UNIVERSITY OF TURKISH AERONAUTICAL ASSOCIATION
INSTITUTE OF SCIENCE AND TECHNOLOGY

ANALYSIS AND INVESTIGATION OF SINUSOIDAL THREE-PHASE INTERLEAVED FLYBACK INVERTER FOR PHOTOVOLTAIC SYSTEMS

MASTER THESIS

Ihssan Jamal FAREED

Department of Electrical and Electronic Engineering

Master of Electrical Engineering

MAY, 2017

UNIVERSITY OF TURKISH AERONAUTICAL ASSOCIATION
INSTITUTE OF SCIENCE AND TECHNOLOGY

ANALYSIS AND INVESTIGATION OF SINUSOIDAL THREE-PHASE INTERLEAVED FLYBACK INVERTER FOR PHOTOVOLTAIC SYSTEMS

MASTER THESIS

Ihssan Jamal FAREED

1403630004

Department of Electrical and Electronic Engineering

Master of Electrical Engineering

Supervisor: Prof. Dr. Doğan ÇALIKOĞLU

MAY, 2017

Ihssan Jamal FAREED, having student number 1403630004 and enrolled in the Master Program at the Institute of Science and Technology at the University of Turkish Aeronautical Association, after meeting all of the required conditions contained in the related regulations, has successfully accomplished, in front of the jury, the presentation of the thesis prepared with the title of "Analysis and Investigation of Sinusoidal Three-Phase Interleaved Flyback Inverter for Photovoltaic Systems".

Supervisor : **Prof. Dr. Doğan ÇALIKOĞLU**
University of Turkish Aeronautical Association ....

Jury Members : **Prof. Dr. Doğan ÇALIKOĞLU**
University of Turkish Aeronautical Association ....

: **Prof. Dr. Remzi YILDIRIM**
University of Ankara Yıldırım Beyazıt ....

: **Yrd. Doç. Dr. Ertan ZENCIR**
University of Turkish Aeronautical Association ....

Thesis Defense Date: 23.05.2017

UNIVERSITY OF TURKISH AERONAUTICAL ASSOCIATION
INSTITUTE OF SCIENCE AND TECHNOLOGY

I hereby declare that all the information in this study I presented as my Master's Thesis, called: Analysis and Investigation of Sinusoidal Three-Phase Interleaved Flyback Inverter for Photovoltaic Systems has been presented in accordance with the academic rules and ethical conduct. I also declare and certify with my honor that I have fully cited and referenced all the sources I made use in this present study.

Ihssan Jamal FAREED

ACKNOWLEDGEMENTS

For My Parents

I am grateful to The Almighty God for helping me to complete this thesis.

I would like to acknowledge my thesis advisor Prof. Dr. Doğan ÇALIKOĞLU at University of Turkish Aeronautical Association for his guidance and encouragement through my research for this thesis. Also, I would like to acknowledge my family for their patience and support through my entire life and my friends and relatives as well.

May 2017 **Ihssan Jamal FAREED**

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

DC : Direct Current
AC : Alternating Current
DCM : Discontinues Conduction Mode
CCM : Continues Conduction Mode
PWM : Pulse Width Modulation
SPWM : Sinusoidal Pulse Width Modulation
SVPWM : Space Vector Pulse Width Modulation
V_{rms} : Root Mean Square Voltage
THD : Total Harmonic Distortion
EMI : Electromagnetic Interference
RFI : Radio Frequency Interference
V_0 : Output Voltage
V_{IN} : Input Voltage
D : Duty Cycle
N_S : Transformer Secondary Winding Turns
N_P : Transformer Primary Winding Turns
L : Inductor
L_m : Magnetizing Inductance
R : Resistor
C : Capacitor
CB : Circuit Breaker
H_Z : Hertz

ABSTRACT

ANALYSIS AND INVESTIGATION OF SINUSOIDAL THREE-PHASE INTERLEAVED FLYBACK INVERTER FOR PHOTOVOLTAIC SYSTEMS

Ihssan Jamal FAREED

Master, Department of Electrical and Electronics Engineering

Supervisor: Prof. Dr. Doğan ÇALIKOĞLU

May 2017, pages 65

This thesis is focused on increasing the power rating of Flyback converter by using interleaving topology. The main achievements of the study are to obtain three phase sinusoidal output with very low THD less than 3%. Increasing the power rating of conventional Flyback converter up to 2.5 KW, and delivering smooth and continuous source power by using three-phase converter which also makes the converter utilize more power from the source especially if PV panels are used. In this thesis SPWM technique is used to control the Flyback converter's switches to obtain half sinusoidal waveform output from the converter with intermediate THD. unfolding inverters use low switching frequency in accordance with the ac load frequency which is 50 Hz are used to unfold the output of the Flyback converter to obtain full AC sinusoidal waveform. Using low switching frequency to control the unfolding inverter leads to minimize the switching losses that leads to increase the efficiency of the converter. Two stage filtering is used to minimize the THD, first stage on the output of the Flyback converter while the second stage is the second order low pass filter that is connected to the load to deliver smooth sinusoidal waveform to the three-phase load.

Keywords: Flyback converter, Harmonics, Interleaved converters, Sinusoidal PWM.

ÖZET

FOTOVOLTAİK SİSTEMLER İÇİN SINÜZOİDAL ÜÇ FAZLI TERMİLATÖRLÜ FLYBACK İNVERTERİNİN ANALİZİ VE İNCELENMESİ

Ihssan Jamal FAREED

Yüksek lisans, Elektrik-Elektronik Mühendisliği Bölümü

Tez Danışmanı: Prof. Dr. Doğan ÇALIKOĞLU

Mayıs 2017, 65 sayfa

Bu tez, aralıklı topoloji kullanarak Flyback dönüştürücünün güç oranını arttırmaya odaklanmıştır. Çalışmanın başlıca başarıları, çok düşük THD değeri% 3'ün altında olan üç fazlı sinüzoidal çıktı elde etmektir. Geleneksel Flyback dönüştürücünün güç oranını 2.5 KW'a çıkarmak ve özellikle PV panelleri kullanılıyorsa konverterin kaynağından daha fazla güç kullanmasını sağlayan üç fazlı dönüştürücü kullanarak pürüzsüz ve sürekli kaynak gücü sunmak. Bu tezde SPWM tekniği, ara gerilim trafosundaki dönüştürücüden yarı sinüzoidal dalga formu çıkışı elde etmek için Flyback konvertörünün anahtarlarını kontrol etmek için kullanılır. Açılan invertörler, tam AC sinüzoidal dalga biçimini elde etmek için Flyback konvertörünün çıkışını açmak için 50 Hz olan AC yük frekansına uygun olarak düşük anahtarlama frekansı kullanır. Açılma frekans çeviriciyi kontrol etmek için düşük anahtarlama frekansının kullanılması, anahtarlama kayıplarını en aza indirgemek için konvertörün verimliliğini arttırmaya yol açar. İki aşamalı filtreleme THD'yi en aza indirgemek için kullanılır, birinci aşamada Flyback konvertörünün çıkışı, ikinci kademe ise üç fazlı yüke pürüzsüz sinüzoidal dalga formu vermesi için yüke bağlı ikinci derece düşük geçiş filtresi.

Anahtar Kelimeler: Flyback dönüştürücü, Harmonik, Araya konan dönüştürücüler, Sinüzoidal PWM.

CHAPTER ONE

INTRODUCTION

1.1 Presentation of The Work

In this work, a two-stage inverter has been designed and simulated to verify the design. The first stage consists of three-phase interleaved Flyback converter and the second stage consists of unfolding inverter. An interleaved Flyback converter can be used for higher power than conventional Flyback converters, also using three-phase system for DC source is more efficient than single phase systems and it results smoother input power that is more efficient especially for PV source. Providing smooth sinusoidal output voltage with low THD. As a result of the designing and simulation, a three-phase interleaved Flyback converter is used to supply three-phase load. This shows that the input power is smother than using conventional Flyback converter, also the output voltage is obtained with THD less than 3% using small LC filter. The main achievement for the interleaved Flyback is the ripple current is less than in the traditional Flyback converters due to dividing the current through the interleaved cells that makes the interleaved Flyback used for higher power than conventional Flyback converter.

1.2 Materials and Methods

This work has been studied, analysed and simulated on specific value of voltage, magnetizing inductance of Flyback converter, switching frequency and load, by using National Instrument Multisim 14.0 simulation software under DCM operation mode. PWM controlling method is used to control the switching of Flyback converter. A constant DC voltage source is used instead of using PV panels for easier analyzation with voltage of 45 V. three phase star Load of 200 V_{rms} 250 W is used that will be supplied by three phase interleaved Flyback converter with sinusoidal output. Unfolding inverter is used with minimum switching frequency is used instead of using PWM technique in the inverting side and that reduces switching losses and increase the overall efficiency.

Flyback converter is an isolated converter topology that uses transforming topology with high frequency switching to boost the voltage by utilizing transforming ability and energy storing of the magnetizing inductance.

Flyback converter is used only for low power application due to the high ripple current in conventional Flyback converter, Interleaving topology that will be discussed in later chapters is utilized with Flyback converters to minimize the ripples of the winding currents of the Flyback and increase the overall efficiency in high power application.

There different controlling technique used to control the switching of the Flyback converter but PWM has special advantage among them that we can obtain sinusoidal voltage with low THD less than 3%.

1.3 Converters in General

Power Electronic has never stopped developing specially with the development of semiconductors that made many researchers work in this field of research and development. Flyback converter has played role in wide range of various researches due to it uses the minimum number of component among the isolated converters.

Francois Forest, has analysis and investigate the idea of using multicell transformers for interleaving Flyback converters in 2007,2009 and 2010. Also, he has showed the designing parameters for multicell transformers. Also, he showed that separated transformers used instead of using multicell transformers. [20]

Young-Ho Kim, Young-Hyok Ji and other researchers showed a controlling technique to improve the efficiency in photovoltaic built in with interleaved Flyback converters in 2013 [27]

Zhiliang Zhang, showed another controlling method to achieve high efficiency of interleaved micro Flyback inverters for PV source grids in 2013 by utilizing the properties of DCM and BCM operation modes for their benefit of hiving less losses [28].

Mingzhi Gao, Min Chen, Qiong Mo, Zhaoming Qian made a research about the output current of the Interleaved Flyback converters in Boundary Conduction Mode (BCM) Operation Mode. analyzing the functional relation between the output current and input current by theoretical derivation and showing the influence of the operation mode to the THD [29].

Yao-Ching Hsieh, studied an interleaved Flyback converter with zero switching voltage, which consists two Flyback converters parallel operated and a shunt inductors connected in between of the diodes leads to minimize the recovery losses on rectifying diodes [30].

Janviere Umuhoza, proposed a design of solar microinverters consists of interleaved Flyback converter with multi stages and regulated using feedback loop for controlling and phase-shifting control. A snubber circuit of resistor, capacitor and diode is used for each stage. A Flyback converter that have the topology of isolating the input and output, and built-in with a full-bridge inverter to obtain a specific frequency and voltage delivered to distant homes load. Simulation and experimental results achieved verifying the idea of the proposed design for solar micro-inverters [31].

Masataka Ishihara, Shota Kimura. Have analyzed and designed the passive components for interleaved Flyback converters with integrated transformers. analyze the quantitative volume and power losses of the integrated transformer and the input capacitor. also, an experimental work has been done to prove the theoretical study [32].

Ramya Chandranadhan, has worked with bridgeless Flyback Rectifier with bi-directional Switches, introducing a control technique for the mode of average current. The proposed control method utilizes a closed feedback loop for voltage, that keeps the fixed output voltage and another closed loop is used to measure the input current. This method for using Flyback converter as rectifier showing that it is suitable to obtain the required voltage from a variable voltage [33].

1.4 Contribution of the work

Photovoltaic (PV) arrays have gained a significant attention in last few years to utilize the nature power and reduce the pollution which caused by normal power generators also because of the high evolution of power electronics [1-2]. Since the utilization of solar energy became so important but in the same time it has low panel voltage, various types of boost converters have been introduced like Boost-Converters, Buck-Boost Converters and Z-source [3-5]. Flyback converter has an advantage among them as it provides electrical isolation and wide range of boosting. Many controlling techniques have been introduced to reduce the distortion (THD) in DC-AC converters although they still suffer from relatively high THD. Also, many kinds of inverters have been introduced to achieve low AC distortion, however high switching frequency is needed leads to lower overall efficiency of the converter [6-7]. Single phase converter with sinusoidal waveform has been introduced to reduce THD in Buck-Boost and Flyback converters which would be used with a simple inverter with less switching frequency which obtains low switching losses and low total harmonic distortion [8-9]. PV panels delivers power to the power converter so the power will take the waveform of the output power so if the converter is single phase the power of the source will be a half positive sinusoidal waveform which means in a time it will be reach zero and also the voltage of the PV panels is not constant with time so a capacitor of high capacity is needed to remain the voltage constant. According to the mentioned drawbacks, an interleaved three phase Flyback converters with sinusoidal waveform shifted by 120^0 between each other and connected to inverters has been studied in this thesis to eliminate the mentioned drawbacks by eliminating the need of PWM techniques which will reduce switching losses and the average power of the source will be higher which means smaller energy bank is needed to be connected to the PV arrays so that the efficiency will be increased, with low total harmonic distortion we can connect the output to an LC filter of smaller size since the output is already has low THD that will result in smoother sinusoidal waveform to be connected to the grid. High THD distortion of the AC waveform has many disadvantages to the AC load especially to rotary loads due to the sudden changing of the flux frequency that results in vibration in the rotor part and it may cause a damage to the load. Also high distortion effects the efficiency of the load so low distortion is required in some load for smooth operation with high efficiency.

.

1.5 Organizing of The Proceeding Chapters

Chapter Two gives an introduction about the topologies that related to this work and shown the differences and their operation principle then Chapter Three shows the operation principle of the interleaved Flyback converter and the analyzation of the converter. Chapter Four shows the simulation, results and conclusion for non-interleaved three phase Flyback converter. Chapter five shows the simulation of the interleaved Flyback converter then in Chapter Six the results of the three-phase interleaved Flyback converter are shown, finally Chapter Seven a Conclusion is given in this chapter and future works that can be done are given.

CHAPTER TWO

CONVERTERS AND INVERTERS PRINCIPLES

2.1 Power Electronic

It is defined as *"The applications of the solid-state electronics with power, electronics and control"* [10].

Generally power electronics deals with two stages Power Converting and Controlling. The control deals with steady state and dynamic characteristics, power deals with converting power signal waveforms to required waveform that needed in the system such as converting the power from DC to AC and from AC to DC.

2.2 Types of Power Electronic Circuits

Generally power electronics are classified into six classifications:

1. Rectifiers
2. AC to DC Converters (Controlled-Rectifiers)
3. AC to AC Converter (AC-Voltage Controller)
4. DC to AC Converter (Inverter)
5. DC to DC Converter (DC-Chopper)
6. Static Switches

2.2.1 Diode Rectifier

A diode rectifier circuits is a circuit that convert an alternative signal (AC alternative current) to a fixed constant signal (DC direct current) and it can be a three-phase circuit or single phase circuit [10-12].

2.2.2 AC to DC Converters (Controlled-Rectifiers)

AC-DC converters which also known as controlled rectifiers are an electrical circuit consists of two switches, which rectify the AC voltage signal to DC voltage signal. The average output voltage is related to the On period of the switches so it can be controlled by varying the duty cycle. As other rectifiers, the source can be either single-phase or three-phase [10-12].

2.2.3 AC to AC Converters

AC-AC converter as also known as AC Voltage Controller is a circuit that obtains a variable output of AC power signal from a fixed AC power signal with bidirectional switches. The obtained voltage is related to the On period of the switches so it can be controlled by varying the duty cycle [10-12].

2.2.4 DC to AC Converters (Inverters)

DC-AC Converters also known as Inverters. They are electrical circuits that inverts the DC voltage to AC voltage. Inverters are used in many application such as Uninterruptable Power Supply (UPS), Adjustable Speed Drivers (ASDs) and other utility application for bulk power transporting. The controlling of the Inverter is done by using PWM techniques. If variable voltage is needed a combination of DC-DC Converter and Inverter is used [10-12].

2.2.5 Static Switches

Power electronic devices is used as contactors, the power supply source is either AC or DC, and the switches are called static switches for AC or switches for DC.

Electronic switches converters convert DC voltage to another DC voltage value by storing the input energy in magnetic storage which is inductor temporarily and then releasing this energy to obtain different voltage values depending on the On period of the switching. The storage might be in magnetic components such as inductors or capacitors. This type of conversion usually has high relative efficiency up to 90%, while voltage regulating with linear converting has lower efficiency due to dissipating the unwanted power as heat. Disadvantage of switching converters are circuit complexity, noise (RFI – EMI) and cost. DC-DC converters can be classified according to the electrical isolation to Isolated converters and Non-Isolated converters. Non-Isolated converters is a converter using transformerless technique which means the input and the output are electrically connected (sharing a common ground point). An Isolated converter is a converter that use transformer technique in which means they does not share a common ground point. Examples of transformerless converters (Non-Isolated Converters) topologies like [10-12]:

1. Buck Converter
2. Boost Converter
3. Buck Boost Converter

And for transformer converters (Isolated Converters) topologies:

4. Push-Pull Converter
5. Forward Converter
6. Flyback Converter

2.2.6 Buck-Converter

It is a switch-mode converter, a step-down Converter that utilizes two types of switches; a transistor and a diode. Energy storing components are inductors and capacitors. The output voltage function for this topology is:

$$V_o = DV_{IN} \tag{2-1}$$

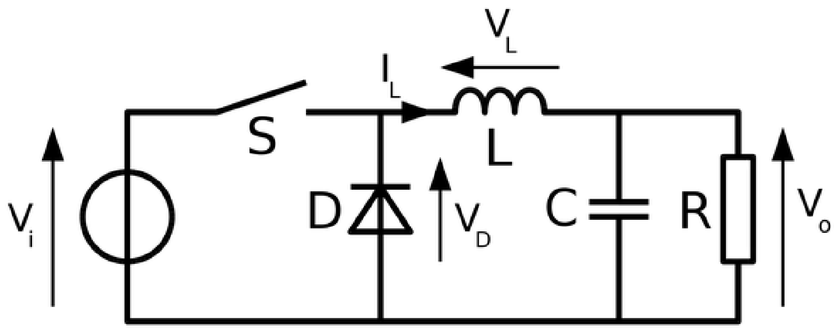


Figure 2.1 : Buck converter [10].

The mentioned formula works when $i_L > 0$ and the converter operated in continuous conduction mode (CCM).

2.2.7 Boost-Converter

It is a switch-mode power supply (SMPS) converter, it is a as step-up converter. It contains of two types of switches; diodes and transistors, and minimally one energy storage component; capacitance or inductance passive component. Theoretically the output can reach infinity but in practice it cannot due to parasitic effect of the components [10-12]. The output voltage equation for this converter is:

$$V_o = \frac{V_{IN}}{1-D}\ (CCM) \qquad (2\text{-}2)$$

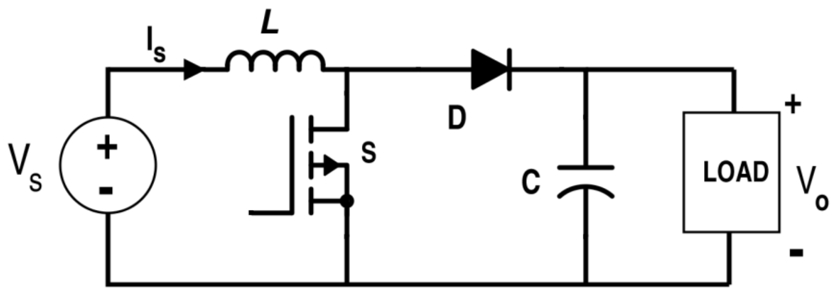


Figure 2.2 : Boost converter [10].

2.2.8 Buck-Boost Converter

A buck-boost converter is a DC-DC switch-mode converter that can convert the input DC voltage to DC Voltage with value of more than or less the input. Its principle is similar to Buck and Boost Converters. The output voltage magnitude based on the duty cycle [10-12]. The output voltage function for buck-boost converter is:

$$V_o = -\left(\frac{D}{1-D}\right) V_{IN}\ \text{(CCM)} \qquad (2\text{-}3)$$

where the polarity will be opposite to the source.

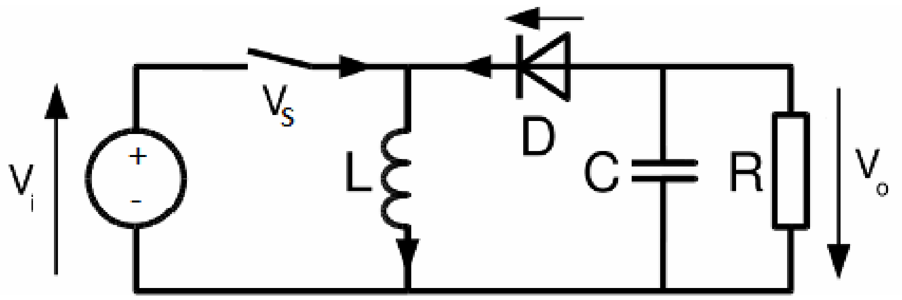


Figure 2.3 : Buck-Boost converter [10].

2.2.9 Push-Pull Converter

A Push-Pull converter is a DC-DC converter that utilizes the ideology of the transformers to convert the DC voltage. The transforming turns-ratio is fixed; however, in many applications the duty cycle controls the output voltage of the converter. The main motivations of Push-Pull converter are their simple circuit and it is able to gain high power so that they are utilized in industrial power applications. Figure 2.4 shows the Push-Pull topology with power up to 300 W [10-12]. The formula of the output voltage is given below:

$$V_0 = 2V_{IN}\left(\frac{N_S}{N_P}\right)D \quad \text{(CCM)} \tag{2-4}$$

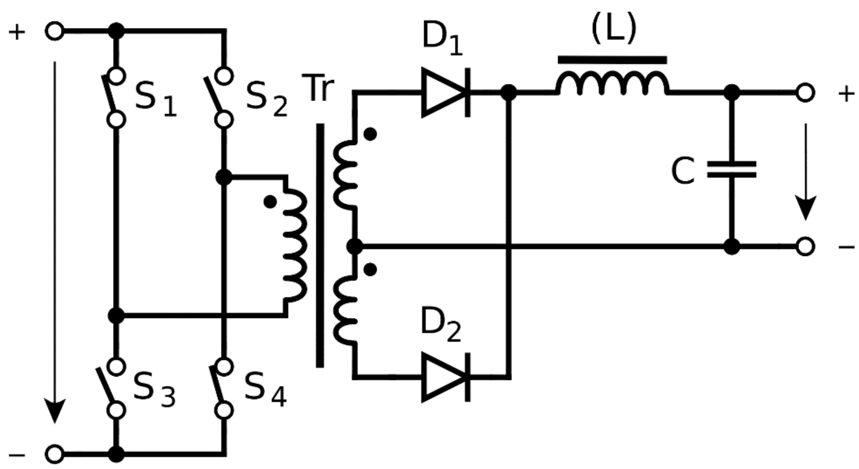


Figure 2.4 : Push-Pull Converter [10].

2.2.10 Forward Converter

A Forward converter is a modified version of Push-Pull Converter by replacing one of the switched with a diode. Single it is less expensive, has less losses and requires less placing space than Push-Pull converters. Forwards Converters are popular converter used for low power application with maximum output power of 250 W [10-12]. The formula of the output voltage is:

$$V_0 = V_{IN}\left(\frac{N_S}{N_P}\right)D \text{ (CCM)} \tag{2-5}$$

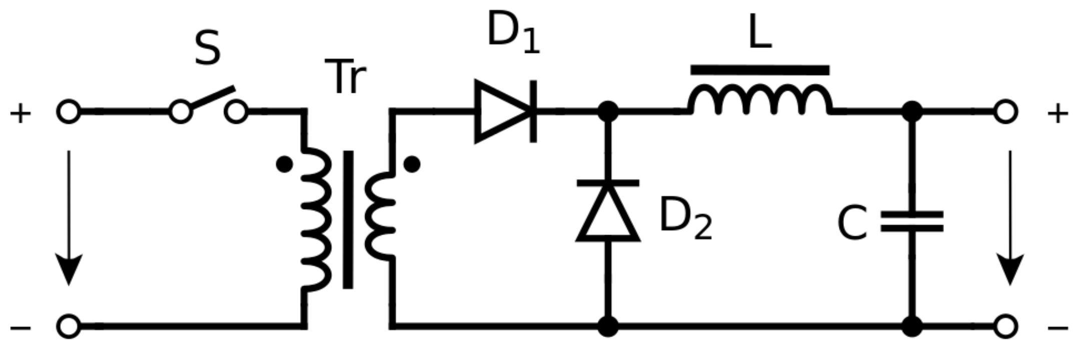


Figure 2.5 : Forward Converter [10].

2.2.11 Flyback Converter

It is an isolated type converter built in with galvanic core isolation. Flyback converters are considered as a Buck-Boost converter that utilize the topology of transformers, so that the load voltage value is varied according to the transforming ratio and duty cycle. Simple design of a Flyback in given in the Figure 2.6 which shows that Flyback has fewer component compared to other topologies. Flyback topology suffer from one main issue which is high inductor current ripple that is solved by using interleaving topology [10-14]. The output voltage equation is given by:

$$V_o = V_{IN}\left(\frac{N_S}{N_P}\right)\left(\frac{D}{D-1}\right) \tag{2-6}$$

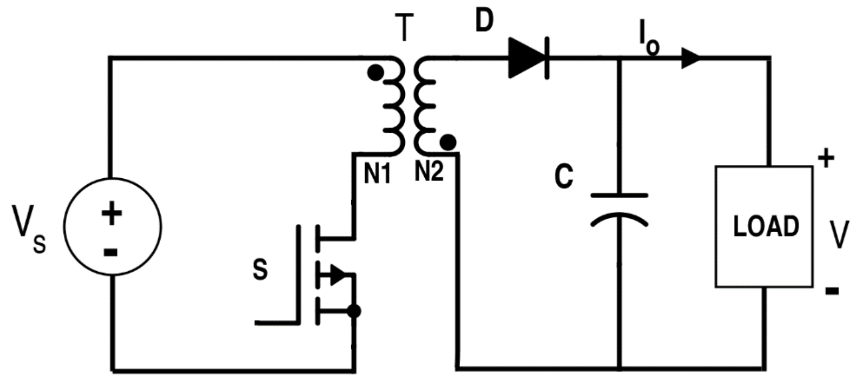


Figure 2.6 : Flyback Converter [10].

Derivation of Flyback converter

Flyback converters are derived from buck-boost converters. The derivation is shown Figure 2.7, where (a) shows the ordinary buck-boost converter's circuit, with two switches types (MOSFET & diode). (b) the inductor has been replaced with two coupled inductors and connected using two wires with a turn ration of 1:1. Inductor's function still not changed, but the two paralleled inductors are equivalent to one inductor with larger wire. In (c) the two windings are disconnected by braking the wires that connect them. Now the two windings are working consequently, the current flows if the primary inductor when Q1 conducts while the current flows in the secondary winding when D1 conducts. The average current of the circuit is the same to the second case (b); however, the currents are divided unequally through the two windings. Since the two inductors are coupled the magnetic field inside the two inductors are identical in both cases.

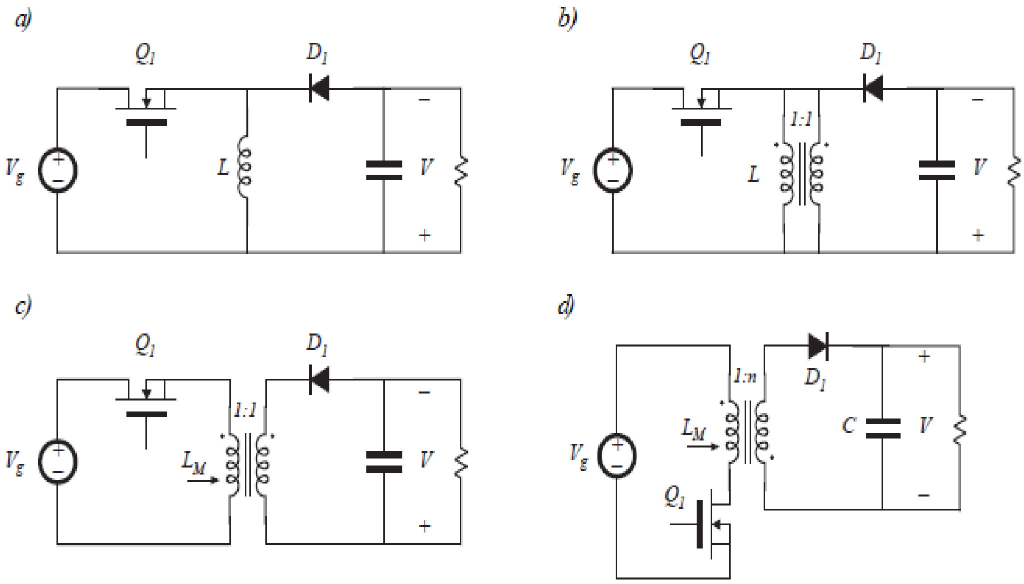


Figure 2.7 : Derivation of Flyback converter [10-13].

The symbol that used for the windings of the Flyback converter is the same symbol that used for the normal transformer also they are called "two-windings inductor". This converter sometimes is called "Flyback Transformer". In ideal transformer, the current flows continuously in both primary and secondary winding while in Flyback converter the current flows in primary winding in On-period of the duty cycle and flows in the secondary winding in Off-period of the duty cycle. (d) illustrates the conventional Flyback converter configurations. The transistor connects the primary winding of the Flyback converter to the ground of the DC source. For better converting optimization, 1: n turns ratio is used. [10-13]

Analyzation of Flyback converters

The analyzation of most of the converters built in with isolated windings is done by taking the simple equivalent circuit of the transformer which consists of two energy storing components; an ideal transformer and magnetizing inductance connected in parallel. The magnetizing inductance behaves according to the usual rules of inductors in addition to volt-second balance when the converter operated in steady-state mode. This applies the average voltage to zero on all windings. For better understanding for the operation of the Flyback converter, the transformer has been replaced with the equivalent circuit described earlier. As shown in Figure 2.8(a) is obtained [13-14].

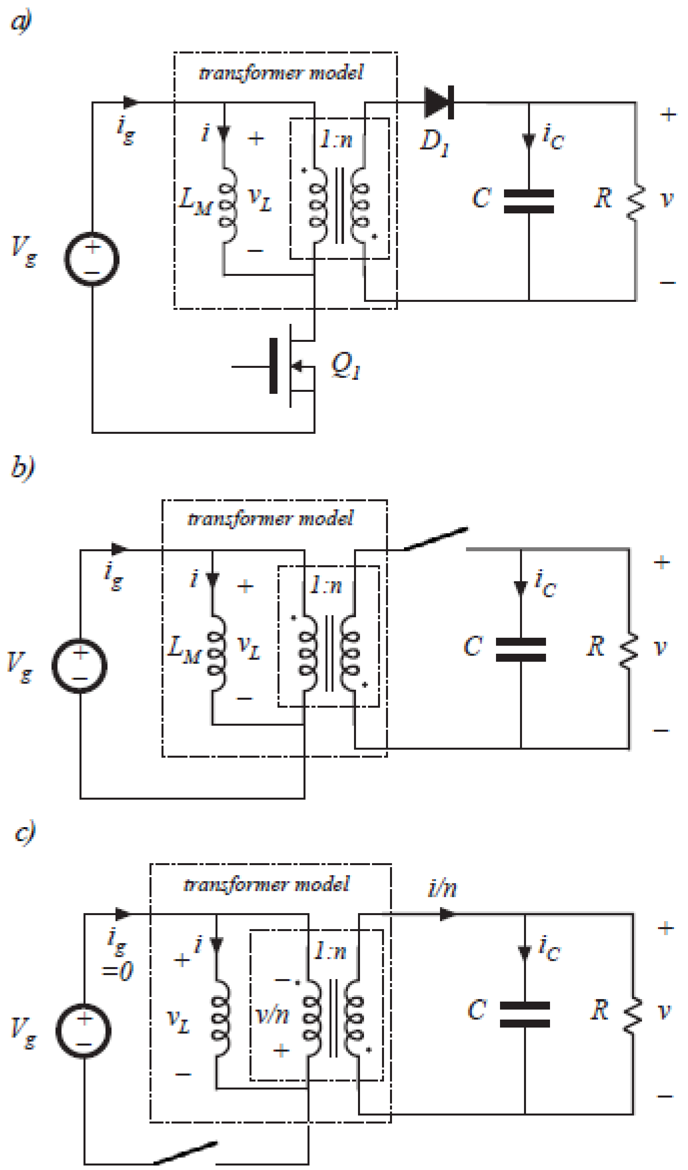


Figure 2.8 : Conduction states of Flyback converter a) Conventional Flyback Converter b) Switched On state c) Switched Off state [10-13].

The L_M works in the same principle as the L of the ordinary buck-boost converters of Figure 2.7 (a). In the first phase when Q1 conducts, L_M stores energy from the source. In the second phase when D1 contacts, the energy that is stored in L_M is delivered to the load. The current and voltage of the inductor are scaled according to duty cycle and the 1: n ratio.

In phase 1, while the transistor Q1 conducts, the diode D1 will be in reversed biased. The converter model will be reduced to Figure 2.8(b). The voltage of the inductor v_L, Current of the capacitor i_C, and dc source voltage $i_g$are given by:

$$v_L = V_g$$
$$i_C = -\frac{v}{R} \qquad (2\text{-}7)$$
$$i_g = i$$

Assuming that the converter is operated with small capacitor voltage and inductor ripple, the output capacitor voltage v and magnetizing current i can be approximately calculated by their dc components V, I respectively by the following equations:

$$v_L = V_g$$
$$i_C = -\frac{V}{R} \qquad (2\text{-}8)$$
$$i_g = I$$

During the phase 2. The transistor Q1 is off and the diode D1 conducts, the circuit will be modelled as it is shown in Figure 2.8(c). The voltage of the magnetizing inductance v_L, the current of the capacitor i_C in the secondary side, and the current of the dc source are calculated by the following equations:

$$v_L = -\frac{v}{n}$$
$$i_c = \frac{i}{n} - \frac{v}{R} \qquad (2\text{-}9)$$
$$i_g = 0$$

The $v_L(t), i_C(t),$ and $i_g(t)$ waveforms are shown in the Figure 2.9.

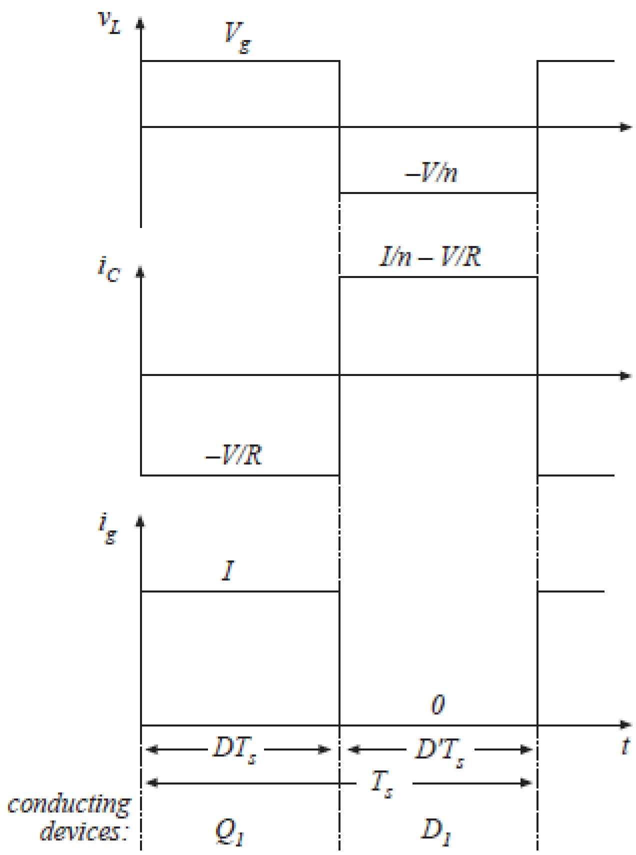


Figure 2.9 : Current States of Flyback Converter [10-13].

2.3 Interleaving of SMPS

Most Switched Mode Power Supply (SMPS) can be connected in parallel with k number of identical converters and this is called interleaving and controlling signal is typically the same with phase shift of 360^0/k, the consequences are different from each converting topology to another there are three main converting topologies has been used in interleaving form (Forward Converter, Push-Pull Converter and Flyback) [20].

2.3.1 Forward

There are two types of interleaving for Forward converters as shown in Figure 2.10, one of them is connecting the secondary side in parallel and the other is connecting the secondary side in series.

1) Parallel Connection: With secondary side connected in parallel, this method requires k number of inductors and transformers operating at the same frequency F

(this applies for k > 2; k=2). This case of connection has one necessary output inductor.

2) Series Connection: With secondary side with series connection, allows combining the rectified voltage waveform. It's not very suitable for low voltage applications due to the drop voltage of series connected diodes. [16], [17].

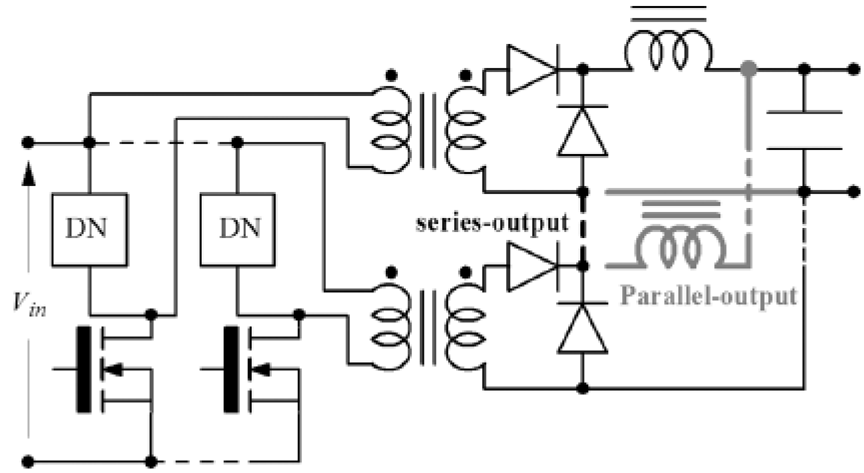


Figure 2.10 : Interleaved Forward Converter [20].

2.3.2 Push-Pull

The push-pull converter as shown in Figure 2.11 is can be interleaved in two options parallel or series. It is suitable for low voltage power conversion with numerous variants [16], [19].

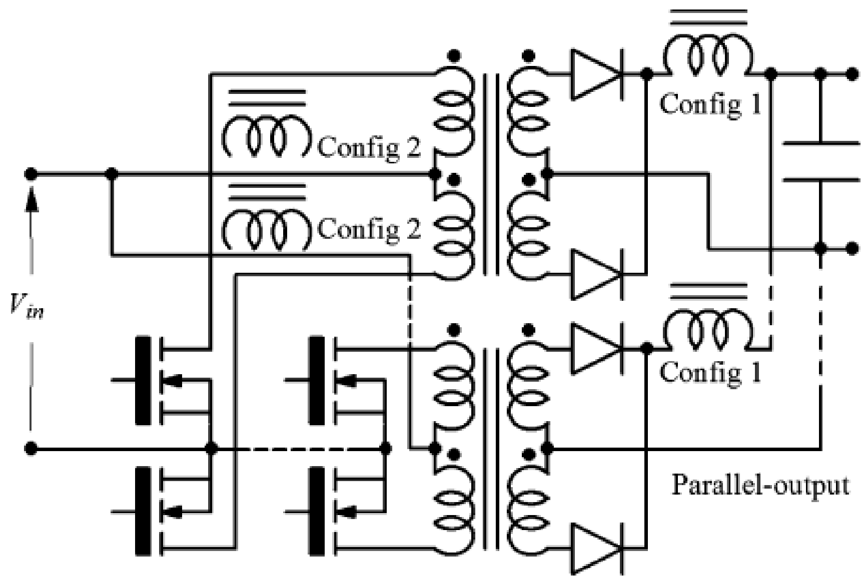


Figure 2.11 : Interleaved Push-Pull Converter [20].

2.3.3 Flyback

Interleaving Flyback Converters as shown in the circuit in Figure 2.12, with two output connection options parallel and series.

1) Parallel Connection: The interleaved Flyback converter with secondary side parallel connected configuration is more known and because the interleaved currents are summed up to a current waveform with multilevel formation in the output of the converter.
2) Series Connection: Secondary series connected option for k number of interleaved connections requires k number of capacitors and k number of diodes series connected on the output side of the converter. This analyzation shows that the parallel connected interleaved Flyback is a suitable choice for high power applications [20].

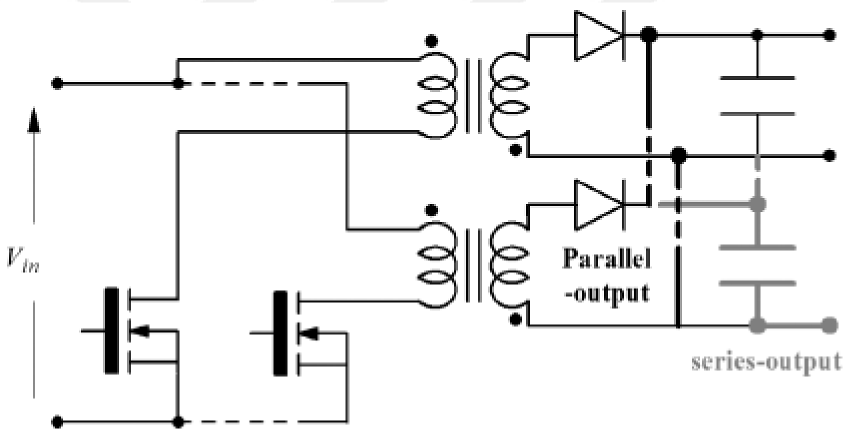


Figure 2.12 : Interleaved Flyback Converter [20].

2.4 Inverters

Inverters takes wide part in power electronic world since and it is developed with the developing of semiconductors. Inverters convert DC power to AC power through varying the polarity of the input DC source with time. The output voltage will have specific frequency depending on the controlling technique that used. The normal output voltage of any inverter is square AC voltage but the amplitude of the output will be related to the inverter type and duty cycle. Generally, the output AC voltage of the inverter has high THD, many techniques has been used to minimize the THD of the output but none of them reached zero THD since most of the inverters use PWM controlling techniques which will be discussed in deep later in this chapter. There many researchers worked in this field of power electronic and many types of inverters have been studied and proposed for both single and three phase power system. An inverter has the following facilities:

a) The output voltage waveform can be square wave or sinewave with low THD.
b) Controlling the voltage can be done by drives of the switches.
c) Some inverters are called PWM inverter due to using the Pulse Width Modulation Techniques.
d) Non-sinusoidal voltage has harmonic distortion that makes them not sinusoidal.
e) Proper control schemes are used to reduce these harmonics.

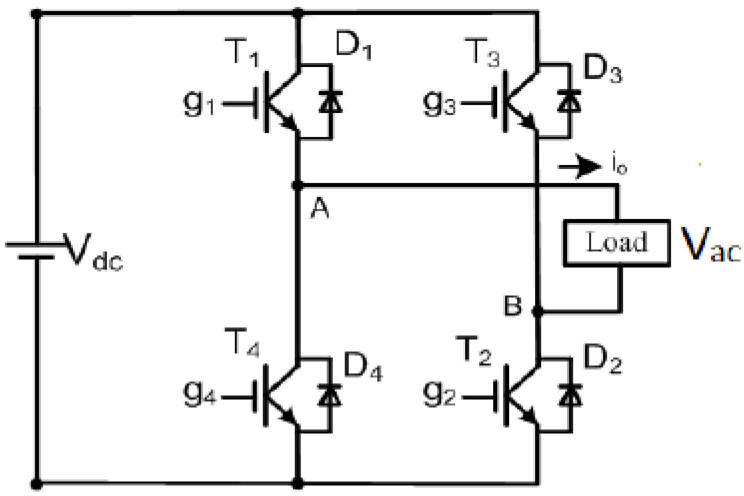


Figure 2.13 : General Schematic of Single Phase Inverter [10-13].

Generally, inverters are classified according their source to two classification VSI and CSI which are the abbreviation for (Voltage Source Inverters) and (Current Source Inverters) respectively. Inverters can work for single or three phase converters.

a) VSI are supplied by constant voltage source while CSI are supplied by constant current source.
b) To convert a voltage source inverter to current source inverter an inductor is connected in series and then changing the supplied voltage to obtain the required current.
c) A VSI and CSI can operate in the voltage control and current control mode respectively.
d) Inverters are used in various applications like uninterrupted power supplies (UPSs), static VAR compensators, induction heating, and etc. [10-12]

Table 2-1 : *Comparison between VSI and CSI.*

VSI	**CSI**
Fixed source voltage	Fixed or adjustable current source
VSIs are supplied by a voltage source with very small impedance.	CSIs are supplied by adjusted current from a voltage source of high impedance.
The nature of the load effects the waveform of the load current and its value.	The nature of the load effects the waveform of the load voltage and its value.
The load doesn't affect the voltage	The load doesn't affect the magnitude of the current
Circuit complexity	Circuit simplicity
Feedback diodes are required	Feedback diodes are not required

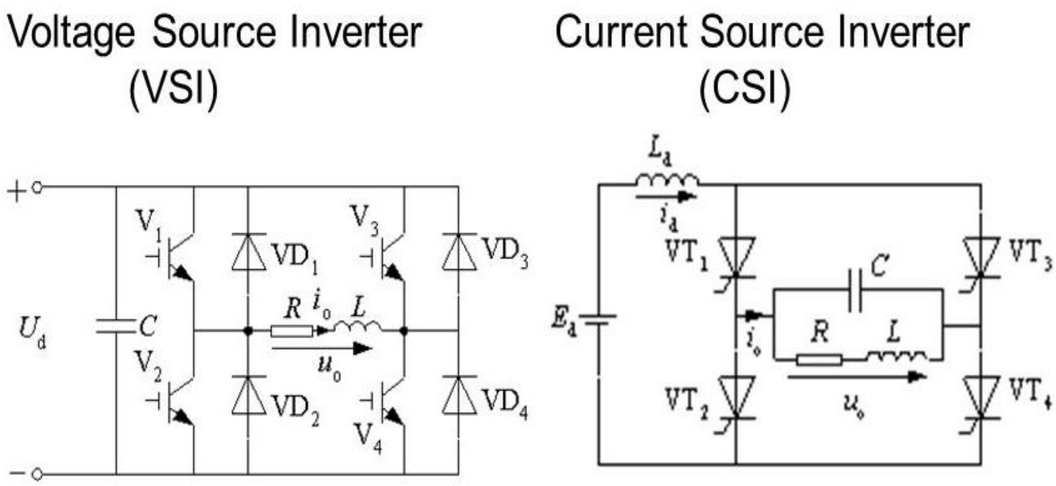


Figure 2.14 : Voltage Source Inverter (VSI) & Current Source Inverter (CSI) [10-13].

2.4.1 Inverter Controlling Techniques

Controlling technique is one of the most important topics that researches focus on. Inverters has relatively high AC voltage distortion which is can be reduced by using proper controlling technique also low-pass filter usually is used to get pure ac voltage but it will increase the cost and losses. Controlling techniques can be divided to two division square voltage out-put and sine voltage output. Square voltage output can be obtained by using bi-directional controlling technique, while sine voltage output can be obtained by using PWM (Pulse Width Modulation) controlling technique which is the most known and used technique in inverters. PWM technique is used to reduce the distortion of the output voltage but still a pure AC voltage can't be obtained from PWM technique without using Low-Pass filters. Many types of PWM techniques have been introduced but the most known two types are SPWM and SVPWM [10-16].

2.4.2 Square Controlling Techniques

Square controlling techniques is one of the most used techniques when only inverting is needed without any controlling to the input signal and it has some advantages due to its low switching frequency, easy to control and low cost. The output of this technique is AC signal with square waveform. This output is most suitable to low-sensitivity applications such as lighting and heating.

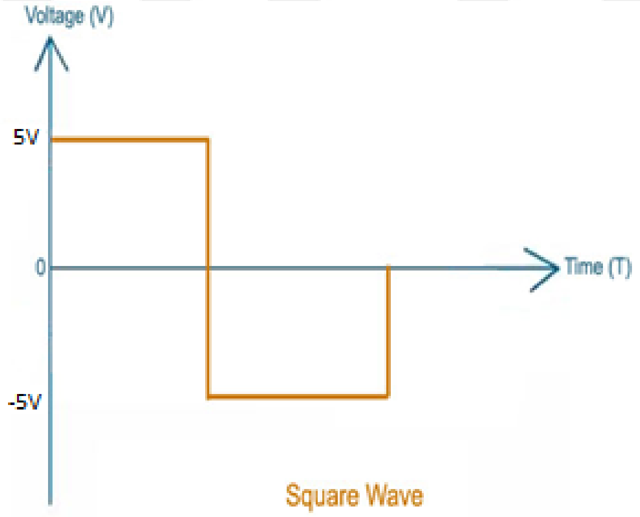


Figure 2.15 : Square Controlling Technique Waveform [10-16].

2.4.3 Sine Controlling Techniques

Pulse Width Modulation (PWM)

it is a modulation technique to convert the analog signal to pulsing signal. This technique is widely used in power electronic especially in converters and inverters topologies and one of the most important advantage of this technique is to reduce the THD of the ac signal when it is used with inverters. The idea concept of this method is to convert the input signal to square wave by controlling the switches, the "on" period of the square wave is controlled by the technique to provide variety "on" and "off" periods to the square wave where the ration of the "on" period to the "off" period is called duty cycle [10-16]

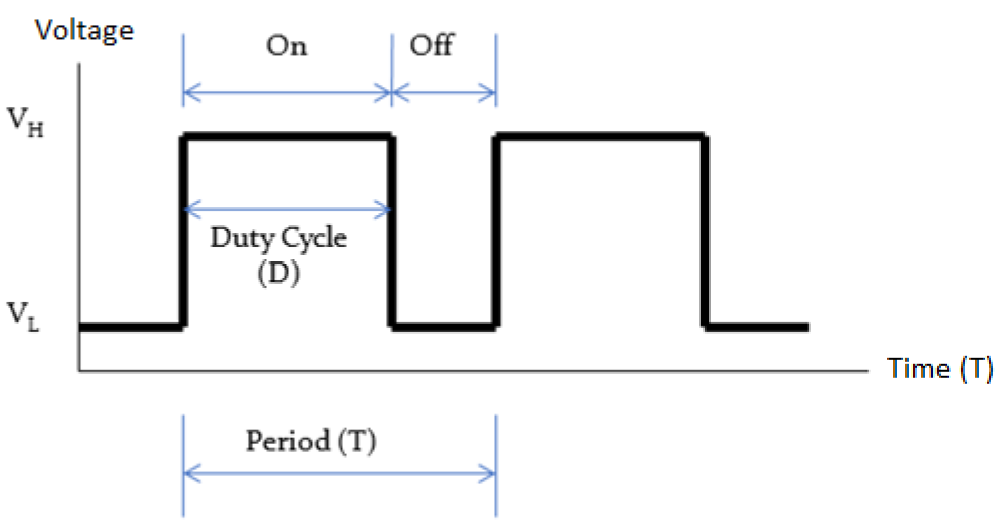


Figure 2.16 : Pulse Width Modulation Controlling Technique [10].

Duty Cycle is calculated by:

$$Duty\ Cycle = \frac{OnTime}{Period}\ 100\% \qquad (2\text{-}10)$$

There are many advantages for this technique:

1. Average value and duty cycle are proportional related.
2. Low power is used in transistors which to switch the signal.
3. High switching frequency is possible due to the development of power electronic.
4. less noise.
5. Less heat dissipation compared to using resistors for intermediate voltage values.

While the disadvantages are:

1. Expensive.
2. Complex circuit.
3. RFI.
4. Voltage sparks.
5. Electromagnetic noise

The generation of the PWM technique signal can be done by using an electronic circuit that has two signal generators, one generates saw tooth signal which is called carrier signal and the second one generates sine wave signal which is called reference signal. A comparator should be used to compare these two signals and gives an output of 5V:

1. When sine is greater than sawtooth PWM is high.
2. When sine is less than sawtooth PWM is low.
3. PWM toggles when sine equals sawtooth.

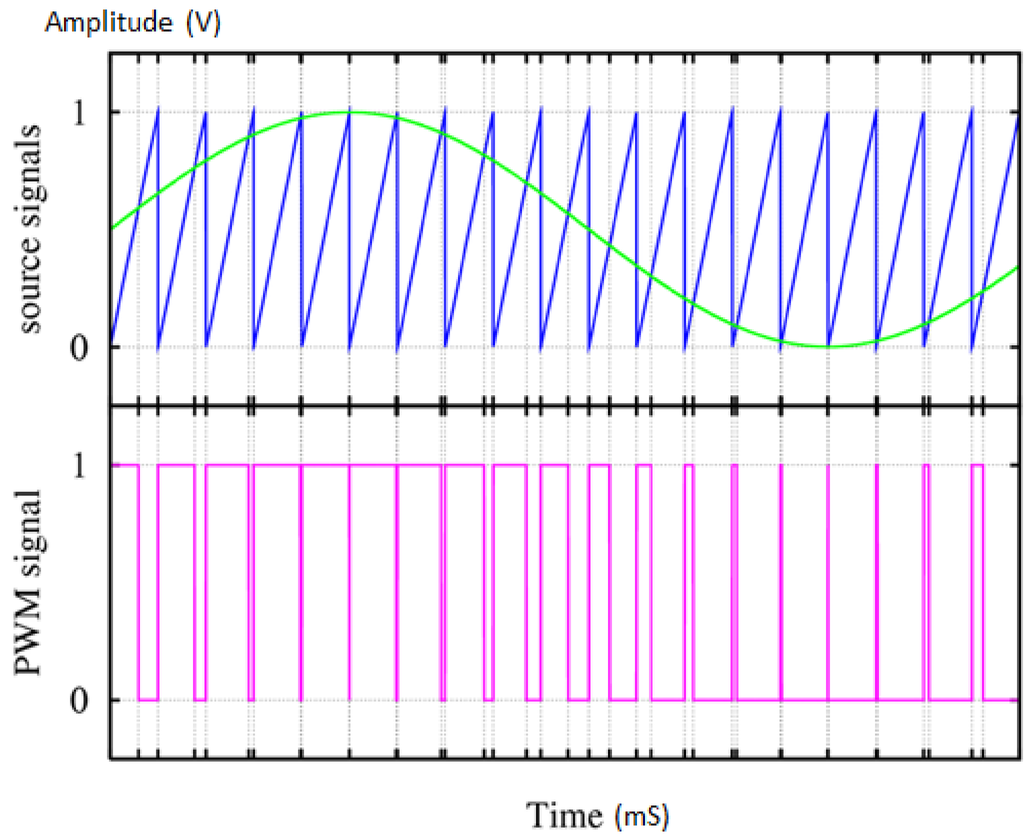


Figure 2.17 : Sinusoidal Pulse Width Modulation Controlling Technique [10].

Choosing the frequency of the carrier signal:

1. Application dependent.
2. Not too low:

    1. Audible frequencies
    2. Twice the inverse of device time constant
    3. 10 Times higher than control system frequency
3. Not too high:
    1. More heat is generated in transistor at high frequencies
    2. At high frequencies, some loads not responding

2.5 Discontinuous Conduction Mode (DCM)

DCM is one of the three known conduction modes that available which are DCM, CCM and BCM which are the abbreviation for Discontinuous Conduction Mode Continuous Conduction Mode and Boundary Conduction Mode respectively which is considered as DCM in principle. The conduction mode express the output current waveform of converter where, in DCM and BCM the waveform of the current will be triangular where the current will reach zero at the end of the period Off-State of the switch and then the current raises to a specific value. DCM appears at large switching ripple enough to reverse the polarity of the switch. The DCM generally occurs in DC-DC converters or AC-DC rectifiers and sometime appears in different types of converters such as inverters or other converting topologies built-in with two quadrant switches. DCM operation mode is usually used in converter applied for high load with large inductor current ripple. [18].

2.5.1 Benefits of DCM in Interleaved Flyback converter

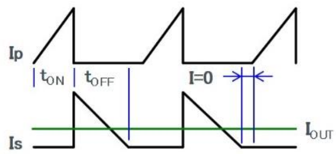
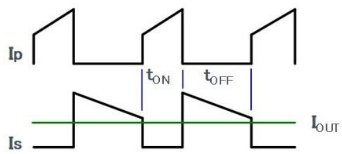
In this work, Discontinuous Conduction Mode is used for the following motivations:

1. Stability and fast dynamic responsivity for considered operating conditions.
2. Doesn't have reverse recovery issues, where the diode shows reverse recovery issue in CCM operation mode which result in EMI problems, noise and additional losses which reduce the overall efficiency. So, DCM prevents all these complications.
3. Eliminate the turn on switching losses.
4. Minimize transformer size.

5. Ease of control. Feedback loops are not needed where a feedback loops are sufficient to obtain a sinusoidally formed current with low THD this makes the control of the converter easier and have less complexity.

Beside the advantages and benefits of using DCM operation mode, there are also several drawbacks. In DCM, the current waveform has high RMD to mean ration (form factor) compared to CCM operation which causes more losses, as a solution for this drawback, every path carrying current should have low resistivity, another disadvantage is the current pulses which have high peak values and discontinuity in the waveform, and for this disadvantage parallel connections for the same converter is a good method to handle the high peaks currents. Nevertheless, all these drawbacks will be reduced by interleaving topology which connects number of flyback converter cell in parallel. Firstly, each cell will have less current peaks due to the interleaving the discontinuity will be the same which will be much decreased when all of the interleaved cells connect at the input source with a common point. All these benefits come from sharing the drawn power evenly among the phase-shifted cells over one period of switching cycle leads to the minimum discontinuity. Table 2-3 gives a comparison between CCM and DCM [7], [17], [25].

Table 2-2 : Comparison between conduction modes for Flyback converter.

Comparison item	Discontinuous mode	Continuous mode
Operation	 Discontinues current waveform	 Continues current waveform
Transformer	Smaller inductance, smaller size and cheaper	Higher inductance, bigger size and more expensive
Rectifying Diode	Fast recovery	Needs a faster recovery type,
Switching transistor	Higher power is allowed	Less power is allowed
Output Capacitor	Higher ripple current	Less ripple current
Efficiency	Less switching losses and higher efficiency	higher switching losses and less efficiency

CHAPTER THREE

WORK PRINCIPLE AND ANALYSIS

3.1 Literature Review

Solar energy which is one of the most important and known green energies and it is also renewable source of energy plays a great role in the energy market and science world currently; Therefore, the development and research in the rise. However, the cost of most of the converting technologies limits the global consumption, the cost is one of the essential points for commercialization especially in small electrical applications. A Flyback converter has motivations due to its simple structure and easy power flow. It recognized as isolated converter and it has an advantage over other isolated converters since it has least number of components that leads to make it the lowest in cost compared to other isolated converters, this advantage due to eliminate the need of two separated storing components which are the inductor and the transformer by combining these two components. In other converting topologies, the energy storing component and transforming component are separated. This motivation leads to lower cost and smaller transformer size. One of the challenges come when designing a transformer with high energy storing. Since the energy is stored in the air gap of the transformer, that makes Flyback converters needs relatively large air gap; however, that results magnetizing inductance to become small. The aforementioned challenge achieves a low leakage inductance for small magnetizing inductance. A Flyback converter's transformer that has large leakage flux and poor coupling will lead to reduce the energy transfer efficiency. The mentioned drawbacks of conventional Flyback converters make it not suitable for high current applications. As a result, Flyback topology is used only for small power applications. Here where interleaving taking in role to solve the aforementioned drawbacks where multi number of cells can be interleaved to increase the power the can be used for an application. But still we will face the problem of high cost and complexity of using low pass filter which can be minimized by using special controlling technique which will be discussed later in in this chapter to obtain sinusoidal waveform with low THD so small low pass filter can be used to deliver smooth sinusoidal waveform with small low pass filter components and minimum THD.

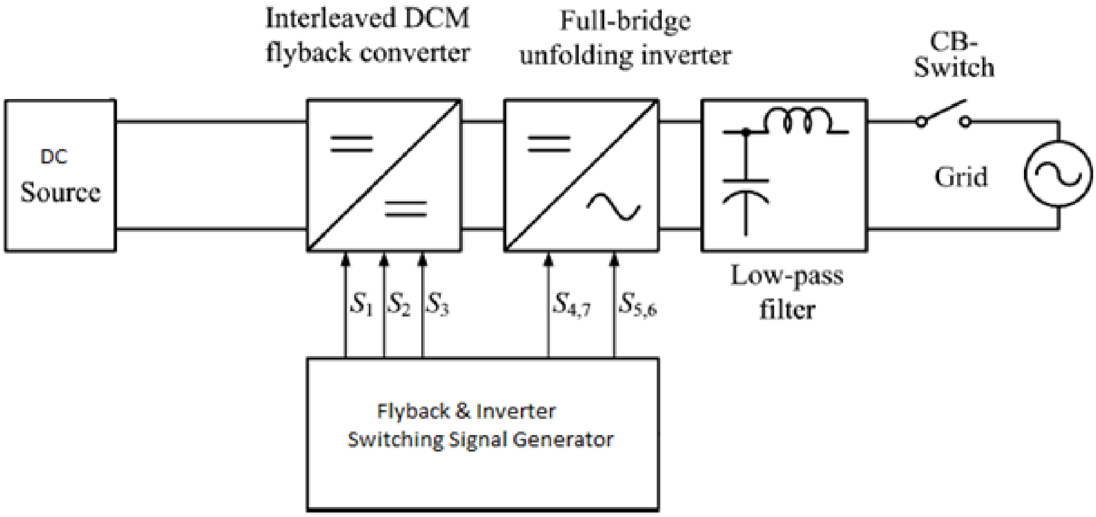


Figure 3.1 : Block diagram of interleaved Flyback converter with unfolding inverter.

In previous researches a decupling capacitor used to be used after the PV panel to maintain the flow power flow of the converter, where in this study using of three phase sinusoidal converter of interleaved Flyback converter

3.2 Operating Principles

DC voltage source is applied to three-phase converters of interleaved Flyback transformer each interleaved Flyback consists of three interleaved cells. Each Flyback converter is connected by switch at the primary side, while a diode is used to connect the secondary side to the inverter. Also, the load side of the topology consists of unfolding full-bridge inverter and a second order LC filter for pure sinusoidal waveform with minimum THD for better interface with the grid, where the topology obtains a sinusoidal output waveform with low THD that makes the cost of the low pass filter low. The unfolding full-bridge inverters are used to unfold the half sinusoidal DC voltage of the converter output to AC voltage without using any modulation techniques. To simplify the principle of the converter, one phase out of three will be explained. The Flyback converter operation is divided for two subintervals, first subinterval when the switches of the primary side that are connected with the ground terminal of the Flyback converter are turned On, and the second subinterval when those switches are opened. In the first subinterval, the current flow from the source to the primary windings of the Flyback converter and an energy stored in form of magnetic field. In this subinterval, no power is transferred to the load directly from the source due to the existence of the diode, so the load is supplied by the C_f and L_F. While in the second subinterval the stored energy in the magnetizing inductance is transferred to the load in current form. The Flyback converter is operated in Discontinues Conduction Mode (DCM) for stability and ease generating of AC current at the grid station in addition for the aforementioned benefits of DCM in Chapter Two. The DCM operation mode produces triangular current pulses of Flyback converter windings under open loop control with each switching period. If PWM controlling technique is used as it is explained before in Chapter Two, a group of triangular pulses with different amplitudes will be formed as explained in Figure 3.2 and Figure 3.3. Specifically, Figure 3.2 shows the input current pulses of the Flyback converter primary winding and Figure 3.3 shows the output current pulses of the Flyback converter secondary winding. The instantaneous currents are composed of peaks with discontinuity that falls in form of sinusoidal due to the controlling scheme of sinusoidal PWM. Figure 3.2 also input current (i_1) that has high switching frequency, the average of the pulsed current ($\bar{\imath}_1$) which has low frequency over one switching cycle and the DC current (I_1) which is the average current over one grid period.

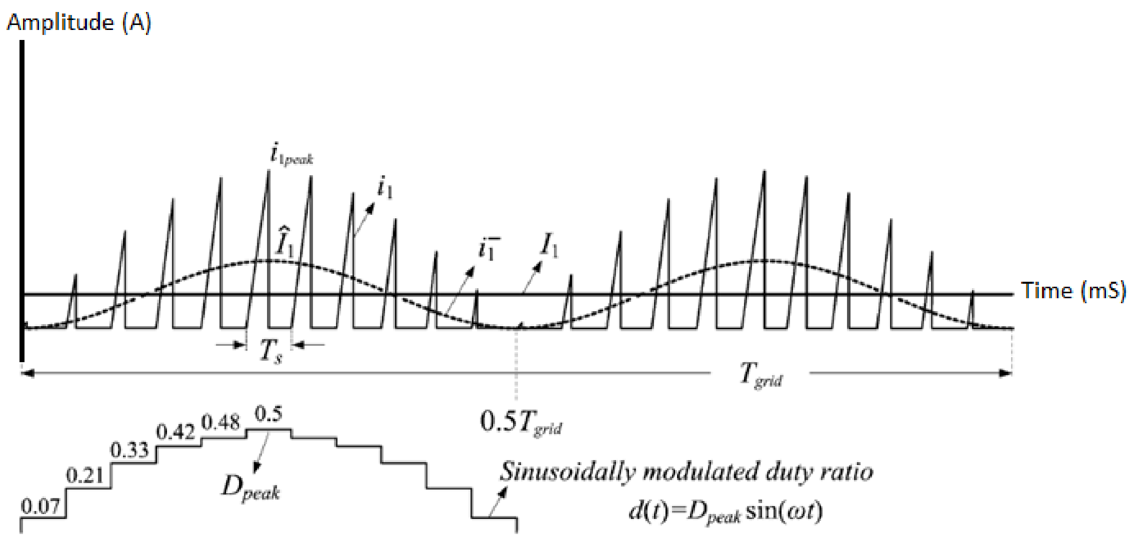


Figure 3.2 : Input Current (i_1), average current (i_1) over one switching period, DC current (I_1) over one grid period.

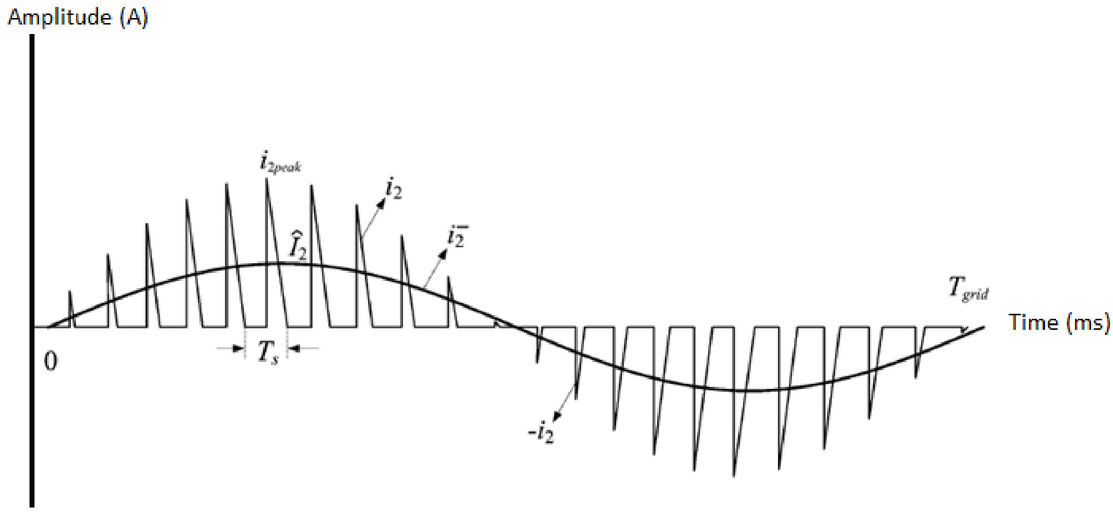


Figure 3.3 : Output current (i_2) after unfolding and Output average current (i_2) over one switching period.

In practice if this topology is applied on PV sources, so any supplied current by it to the grid, it will cause variation in the supplied voltage. The variation at the terminals should be small so a decoupling capacitor should be placed at the source and sized in which only the DC current is applied by the source and both low and high frequencies are bypassed. In this work, an ideal voltage DC source is used for the ease of analyzation and implementation. Since the unfolding inverter is used only to unfold the sinusoidal modulated output of the converter to AC output, the switched of the inverter are operated with line frequency which is considered very low frequency compared with the switching frequency used in modulation. The losses of the switches are decreased and just conducting losses are involved for these reasons, the unfolding inverter bridge can use thyristors or transistors switches due to the low switching frequency to reduce the cost [21-24].

3.3 Interleaved Flyback using intercell Transformer

Flyback converter can be implemented using intercell transformers which is also known as inter-phase transformer and sometimes it is called improperly coupled inductors. Its basic principle has been presented and discussed widely in [21] - [24] like in the Figure 3.4. the function of this converter in ideal cases is to sum-up the generated voltage by k communication.

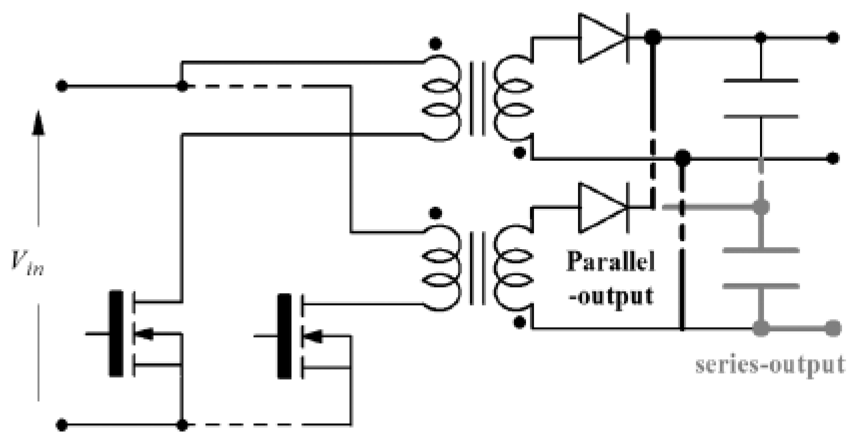


Figure 3.4 : Circuit Diagram of interleaved Flyback Converter.

3.4 Converter Analysis

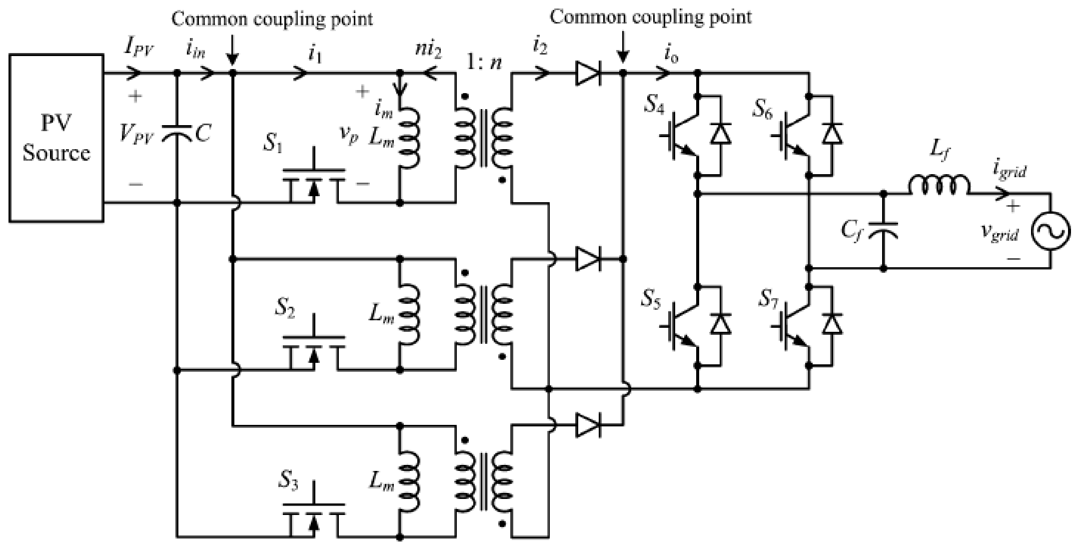


Figure 3.5 : schematic Circuit of the one phase of the interleaved Flyback converter based on three interleaved cells.

The analyzation of interleaved Flyback converter is discussed and based on the schematic diagram shown in Figure 3.5 which shows only one phase of three cell and the analyzation will consider only the first cell of the first phase. The analyzation is taken through one switching period and when the duty cycle value at the peak value and grid-voltage at its peaks value. Figure 3.6 explains the controlling signal for one cell of the interleaved Flyback cells through one switching period, the primary winding voltage of the Flyback converter (v_p), and magnetizing current (i_m) with its secondary and primary currents $i_1$and i_2 respectively over the chosen switching interval where the value of duty cycle at the peak (D_{peak}). notice that the waveform represents discontinuous conduction operation mode [20], [26].

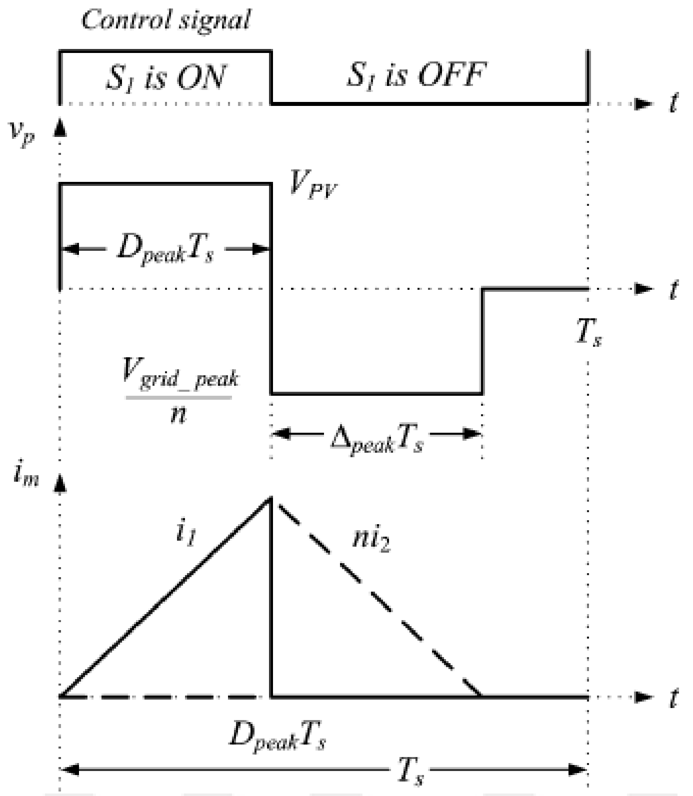


Figure 3.6 : Flyback switching control signal.

3.4.1 Analyzation of Flyback Converter in On State

When switch S_1 is On Figure 3.5 the DC source voltage is supplied to the primary windings of the first Flyback cell and a current flow in the primary winding of the converter. The current increase linearly with positive slope with time from zero initial value assuming that the input value is constant. The current is stored as energy in the source side winding of the Flyback converter. The Flyback input current and magnetizing current can be defined as:

$$i_1 = i_m = \frac{V_{in}}{L_m} t \tag{3-1}$$

Where L_m is the Flyback magnetizing inductance. The current reaches the maximum value at the end of this subinterval and can be expressed as:

$$i_{1peak} = i_{mpeak} = \frac{V_{in} D_{peak}}{L_m F_s} \tag{3-2}$$

Where F_s represents the switching frequency. This maximum current value is reached when the highest value of duty cycle is reached where the duty cycle is sinusoidal modulated. The area that will be drawn from this triangular formed current gives peak value component with twice frequency of the grid current, triangular formed current also shows the maximum value of the current with low frequency component which is given by:

$$\hat{I}_1 = \frac{V_{in} D_{peak}^2}{2 L_m F_s} \quad (3\text{-}3)$$

The average DC current (I_1) that is drawn from the input source is taken from the half of this current.

$$I_1 = \frac{I_{in}}{n_{cell}} = \frac{V_{in} D_{peak}^2}{4 L_m F_s} \quad (3\text{-}4)$$

Where I_{in}; the delivered current from DC input supplier and n_{cell}; number of interleaved cells of the Flyback converter of one phase. Consequently, the relation between the input power and converter parameter can be given by:

$$P_{in} = V_{in} I_{in} = \frac{n_{cell} V_{in}^2 D_{peak}^2}{4 L_m F_s} \quad (3\text{-}5)$$

When a design for implementation is needed the desired value of the Flyback (L_m) is found by (3-5) depending on the selection of the frequency for the converter switches, the best number of the interleaved cells and the best D_{peak} value. The D_{peak} is generated according to desired output voltage or by the MPPT controller of the PV panels to harvest the maximum solar energy.

3.4.2 Analyzation of Flyback Converter in Off State

When S_1 is switched Off in Figure 3.5 the voltage of the primary side windings of the converter turns negative to the load voltage after transferring and scaling by the turns ratio as shown in Figure 3.6, the current of the secondary winding of the first interleaved cell can be expressed as:

$$n i_2 = i_m = \frac{\hat{V}_{\text{grid}}}{n\, L_m}\, t \quad (3\text{-}6)$$

Where $\hat{V}_{\text{grid}}$ is the maximum of the load voltage and n is the secondary to primary turns ratio. in the end of the Off-switching period, the magnetizing currents are decreased to zero in linear form. Since the converter works in DCM. The change in current is given by:

$$n i_{2peak} = i_{mpeak} = \frac{\hat{V}_{grid} \Delta_{peak}}{n\, L_m F_s} \quad (3\text{-}7)$$

Where Δ_{peak} is the time ratio that is needed to reset the magnetizing current to zero as shown in Figure 3.6 and it is equated by taking the area across the primary voltage v_p as given below:

$$\Delta_{peak} = \frac{nV_{in}D_{peak}}{\hat{V}_{grid}} \tag{3-8}$$

Knowing Δ_{peak} finds the maximum value of the instantaneous average for current of the Flyback output ($\bar{\iota}_2$), it is represented by the largest triangular area. Following equation gives this peak value:

$$\hat{I}_2 = \frac{\hat{I}_{grid}}{n_{cell}} = \frac{V_{in}^2 D_{peak}^2}{2L_m F_s \hat{V}_{grid}} \tag{3-9}$$

The above formula also gives the maximum current value that drawn from each interleaved cell. Comparing (3-5) and (3-9) verifies that the input power equal to the delivered power to the grid in an ideal converter. Gives the following equation:

$$P_{in} = V_{in}I_{in} = \frac{n_{cell}V_{in}^2 D_{peak}^2}{4L_m F_s} = \frac{\hat{V}_{grid}\hat{I}_{grid}}{2} = P_{grid} \tag{3-10}$$

assuming $\Delta_{peak} = 1 - D_{peak}$ and by (3-8) the turn ratio of the Flyback transformer can be calculated by:

$$n = \frac{\hat{V}_{grid}(1 - D_{peak})}{V_{in}\, D_{peak}} \tag{3-11}$$

The airgap length of the Flyback transformer can be calculated by using the following expression:

$$l_g = \frac{N^2 \mu_0 A_{core}}{L_m} \tag{3-12}$$

Where N is number of primary winding turns of Flyback converter cell, μ_0 is the air permeability and A_{core} is the cross-section area of the core.

Maximum voltage stress on the switched of the Flyback converter on Off-period can be found by the following expression:

$$V_{SWmax} = V_{inMax} + \frac{\hat{V}_{grid\_max}}{n} + \Delta V \tag{3-13}$$

Where V_{inmax} is the maximum input voltage considering if non-constant input voltage in full time period. $\hat{V}_{grid\_max}$ is peak value of the output voltage. ΔV is the transient voltage that caused due to the parasitic effect in the converter in Off-period and due to the leakage inductance of the Flyback transformer. Snubber circuit or voltage clamp are generally used to reduce the transient. [20] - [23], [26].

CHAPTER FOUR

THREE-PHASE FLYBACK-BASED INVERTER WITH SINUSOIDAL OUTPUT

4.1 Overview

A Flyback converter with special control technique is designed and analysed. The designed Flyback converter has one DC input and AC Output. The control of the converter is designed to achieve a half sinusoidal waveform in the DC side (before the inverter) the reason of having a half sinusoidal waveform to minimize THD and reduce the size of the low pass filter in the output (AC side) and reducing the losses of the switches of the inverter due to the elimination of PWM techniques. The DC half sinusoidal waveform is connected to a bipolar inverter to invert the half sinusoidal waveform to fully sinusoidal waveform. A three-phase sinusoidal waveform reduced the current ripple of the transformer also leaded to have continuous input power waveform which leaded to higher converter efficiency. Interleaved Flyback converters are needed to minimize the current ripple further and increase the maximum power of the Flyback converters which achieved by connecting multiple Flyback transformer in parallel with switching phase shift of 360/n where n is the number of Flyback cells. The sinusoidal waveform has been achieved by varying the duty cycle with time which will be explained in this chapter.

The overmentioned converter has been obtained in two steps, firstly a sinusoidal Flyback converter without an interleaved converter has been designed then for each phase the Flyback has been replaced by an interleaved Flyback converter.

4.2 Three Phase Sinusoidal Flyback Converter

The first work that has been implemented is to design a converter of three-phase converter with Flyback transformer connected to a bipolar inverter. A DC voltage input is connected to three Flyback transformers, each transformer has different duty cycle signal, each duty cycle is shifted by 120 degree with high switching frequency to have sinusoidal waveform.

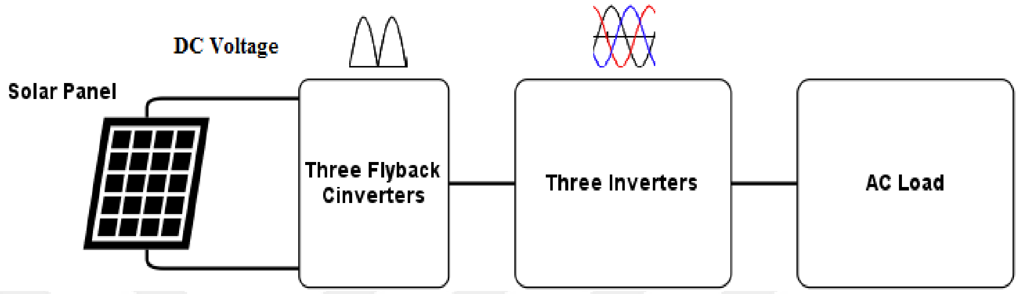


Figure 4.1 : General Block Diagram of Three-Phase Non-Interleaved Flyback Converter.

4.3 Operation Principle

The proposed Flyback which is shown on Figure 4.2 works similarly to the traditional Flyback converter but it has two coupled inductors in the secondary side connected in common point. Each inductor connected to a capacitor with a diode so the capacitors connected in series which leads to have 2Vc on the load.

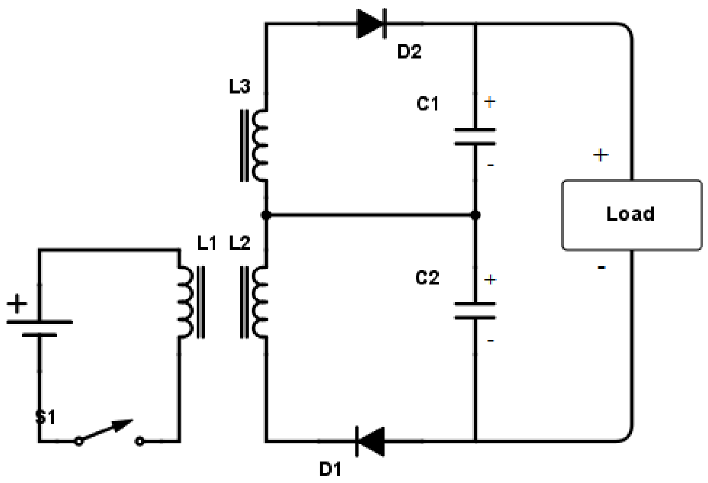


Figure 4.2 : Circuit Diagram of single Flyback cell converter.

Mode I:

In this mode S1 is closed so the current will flow in the primary inductor and energy from the source will be stored in L1 and D1, D2 are in open state as shown in Figure 4.3. this mode ends when S1 is opened.

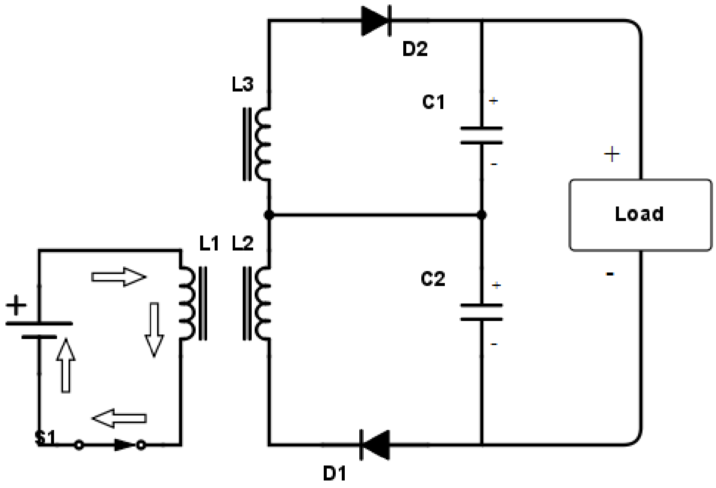


Figure 4.3 : Mode I of Single Flyback Cell Converter.

Mode II:

This mode starts when S1 is opened. In this mode D1, D2 are conducted and the energy stored in L1 will flow from L2, L3 through D1, D2 respectively and charge C1, C2, since the secondary inductors will flow a current oppositely in the common point and since they both work as the same time and having the same energy, that leads to have a zero current in the common wire as shown in Figure 4.4. This mode ends when S1 is closed.

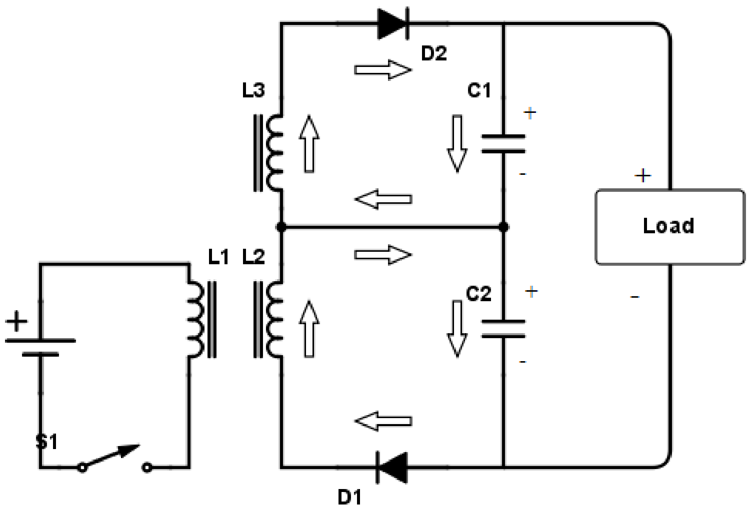


Figure 4.4 : Mode II of Single Flyback Cell Converter.

The sequence will repeat with different duty cycle which leads to have a half sinusoidal output. The control signal for each Flyback differ by the carrier signal, each one has a phase shift of 120^0 between each other which leads to have three signal in the output. First Flyback will have an output of half sinusoidal with phase shift of 0^0, the second one will have an output of half sinusoidal with phase shift of 120^0 and the third one will have an output of a half sinusoidal with phase shift of 240^0. An inverter with π period of on and π of off is needed to obtain an AC output with the desired phase shift for each Flyback. The output of the three Flyback converters can be connected to a star or delta AC load. The complete circuit shown in Figure 4.5.

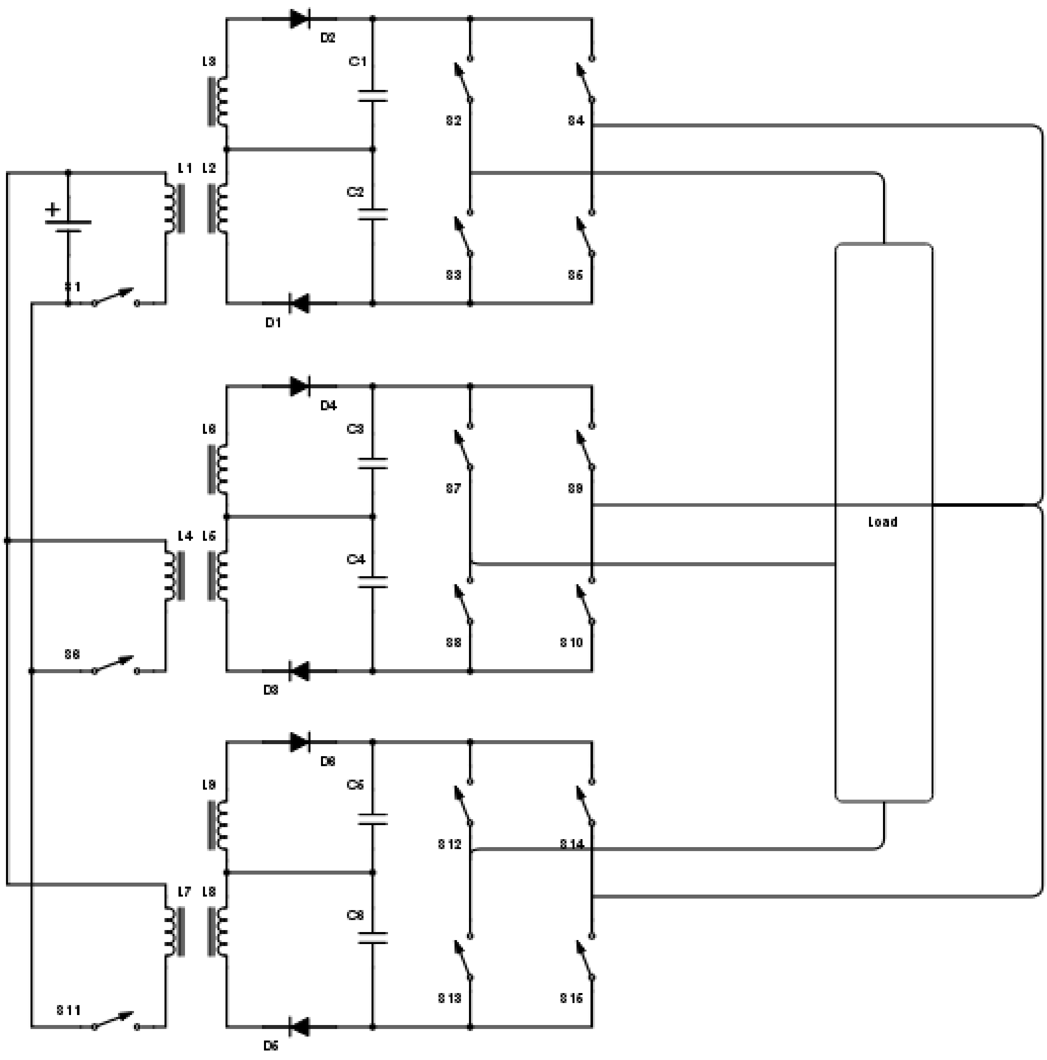


Figure 4.5 : Circuit Diagram of Three Phase Non-Interleaved Flyback System.

4.4 Controlling Technique

The Figure 4.9 shows the carrier signal and the reference signal. The carrier frequency has high frequency compared to the reference signal. As shown the reference signal is not fixed in this converter and it refers to the duty cycle, so to have a sinusoidal DC voltage output the duty cycle needed to be variable starting from zero then to the maximum value that needed then back to zero in waveform of half sinusoidal and keep repeating and this way a waveform of halves sinusoidal is achieved. When the reference signal is higher than the carrier signal, the switch

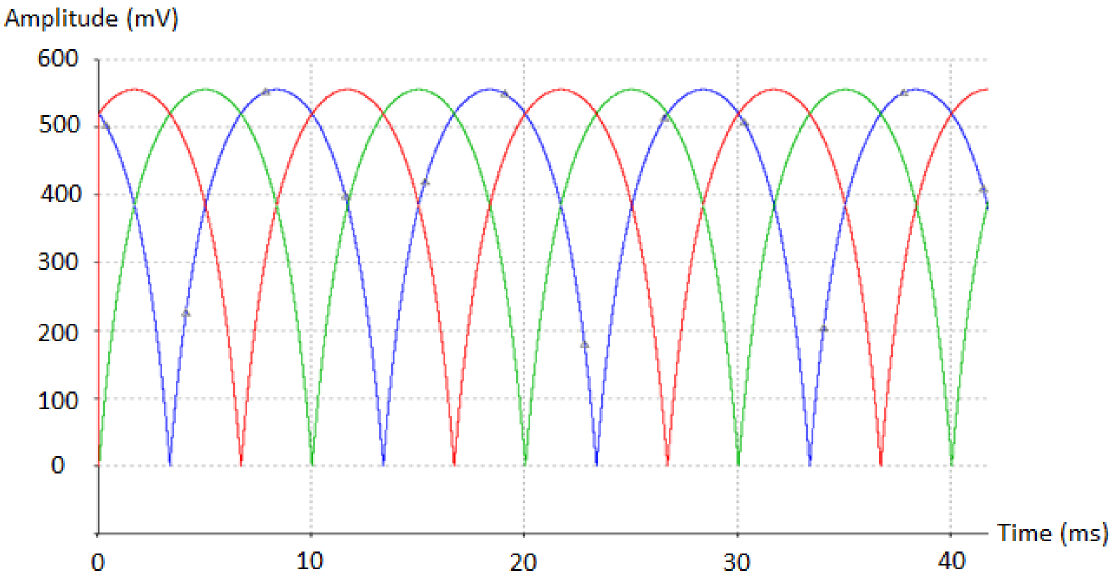


Figure 4.6 : Duty Cycle of three-phase non-interleaved Flyback converter with maximum value of 0.55.

will conduct which leads to charge the primary inductance of the Flyback transformer with a specific energy depends on the on state, in the off state the sorted energy will be transferred to the secondary side of the Flyback transformer with voltage of:

$$V_o = D\, V_{in} \frac{N_2}{N_1} \qquad (4\text{-}1)$$

When the duty cycle increases, the output voltage will be increased.

4.5 Experimental Results

A 10 ohms sinusoidal AC load connected to a three-phase sinusoidal Flyback converter has been simulated in National Instrument (Multisim) software with the following specification: V_{in}=12V, V_{out} = 30, Fs = 100KHz with duty cycle of half sinusoidal waveform with maximum value of 0.555. L1, L4, L7=1mH & L2, L3, L5, L6, L8, L9=2mH C1=C2=C3=C4=C5=C6=2.5uF.

As shown below in Figure 4.7a -the output voltage of the proposed three phase sinusoidal Flyback without low pass filter we can obtain a sinusoidal voltage with THD less than 6% as shown in Figure 4.11, Figure 4.7b shows output current, in Figure 4.8 show the output voltage of the first Flyback and Figure 4.9 show the duty cycle with time. LC filter can be added to the load to ensure smooth sinusoidal waveform.

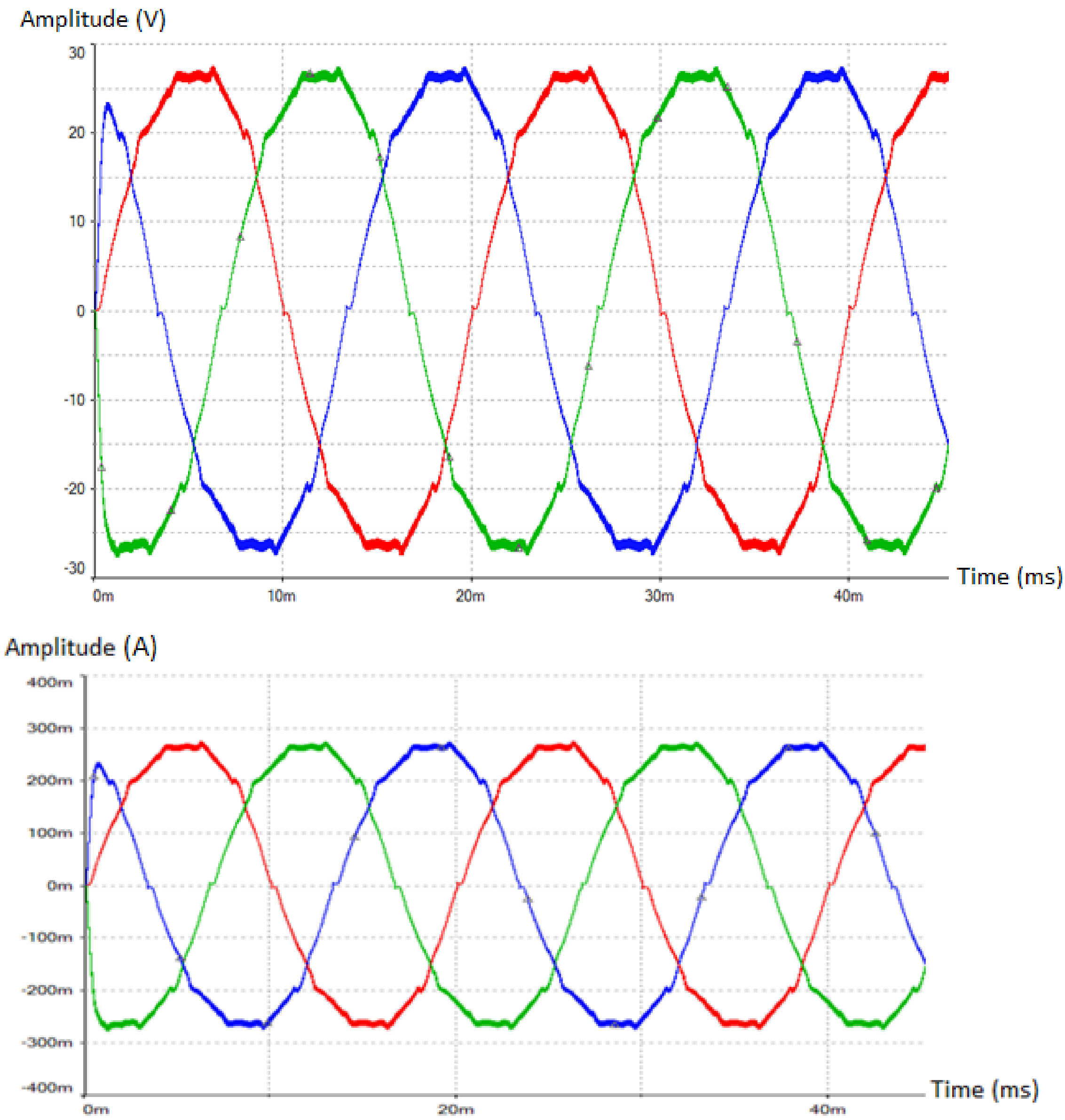


Figure 4.7 : (a) Load Voltage (b) Load Current.

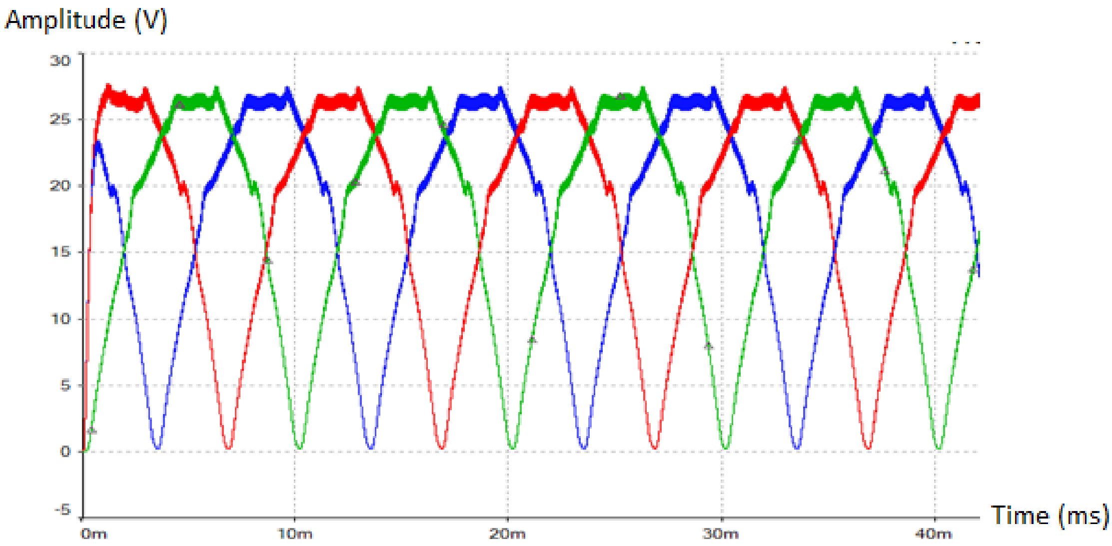


Figure 4.8 : Output Voltage of the three phase Flyback.

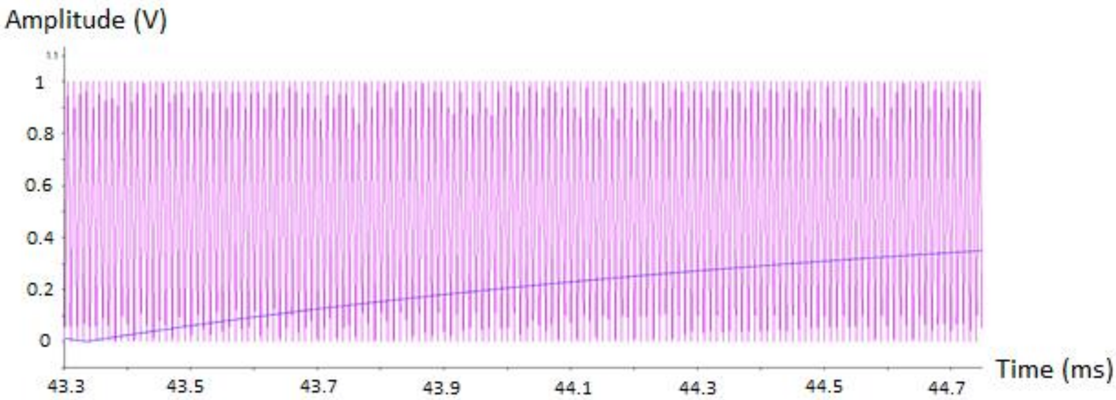


Figure 4.9 : Carrier and Reference Signal.

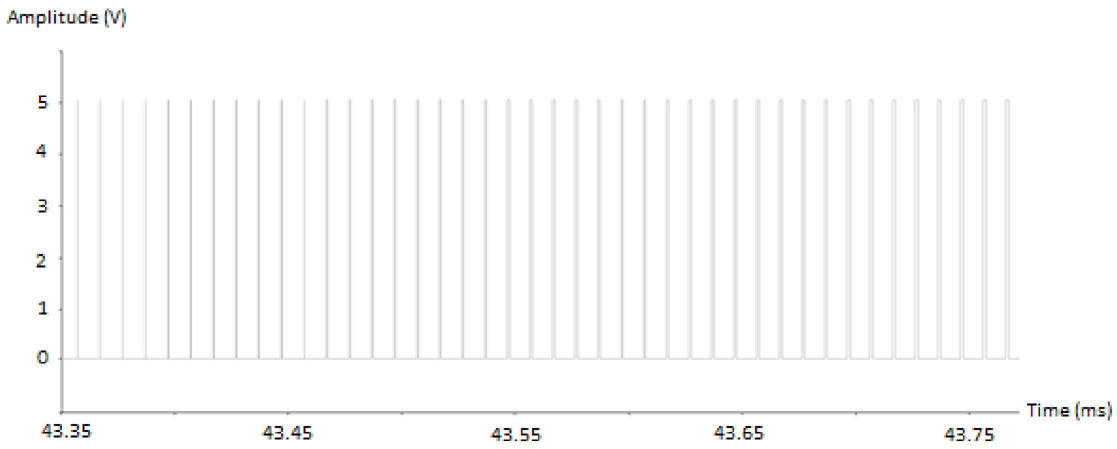


Figure 4.10 : Controlling Signal of one switch of Flyback converter.

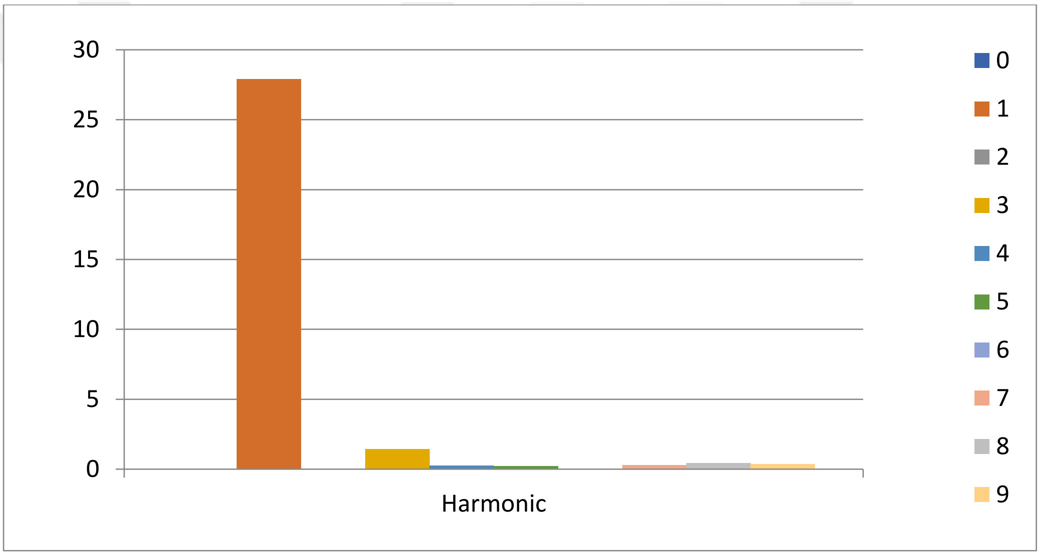


Figure 4.11 : Harmonics of First Phase Load Voltage.

4.6 Conclusion

Single DC voltage source is connected to a Flyback converter to obtain a DC output with half sinusoidal waveform. A three-phase sinusoidal output has been obtained from half sinusoidal outputs of Flyback converters so that minimization of THD obtained with less switching frequency. PV panels can be connected to a three-phase load with smoother power delivering. using the proposed three-phase Flyback converter leaded to have higher average power compared with the ordinary system but still the input power waveform reaches zero values so, an interleaved Flyback converter can be used.

CHAPTER FIVE

SIMULATION OF THREE-PHASE INTERLEAVED FLYBACK INVERTER WITH SINUSOIDAL OUTPUT WAVEFORM

5.1 Overview

Based on previous studies and the achievement that has been obtained from the previous chapter an interleaved Flyback converter is needed to achieve the aim of the study which is having a three-phase output with sinusoidal waveform with minimum THD, high efficiency and utilize the input power sufficiently with smooth power waveform. The interleaved converter consists of three interleaved Flyback converters, each Flyback is sifted by 120^0 to obtain a three-phase voltage output. Each interleaved Flyback converter consists of three Flyback cells interleaved by 120^0 between each two cells. Shifting each cell by 120^0 leads to reduce the ripple current in each cell also divide the power to each cell which leads to utilize the Flyback converter in higher power applications than the conventional Flyback converter which can be used only for small current applications. The controlling of this converter is done by controlling technique which will be explained later in this chapter. The converter consists of three interleaved Flyback converters, switches, input DC power, inverter and LC filter. The inverter which is used for the proposed converter is used only for convert the DC half sinusoidal waveform to AC sinusoidal wave form without any modulation techniques by using reference frequency of 50 Hz which means very low switching frequency compared with other techniques leads to reduce losses of the switching in the inverter and voltages stress on the switches. Realistic component has been used in the simulation, an IGBT of model IRG4PC40UPBF has been used for Flyback converter, a transistor of ON resistance10m Ω, OFF resistance 1M Ω and diode forward drop voltage of 0.7 V has been used for the inverters. A second order LC filter of 10 µF and 1 mH has been used.

5.2 Block Diagram and operation

The block diagram consists of a DC voltage source that represented by a constant DC voltage source in this work, DC-DC converter which is represented by three-phase converter each phase consists of three interleaved Flyback cells. Each phase is shifted by 120^0 and according to interleaving converter and the number of cells that is used in this work that makes the shifting between each two-interleaved cell is 120^0. Unfolding inverters are used to unfold the sinusoidal DC Voltage output of the Flyback converter to AC voltage to be connected to the grid load.

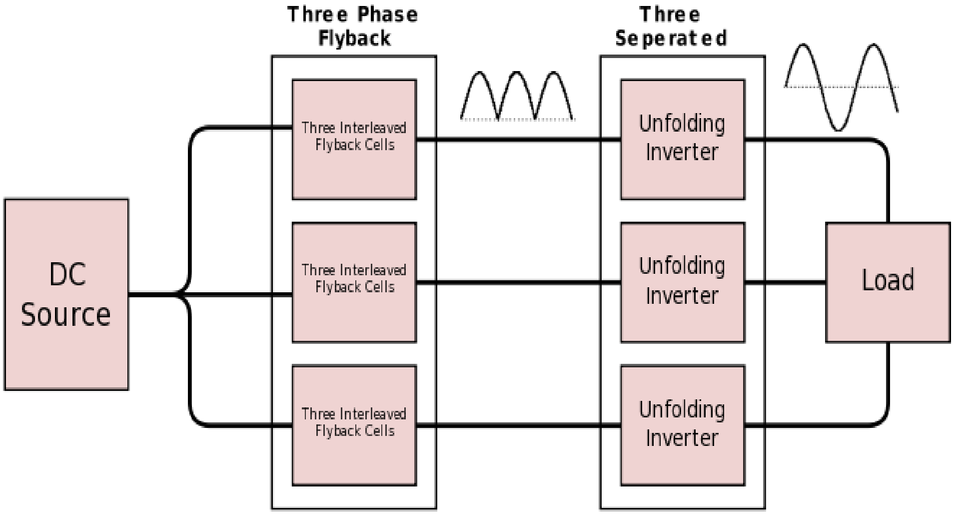


Figure 5.1 : General Block Diagram of Three-Phase Interleaved Flyback Converter.

The DC source apply constant voltage to the three phase Flyback converter, each cell is controlled by separated switch, each phase will have a reference signal that control the duty cycle and varies with shape of half sinusoidal as shown Figure 5.2

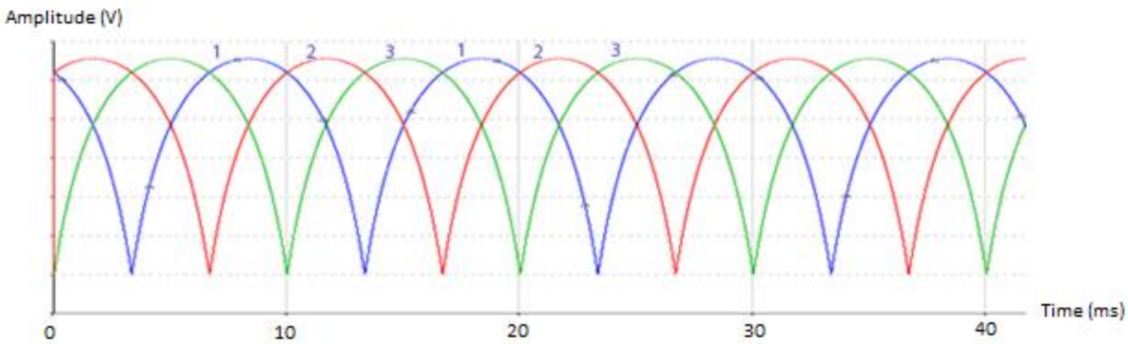


Figure 5.2 : Duty Cycle of three phase interleaved Flyback converter.

All the cell of each phase will have the same reference signal with a carrier signal shifted by 120^0 as shown the Figure 5.3.

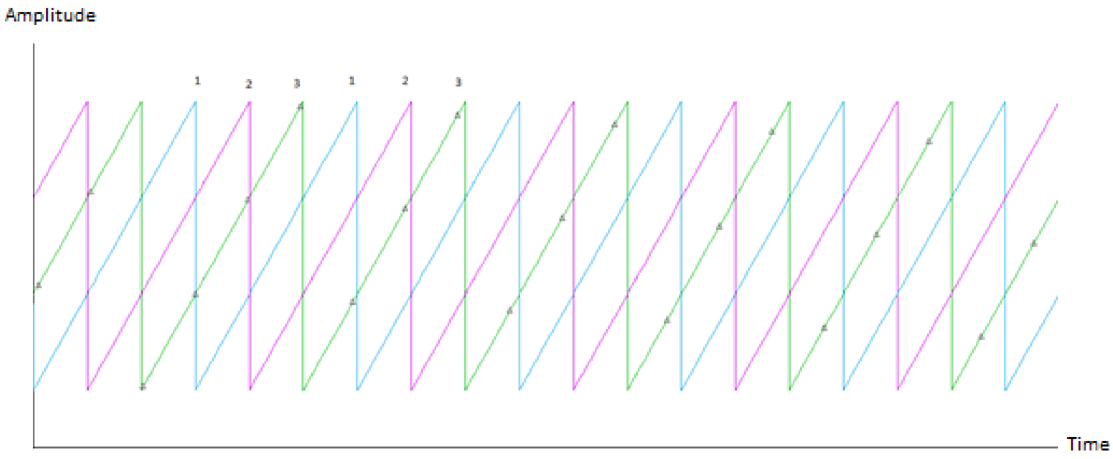


Figure 5.3 : Carrier Signal of The Three Interleaved Cell of One Phase.

In result the controlling signal of each cell will be different, taking the first cell of first phase will show

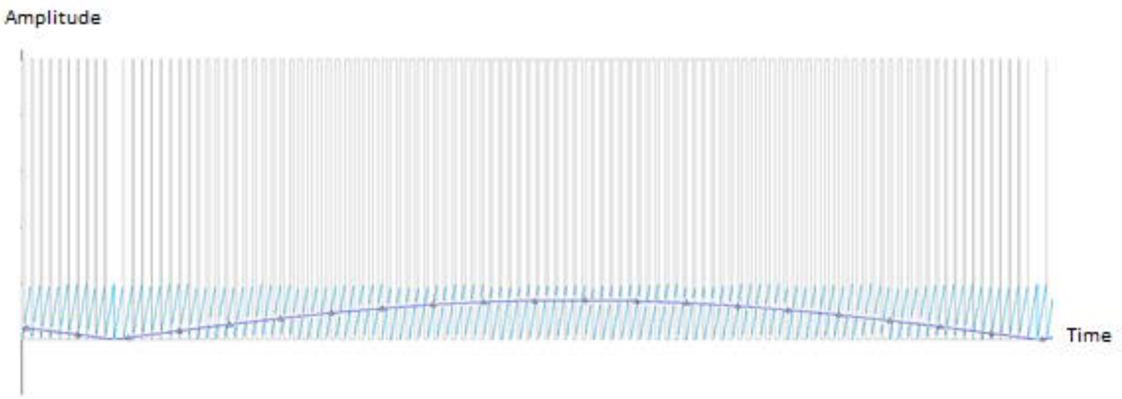


Figure 5.4 : Carrier Signal and Reference Signal and Controlling Signal of The First Interleaved Cell of First Phase.

This controlling technique will result an output of half sinusoidal voltage and current as well which makes the THD much lower.

Figure 5.5 shows the schematic diagram of the converter for one phase only which in inplementation there will be three phases are all connected to the same voltage source. The output of each phase will be a half sinusoidal. The outout of each phase will be connected to an unfoldeing inverter that unfold the output voltage of the interleaved flyaback converter to sinusoidal AC voltage.

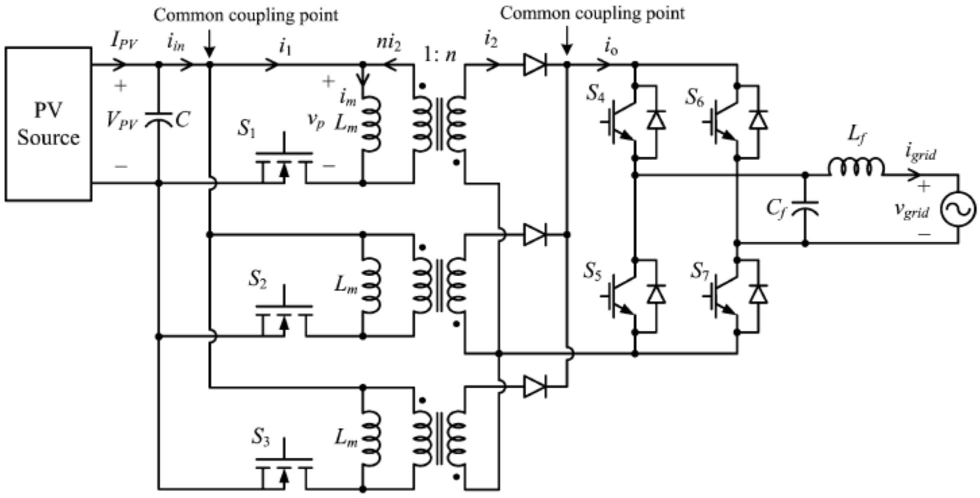


Figure 5.5 : Circuit Diagram of the First Phase of interleaved Flyback converter.

Figure 5.6 below shows the implemented diagram using Multisim

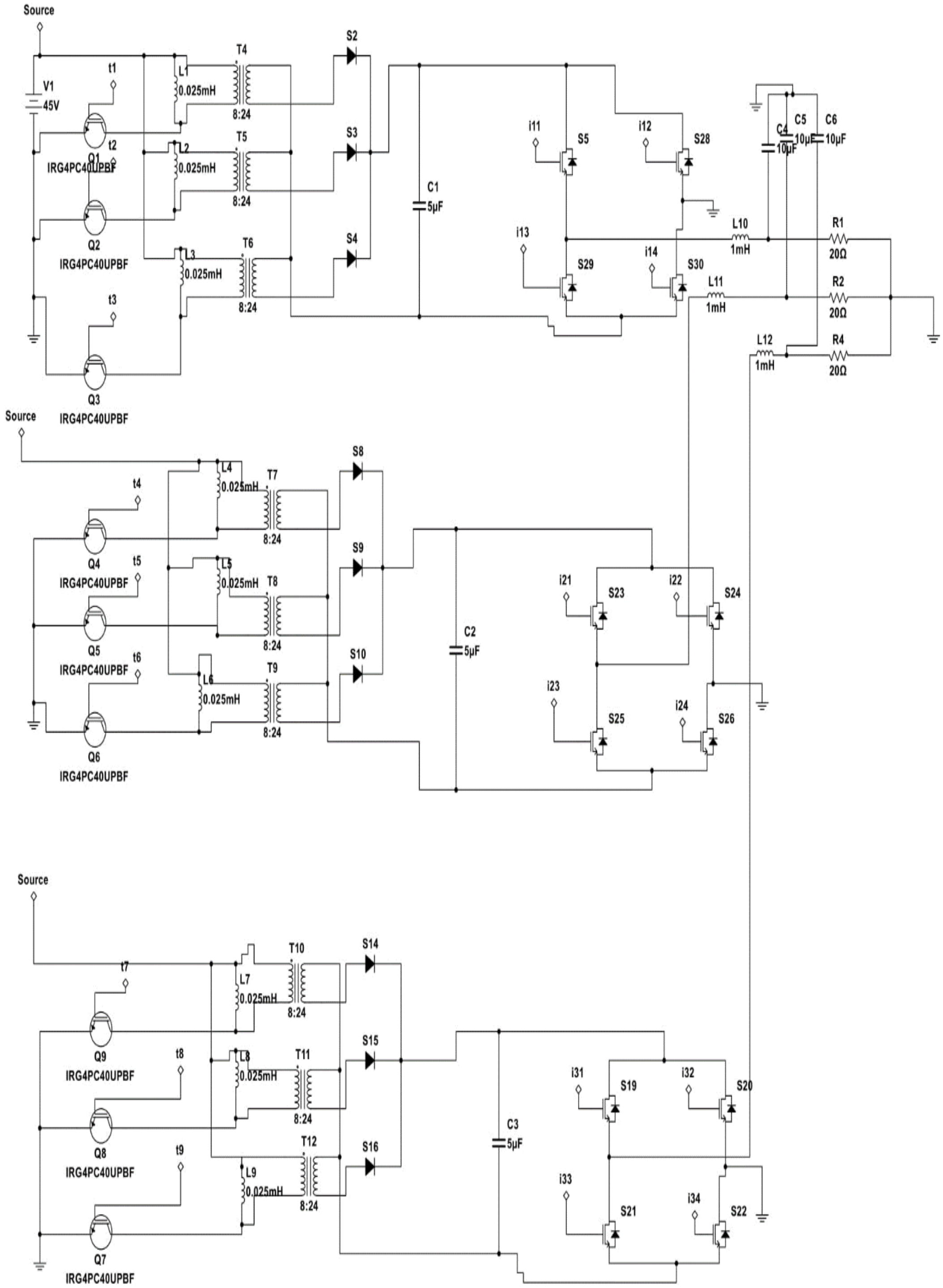


Figure 5.6 : Simulation Circuit of Three Phase Interleaved Flyback Converter.

CHAPTER SIX

SIMULATION RESULTS & COMMENTS

A simulation has been done to prove the theory of this work by using a simulation software National Instrument Multisim 14.0. Three Phase load of 20 ohms supplied by three phase interleaved Flyback converter. Each interleaved Flyback converter consists of three interleaved cell with turn ration of 3 with magnetizing inductance of 25 μH for each cell the converter is supplied by constant DC voltage source of 45V with switching frequency of 10KHz and the frequency of the output voltage has frequency of 50 Hz and 200 V_{rms}.

6.1 Flyback Converter Control

The controlling signal that has been generated uses PWM technique. Where a comparator is used for a reference signal varies as half sinusoidal waveform of 100Hz and a triangular carrier signal of 10KHz which is the switching frequency. For each cell, different controlling signal is generated as shown in Figure 6.1 shows the signal generator for the three phases where the triangular signal is shifted by 120^0 between each two cells.

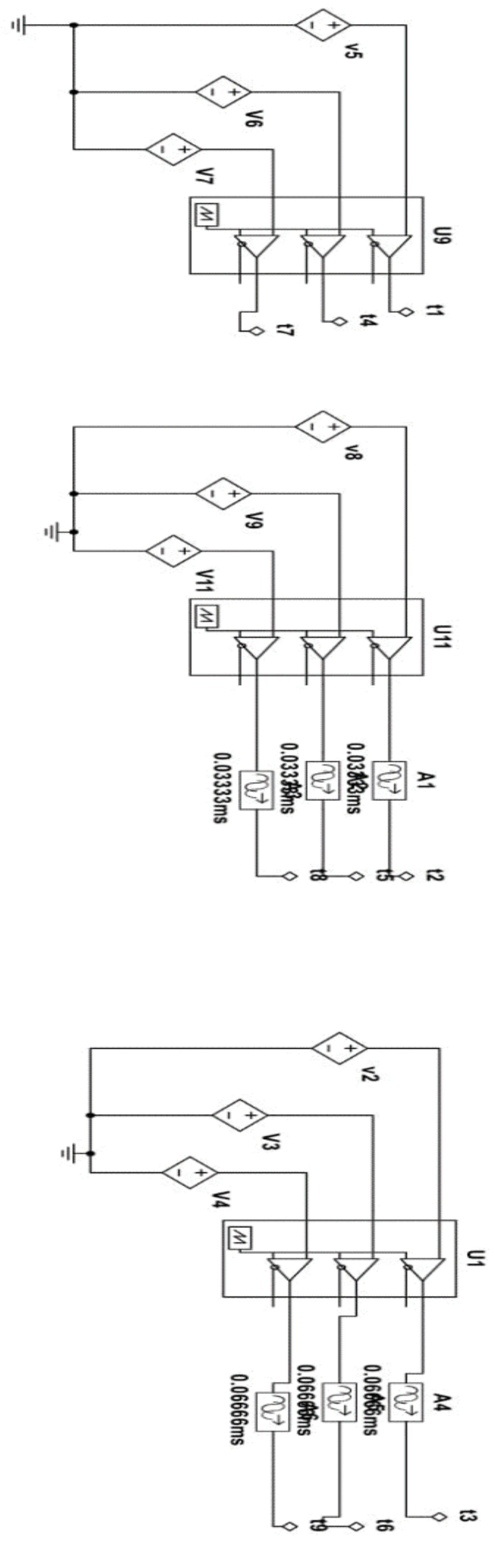


Figure 6.1 : Controlling Signal Generator of The Three Phase of The Interleaved Flyback Converter.

Figure 6.2 shows the carrier and reference signals for first cell of the first phase. Notice that in Figure 6.2 the duty cycle is varying with the time so the output of the Flyback converter will be sinusoidal.

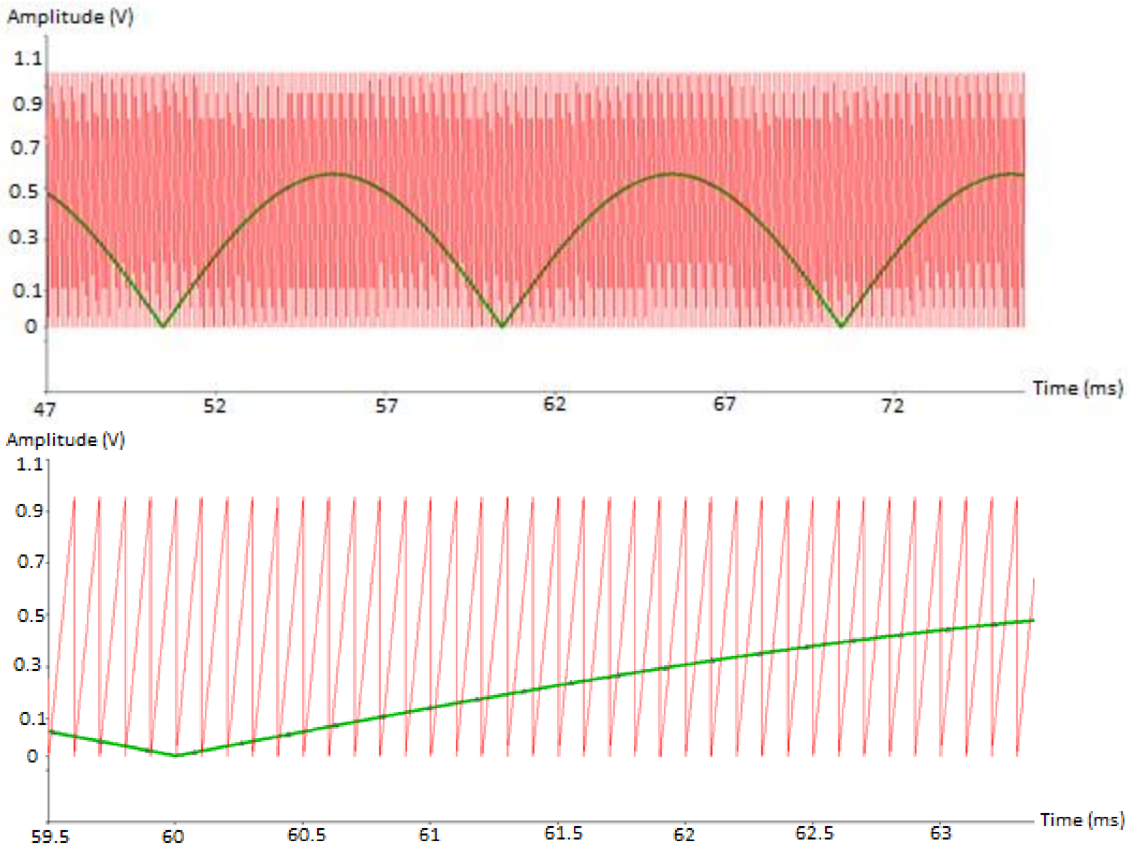
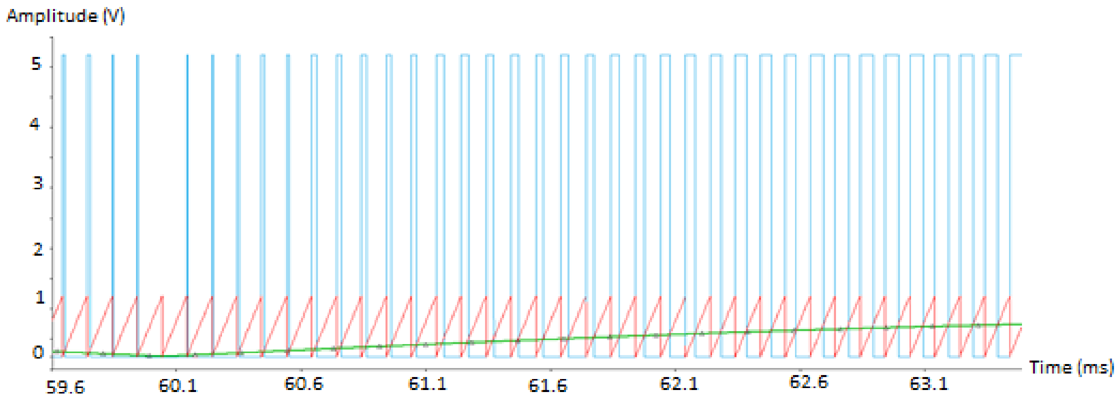


Figure 6.2 : Carrier Signal and Reference Signal of the first cell of the first phase.



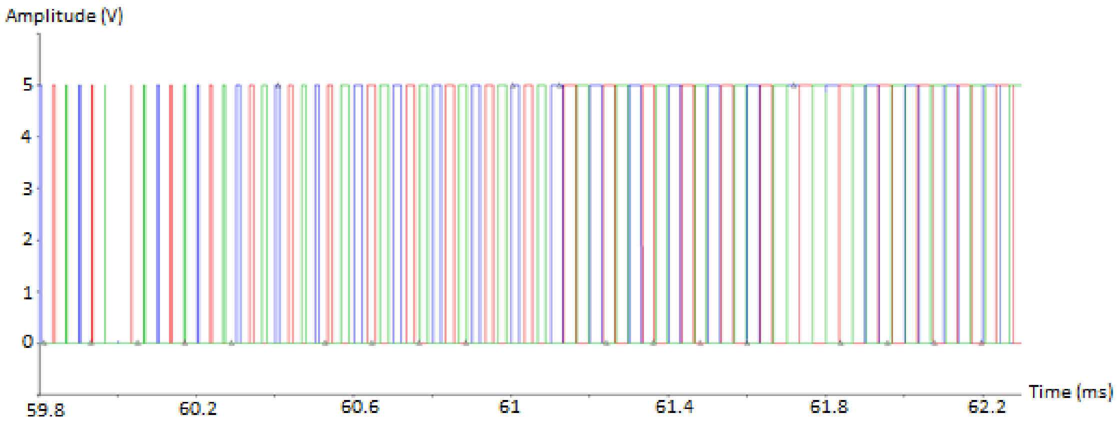


Figure 6.3 : a) Carrier Signal, Reference Signal and Controlling Signal of the first cell of the first phase b) Controlling Signal of all interleaved cell of the first phase.

Figure 6.4 shows the three-carrier signal for the interleaved Flyback cells with the reference signal. Notice the shifting between each signal is 120^0 that lead to reduce the ripple current on the Flyback cells

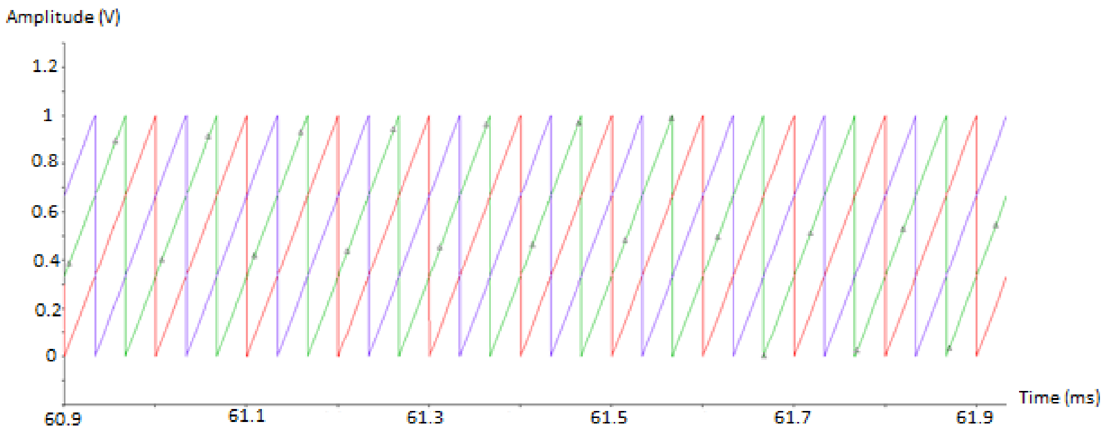


Figure 6.4 : The Three Carrier Signal for The Interleaved Flyback Cells.

Notice in the Figure 6.5 the duty cycle is varying from zero to maximum then to zero with frequency of $100Hz$ and each one is shifted by 120^0 depending on the phase. Each duty is applied on all interleaved Flyback cells of the corresponding phase.

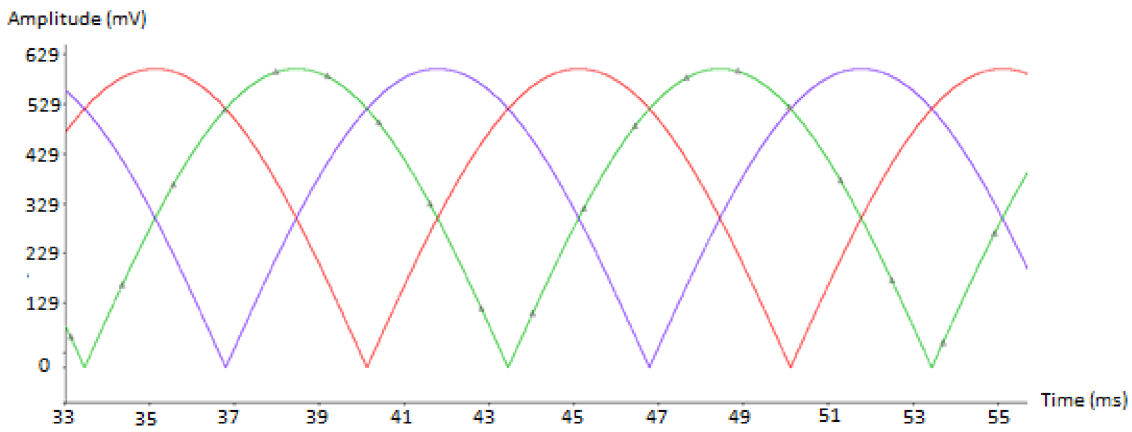


Figure 6.5 : The Three Reference Signals for the three phases of Interleaved Flyback Cells.

6.2 Flyback Primary & Secondary Windings Current

The interleaving topology makes the current divided on the interleaved Flyback cell winding that makes the ripple current less that the basic Flyback converter.

Figure 6.6 shows the input current for the first cell of the first phase of the interleaved Flyback converter. Notice that the current is sinusoidal formed and operated in DCM operation mode as discussed earlier in chapter 3 and that because of the controlling technique that used for interleaved Flyback converter. The peak current that reached in the primary windings 104 A where the secondary current will be 34.5 A due to the turn ratio of the Flyback converter which is 3

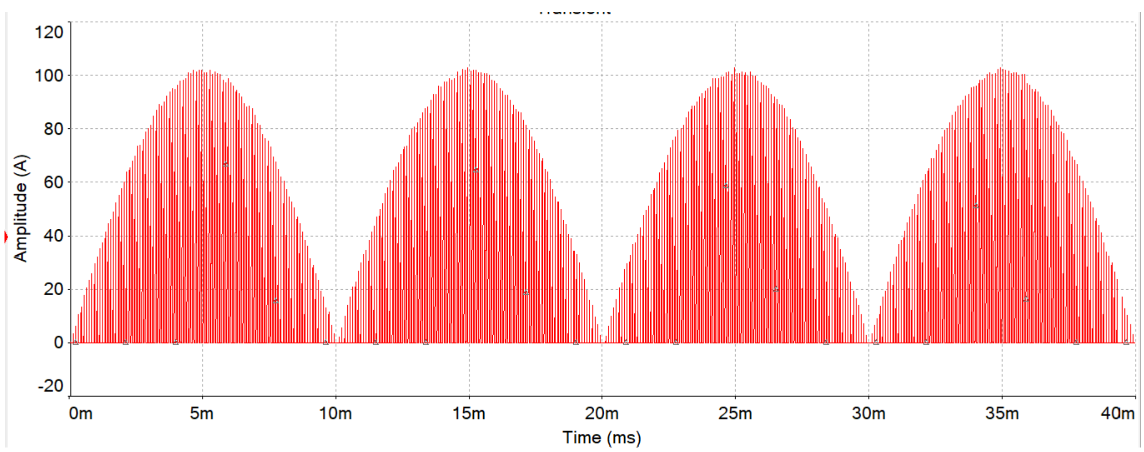


Figure 6.6 : Primary Winding Current of The First Cell of The First Phase.

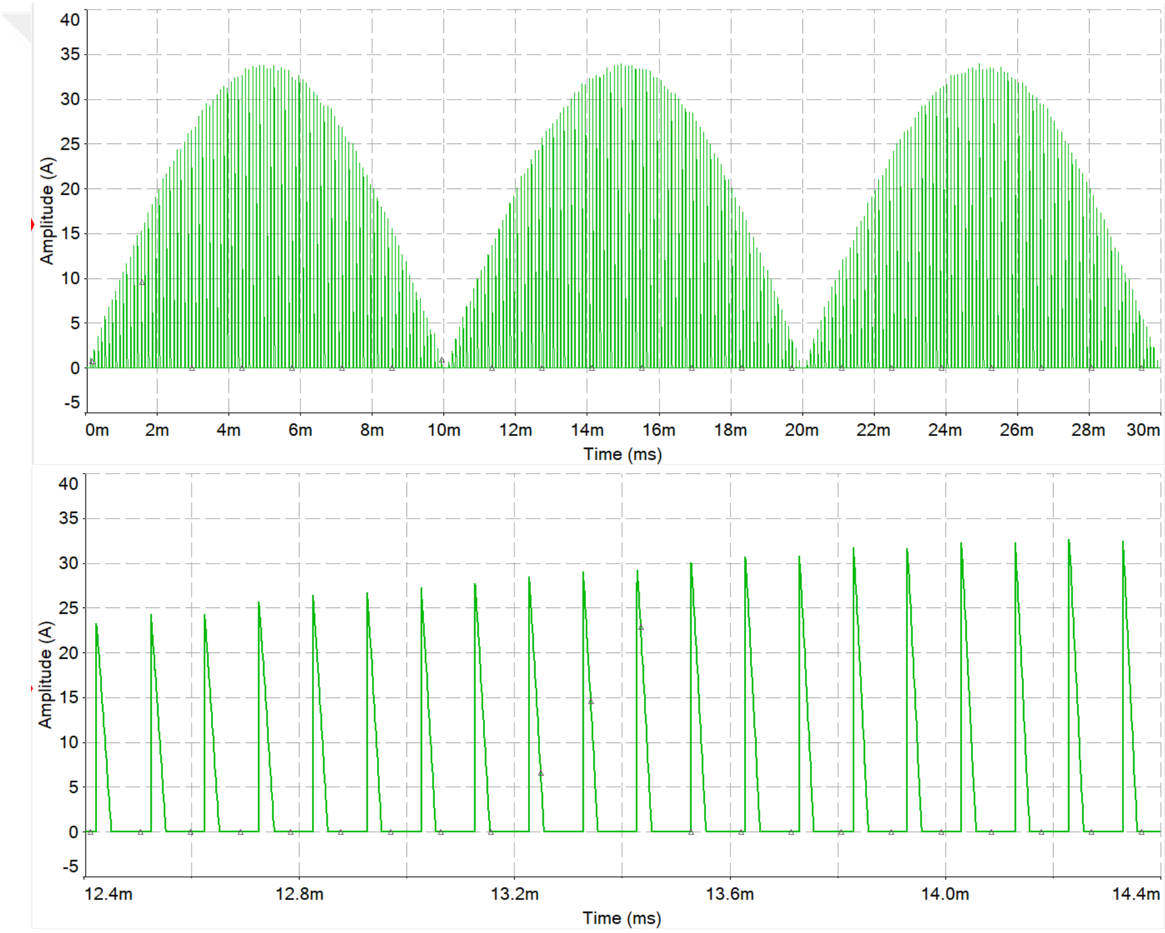


Figure 6.7 : Secondary Winding Current of The First Cell of The First Phase.

Figure 6.8 shows current of one cycle for all three interleaved Flyback cells, notice the current is divided on all cells and shifted by 120^0.

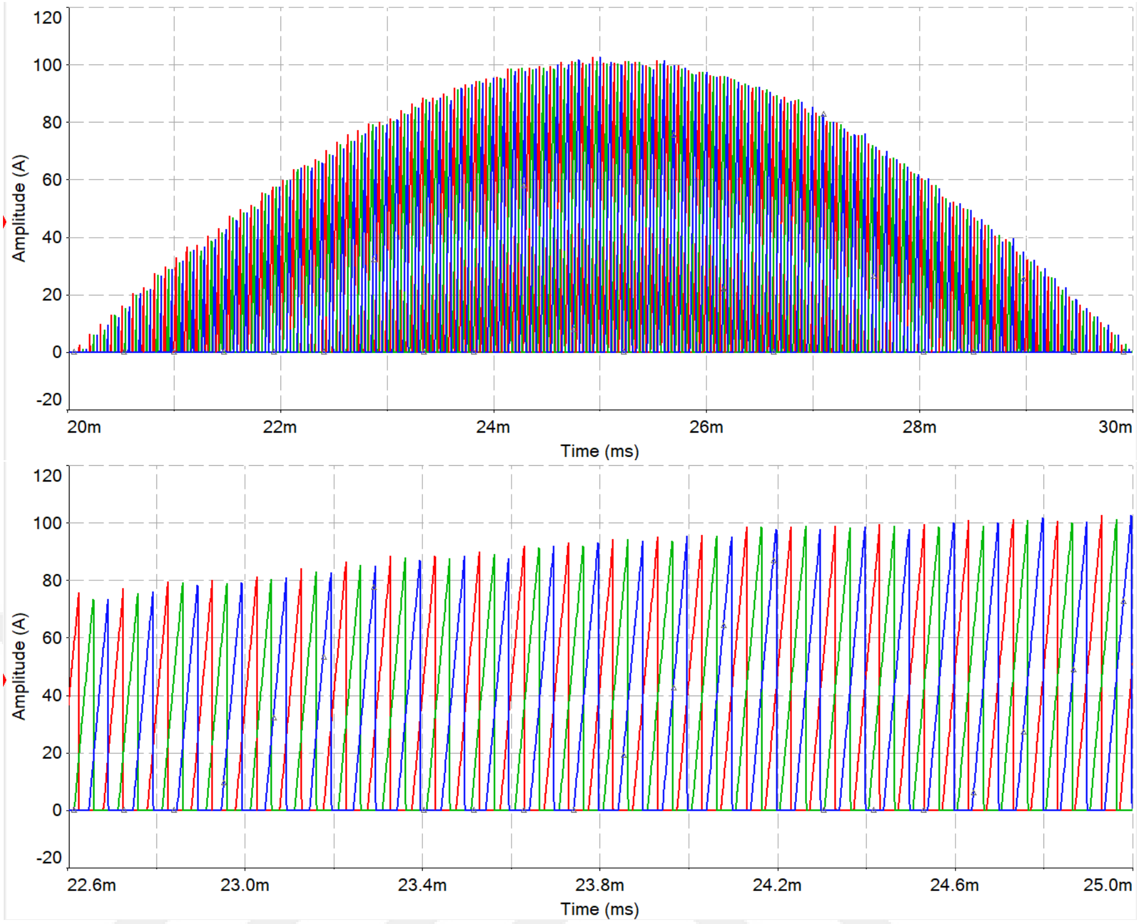


Figure 6.8 : Current of One Cycle for All Three Interleaved Flyback Cells.

Considering the three-phase converter of Flyback converter that result in utilizing more power than single phase converter. As shown in the Figure 6.9.

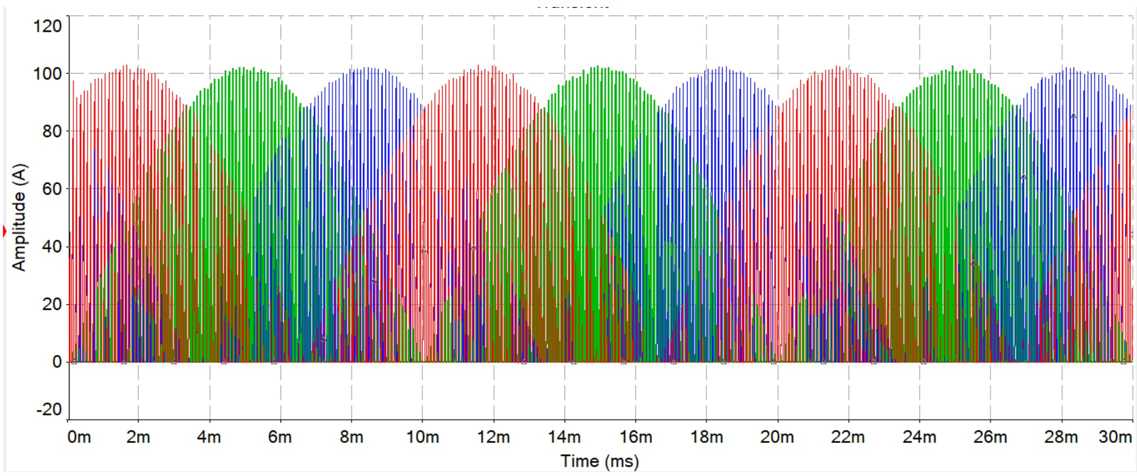


Figure 6.9 : Current for One Interleaved Flyback Cell of all phases.

6.3 Flyback Converter Output Voltage

The controlling technique that used in this work with the capacitor that used in the output of the Flyback converter result in have sinusoidal voltage with 100 Hz frequency that needs only to be unfolded to be AC sinusoidal Voltage as shown in the Figure 6.10

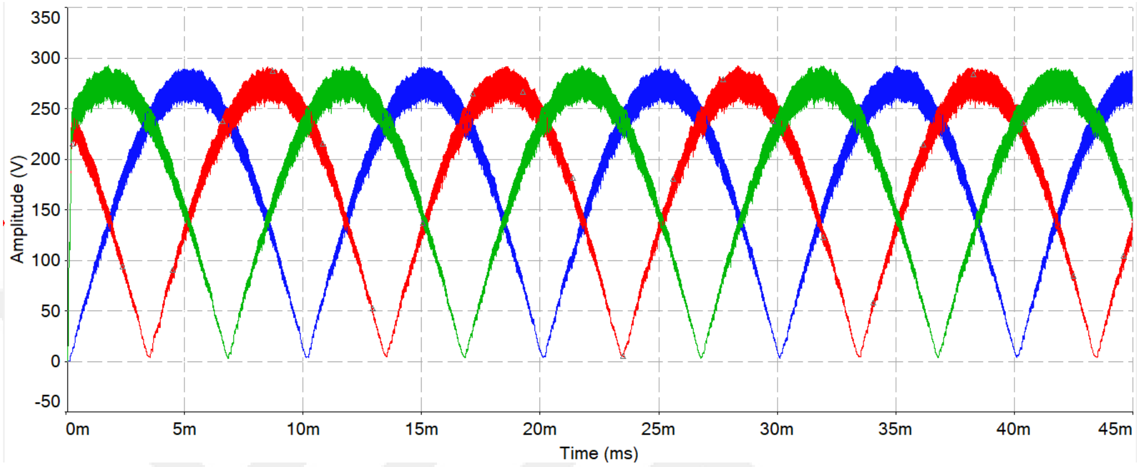


Figure 6.10 : Output Voltage of Three Phase Flyback Converter.

Notice that the voltage has low THD without the using any low pass filter.

6.4 Inverter Control

The controlling signal that used for controlling the inverters of Flyback signal is shown in Figure 6.11, notice that it has the frequency of output voltage 50Hz just to unfold the output voltage of the Flyback converter to AC voltage. The low frequency of the inverter reduces the switching losses which leads to decrease the overall losses which increases the efficiency as discussed earlier.

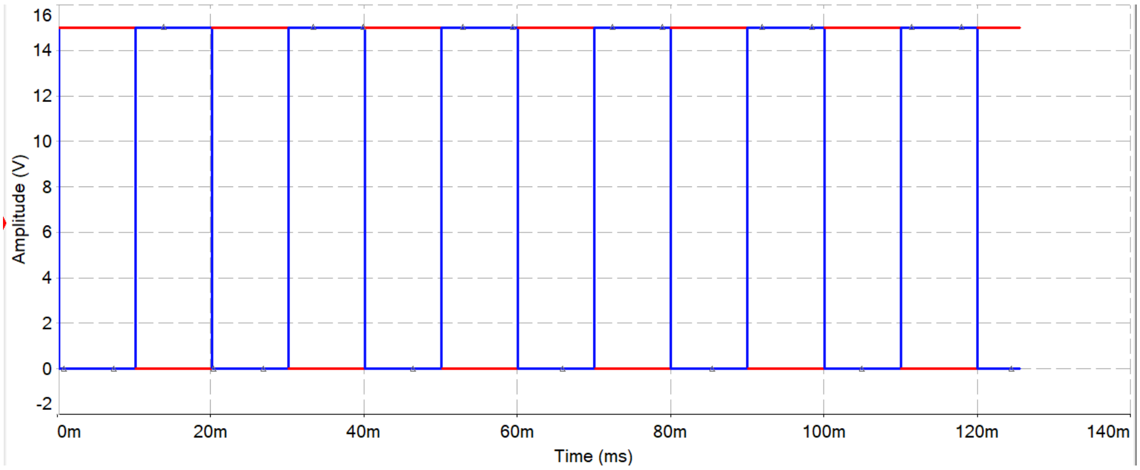
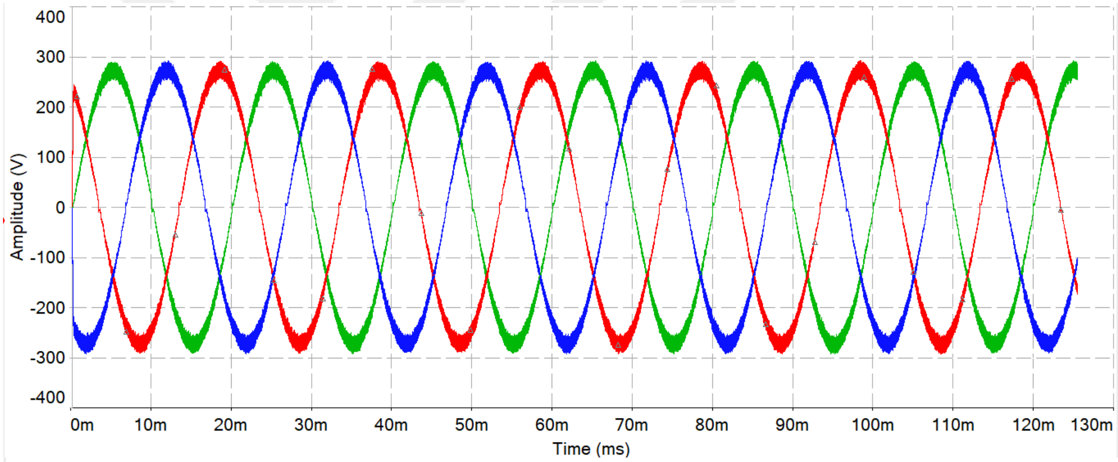


Figure 6.11 : Unfolding Inverter Controlling Signal.

6.5 Load Components

Figure 6.12 shows the three-phase load voltage, current and power.



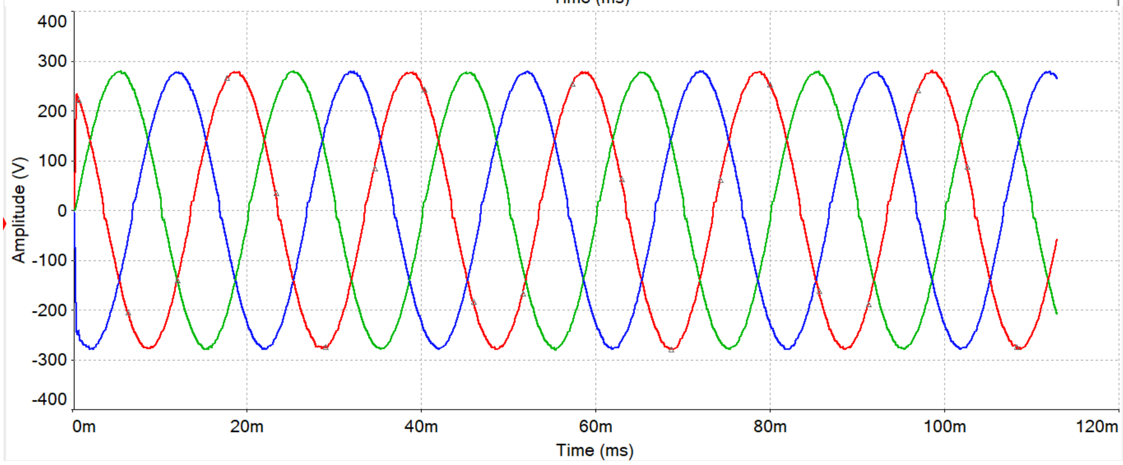


Figure 6.12 : a) Load Voltage (without LC Filter) b) Load Voltage (with LC filter) .

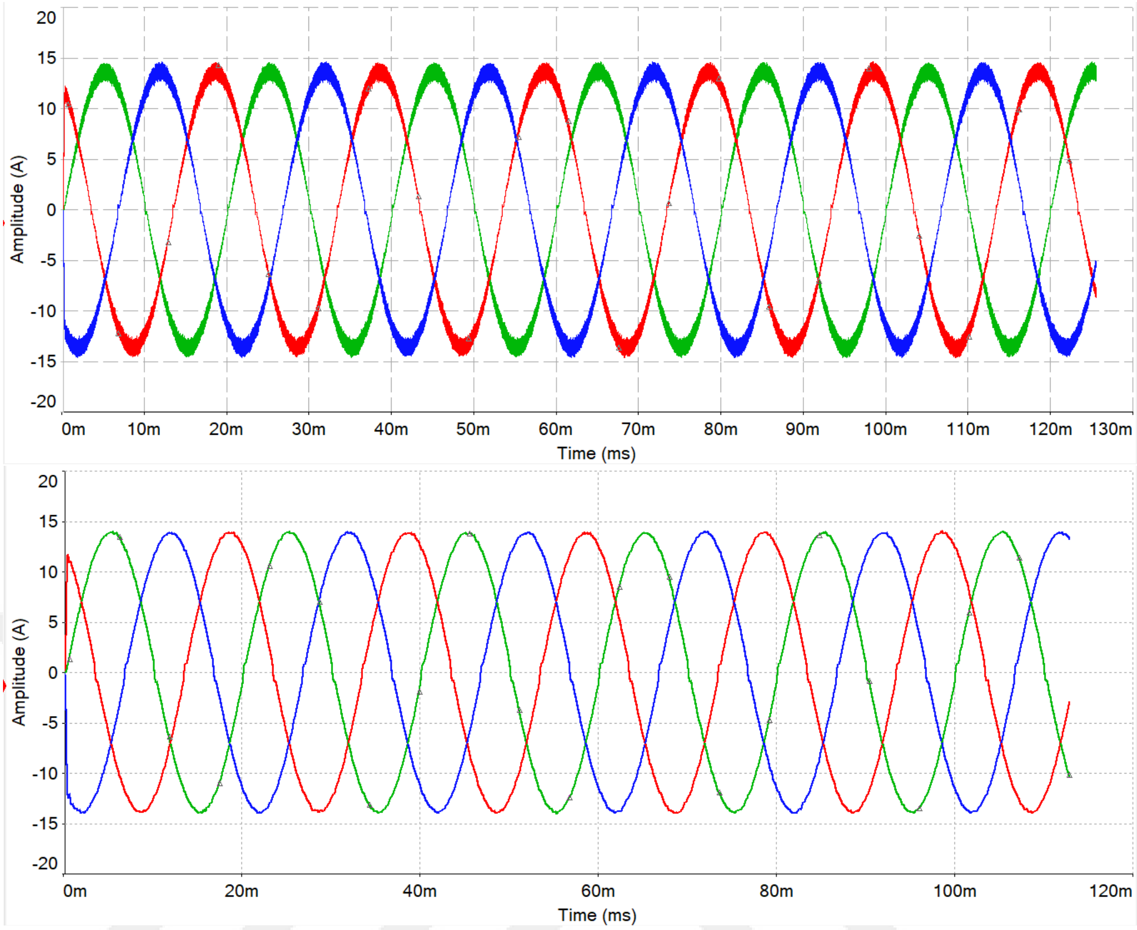


Figure 6.13 : a) Load Current (without LC filter) b) Load Current (with LC filter).

Notice that the THD percentage of the load voltage is low even without using LC filter, but LC filter is used to supply a smooth voltage and current with THD of less than 3%

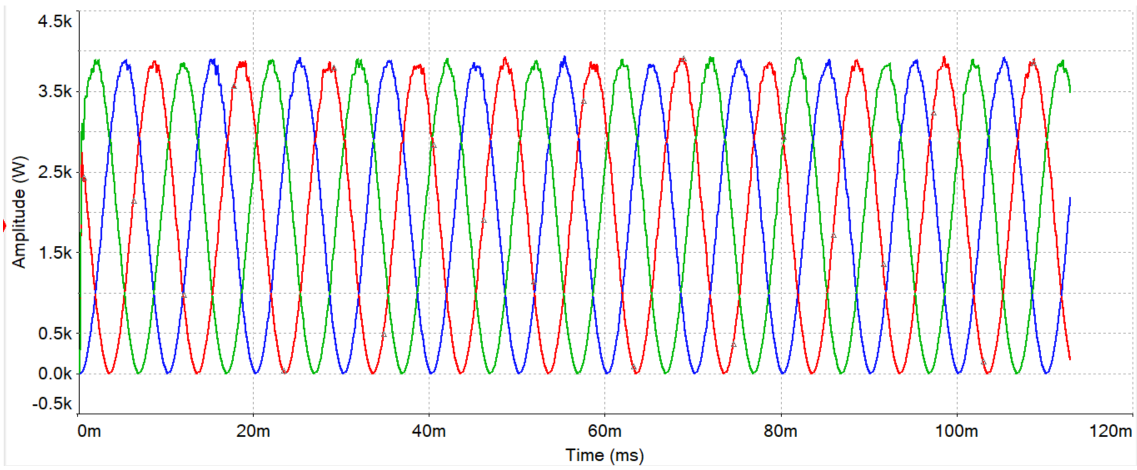


Figure 6.14 : Load Power.

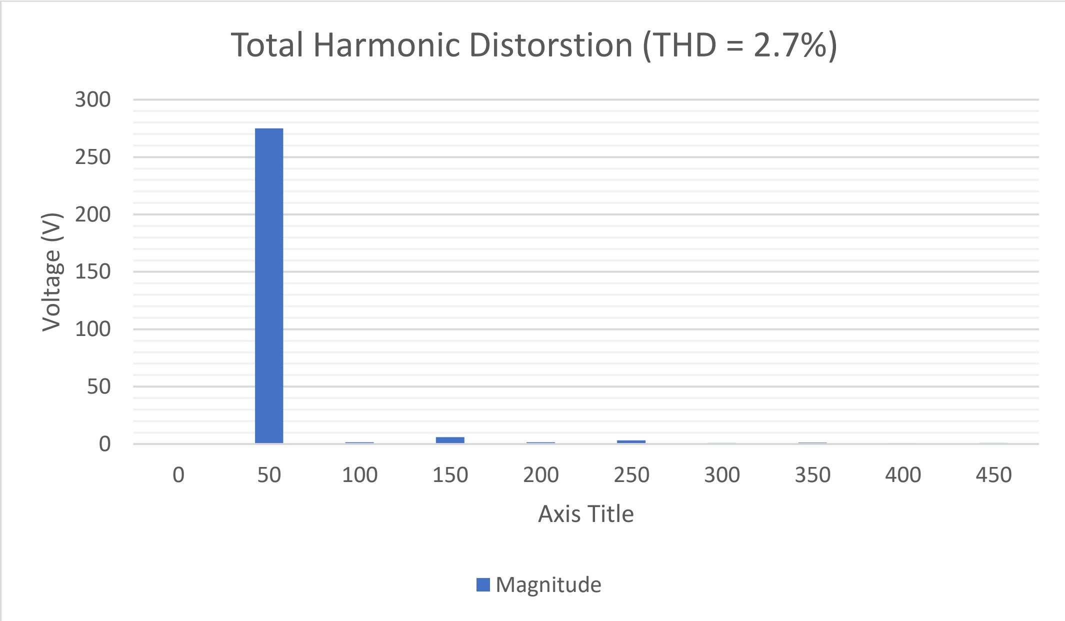


Figure 6.15 : Total Harmonic Distortion for load voltage with LC filter.

CHAPTER SEVEN

CONCLUSIONS AND FUTURE WORKS

7.1 Conclusions

According to the previous studies and to this work a general conclusion can be made, interleaving topology increases the rating power of the converter also it can minimize the windings (transformers) sizes, with the increase of number of interleaved cells, current ripple on the windings is reduced leads to reducing losses and size and increase the efficiency. Flyback converter is used in higher power application (up to 2.5 KW) than conventional Flyback converter which is used for maximum 700 W if interleaving technique is used. Controlling the duty cycle as discussed in previous chapters can be done by using sinusoidal PWM technique with high frequency to achieve a sinusoidal output voltage that only requires to be unfolded to be an AC sinusoidal voltage. This technique can be used in various converters types to minimize the frequency of the switching in the inverters leading to reduce the losses of the switching. This controlling technique that is used in this work has good advantage that reduce the capital cost by reducing the size of low-pass filter. Using three-phase converter is more efficient than using single phase converters, because in three-phase converter more power is utilized in one full cycle period than in single phase converters with smoother waveform. Flyback converter has special advantages among the rest converters, it has the minimum number of components which means it costs less also it can boost the voltage easier due to transforming capability.

7.2 Future Works

For future work:

- optimum number of interleaved cell can be studied to see what is the number of cells that has highest efficiency with low cost
- hardware implementation can be done for constant DC Voltage or PV panels.

REFERENCES

[1] Q. Li and P. Wolfs, “A review of the single phase photovoltaic module integrated converter topologies with three different DC link configurations,” IEEE Trans. Power Electron., vol. 23, no. 3, pp. 1320–1333, May 2008.

[2] D. Meneses, F. Blaabjerg, Ó. García, and J. A. Cobos, “Review and comparison of step-up transformerless topologies for photovoltaic AC-Module application,” IEEE Trans. Power Electron., vol. 28, no. 6, pp. 2649–2663, Jun. 2013.

[3] N. Mohan, W. P. Robbin, and T. Undeland, Power Electronics: Converters, Applications, and Design, 2nd ed. New York: Wiley, 1995.

[4] X. P. Fang, Z. M. Qian, and F. Z. Peng, “Single-phase Z-source PWM ac–ac converters,” IEEE Power Electron. Lett., vol. 3, no. 4, pp. 121–124, Dec. 2005.

[5] R. A. Pinto, et. aI, "A Bidirectional Buck-Boost Converter to SupplyLEDs from Battery during the Peak Load Time," IECON 2011 - 371h Annual Conference of IEEE Industrial Electronics Society, 2011.

[6] S. Kaitwanidvilai, P. Piyarungsan “Harmonic Reduction in PWM AC Voltage Controller using Genetic Algorithm and Neural network” MECS2007, Vol. 2, pp.1674-1679.

[7] Sanchis, P., Ursua, A., Gubia, E., and Marroyo, L.: ‘Design and experimental operation of a control strategy for the buck-boost DC-AC inverter’, IEE Proc., Electr. Power Appl., 2005, 152, (3), pp. 660–668

[8] Shih-Ming Chen, Chen-Yu Wang, Tsorng-Juu Liang " A Novel Sinusoidal Boost-Flyback CCM/DCM DCDC Converter", 2014

[9] Mohamed C. Ghanem, Kamal Al-Haddad, Senior Member, IEEE, and Gilles Roy, Member, IEEE A New Control Strategy to Achieve Sinusoidal Line Current in a Cascade Buck-Boost Converter, 1996.

[10] "Power Electronics Circuits, Devices and Applications", Third Edition, Muhammad H. Rashid

[11] "Advanced Power Electronics", Dr. Taufik

[12] "Introduction to Power Electronics", Dr. Taufik

[13] N. AN4137, “Design guidelines for off-line Flyback converters using fairchild power switch (fps),” 2009.

[14] The Flyback Converter Lecture notes ECEN4517

[15] MC9S12C Family, MC9S12GC Family Reference Manual, (pp. 347-382)

[16] M. T. Zhang, M. M. Jovanovic, and F. C. Lee, “Analysis and evaluation of interleaving techniques in forward converters,” IEEE Trans. Power Electron., vol. 13, no. 4, pp. 690–698, Jul. 1998.

[17] L.-P. Wong, D. K.-W. Cheng, M. H. L. Chow, and Y.-S. Lee, “Interleaved three-phase forward converter using integrated transformer,” IEEE Trans. Ind. Electron., vol. 52, no. 5, pp. 1246–1260, Oct. 2005.

[18] C.-W. Roh, S.-H. Han, S.-. S. Hong, S.-C. Sakong, and M.-J. Youn, “Dual-coupled inductor-fed DC/DC converter for battery drive applications,” IEEE Trans. Ind. Electron., vol. 51, no. 3, pp. 577–584, Jun. 2004.

[19] R.-T. Chen and Y.-Y. Chen, “Single-stage push-pull boost converter with integrated magnetic and input current shaping technique,” IEEE Trans. Power Electron., vol. 21, no. 5, pp. 1193–1203, Sep. 2006.

[20] F. Forest, T. Meynard, E. Labour´e, V. Costan, and J.-J. Huselstein, “A multi-cell interleaved Flyback using intercell transformers,” IEEE Trans. Power Electron., vol. 22, no. 5, pp. 1662–1671, Sep. 2007.

[21] G. Park and S. I. Kim, “Modeling and analysis of multi-interphase transformers for connecting power converters in parallel,” in Proce. PESC’97, 1997, vol. 2, pp. 1164–1170.

[22] P.-L. Wong, P. Xu, B. Yang, and F. C. Lee, “Performance improvements of interleaving VRMS with coupling inductors,” in Proc. APEC’00, 2000, pp. 973–978.

[23] P. Zumel, O. Garcia, J. A. Cobos, and J. Uceda, “Tight magnetic coupling in multiphase interleaved converters based on simple transformers,” in Proc. APEC’05, 2005, vol. 1, pp. 385–391.

[24] J. Czogalla, J. Li, and C. R. Sullivan, “Automotive application of multiphase coupled inductor DC-DC converter,” in Proc. IAS 2003, 2003, vol. 3, pp. 1524–1529.

[25] Robert W. Erickson, Dragan Maksimović,” Fundamentals of Power Electronics” 2001.

[26] Tamyurek, Bunyamin, and Bilgehan Kirimer."An Interleaved High-Power Flyback Inverter for Photovoltaic Applications", IEEE Transactions on Power Electronics, 2015.

[27] Young-Ho Kim, Young-Hyok Ji, Jun-Gu Kim, Yong-Chae Jung, And Chung-Yuen Won, “A New Control Strategy for Improving Weighted Efficiency in Photovoltaic AC Module-Type Interleaved Flyback Inverters” IEEE Transactions On Power Electronics, 2013

[28] Zhiliang Zhang. “An Optimal Control Method for Photovoltaic Grid-tied Interleaved Flyback Micro-inverter to Achieve High Efficiency in Wide Load Range”, IEEE, 2013

[29] Mingzhi Gao, Min Chen, Qiong Mo, Zhaoming Qian, “Research on Output Current of Interleaved-flyback in Boundary Conduction Mode for Photovoltaic AC Module Application”, IEEE Transactions on Power Electronics, 2011

[30] Yao-Ching Hsieh, Ming-Ren Chen, and Hung-Liang Cheng, “An Interleaved Flyback Converter Featured with Zero-Voltage Transition”, IEEE Transactions on Power Electronics, 2011

[31] Janviere Umuhoza, Yuzhi Zhang, Yusi Liu, Joe Moquin Chris Farnell, H. Alan Mantooth, “Interleaved Flyback Based Micro-inverter for Residential Photovoltaic Application in Remote Areas”, University of Arkansas, 2015

[32] Masataka Ishihara, Shota Kimura, Wilmar Martinez, and Masayoshi Yamamoto, “Analysis and Design of Passive Components for Interleaved Flyback Converter with Integrated Transformer”, Shimane University, 2015

[33] Ramya Chandranadhan, Renjini.G, “Average current mode Control of Improved Bridgeless Flyback Rectifier with Bidirectional Switch”, 2015

CURRICULUM VITAE

PERSONAL INFORMATION

Name, Surname : Ihssan FAREED

Date and Place of Birth : 27.02.1992/Iraq – Baghdad

Marital Status : Single

Phone : 009647701827031

E-mail : ihssanjamall@yahoo.com

EDUCATION

High School : Alshamyia Secondary School. 2009

Undergraduate : Foundation of Technical Education / College of Electrical and Electronic Techniques

WORK EXPERIENCE

Languages

Mother Tongue(s): Arabic

Other Languages: English (Very Good), Turkish (Beginner)

Computer Use: Excellent

Computer Programming Techniques: VisualBasic,SQL (Very Good), HTML, CSS, JavaScript, PHP, JAVA (Good)

INTERESTS AND HOBBIES

Walking, Jogging, Football, Swimming, Music.