aim of analyzing its performance. Figure(3.8) shows the simulation circuit of the power processing unit, which is built in the Simulink environment.

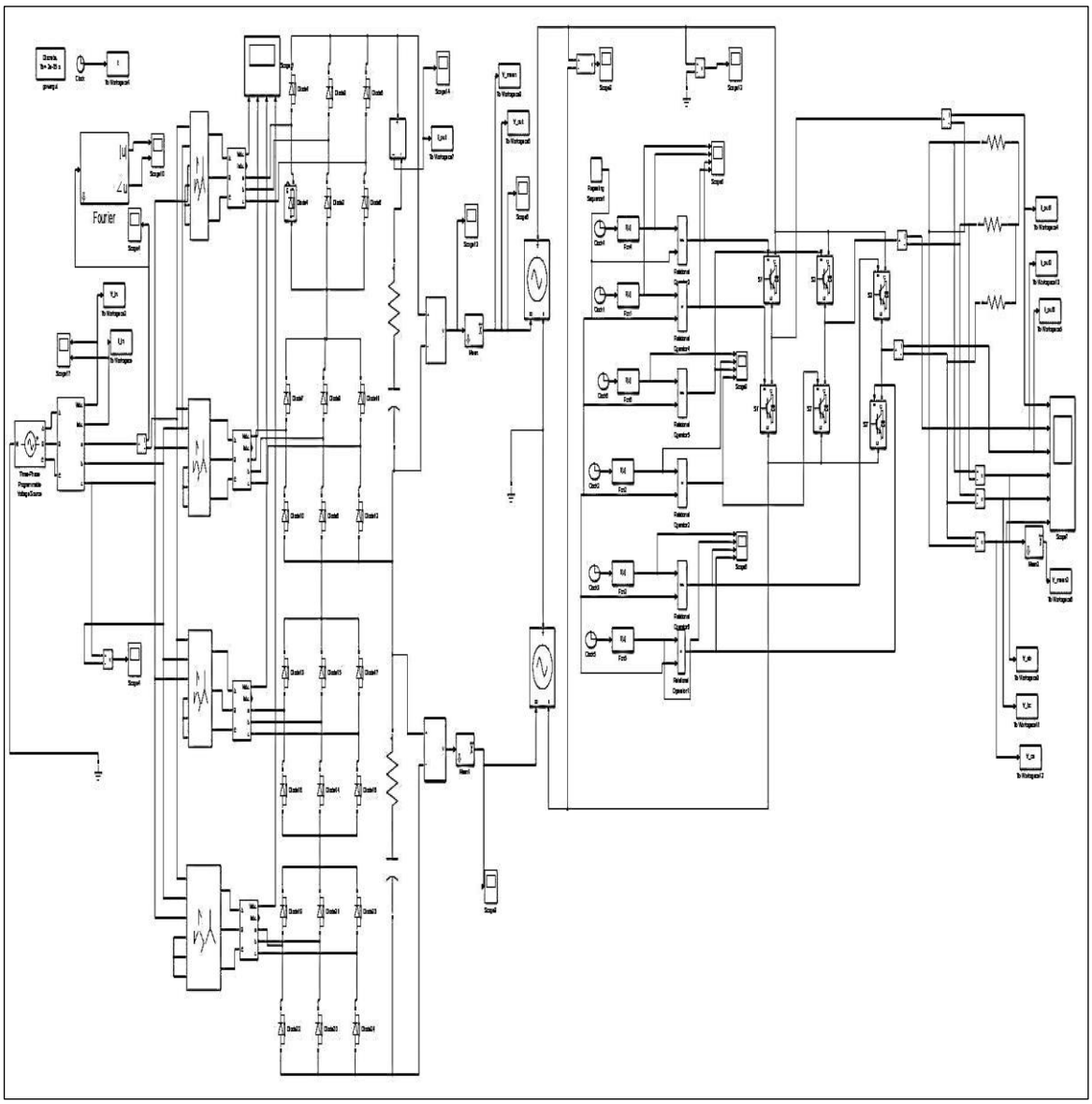


Figure (3.8) Simulation circuit of power processing unit.

Case (1): Simulation of Power Processing Unit by using R load

Initially, the power processing unit is simulated using a resistance load. The voltage and current at the input are shown in the figure(3.9) a and b respectively.

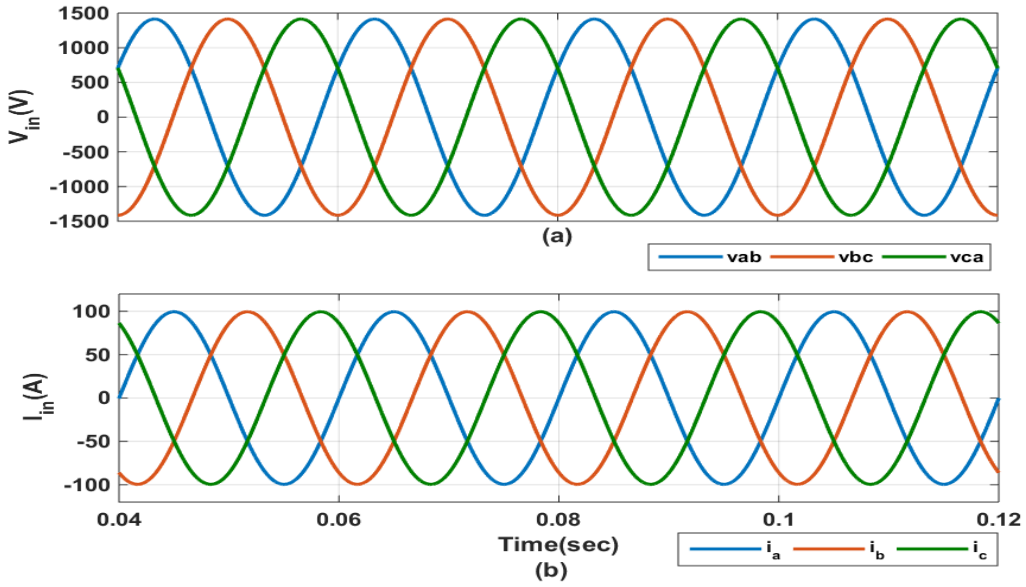


Figure (3.9) (a) Input voltage and (b) Input current of the power processing unit with R load.

Here, our objective is to study and analyze the inverter performance with and without a capacitor at the output of the 24 pulse rectifier. Figure (3.10) a and b depicts the output voltage and it's DC content from the rectifier. It's clear that the inverter obtains an input voltage that very closely match, that of a battery. Moreover, even if the capacitor is removed, the input voltage is still acceptable, however a decrease in the mean is observed as shown in figure (3.11) a and c. Figure (3.11) b shows the input DC current to the inverter, with a tolerated ripple content.

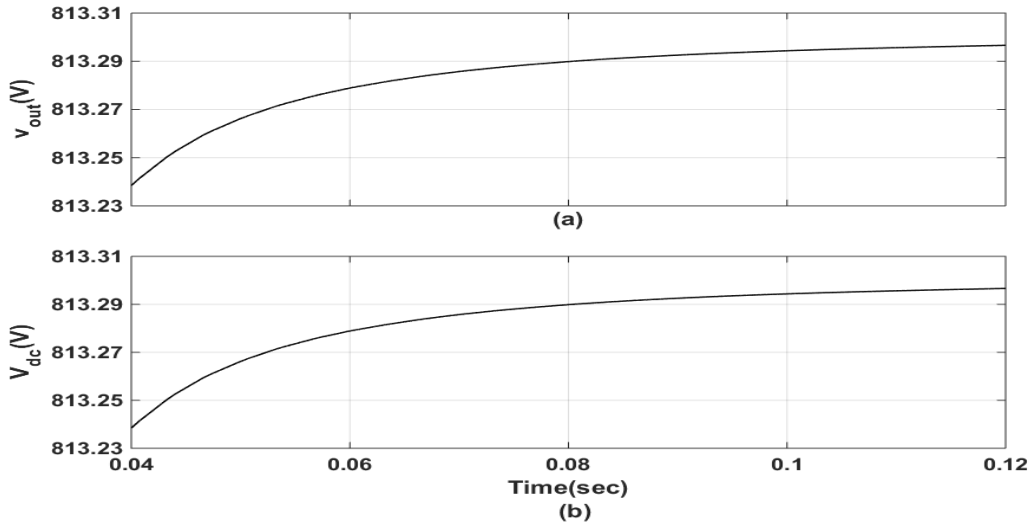


Figure (3.10) (a) Output voltage and (b) Mean voltage of the power processing unit with a capacitor at rectifier I/P .

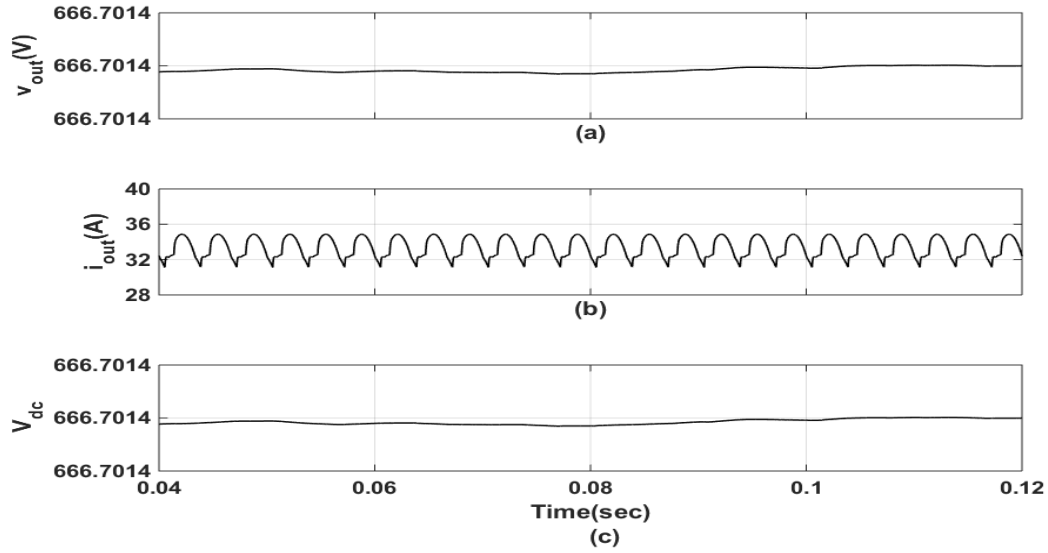


Figure (3.11) (a) Output voltage, (b) Output current and (c) Mean voltage for the power processing unit without a capacitor at rectifier I/P.

The output results of the power unit (at the inverter terminals) are shown in figure (3.12), figure(3.13), and figure (3.14).

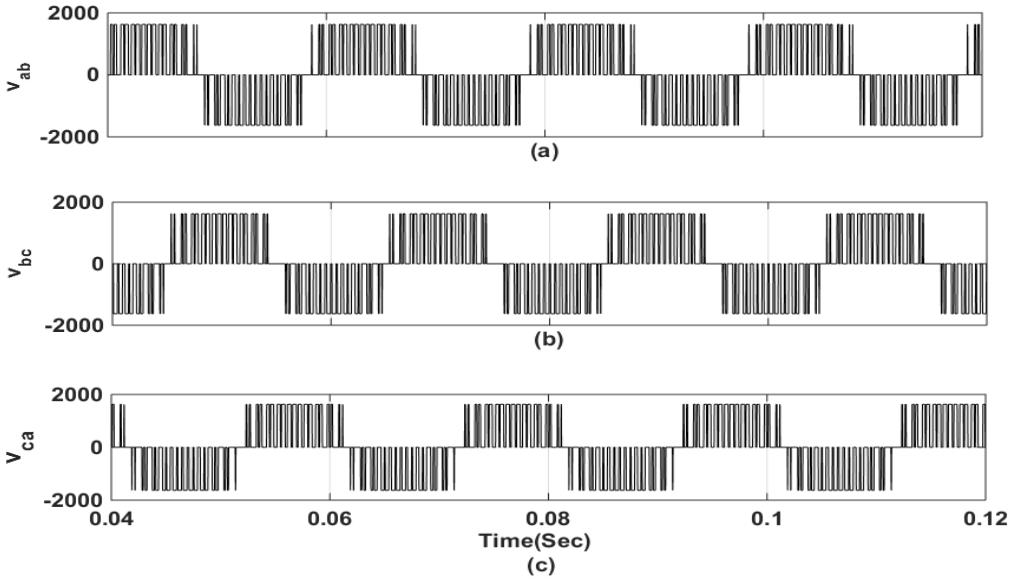


Figure (3.12) (a)L-L voltage ,V_{ab}, (b) L-L voltage, V_{bc}, and (c) L-L voltage , V_{ca} of the inverter output of power unit.

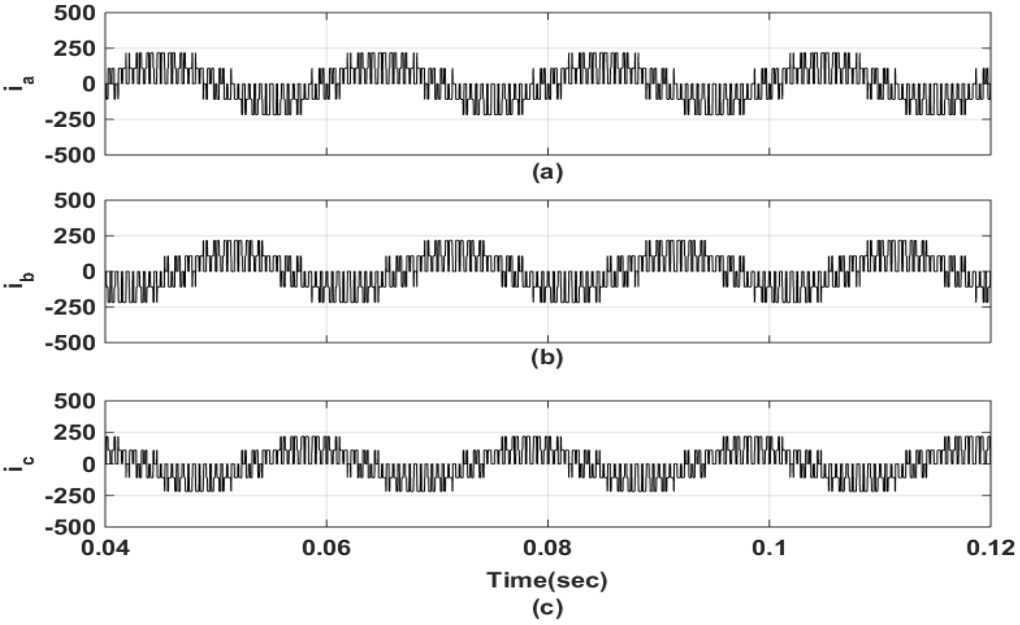


Figure (3.13) (a) i_a ,(b) i_b and (c) i_c output currents of the inverter output terminals with R load.

Figure (3.14) shows the mean voltage content in the output of the inverter. It is clear that the mean voltage settles to zero of steady state.

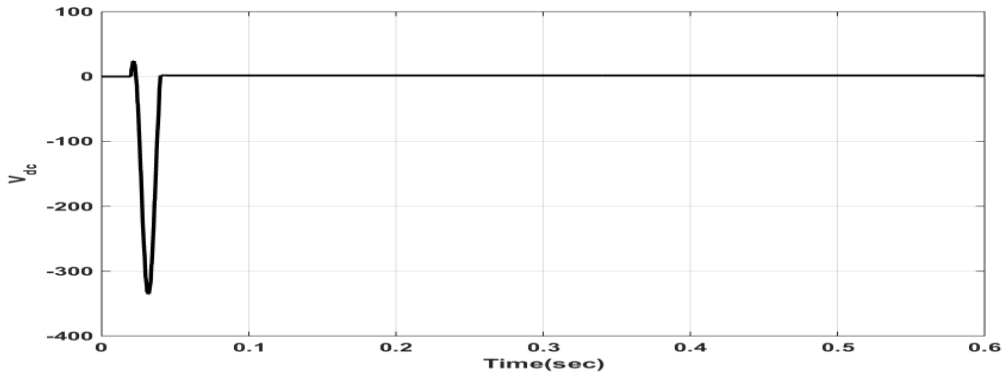


Figure (3.14) Mean voltage in the inverter output voltage with R load.

Case (2): Simulation of Power Processing Unit by using RL load

The simulation was repeated on the same circuit above, but using a resistance with an inductive load. Figure (3.15) shows the shape of the waveforms for input voltages and currents, which satisfies a lagging current condition.

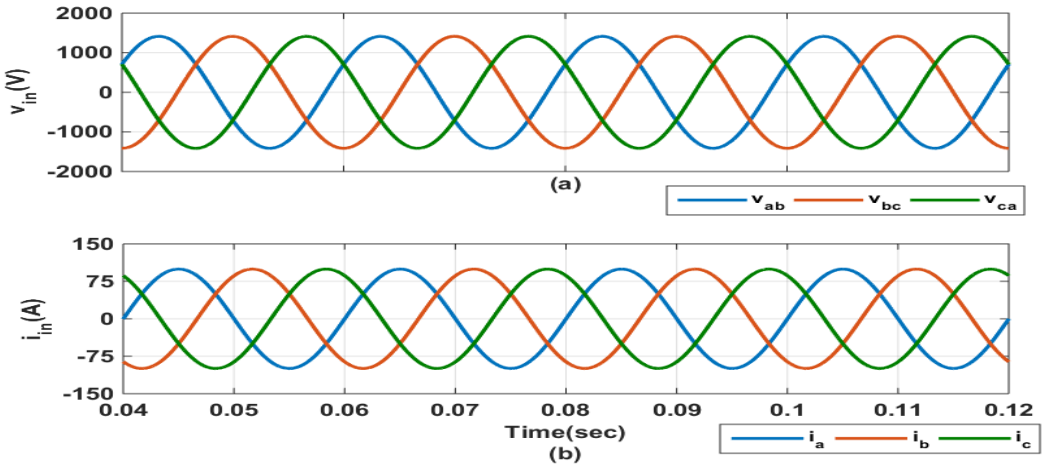


Figure (3.15) (a) Input voltage and (b) Input current of the power processing unit with RL load.

Since the load in this part of the simulation is different from that of section (3.3- case (1), it is observed that the performance of the 24 pulse rectifier is completely independent regardless of the loading condition at the inverter terminals. This is clear from figure (3.16) a and b, where the output and mean

values of voltage are the same as those depicted in figure (3.10) for the pure resistive load. The same conclusion can be extended to the case where no capacitor is present at the output of the rectifier. This is clear from figure(3.17) being identical to that of figure (3.11).

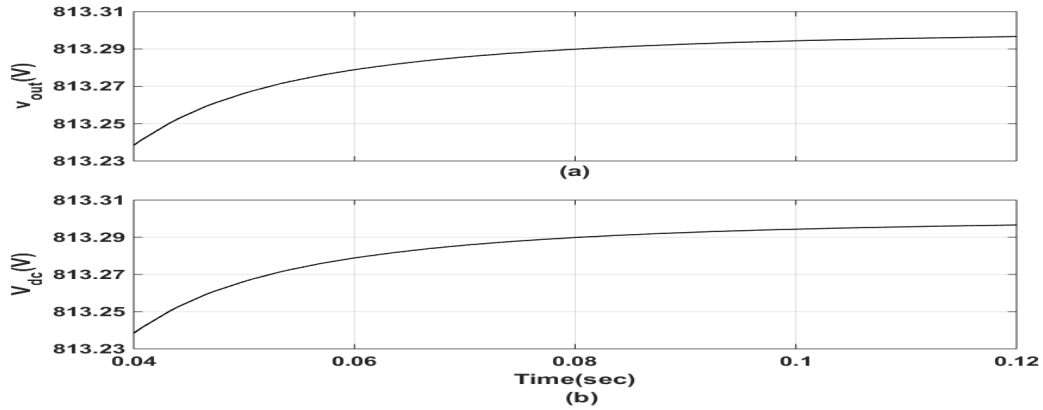


Figure (3.16) (a) Output voltage and (b) Mean voltage at rectifier terminals with C for RL load inverter loading.

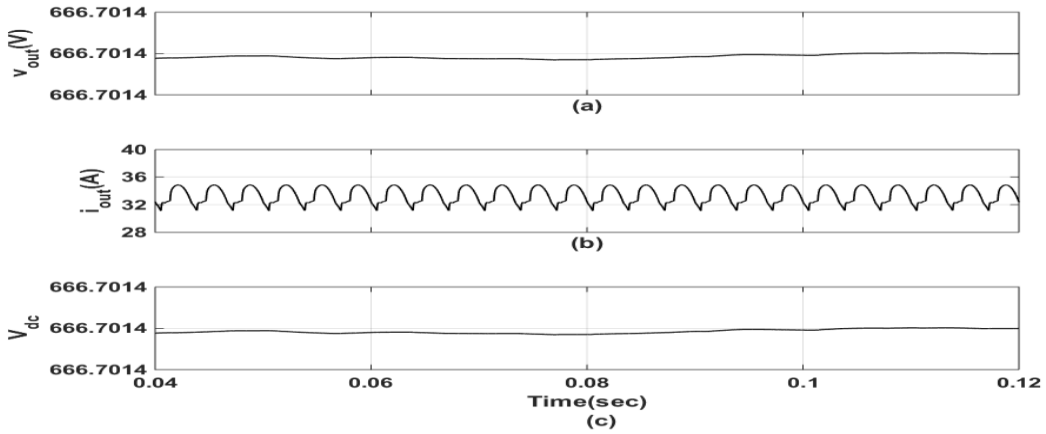


Figure (3.17) (a) Output voltage, (b) Output current and (c)Mean voltage rectifier terminals without C for RL load inverter loading.

For this loading condition, the output line-line voltage , phase currents and mean voltage content are shown in figure (3.18), figure (3.19), and figure(3.20) respectively.

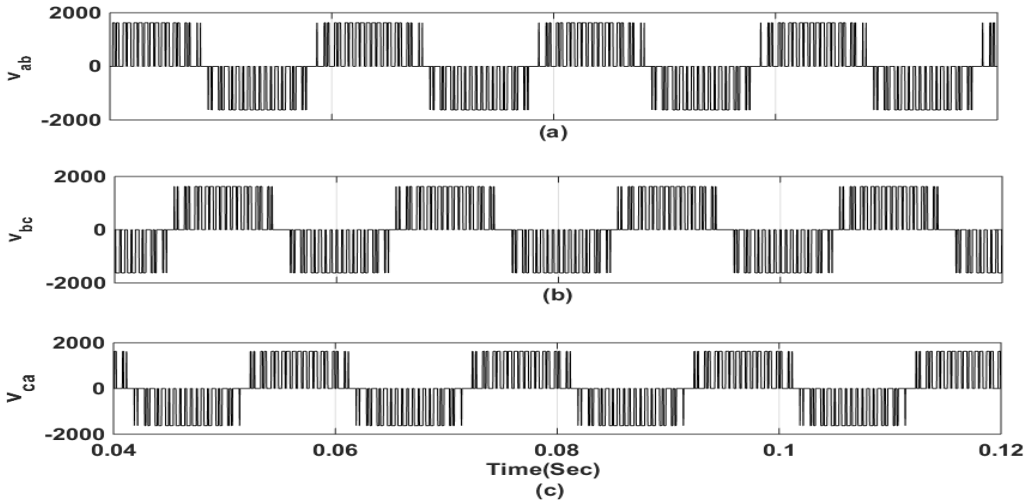


Figure (3.18) (a)L-L voltage ,V_{ab}, (b) L-L voltage , V_{bc}, and (c) L-L voltage , V_{ca} at the inverter with RL loading.

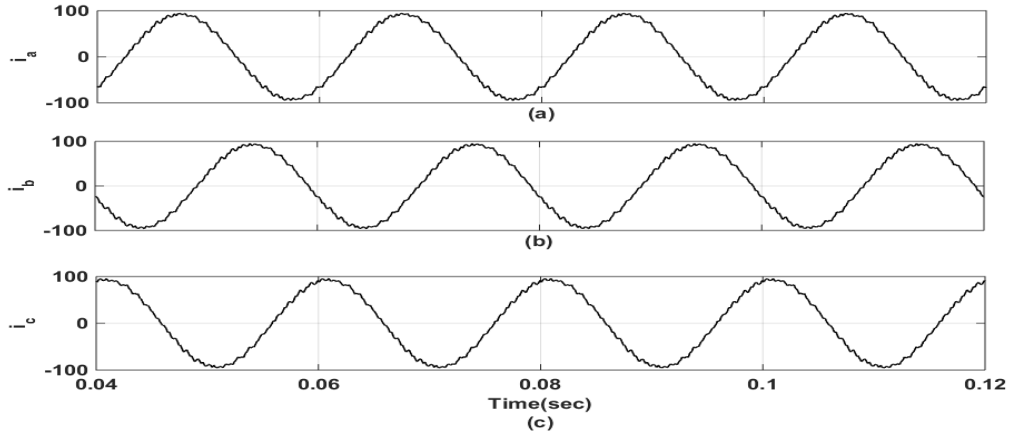


Figure (3.19) (a) i_a , (b) i_b and (c) i_c output currents at the inverter terminals with RL loading.

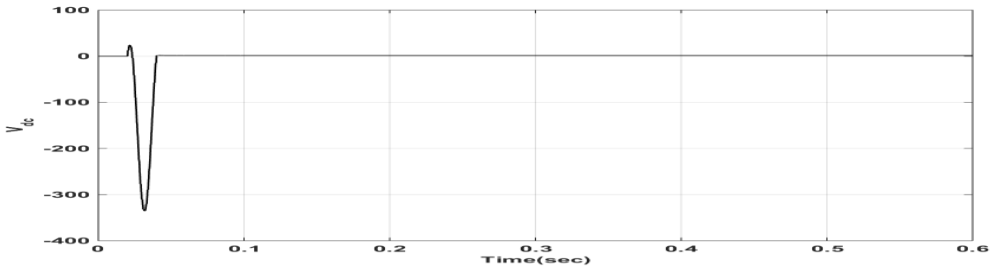


Figure (3.20) Mean voltage content in the output voltage of the inverter.

In this case the output current preserves a sinusoidal shape due to the filter inductance load.

3.4. Simulation of Power Processing Unit under Various Combinations of Transformer Connection

After completing the simulation of variable loads using four zigzag transformers and evaluating the results, the objective now is to analyze the inverter operation with different combinations of transformers at the input of the 24-pulse multiphase rectifier. In that context, this part of the simulation contribute answers to the following questions,

1. Will a change in the pattern of phase shift effect the operation of the DC/AC converter ?
2. Dose a change in phase shift pattern effect the size of transformer ? i.e. the apparent power of the required transformer.

For the sake of simplicity, only an RL load is considered in the simulation of this part.

Case (1): Simulation of Power Processing Unit by Connecting a Star/Star-3Zigzag Transformer

In this part, the transformer at the input of the rectifier has one star/star transformer and three zigzag. The star/star provides a phase of 0^o while the zigzag windings provide 15^o, 30^o, and $^-15^o$. Figure (3.21) shows the input voltage and current for this case. It's clear that the current drops to about 75 A, from about 100 A which was depicted in figure (3.15). On the other hand, the output and mean voltage with and without a capacitor are shown in figure (3.22) and figure (3.23) respectively, which shows no change at all from the previous sections. Analyzing the inverter performance for this condition, it is clear that the performance is identical to that of the previous section as shown in figure (3.24), figure (3.25), and figure (3.26) respectively.

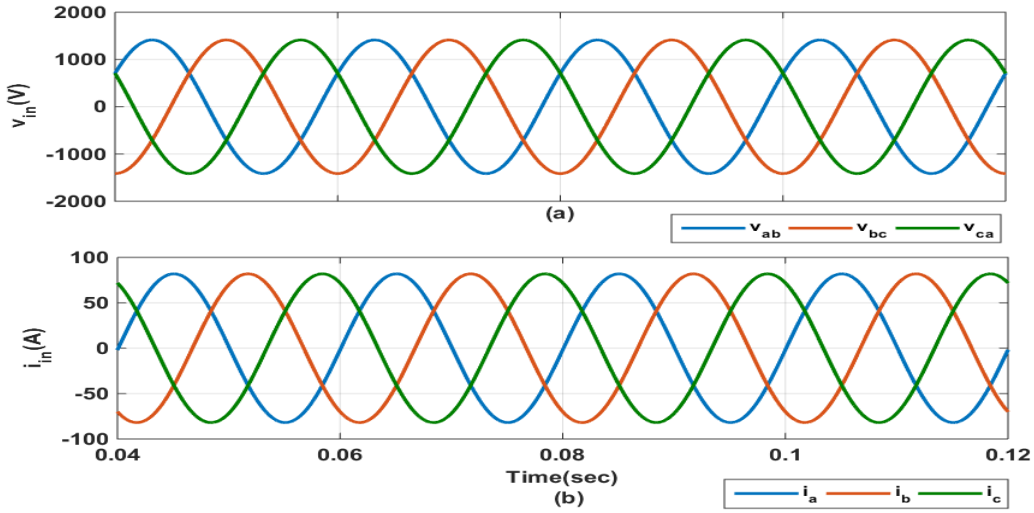


Figure (3.21) (a) Input voltage and (b) Input current for the 24 pulse rectifier with Y/Y and 3 zigzag transformers with RL load.

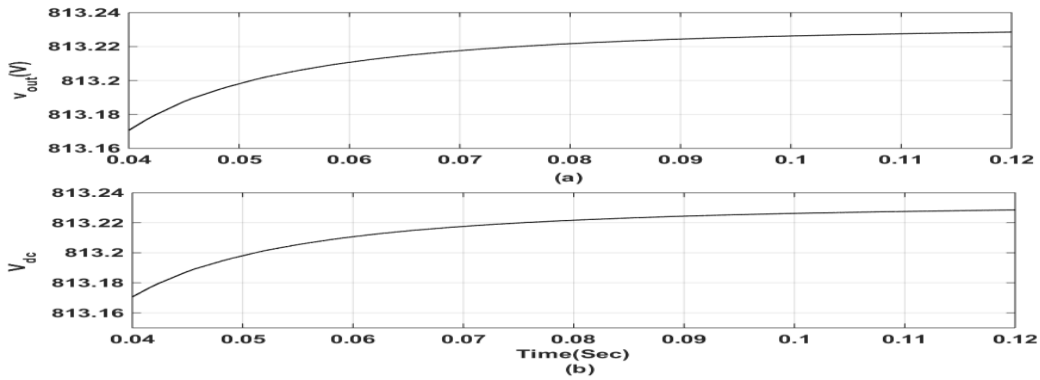


Figure (3.22) (a) Output voltage and (b) Mean voltage at rectifier output with Y/Y and 3zigzag transformer with C, and RL inverter loading.

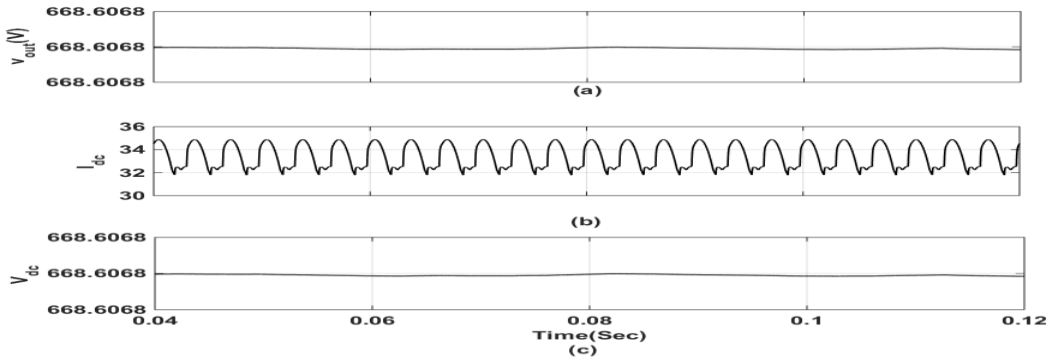


Figure (3.23) (a) Output voltage, (b) Output current and (c) Mean voltage of rectifier with 1Y/Y and 3zigzag transformer without C for RL inverter loading.

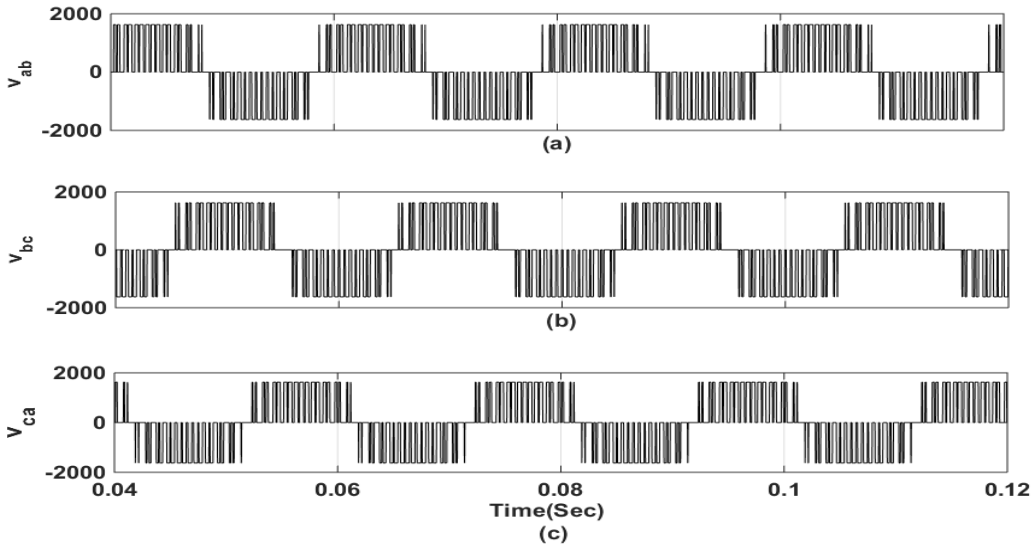


Figure (3.24) (a) L-L voltage ,V_{ab}, (b) L-L voltage , V_{bc} ,and (c) L-L voltage , V_{ca} for 1Y/Y and 3zigzag transformer connection.

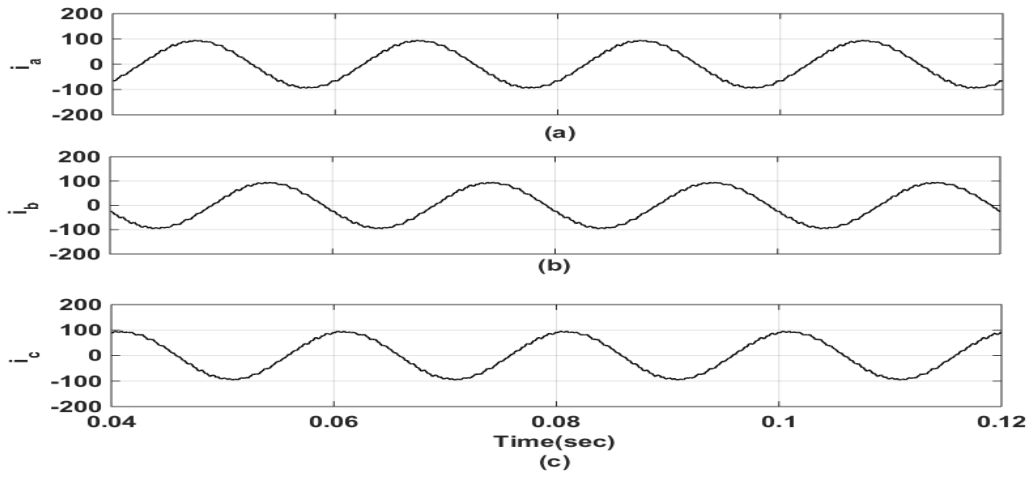


Figure (3.25) (a) i_a , (b) i_b and (c) i_c output current for inverter with 1Y/Y and 3zigzag transformer.

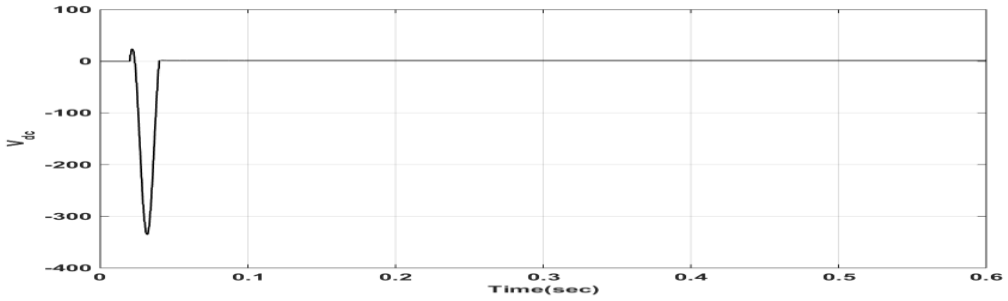


Figure (3.26) Mean voltage for inverter with 1Y/Y and 3zigzag transformer.

Case (2): Simulation of Power Processing Unit by Connecting One Star/Delta and Three Zigzag Transformers

To achieve a phase shift of 15^o, here, one pattern is to connect a zigzag transformer to the circuit to provide a phase shift of 15^o, and to obtain a phase shift of 30^o through a star/delta transformer. The two zigzag transformers are used to provide the phase shift 45^o and 60^o. Figure (3.27) presents the input waves of the voltage and current that were extracted after executing the simulation. With this pattern the phase shift is defined as, 15^o, 30^o, 45^o and 60^o.

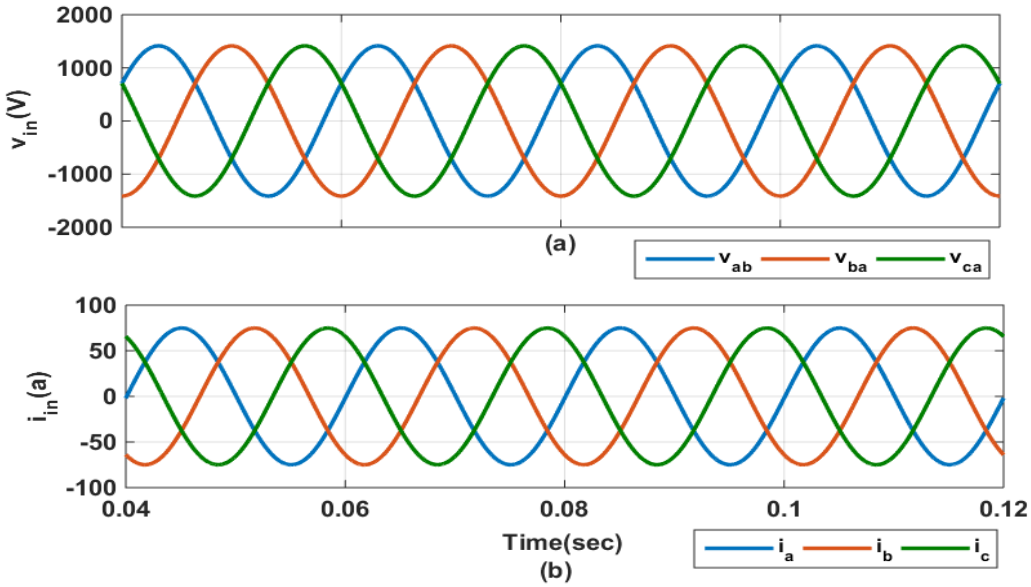


Figure (3.27) (a) Input voltage and (b) Input current for inverter with 1Y/Δ and 3zigzag transformer.

As in the previous case, the input current drops to about 75 A of the peak value. The rectifier with this transformer pattern has the same mean output voltage as with 1 Y/Y and 3zigzag. The outputs of the total circuit are illustrated by the waves shown in figure (3.28), figure (3.29), and figure (3.30).

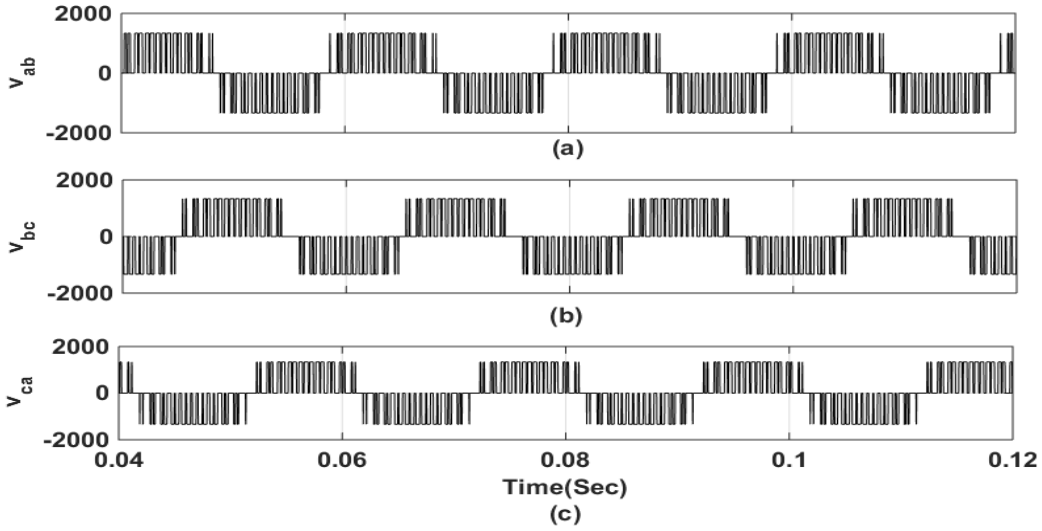


Figure (3.28) (a)L-L voltage ,V_{ab},(b) L-L voltage, V_{bc}, and (c) L-L voltage , V_{ca} at inverter output with $1Y/\Delta$ and 3zigzag transformer.

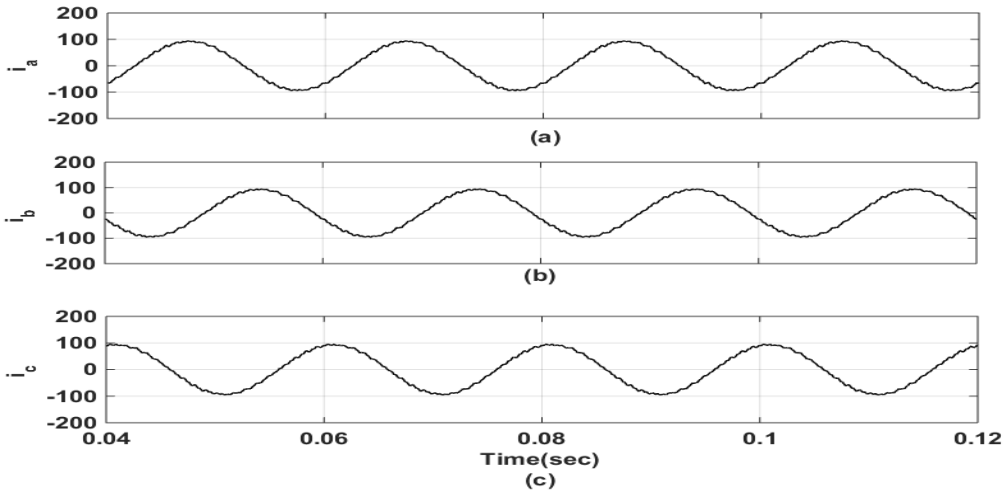


Figure (3.29) (a) i_a , (b) i_b and (c) i_c output currents for inverter with $1Y/\Delta$ and 3zigzag transformer.

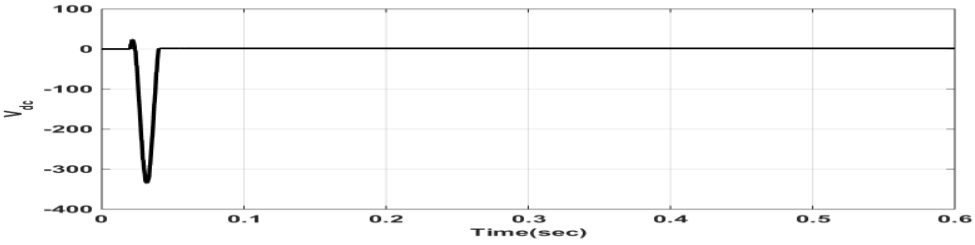


Figure (3.30) Mean voltage content in inverter output with $1Y/\Delta$ and 3zigzag transformers at rectifier input.

Case (3): Simulation of Power Processing Unit by Connecting Star/Star, Star/Delta, and Two Zigzag Transformers

Two zigzag transformers were used to provide us with a phase shift of 15^o and $^-15^o$, while the phase shift of 30^o was used as a star/delta transformer, while the phase shift of 0^o was achieved by the star/star transformer. Thus, the phase difference required to operate the rectifier is 0^o,15^o, 30^o, and $^-15^o$. Results for this case are shown in the figure (3.31), figure (3.32), figure (3.33), figure(3.34).

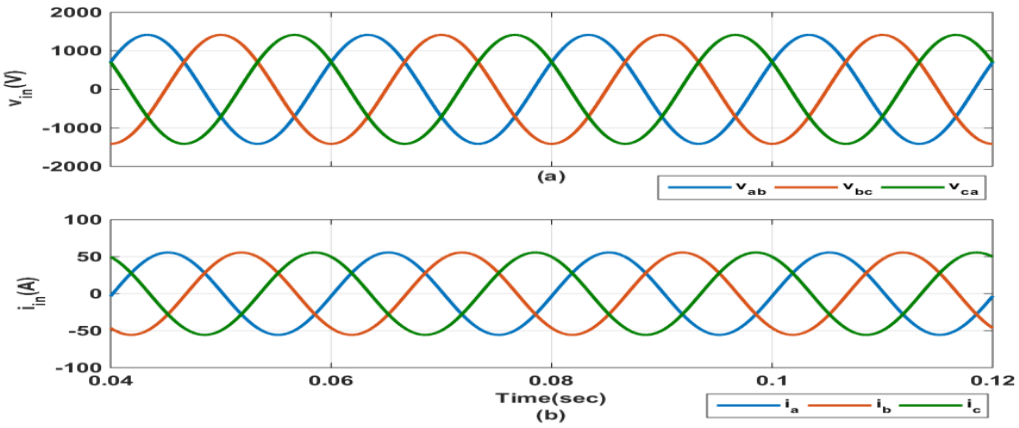


Figure (3.31) (a) Input voltage &(b) Input current for Y/Y , Y/Δ and 2zigzag transformers

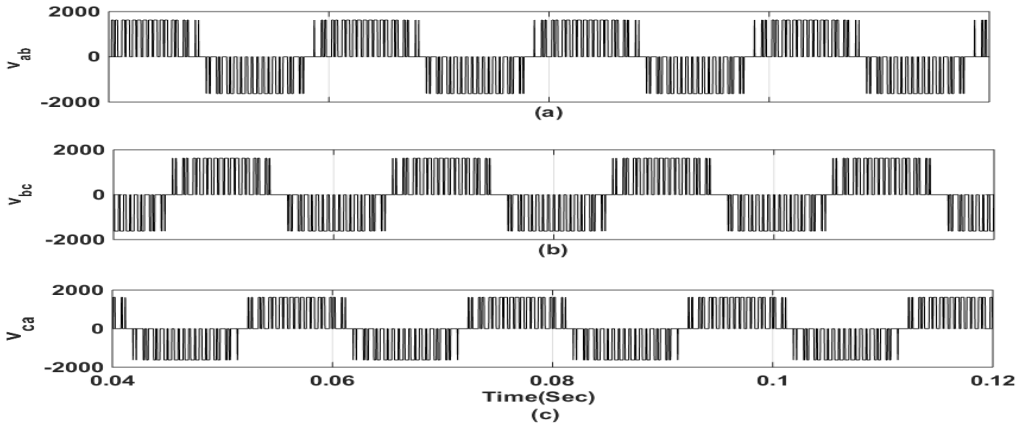


Figure (3.32) (a) L-L voltage ,V_{ab},(b) L-L voltage , V_{bc},and (c) L-L voltage , V_{ca} for 1Y/Y , $1Y/\Delta$ and 2zigzag transformers

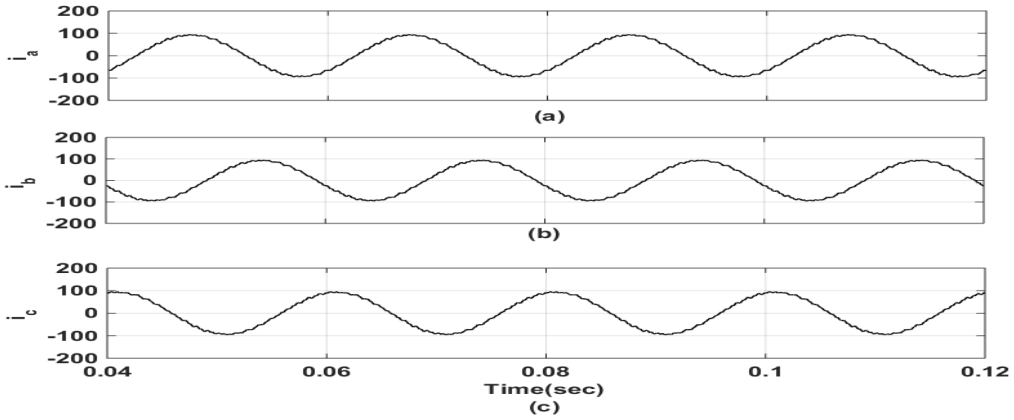


Figure (3.33) (a) i_a , (b) i_b and (c) i_c output current for 1Y/Y , 1Y/Δ and 2zigzag transformers.

The effect is clear as for as the input current is concerned in figure (3.31). The peak value of current drops to 50 A which results in a significant reduction in transformer KVA, as shown in the calculation section.

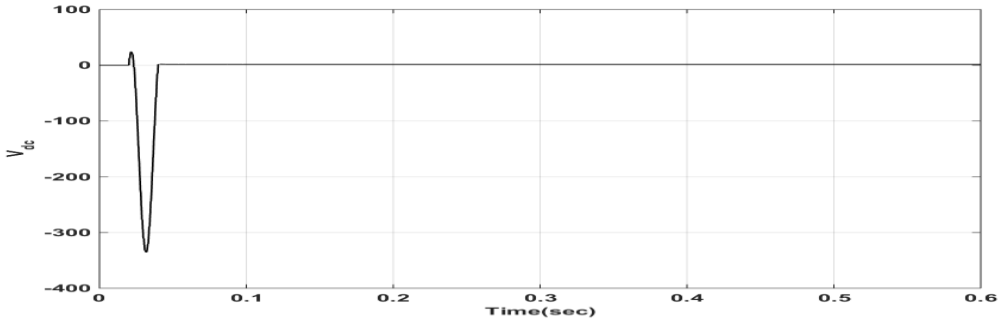


Figure (3.34) Mean voltage content in the output of the inverter with 1Y/Y , 1Y/Δ and 2zigzag transformers.

3.5 Discussion of Simulation Results

Table (3.2) shows the values of the most important waves obtained from the work:-

Table (3.2): Simulation Results from Work

simulation Results of circuit of a 24 pulse rectifier						
	V_{in}	I_{in}	$V_{(out)}$	Ripple in $V_{(out)}$	I_{out}	Ripple in I_{out}
Case1	1414	175	1330-1306	24	65-66	1
Case2	1414	175	1354-1296	58	65-66	1
Case3	1414	100	1480			

Simulation Results of Power Processing Unit 4 zigzag					
	V_{in}	I_{in}	$V_{(out)}$	$V_{(out)inverter}$	$I_{(out)inverter}$
Case1	1414	100	813	1800	250
Case2	1414	100	813	1800	100

Simulation Result of Power Processing Unit under Various Combinations of Transformer Connection					
	V_{in}	I_{in}	$V_{dc\ (out)}$	$V_{(out)inverter}$	$I_{(out)inverter}$
Case1: 1Star/Star-3Zigzag	1414	100	813	1800	100
Case2: 3zigzag , 1 star/delta	1414	75	813	1800	100
Case3 : 2zigzag , 1 star/star ,1 star/delta	1414	50	813	1800	100

Through the results obtained from conducting simulations on several circuits using variable loads, and based on the mentioned table (3.2) , we note the following:-

1- For multiphase 24 pulse rectifier circuits, the ripple content in the output voltage is small compared to other rectifier circuits. Also, the frequency of ripple oscillations is at 1200 HZ.

2- The presence of the capacitor with very small resistance at the rectifier circuit output clearly helped to filter the voltage waves and reduce the ripple to the extent that it became very close to the DC form. It is observed that a capacitor value of $0.0001 \times 10^{-6}\ \mu F$ is sufficient enough to bring the voltage to that of a pure DC.

3- The capacitor despite the small value rises the output mean voltage from 668 V to 813 V as depicted for example in figure(3.16) and figure(3.17).

4- Different loads were used for the back-to-back converter circuit. In all loads it is observed that the input current is sinusoidal as shown in figure (3.9), and figure(3.15). Hence, the use of this rectifier in grid tie applications satisfies standards of harmonic penetrations.

5- In all loading conditions, the rectifier performance is the same as far as the output DC voltage is concerned.

6- The performance of the inverter, which is the second converter in the power unit shows very good performance when coupled with the multiphase rectifier. As depicted in simulation results, for example figure (3.20), the mean voltage content in the output of the inverter is zero at steady state. It is interesting to observe this for all type of loading conditions. Therefore, there's a clear independence of rectifier operation from the inverter loading condition.

7- More than one combination was used to provide the phase difference required for the multi-phase rectifier circuit. Some of the zigzag

transformers were replaced with star / star or star / delta or both star / star and star / delta. The aim of this part of the simulation is to observe the apparent power size of the system under different transformer combinations. It is observed that if all transformers are zigzag, the current peak is at nearly 95.5 A per phase with a phase pattern of $15^o, 30^o, 45^o$ and 60^o. However, if a one of the zigzag is substituted with one star/delta with the same pattern as above, the current peaks decrease nearly to 75 A per phase. Hence, it is clear that the best pattern which decreases the input current is the one that assigns small phase shifts to zigzag transformers such that the relationship in (2.28) holds, i.e., phase shifts are less than 20^o.

3.6. Fourier Analyses and Calculations from Simulation Results

Based on the simulation results shown in this chapter, the Fourier analyses of the power processing unit is carried out according to the type of loading, considering up the 9th harmonic.

- For an R load, the Fourier expression of output voltage is,

$$v_{rect.(R)}(\omega t) = 1322 - 27.222\,cos\ (4\pi t) + 10.3869\,cos\,(6\pi t) - 5.5397\,cos\ (8\pi t) + 3.4623\,cos\,(10\pi t) - 2.3742\,cos\,(12\pi t) + 1.7312\,cos\ (14\pi t) - 1.3190\,cos\ (16\pi t) + 1.0387 cos\,(18\pi t) \quad (3.1)$$

For output current the Fourier expression is,

$$i_{rect.(R)}\,(\omega t) = \frac{v_{rect.(\omega t)}}{R} \quad (3.2)$$

$$i_{rect.(R)}(\omega t) = 66.1 - 1.3849\,cos\ (4\pi t) + 0.1593\,cos\ (6\pi t) - 0.277\,cos\ (8\pi t) + 0.1731\,cos\ (10\pi t) - 0.1187\,cos\ (12\pi t) + 0.0866\,cos\ (14\pi t) - 0.0659\,cos\ (16\pi t) + 0.0519\,cos\ (18\pi t)$$

- For an RL-Load , the Fourier analyses is,

$$v_{rect.(RL)}(\omega t) = 1322 - 27.222\,cos\ (4\pi t) + 10.3869\,cos\ (6\pi t) - 5.5397\,cos\ (8\pi t) + 3.4623\,cos\ (10\pi t) - 2.3742\,cos\ (12\pi t) + 1.7312\,cos\ (14\pi t) - 1.3190\,cos\ (16\pi t) + 1.0387\,cos\ (18\pi t) \qquad (3.3)$$

For output current the Fourier expression is,

$$i_{rect.(RL)}\ (\omega t) = \frac{v_{rect.(\omega t)}}{Z_L} \qquad (3.4)$$

Where ; $Z_L = \sqrt{R^2 + (n\omega L)^2}$ (3.5)

$$i_{rect.}(\omega t) = 66.1 - 0.649\ cos\ (4\pi t - 62.053) + 0.1732\,cos\ (6\pi t - 70.522) - 0.071\ cos\ (8\pi t - 75.143) + 0.0359\ cos\ (10\pi t - 78.019) - 0.0207\,cos\ (12\pi t - 79.971) + 0.013\ cos\ (14\pi t - 81.38) - 0.0087\,cos\ (16\pi t - 82.445) + 0.0061\,cos\ (18\pi t - 83.276)$$

- For an RC-Load , the Fourier expression is,

$$v_{rect.}(\omega t) = 1450 - 27.222\,cos\ (4\pi t) + 10.3869cos\ (6\pi t) - 5.5397\,cos\ (8\pi t) + 3.4623cos\ (10\pi t) - 2.3742\,cos\ (12\pi t) + 1.7312\,cos\ (14\pi t) - 1.3190\,cos\ (16\pi t) + 1.0387cos\ (18\pi t) \qquad (3.6)$$

For output current the Fourier expression is,

$$i_{rect.(RC)}\,(\omega t) = \frac{v_{rect.(\omega t)}}{Z_c} \tag{3.7}$$

Where ; $Z_c = \sqrt{R^2 + (\frac{1}{n\omega c})^2}$ (3.8)

$i_{rect.}(\omega t) = 72.5 - 0.1727\,cos\,(4\pi t + 82.837) + 0.0962\,cos\,(6\pi t + 79.325) - 0.0675\,cos\,(8\pi t + 75.892) + 0.0519\,cos\,(10\pi t + 72.559) - 0.0419\,cos\,(12\pi t + 69.344) + 0.0348\,cos\,(14\pi t + 66.259) - 0.0296\,cos\,(16\pi t - 63.313) + 0.0256\,cos\,(18\pi t + 60.512).$

3.7 Calculations of Apparent Power for Multi-Phase Transformer

In this part, the objective is to calculate the apparent power at input terminals of rectifier. Here, calculations are made for each pattern of phase shift considered in the simulation part. The calculations are summarized as;

- **Phase Shift Pattern is (15^o , 30^o, 45^o, 60^o)**

To achieve this sequence of phase shift, two ways of connecting the transformers were used, and for each way, an RL load is considered. Through the results obtained from the simulation is used to calculate the apparent power ,which is represented by the following expression,

$$|S| = \frac{\sqrt{3}V_m}{\sqrt{2}} * \frac{I_{in}}{\sqrt{2}} \tag{3.9}$$

Case (1) ,when the connection consists of 4 zigzag transformers ,

$$|S|_{(RL)} = \frac{\sqrt{3} * 1414}{\sqrt{2}} * \frac{99.5}{\sqrt{2}} = 243.6874\ KVA$$

Case (2) ,when the connection consists of 3 zigzag transformers and 1Star/Delta transformer,

$$|S|_{(RL)} = \frac{\sqrt{3} * 1414}{\sqrt{2}} * \frac{75}{\sqrt{2}} = 91.8419\ \text{Kw}$$

- **Phase Shift Pattern is ($^{-}15^{o}$, 0^{o} , 15^{o} ,30^{o})**

Also two ways of connection transformers were used, and for each, load was used an RL.

Case(1), when the connection consists of 3zigzag transformers and 1Star/Star transformer,

$$|S|_{(RL)} = \frac{\sqrt{3} * 1414}{\sqrt{2}} * \frac{81.85}{\sqrt{2}} = 200.4604\ \text{KVA}$$

Case (2) ,when the connection consists of 2 zigzag, 1Y/Δ, and 1 Y/Y transformers,

$$|S|_{(RL)} = \frac{\sqrt{3} * 1414}{\sqrt{2}} * \frac{55.55}{\sqrt{2}} = 68.0243\ KVA$$

Hence, the percentage decrease in size of transformer is, (compared to all zigzag connections)

$$\%\Delta S = \frac{243.687 - 91.8419}{243.687} x\ 100\% = 60.31\%$$

$$\%\Delta S = \frac{243.687 - 200.4604}{243.687} x\ 100\% = 17.73\%$$

$$\%\Delta S = \frac{243.687 - 68.082}{243.687} x\ 100\% = 72.08\%$$

Chapter Four: Power Processing based on a Three Phase Pulse Width Modulated Rectifier and Inverter

4.1 Introduction

In this chapter, the objective is to build a power processing unit based on two PWM converters. In that aspect, the main aim is to study the performance of the unit under a PWM AC/DC converter and compare the overall performance with the results of chapter three. Here, the comparison is primarily concerned with the shape of the input current, the size of the elements, such as link capacitors and the complexity of the circuit. The chapter starts with analyzing PWM rectifier to evaluate performance and then simulating this converter with the three phase PWM inverter. In this chapter, we will consider R and RL loads only.

4.2 Pulse Width Modulated Rectifiers

This rectifier circuit is shown in figure (4.1) for a two level topology along with the PWM modulation scheme in the Simulink environment. Here, as a first step the DC link capacitor and source impedance need to be calculated. To provide a technical comparison the voltage/frequency of the input is maintained at the same values as in chapter three.

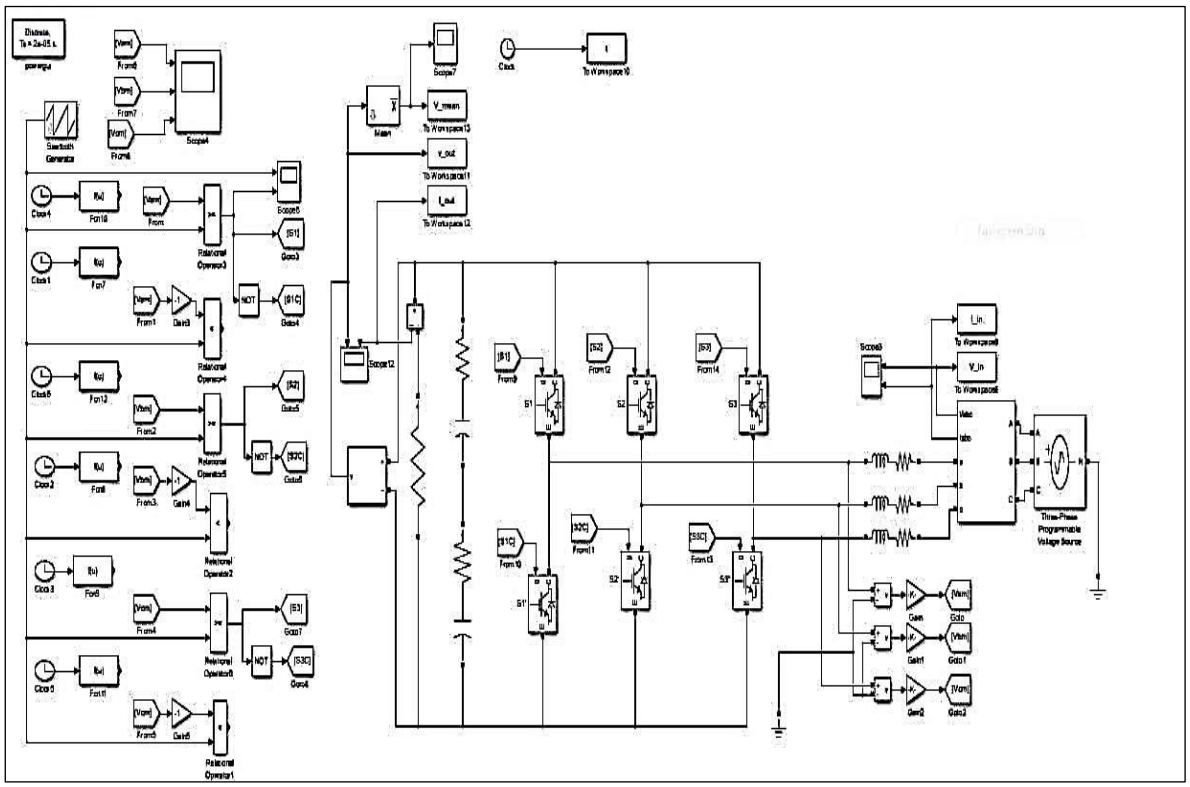


Figure (4.1) Simulation of PWM rectifier circuit in Simulink environment.

4.2.1 Calculation of DC link capacitor

For the purpose of building a rectifier circuit, a capacitor with specific values must be used. At the O/P DC terminals the value for the capacitance are determined by performing mathematical calculations, based on the following equation**[28,29]**,

$$\frac{1}{2\Delta V R_L} \leq C \leq \frac{t_r}{0.74 R_L} \tag{4.1}$$

Where,

R_L: is load resistance .

ΔV : is the amount of ripple specified in the output voltage.

t_r: is the rise time of the response.

ω : is the angular frequency.

In this study, the value of ΔV is calculated based on a percentage ripple content of 5%. The rise time used in this work is 0.08 sec. based on equation (4.1) the value of C is,

$$378.214\ \mu F\ \leq C \leq 5405.405\ \mu F$$

In the simulations a value of 1000 μF is considered.

4.2.2 Source Impedance at AC Input

A source impedance is usually connected at the input of the PWM rectifier **[29]**. To calculate this impedance, it is usual to assume a value for the resistance R. The inductance can be calculated from equation**[28,29]**,

$$\frac{15v_s}{p}\left(\frac{\sqrt{2}v_s\omega {T_s}^2}{4}+\frac{V_{dc}}{3}\ T_s\right)\leq L \leq \frac{0.9\ {v_s}^2}{P\omega} \qquad (4.2)$$

As a first step, the switching frequency considered in this chapter is the same as that of chapter three ,which is 1000 Hz. Assuming R=0.2 Ω**[29]**, the inductance is,

$$62.994mH \leq L \leq\ 16.4mH$$

It is clear that at low switching frequency , equation (4.2) give ranges that are impractical. Therefore , a switching frequency of 10000 Hz **[29]**, is used for the PWM rectifier to calculate the required inductance with the above switching frequency**[30]**, the inductance is found to be $\approx 15\ mH$. Here, the power is calculated as ,

$$P = \frac{{V_{dc}}^2}{R_L}$$

4.2.3 Simulation of PWM Circuit Rectifier

After extracting the values required to simulate the circuit accurately, and using the PWM with an AC source to generate the switching pulses for the rectifier switches. The simulation was carried out using the value of the switching frequency used in the third chapter (1000 Hz) and the value that achieves a correct inductance value according to equation (4.2). One point worth mentioning here, is that the PWM is simulated at 1000 Hz of switching frequency, with an inductance of 15 mH as calculated in previous section. Since this frequency value cannot achieve the equation that gives an accurate inductance value for the circuit, so the same inductance value that is achieved by the switching frequency 10000 was used $L = 15\,mH$. A resistance load was used only with a value similar to the value of the load in the third chapter, which is 20 Ω, and the results were obtained, as shown in figure (4.2) for the input at the rectifier terminals.

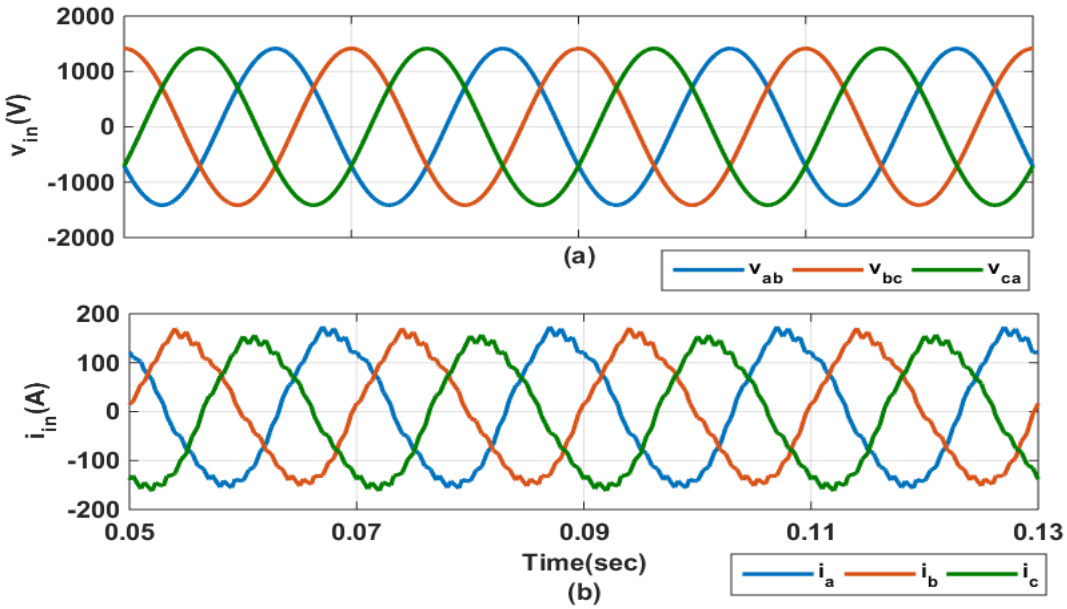


Figure (4.2) (a) Input voltage and (b) Input current for a PWM rectifier with R load at $f_s = 1000Hz$

To find out the behavior of this circuit with the same data as the multi-phase rectifier circuit, the results extracted from the simulation at the output of the rectifier are shown in figure (4.3).

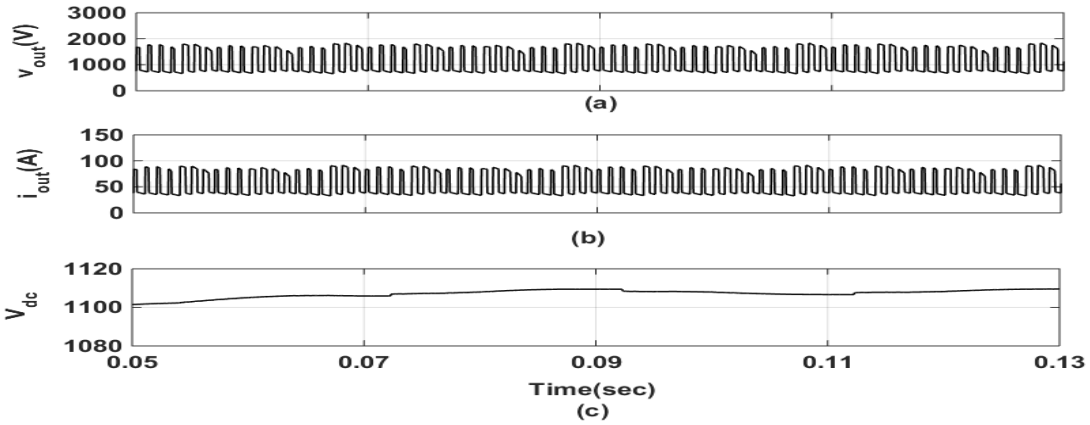


Figure (4.3) (a) Output voltage, (b) Output current and (c) Mean voltage of a PWM rectifier with R-load at switching frequency of 1000 Hz.

The PWM rectifier is now loaded by an RL load with the same values used in the third chapter, where $R = 20\,\Omega$ and $L = 60\,mH$, and the input waves are extracted as shown in the figure (4.4), and the output waves shown in the figure (4.5),

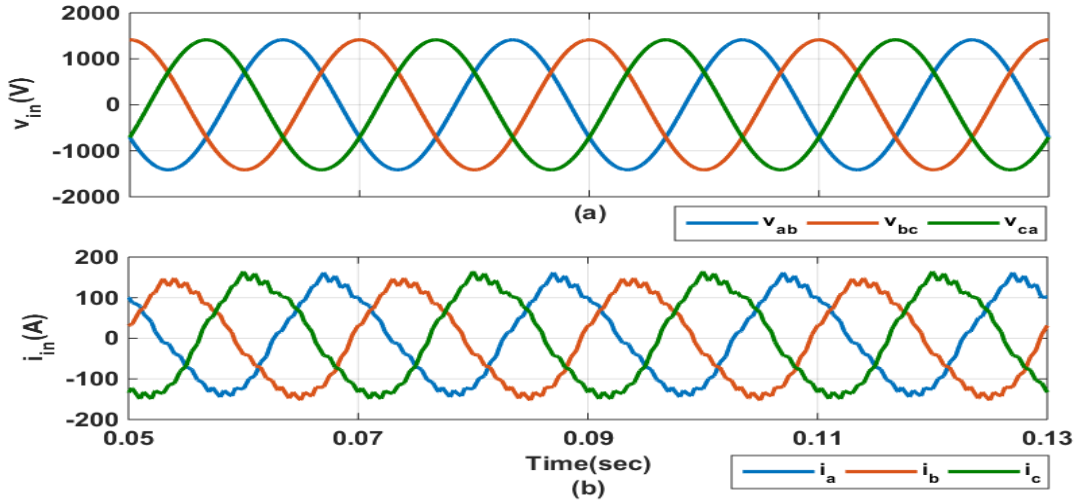


Figure (4.4) (a) Input voltage and (b) Input current for PWM rectifier with RL load at $f_s = 1000$Hz.

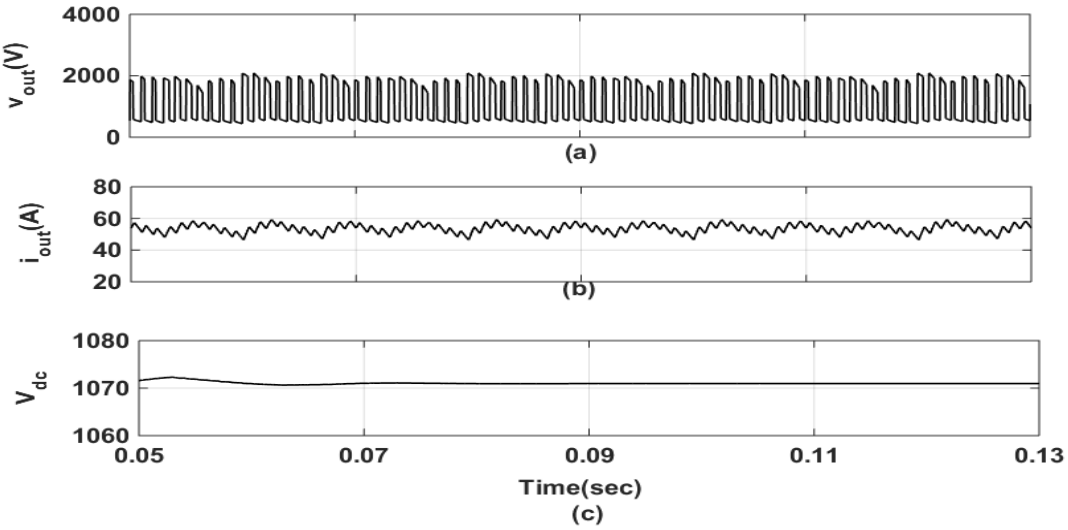


Figure (4.5) (a) Output voltage, (b) Output current and (c) Mean voltage an RL load fed by PWM rectifier at $f_s = 1000$Hz.

From the simulation results, it is clear that the output voltage at the rectifier suffers from considerable ripple under R and RL load. This ripple is present even with a large DC link capacitor (1000μf) at the output terminals. Farther more, the current at the AC terminals shows considerable ripple content.

4.2.4 Simulation of PWM Circuit Rectifier under High Switching Frequency

In this part of the simulation the switching frequency is changed to 10000Hz **[29]**. The objective is to study the input and output quantities in this condition. Figure (4.6) shows the input quantities in this case, while figure (4.7) shows the output quantities.

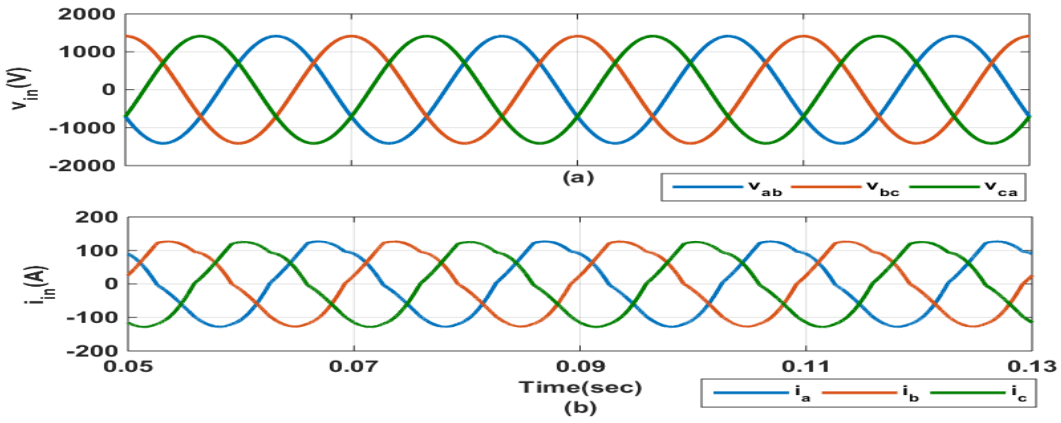


Figure (4.6) (a) Input voltage and (b) Input current for a PWM rectifier with R load at $f_s = 10000Hz$

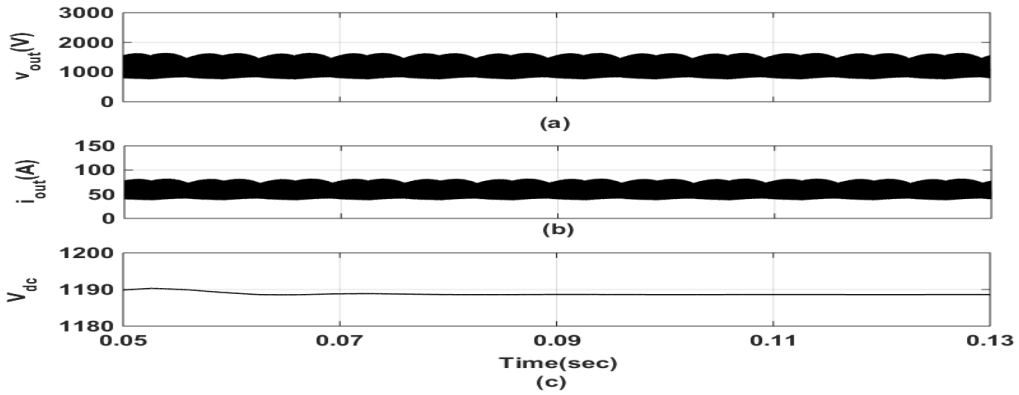


Figure (4.7) (a) Output voltage, (b) Output current and (c) Mean voltage of a PWM rectifier with R-load at switching frequency of 10000 Hz.

At an RL loading condition figure(4.8) and figure(4.9) depicts voltage and current waveforms for input /output of rectifier respectively.

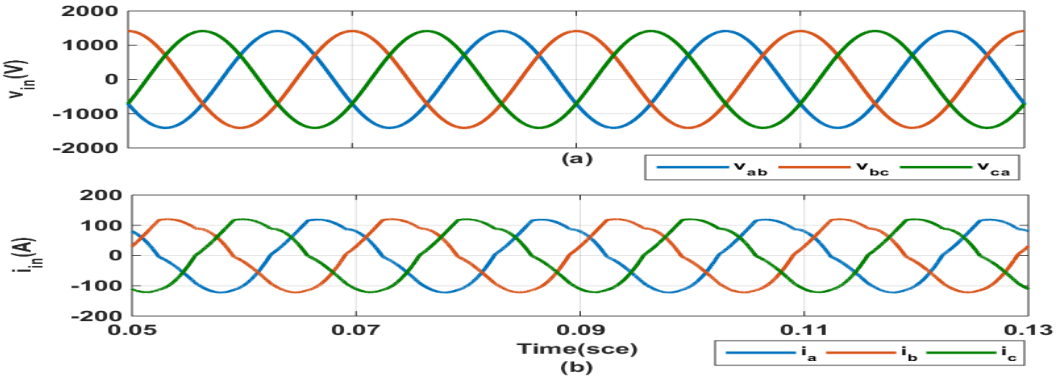


Figure (4.8) (a) Input voltage and (b) Input current for PWM rectifier with RL load at $f_s = 10000Hz$.

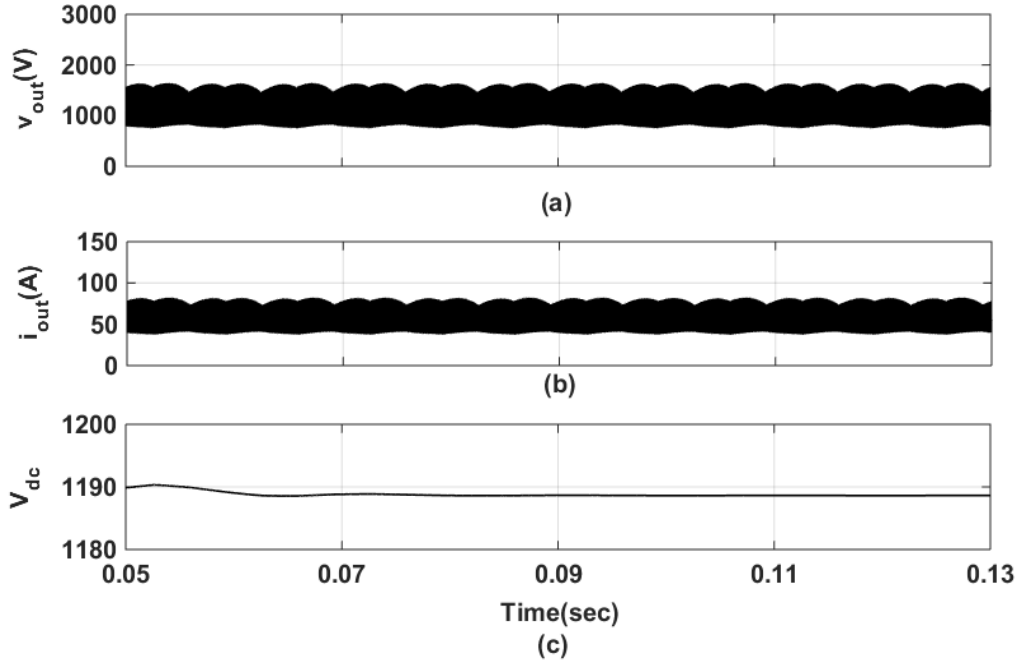


Figure (4.9) (a) Output voltage, (b) Output current and (c) Mean voltage an RL load fed by PWM rectifier at $f_s = 10000$Hz.

4.2.5 Discussion of Simulation Results for PWM Rectifier Circuit

At a switching frequency of 1000 Hz, the output voltage suffers from high ripple. For example at R load the figure (4.3) shows a maximum and minimum voltage are (1800) V and (700) V respectively, with a mean voltage of approximately (1110) V. However at a switching frequency of 10000 Hz in figure (4.7) the maximum and minimum voltage are (1620) V and (760) V respectively, with a mean voltage of (1190) V. Not to be missed also, the shape of the input current waves, which at both switching frequencies is not very smoothly sinusoidal, but in the case of the switching frequency 1000Hz it is less smooth than the corresponding waveforms at switching frequency 10000Hz.

4.3 Simulation of Power Unit with PWM Rectifier and Inverter

After conducting the simulation on the PWM rectifier circuit separately and analyzing the behavior of the circuit, the simulation file is updated such that the PWM rectifier now supplies DC voltage to the three phase inverter as shown in figure (4.10). Regarding the inductance connected with the AC source, it is not possible to use the same values in the PWM rectifier circuit only, because the equation (4.2) that it achieves does not apply to the PWM rectifier circuit with the inverter. For the purpose of obtaining a current waveform at the input closer to the sinusoidal shape, more than one value of the inductance was tested and the value of 80 Henry was adopted. The circuit is simulated with a switching frequency of 10000 Hz for rectifier and 1000 Hz for inverter.

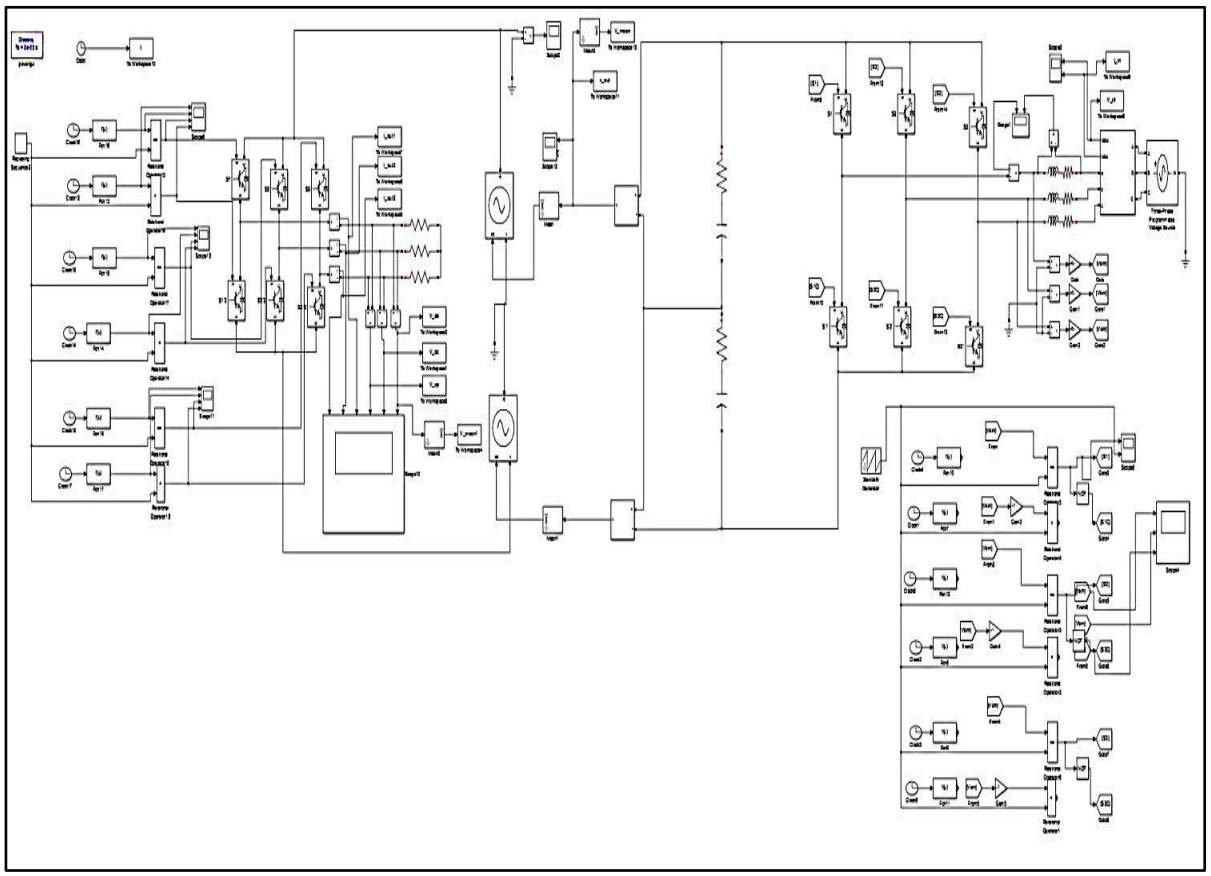


Figure (4.10) PWM rectifier with inverter circuit in Simulink environment.

4.3.1 Simulation of Power Unit with PWM Rectifier and Inverter with Resistive load

A three phase resistive load is connected with the circuit, and the results extracted from the simulation of the circuit are shown in figures (4.11-4.15) below.

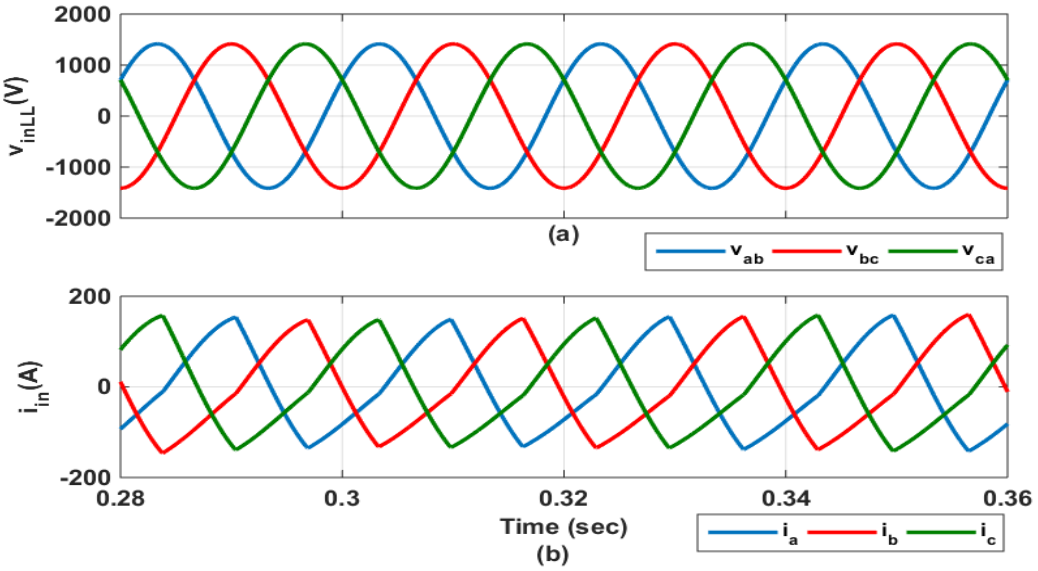


Figure (4.11) (a) Input voltage and (b) Input current of PWM rectifier with an R loaded inverter

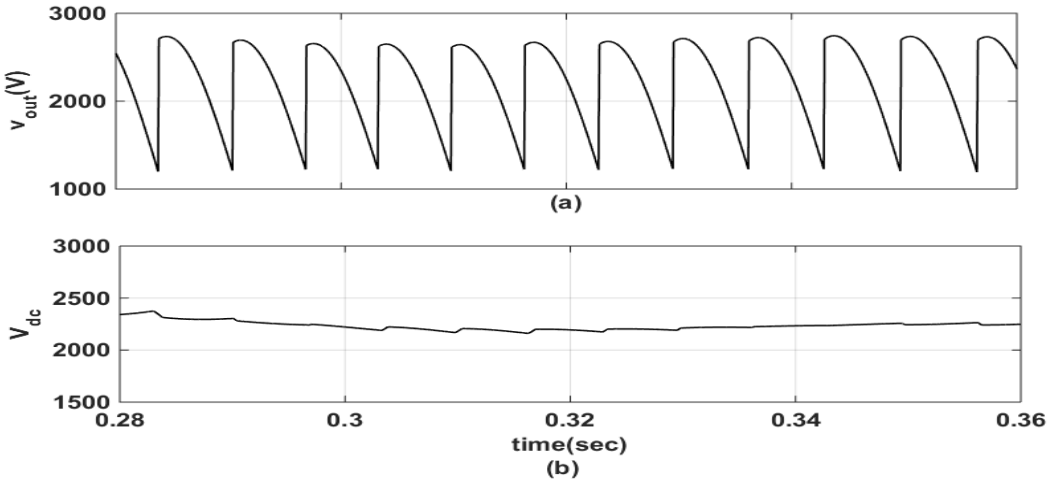


Figure (4.12) (a) Output voltage of rectifier, (b) Mean voltage of PWM rectifier with an R loaded inverter.

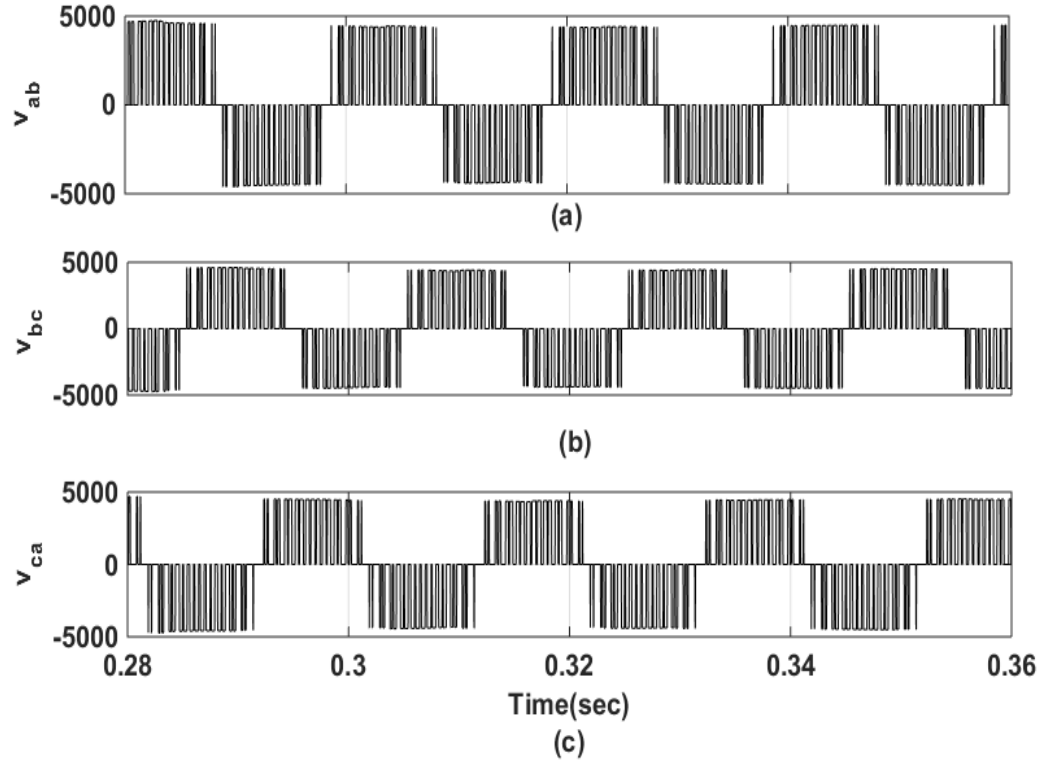


Figure (4.13) (a) L-L voltage,V_{ab}, (b) L-L voltage,V_{bc}, and (c) L-L voltage, V_{ca} of inverter with R load.

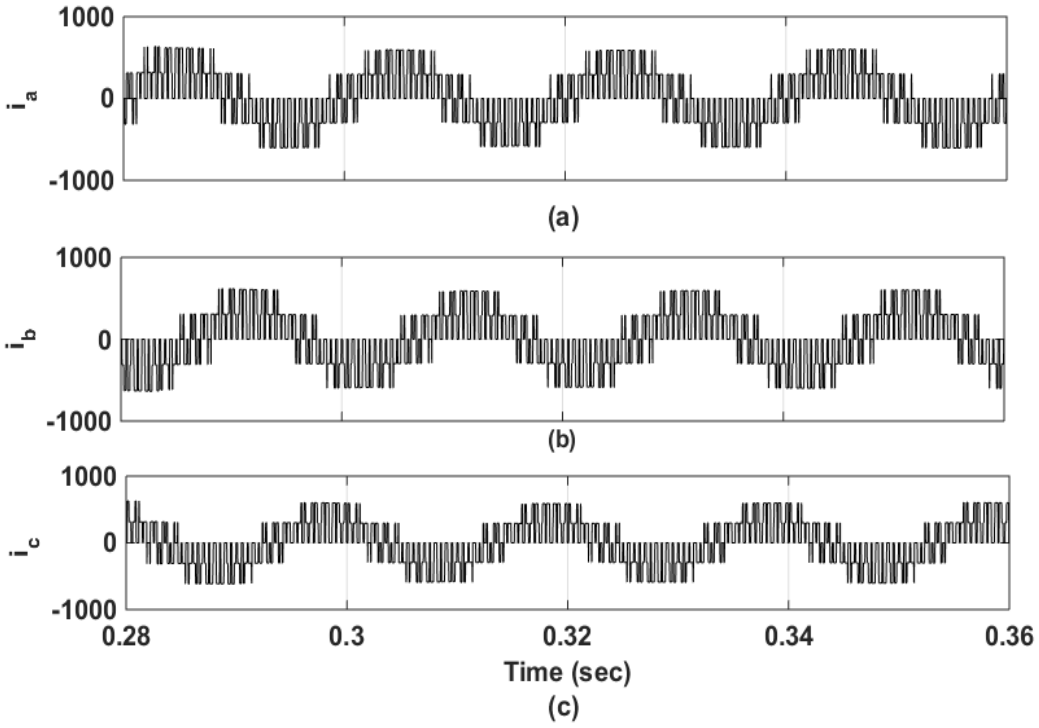


Figure (4.14) (a) i_a, (b) i_b and (c) i_c output current of inverter with R load.

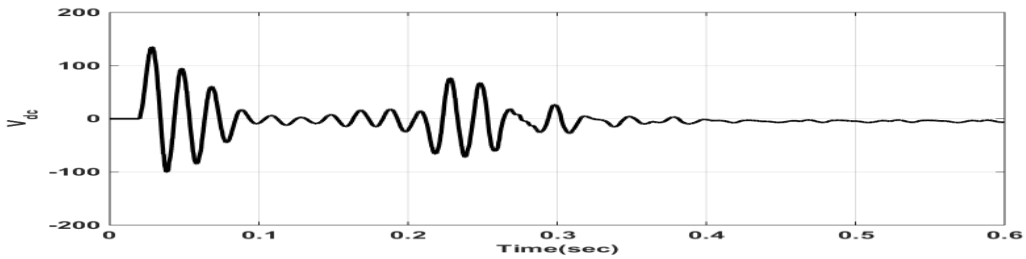


Figure (4.15) Mean voltage content in inverter output voltage.

From the simulation results, there is an increase in mean voltage, however the input current shows distortion. Also, the mean voltage content shows a slow response in reaching the target value of zero.

4.3.2 Simulation of Power Unit with PWM Rectifier and Inverter with RL load

The same circuit was repeated with the use of a RL type load and extracting the results depicted in figure (4.16 - 4.20) for both converters.

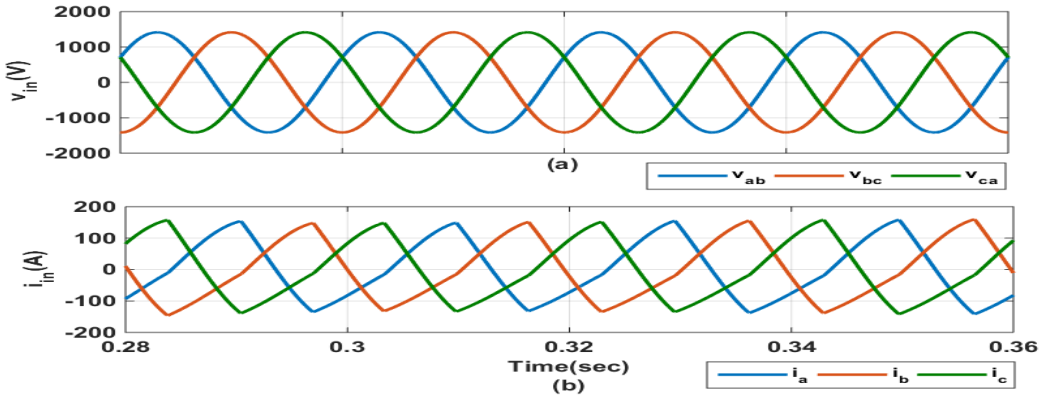


Figure (4.16) (a) Input voltage and (b) Input current at rectifier input with RL loaded inverter.

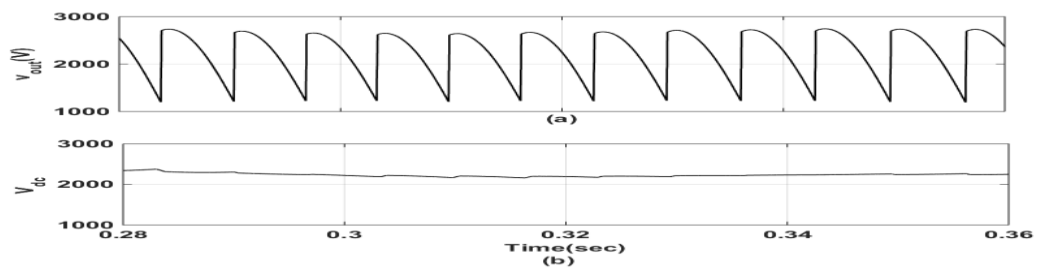


Figure (4.17) (a) Output voltage of rectifier, (b) Mean voltage of rectifier with RL loaded inverter.

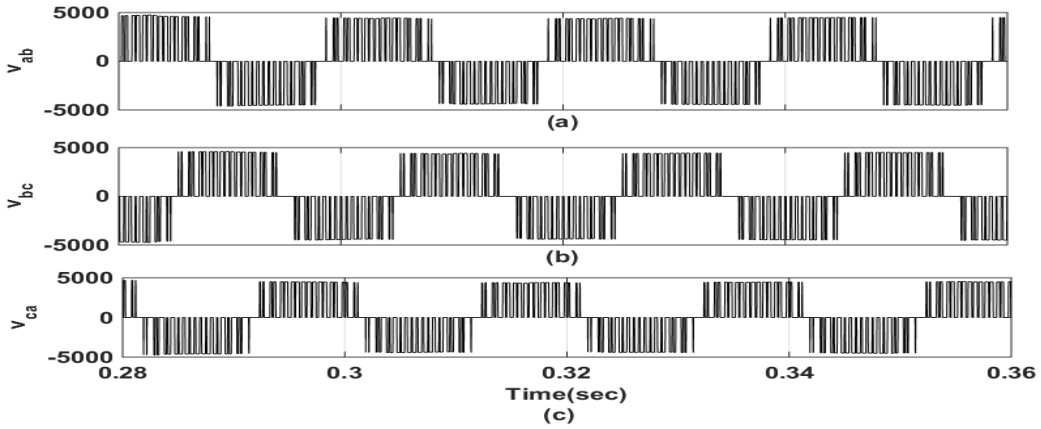


Figure (4.18) (a) L-L voltage ,V_{ab}, (b) L-L voltage , V_{bc}, and (c)L-L voltage , V_{ca} of inverter with RL load.

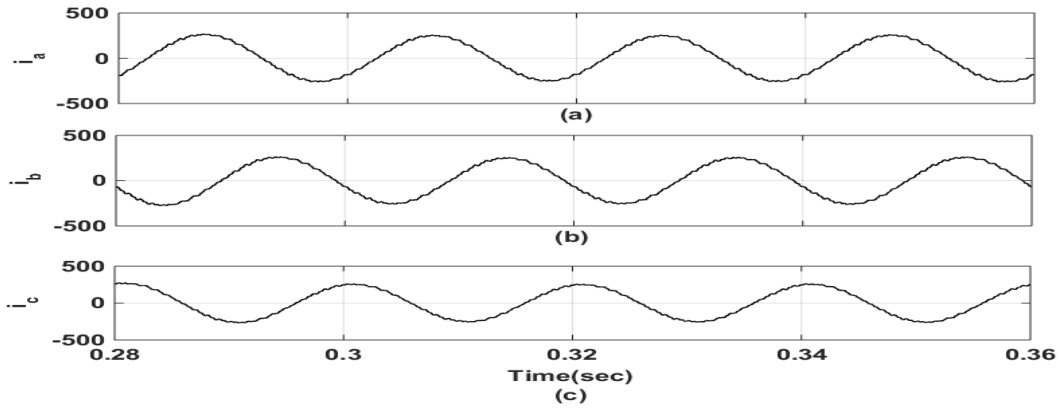


Figure (4.19) (a) i_a , (b) i_b and (c) i_c output current of inverter with RL load.

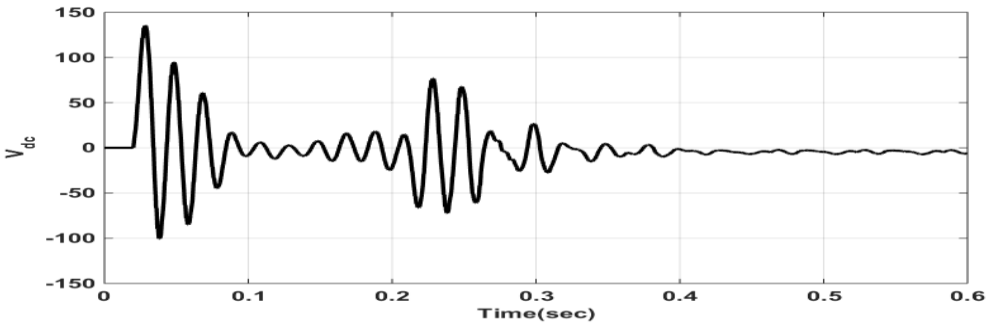


Figure (4.20) Mean voltage content in output voltage of inverter with RL load.

Here approximately, the amplitude of the inverter output voltage match that of an R load. Also, the response of the mean voltage content is nearly the same as that of R load case.

4.4 Simulation Results

In order to make the results obtained more clear, Table 4.1 was made, which contains most of the values of the waves resulting from the simulation

Table (4.1): Simulation Results from Work

Simulation Results of PWM Circuit Rectifier						
Simulation of PWM Circuit Rectifier under 1000 Hz Switching Frequency						
	V_{in}	I_{in}	$V_{(out)}$	Ripple in $V_{(out)}$	I_{out}	Ripple in $I_{(out)}$
R-load	1414	170	1800-650	1150	90-35	55
RL-load	1414	170	2090-450	1640	60-45	15
Simulation of PWM Circuit Rectifier under 10000 Hz Switching Frequency						
	V_{in}	I_{in}	$V_{(out)}$	Ripple in $V_{(out)}$	I_{out}	Ripple in $I_{(out)}$
R-load	1414	125	1620-760	860	80-40	40
RL-load	1414	125	1750-525	1225	58-53	5
Simulation Results of Power Unit with PWM Rectifier and Inverter						
	V_{in}	I_{in}	$V_{dc\ (out)}$	$V_{(out)inverter}$	$I_{(out)inverter}$	
R-load	1414	150	2250	4500	600	
RL-load	1414	150	2250	4500	250	

4.5 Comparison Between Performances of Multiphase versus Pulse Width Modulated Rectifiers in Standalone and Power Processing Unit Applications

At this point, the performance of the twenty four pulse rectifier was studied in applications of single load (or standalone) and with a three phase

PWM inverter as illustrated through the simulation results presented in chapter three of this project. On the other hand, in this chapter the PWM rectifier was considered with exactly the same loading condition, i.e. either a standalone load or the three phase inverter. Based on the simulation results of both chapters three and four, a comparison is shown in **table 4.2** below.

Table (4.2) Comparison Between Performances of Power Unit Based on Multiphase and PWM Rectifier and Three Phase PWM

	Multiphase Rectifier and 3∅ inverter	**PWM Rectifier and 3∅ inverter**
1	The capacitor that was used is very small $0.0001\mu F$. This due to the fact that the voltage obtained suffer from little ripples.	A capacitor with a value of 1000 μF was used, which is a large value. Here, the ripples obtained are high which requires strong filtering.
2	The diodes are simple and inexpensive devices and no circuit is required for switching.	This rectifier requires IGBTs which require extra control circuits to generate the switching pulses.
3	Conduction losses are small in this type of rectifier.	High losses are incurred due to the high switching frequency for the rectifier.
4	This rectifier doesn't need an inductance at the input AC terminals. Zigzag (or other winding) transformers used here have eliminated the need for them because they contain inductance. Even if star/star or star/delta transformers are connected, they have a small internal inductance.	In order to function properly, the circuit needs an inductance that depends on many factors, one of them is the switching frequency. Since higher switching frequency is required, a higher inductance is needed **[30]**.

5	The input current waves are sinusoidal in shape. Hence, this fulfills utility requirements when such power processing units are connected to public grids.	The input current waves are not smoothly sinusoidal, and cannot be obtained in a perfect sinusoidal form. Even with a higher inductance value, the current does not match that of a multiphase rectifier.
6	It can be observed that the output mean voltage content in the output voltage of the inverter attains zero value quickly. For example from figure (3.14) the response settles in about 0.04 Sec.	The mean voltage content takes a considerable time to settle to zero. In figure (4.15) , the this time is around 0.28 sec.
7	This type of rectifier does need a multi –winding transformer which adds cost. However, a circuit to control the voltage at the DC link capacitor is not necessary.	PWM rectifier doesn't need a multi-winding transformer . However, a closed loop control circuit is required to maintain a constant voltage across the DC link as reported in **[31-34]**.
8	The circuit is not complicated in components and size, a part from the transformer.	The circuit is considered complex in terms of large size and number of components.
9	From Tables (3.2) and (4.1) one notices that the ripple in the output current and voltage of the rectifier is small.	The ripple in the output current and voltage of the rectifier is high as mentioned in the tables (3.2) and (4.1).

Chapter Five: Conclusions and Future Works

5.1 Conclusions

Based on the results presented in this work, the following are the most important conclusions drawn:

1- The multiphase rectifier provides more advantages in terms of the quality of the output voltage and response.
2- The lack of ripple in the rectifier output advocated for a small capacitor value. This will in turn reduce the capacitor required.
3- The mean voltage content in the inverter output voltage which is fed by a multiphase rectifier shows a quick response in attaining a zero value.
4- The PWM rectifier shows a considerable ripple in the output voltage even with a large value capacitor.
5- The presence of a transformer in multiphase rectifier provides a mean of smoothing the input current which fulfills the utility grid harmonic requirement.
6- Although the size of the transformer may be an obstacle as far as multiphase rectifiers are concerned, however this work has shown that the required transformer KVA is significantly reduced by altering the phase shift.
7- Based on the comparison provided in this work, the multiphase proves itself a more practical converter. First, the PWM requires a high switching frequency which increases the switching conduction compared to the multiphase rectifier. Second, the quality of input current is well suitable for utility grid applications.

5.2 Suggestions for Future Works

After completing this work, the following could be potential future work:

1- Investigate the performance of the power processing unit with a multiphase rectifier and a multilevel converter, such as the neutral point clamped (NPC) or multilevel modular converter (MMC).
2- Study the behaviour of the multiphase rectifier based power processing unit in grid tied applications for real and reactive power injection.
3- Implementing a control system for the DC/AC converter to inject real and reactive power into a utility grid
4- Experimental implementation of the multiphase and PWM rectifiers in applications related to renewable energy sources.
5- Investigate the performance of the power processing unit in soft opening points (SOP).

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الخلاصة

تعتبر دوائر تحويل الطاقة إلكترونية من أكبر العوامل التي ساهمت في تطوير مجال الطاقة . أصبحت مساهمتها هذه أكثر وضوحًا بعد التطبيق المكثف والواسع لمصادر الطاقة المتجددة في جميع أنحاء العالم. يتطلب ربط وتكييف الطاقة من هذه المصادر المتجددة محولًا واحدًا أو أكثر لتحقيق الاهداف المراد الوصول اليها.

تهدف هذه الدراسة إلى بناء وحدة معالجة الطاقة ، والتي تتكون من محولين. الأول يعمل كمحول جهد تيار متردد / جهد تيار مستمر ، بينما يعمل الثاني كمحول جهد تيار مستمر / جهد متردد متردد. في هذا العمل ، تم بناء المحول الأول من مقوم نبضات حيث يكون يخرج أربعة وعشرين نبضة. باستخدام برنامج او منصة MATLAB / Simulink ، تم بناء هذا المقوم ومحاكاته.

في البداية ، تتمثل المهمة في فحص أداء المقومات في ظل ظروف تحميل مختلفة. بعد ذلك ، يتم تمديد وتوسيع العمل بحيث يتم تحميل المقوم أعلاه بواسطة عاكس معدل عرض النبضة ثلاثي الطور. يتم محاكاة المحول الأخير في ظل ظروف تحميل مختلفة .تؤكد النتائج جدوى المقوم متعدد الأطوار في توفير جهد تيار مستمر يحاكي تقريبًا حزمة البطارية .والذي بدوره يوفر اداء وعمل للعاكس مرضي للغاية ، ناهيك عن جودة التيار عند أطراف إدخال المعدل.

يتم تقييم أداء العاكس في هذا العمل بناءً على جودة الجهد الناتج واستجابته في الوصول إلى المتوسط الصفري. علاوة على ذلك ، النتائج التي تم الإشارة والتوضيح عنها في وثائق هذا العمل تشير إلى أن حجم المحول ، الذي يوفر انتقال الطور الضروري بين المقومات الداخلة في بناء الدائرة ، يمكن تقليل حجمها بشكل كبير عن طريق تغيير نمط ترتيب إزاحة الطور.

يقدم العمل أيضًا مقارنة بين وحدة معالجة قدرة ذات مقوم متعدد الأطوار ومقوم معدل عرض النبضة . هنا ، يتم تحليل محول جهد التيار المستمر / جهد التيار المتردد في ظل نفس الظروف مثل تلك الموجودة في الوحدة القائمة على المعدل متعدد الأطوار. يستنتج من المقارنة أنه يتم الحصول على العديد من المزايا من وحدة معالجة الطاقة مع المعدل متعدد الأطوار.

جمهورية العراق
وزارة التعليم العالي والبحث العلمي
جامعة بابل
كلية الهندسة / قسم الهندسة
الكهربائية

تحليل عاكس ثلاثي الطور مغذى من مقوم متعدد الاطوار لتطبيقات معالجة القدرة

بحث

مقدم الى كلية الهندسة في جامعة بابل كجزء من متطلبات نيل درجة الدبلوم العالي في الهندسة / الهندسة الكهربائية.

من قبل:
سلوان سعد محمد علي عبد الله

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