New Hybrid PWM Technique for Dual Buck Invertor

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***Abstract*- The paper explains about general introduction to the inverter, different types of inverter and applications of the inverters in the various fields.**

Dual Buck Full-Bridge Inverter topology, different PWM switching methods with description, design of DBFBI and selection of switching devices are discussed in the present chapter.

On the other hand, this paper also states the implementation of SIMULINK blocks of Dual Buck Inverter with PWM control unit, results obtained and discusses the analysis of various results.

Also, the results obtained from simulation work are analyzed. Total harmonic distortion present in the AC output current under different bipolar PWM methods is calculated. Few important conclusions drawn out of the present project work and scope for the future work have been analysed.

Index terms- Invertors, Dual buck, DBFBI, SIMULINK, PWM method

I. INTRODUCTION

The world energy demand increasing at an exponential rate, the search for energy sources other than fossil fuel is no longer a luxury. Although the fossil fuels offer a temporary solution to this energy crisis, they cause the emission of carbon dioxide and other greenhouse gases, which are harmful to the environment. This has paved the way for research on renewable energy technology and other researches in the field of power electronics and hence, the cost of utilizing the renewable energy is at an ever decreasing rate. One such of sources of renewable energy, the Sun, offers unlimited energy for harnessing and for this reason, Photovoltaic (PV) systems consisting of PV modules, for generating environmental friendly power are gaining more and more recognition with the each passing day. The PV comprise of several solar cells, which convert the energy of sunlight directly into electricity and they are connected as required to provide desired level of current and voltage as shown in Fig. 1.1. They produce electricity due to a quantum mechanical process known as the "Photovoltaic Effect". The major drawback of PV systems in that their cost is much high compared to the conventional sources such as fossil fuels and their efficiency are also quite low.

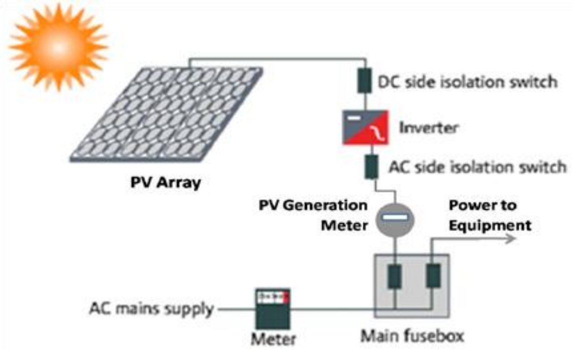


Fig. 1.1: Typical PV system configuration

Power semiconductor devices represent the heart of the modern power electronics and are being extensively used in power electronic converters in the form of a matrix of ON or OFF switches and helps to convert power from one form to another. There are four basic conversion functions that normally can be implemented such as AC-AC, AC-DC, DC-DC and DC-AC. Inverter is one of the converter families which are called DC-AC converters. It converts DC power to AC power and then to a symmetric AC output voltage, at desired magnitude and frequency. In other words, it is a power adapter. It can allow a battery based independent power system to run conventional appliances through conventional home wiring. The DC power input to inverter is obtained from the existing power supply network. It can be a battery, photovoltaic, wind energy, fuel cell or other DC sources.

Full-bridge inverters are used in UPS or Renewable energy systems or Emergency lighting system, Solar Inverter, as well as Solar Micro-Inverter used in photovoltaic as a component of a PV system. For AC motors, applications include Variable Frequency Drives, Motor Soft Starters and Excitation systems. Disadvantages of Full-bridge inverter are low efficiency, high circulation current, high-output AC current distortion and high cost. Dual buck inverter has been designed for the photovoltaic system, which has high efficiency, high reliability, low circulation current, low-output current distortion and low cost [8].

Sinusoidal Pulse Width Modulation (SPWM) is widely used in power electronics to digitize the power so that a sequence of voltage pulses that can be generated by the ON and OFF of the power switches. SPWM is the majorly used method in motor control and inverter application. SPWM is the switching techniques are characterized by constant amplitude with different duty cycles for each period. The width of this pulse is modulated in order to obtain inverter output voltage control and to reduce its harmonic content and Zero-Crossing Distortion (ZCD) [4].

In the present project work the Dual Buck Full-Bridge Inverter has been designed which has high efficiency, high reliability, low circulation current and low-output AC current distortion. However, conventional PWM techniques employed for Full-Bridge inverters suffer from certain limitations or disadvantages. Keeping this in mind, a literature survey is carried out in the next section to identify the weaknesses of the conventional PWM techniques and the means of overcoming them.

1.2 Literature survey

In the present project work, a Dual Buck Full-Bridge Voltage Source Inverter topology is considered for the analysis. It is identified that such an inverter suffers from higher circulation current and zero crossing distortion problem. A brief literature review conducted in this context is presented in this section.

Soeren Baekhoej Kjaer, John K. Pedersen and Frede Blaabjerg present a work on Inverter technologies for connecting photovoltaic (PV) modules to a single-phase grid. Various inverter topologies are presented, compared and evaluated against demands, lifetime, components ratings and cost. Inverter interfacing PV module with the grid involves two major tasks. One is to ensure that the PV module is operated at the maximum power point. The other is to inject a sinusoidal current into the grid [1].

Zhilei Yao, Lan Xiao and Yangguang Yan developed a model of dual buck full-bridge inverter with hysteresis current control which is used to solve the Shoot through problems in conventional bridge type inverter. The comparisons among other inverters and the Dual buck full-bridge inverter demonstrated that the inverter developed in this work is more attractive than other inverters [2].

Baifeng Chen, Pengwei Sun, Chuang Liu, Chien-Liang Chen, Jih-Sheng Lai and Wensong Yu developed a different PWM methods and it is identified that in a Traditional Bipolar PWM (TBPWM) switching technique has circulating current. In order to overcome the drawback of circulating current in TB-PWM method, an Improved Bipolar PWM (IB-PWM) technique has been proposed in their work. However, even in this improved method, there is still the problem of zero-crossing distortion [3].

Pankaj H. Zope, Pravin G. Bhangale, Prashant Sonare and S. R. Suralkar discussed Sinusoidal Pulse Width Modulation (SPWM) switching methods which are widely used in power electronics. SPWM techniques are characterized by constant amplitude pulses with different duty cycle for each period. The width of this pulses are modulated to obtain inverter output voltage control and to reduce its harmonic content. SPWM is the mostly used method in motor control and inverter application [4].

Thus, the motivation for the present project work is to propose altogether New PWM technique that can overcome the drawbacks of Dual buck full-bridge Inverter that reduces switching circulating current and minimize zero-crossing distortion problem. Clear objective of the work proposed is stated in the next section.

1.3 Objective

Compared to other available Full-Bridge Inverters, the new inverter proposed should have following features. First of all, it should eliminate the possibility of shoot through problems, which are major failure of traditional Voltage Source Inverters (VSI). It should avoid the dead time to fully utilize the PWM output voltage and maximize the energy transfer to the load.

The present project work aims at comparing the performance of three different Pulse Width Modulation (PWM) switching techniques applied for Dual Buck Inverter viz., Traditional Bipolar PWM technique, Improved Bipolar PWM technique and New PWM technique. Clear objectives of the proposed work are

- To study the circulation current encountered in Traditional Bipolar PWM method.
- To study the zero-crossing distortion problem encountered in Improved Bipolar PWM method.
- Proposed New Pulse Width Modulation (PWM) method that will inherit advantages and overcome the disadvantages of conventional PWM methods presently available.

II. INVERTERS - AN OVERVIEW

2.1 Introduction

Inverter is an electronic device or circuitry that changes direct current (DC) to alternating current (AC). The input voltage, output voltage and frequency, and overall power handling depend on the design of the specific device or circuitry. The inverter does not produce any power; the power is provided by the DC source. The DC power input to the inverter is obtained from an existing power supply network, rotating alternator through a rectifier or a battery, fuel cell and photovoltaic array.

2.1.1 Sources of Input Voltage to the Inverter

A typical power inverter device or circuit requires a relatively stable DC power source capable of supplying enough current for the intended power demands of the system. The input voltage depends on the design and purpose of the inverter. Examples include:

- 12V DC, for smaller consumer and commercial inverters that typically run from a rechargeable 12 V lead acid Battery or automotive electrical outlet.
- 24, 36 and 48V DC, which are common standards for home energy systems.
- 200 to 400V DC, when power is from photovoltaic solar panels.
- 300 to 450V DC, when power is from electric vehicle battery packs in vehicle-to-grid systems.
- Hundreds of thousands of volts, where the inverter is part of a High-Voltage Direct Current (HVDC) power transmission system.

2.1.2 Different forms of Output Waveform

An inverter can produce a square wave, modified sine wave, pulsed sine wave, pulse width modulated wave or sine wave depending on circuit design. The two dominant commercialized waveform types of inverters are modified sine wave and sine wave.

• Square wave

This is one of the simplest waveforms an inverter design can produce and is best suited to low-sensitivity applications such as lighting and heating. Square wave output can produce "Humming" when connected to audio equipment and is generally unsuitable for sensitive electronics.

• Sine Wave

A power inverter device which produces a multiple step sinusoidal AC waveform is referred to as a sine wave inverter. To more clearly distinguish the inverters with outputs of much less distortion than the modified sine wave (three steps) inverter designs, the manufacturers often use the phrase pure sine wave inverter. Almost all consumer grade inverters that are sold as a "Pure Sine Wave Inverter" do not produce a smooth sine wave output at all, just a less choppy output than the square wave (two step) and modified sine wave (three step) inverters. However, this is not critical for most electronics as they deal with the output quite well.

• Modified Sine Wave

The modified sine wave output of such an inverter is the sum of two square waves one of which is phase shifted 90 degrees relative to the other. The result is three level waveform with equal intervals of zero volts; peak positive volts; zero volts; peak negative volts and then zero volts. This sequence is repeated. The resultant wave very roughly resembles the shape of a sine wave. Most inexpensive consumer power inverters produce a modified sine wave rather than a pure sine wave.

2.1.3 Output Frequency of the Inverter

The AC output frequency of a power inverter device is usually the same as standard power line frequency, 50 or 60 Hertz. If the output of the device or circuit is to be further conditioned (for example stepped up) then the frequency may be much higher for good transformer efficiency.

2.1.4 Typical Output Voltage of the Inverter

The AC output voltage of a power inverter is often regulated to be same as the grid line voltage, typically 120V or 240V AC at the distribution level, even when there are changes in the load that the inverter is driving. This allows the inverter to power numerous devices designed for standard line power. Some inverters also allow selectable or continuously variable output voltages.

2.1.5 Output Power Rating of the Inverter

A power inverter will often have an overall power rating expressed in watts or kilowatts. This describes the power that will be available to the device the inverter is driving and, indirectly, the power that will be needed from the DC source. Smaller popular consumer and commercial devices designed to mimic line power typically range from 150 to 3000 Watts [9].

2.2 Different forms of Output Waveform

Inverters are of many different types. Some are On-Grid type inverters, some are Off-Grid type inverters, some are Dual-Line inverters, some are Line-Interactive type inverters etc. These inverters are further classified according to their output types, likewise if it gives pure sine wave output then they are called sine inverters, modified sine waves and square waves are respectively called modified sine wave inverters and general inverters. Pure sine wave inverters have proved to be the most influencing discovery of the recent times as it has eased the need to replace highly costly, large in size and comparably less fuel efficient generators. Before the discovery of sine wave inverters it was almost impossible to imagine about efficient hybrid cars, which have become the most precious invention of the modern ages as it has given a sense of relief to customers tiered of regular price hikes of fuels. Inverters can be broadly classified into two types depending upon the input DC power feeding to the inverters, voltage source and current source inverters. A Voltage-Fed Inverter (VFI) or more generally a Voltage Source Inverter (VSI) is one in which the DC source has small or negligible impedance. The voltage at the input terminals is constant. A Current Source Inverter (CSI) is fed with adjustable current from the DC source of the high impedance that is from a constant DC source [8].

2.3 Output Frequency of the Inverter

Now-a-days inverters find diverse uses and applications in a daily life, due to their function of converting DC to AC. Some applications of the inverters in different fields are as follows: DC Power Utilization

An inverter converts the DC electricity from sources such as batteries or fuel cells to AC electricity. The electricity can be at any required voltage. In particular, it can operate AC equipment designed for mains operation, or rectified to produce DC at any desired voltage.

Grid-Tie inverters can feed energy back into distribution network because they produce alternating current with the same wave shape and frequency as supplied by the distribution system. They can also switch OFF automatically in the event of a blackout.

Micro-Inverters convert direct current from individual solar panels into alternating current for the electric grid.

Fig. 2.1: A typical Stand-Alone Inverter

Fig. 2.2: Inverter for grid connected PV

Uninterrupted Power Supplies

An Uninterrupted Power Supply (UPS) is a device which supplies the stored electrical power to the load in case of main power cut-off or blackout. One type of UPS uses batteries to store power and an inverter to supply AC power from the batteries when main power is not available. When main power is restored, a rectifier is used to supply DC power to recharge the batteries. It is widely used at domestic and commercial level in countries facing power outages.

Motor Speed Control

Inverters circuits designed to produce a variable output voltage range are often used within motor speed controllers. The DC power for the inverter section can be derived from a normal AC wall outlet or some other source. Control and feedback circuitry is used to adjust the final output of the inverter section which will ultimately determine the speed of the motor operating under its mechanical load. Motor speed control needs are numerous and include things like: industrial motor driven equipment, electric vehicles, rail transport systems and power tools. Switching states are developed for positive, negative and zero voltages. The generated gate pulses are given to each switch in accordance with the developed pattern and thus the output is obtained.

Inverters Utility in Power Grid

Grid-Tied inverters are designed to feed into the electric power distribution system. They transfer synchronously with the line and have as little harmonic content as possible. They also need a means of detecting the presence of utility power for safety reasons, so as not to continue to dangerously feed power to the grid during a power outage. Solar

Power Plant

A solar inverter is a balance of system component of a photovoltaic system and can be used for both On-Grid and Off-Grid systems. Solar inverters have special functions adapted for use with photovoltaic arrays, including maximum power point tracking and anti-islanding protection. Solar Micro-Inverters differ from conventional inverters, as an individual Micro-Inverter is attached to each solar panel. This can improve the overall efficiency of the system. The output from several Micro-Inverters is then combined and often fed to the electrical grid.

Induction Heating

Inverters convert low frequency main AC power to a higher frequency for using induction heating. To do this, AC power is first rectified to provide DC power. The inverter then changes the DC power to high frequency AC power. Variable-Frequency Drives

A Variable-Frequency Drive (VFD) controls the operating speed of an AC motor by controlling the frequency and voltage of the power supplied to the motor. An inverter provides the controlled power. In most cases, the VFD includes a rectifier so that DC power for the inverter can be provided from main AC power. Since an inverter is the key component, VFD are sometimes called inverter drives or just inverters.

High Voltage DC Power Transmission

With HVDC power transmission, AC power is rectified and High Voltage DC power is transmitted to another location. At the receiving location, an inverter in a static inverter plant converts the power back to AC. The inverter must be synchronized with grid frequency and phase and minimize harmonic generation.

III. METHODOLOGY

3.1 Introduction

The standard Half-Bridge or Full-Bridge inverter is typical Voltage Source Inverter with two active switches in one phase leg. It need dead time to prevent shoot through problem between the switches in one leg. Because of dead time effect, the output waveforms can be distorted and the equivalent transferred energy of Pulse Width Modulation (PWM) is reduced. Even with added dead time, shoot through is still the dominant failure of circuit, especially at some fault condition. In addition, with higher DC bus voltage operation, this standard inverter cannot simply employ power MOSFETs as active switches due to reverse recovery problem of the body diode of MOSFETs.

To utilize the benefits of power MOSFETs, such as lower switching loss, resistive conduction voltage drops and fast switching speed that allows reduction of current ripple and the size of passive components, Dual Buck Half-Bridge and Full-Bridge Inverters had been proposed. Dual Buck Inverter typically has two buck inverter with one working at positive half cycle while the other one operating at the negative half cycle.

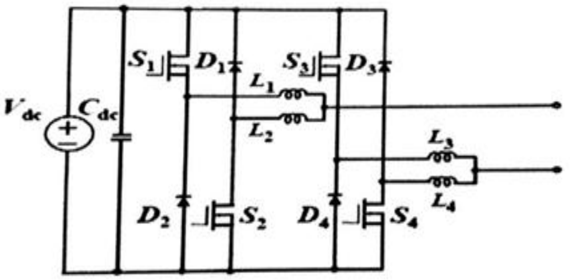


Fig. 3.1: Circuit configuration of Dual Buck Full-Bridge VSI with MOSFETs.

The Dual Buck Full-Bridge inverter shown in Fig. 3.1 does not need dead time and totally eliminates the shoot through concerns, which leads to greatly enhanced system reliability. The body diode of MOSFETs never conducts and the external diodes D1 to D4 can be independently selected to minimize switching losses [2]. This Dual Buck Inverter topology is modeled in MATLAB\Simulink platform and different PWM methods are applied to Dual Buck Inverter discussed in the next section.

3.2 PWM METHODS FOR DUAL BUCK INVERTER

In PWM techniques there are multiple numbers of output pulses per half cycle and pulses of different width. The width of each pulse is varying in proportion to the amplitude of a sine wave evaluated at the center of same pulse. Gating signals are generated by comparing a sinusoidal reference signal with a high frequency triangular signal. The reference signal frequency determines the frequency of the inverter output voltage. There are two types in SPWM switching technique and they are Unipolar and Bipolar switching technique. In Bipolar SPWM switching technique different methods are there and they are discussed in the next section.

3.2.1 Traditional Bipolar PWM Method

Fig.1 shows the block schematic of control signal generating unit used in Traditional Bipolar PWM inverter. Dual to common mode Vdc/2 so the proposed Dual Buck Full-Bridge Inverter could adopt the new PWM method. This method requires two pair of MOSFETs switching complimentarily which would lead to circulating current and decrease efficiency.

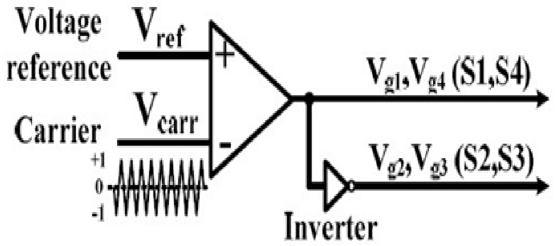
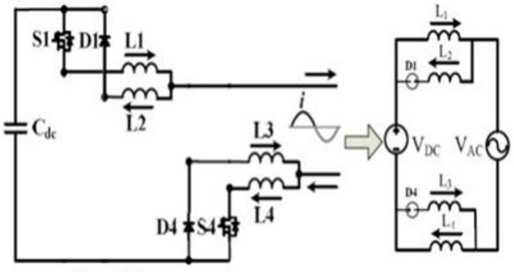


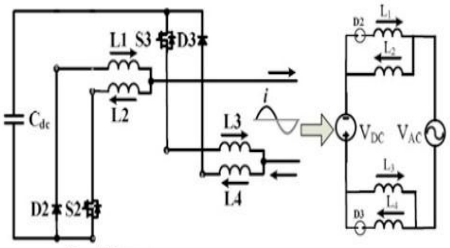
Fig. 3.2: Block schematic of Traditional Bipolar PWM switching control unit.

Operating mode and equivalent circuit under TB-PWM method

The operating mode and equivalent circuit under TB-PWM is shown in Fig. 3.3. S1+S4 and S2+S3 would conduct complimentarily, so each inductor has current. When S1 and S4 are conducting, freewheeling current of L2 and L3 would circle back to DC bus through D1 and D4. When S2 and S3 are conducting, freewheeling current of L1 and L4 would circle back to DC bus through D2 and D3.



S1 and S4 turn on



S2 and S3 turn on

Fig. 3.3: Operating mode and equivalent circuits under TB-PWM method

This circulating current appears both in positive and negative half cycle resulting in decrease of efficiency of the inverter. Hence a method is suggested in the next section which enables to minimize the circulation current.

3.2.2 Improved Bipolar PWM method

In order to overcome the drawback of circulation current in traditional bipolar PWM method, an

Improved Bipolar PWM (IB-PWM) method has been proposed, the operating principle is to let each inductor operate under positive or negative half cycle current. So PWM should be fed to the switching considering the current polarity. The improved bipolar PWM method takes into account of the current polarity and the block diagram is shown in Fig. 3.4.

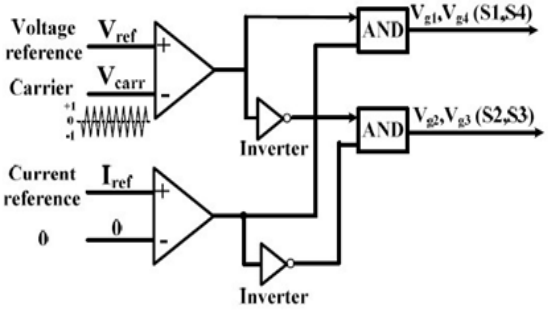
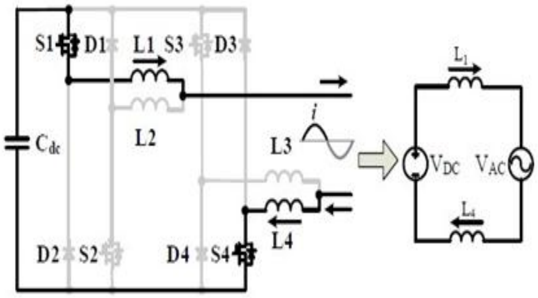


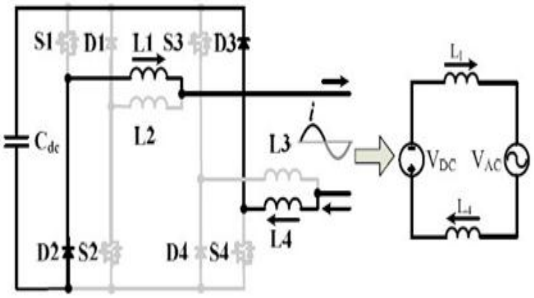
Fig. 3.4: Block schematic of Improved Bipolar PWM switching control unit.

Operating mode and equivalent circuit under IB-PWM method

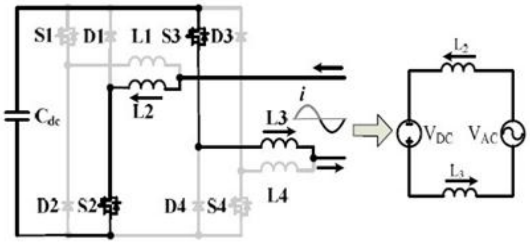
The operating model and equivalent circuits are shown in Fig. 3.5(a), (b), (c), and (d), S1 and S4 will switch during positive half cycle current and freewheeling current will go through D2 and D3, S2 and S3 will switch during negative half cycle current, freewheeling current would go through D1 and D4.



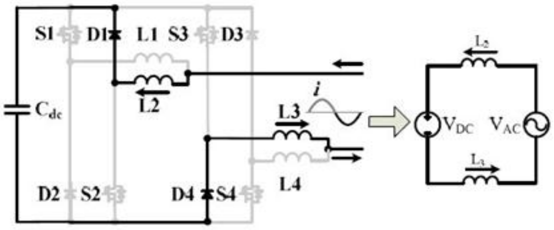
(a). Positive current, S1 & S4 turn ON



(b). Positive current, D1 & D3 free-wheeling



(c). Negative current, S2 & S3 turn ON



(d). Negative current D1 & D4 free-wheeling.

Fig. 3.5: Operating mode and equivalent circuits under IB-PWM method.

With bipolar modulation, the switching ON and OFF time will have following relationship to Vref.

$$T_{ON} = D \cdot T = \frac{1 + Vref}{2} \cdot T \qquad (3.1)$$

The Volt-Second balance equation on inductor is

$$(V_{DC} - V_{AC}) \cdot T_{ON} + (-V_{DC} - V_{AC}) \cdot T_{OFF} \qquad (3.2)$$

When inductor current is under Continuous Conduction Mode (CCM) condition, TB-PWM method has same Volt-Second balance equation, which is:

$$(V_{DC} - V_{AC}) \cdot D \cdot T + (-V_{DC} - V_{AC})(1 - D)T = 0$$

(3.3)

However, during Discontinuous Conduction Mode (DCM) condition of unity PF operation, VoltSecond equation for IB-PWM method would be:

$$V_{DC} T_{ON} + (-V_{DC}) T_{OFF} \qquad (3.4)$$

So, if Vref = 0, switching ON and OFF time would be:

$$T_{ON} = T_{OFF} = 0.5T \qquad (3.5)$$

Then ripple current and average current would be:

$$\Delta i = \frac{V_{DC}}{L} \times 0.5T \qquad (3.6)$$

$$I_{avg} = \frac{V_{DC}}{2L} \times 0.5T \qquad (3.7)$$

Assume Vref and output current Iac are in phase, when current is positive and S1+S4 are switching, the relationship between the duty cycle (D) and Vref is

$$D = \frac{1 + Vref}{2} \; (V_{ref} \geq 0) \qquad (3.8)$$

Only when Vref decreases to -1, DCM condition could let D and current decrease to 0.

When current is negative and S2+S3 are switching, the relationship between the duty cycle (D) and Vref is:

$$D = \frac{1 - Vref}{2}\left(V_{ref} \leq 0\right) \qquad (3.9)$$

Only when Vref increases to 1, DCM condition could let D and current increase to 0. So during zero-crossing of current, the switching model would change between S1+S4 and S2+S3, the voltage reference is expected to change between -1 and +1 instantly. It can be seen that at the zero-crossing period, D is approaching 50%. Therefore, the current ripple at zero-crossing region is not zero. The same analysis applies to the negative half cycle. When the positive half cycle current connects with the negative half cycle current, it will create a jump at zero-crossing will reflect on a voltage jump on the output capacitor. At the zero-crossing region, D is almost 0.5 and the output will be distorted at zero-crossing. The Total Harmonic Distortion (THD) of output current is 17.32%, which is mainly coming from zero-crossing distortion [3]. This distortion minimized by employing a New PWM method in the next section.

3.2.3 Proposed New PWM method

As discussed in last section, the current distortion happened at DCM region and the reason is that without active switch working during turn OFF, AC output current could only be either positive or negative in negative cycle and polarity of current results in the current distortion. This method combines the advantage of TB-PWM (No zero-crossing distortion) and IB-PWM (No circulation current).

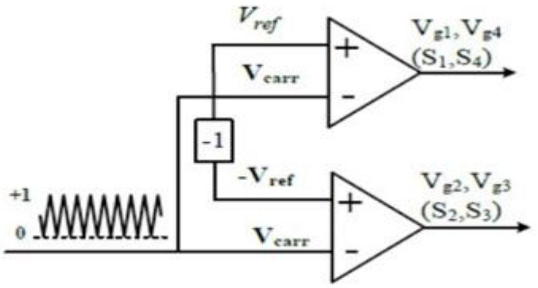


Fig. 3.6: Block schematic of New PWM switching control unit.

Realization of New PWM method which adopts the unipolar method but the PWM gating pattern is still bipolar. New PWM method for bipolar PWM has been proposed, which provides zero percent duty cycle at zero-crossing. With the zero percent duty cycle at zero crossing, inductor current would go into DCM. So, the current distortion at zero crossing would be improved. The Total Harmonic Distortion (THD) of output AC current is reduced to 6.2%, giving a better sine wave. The inverter is designed in the next section and simulation results are verified in the forthcoming chapters.

3.3 Design analysis of Dual Buck Inverter

Design of a Dual Buck Inverter implies design of Buck circuit, DC link capacitor and LCL filter. Design procedure and values of the components employed are stated in the sub-sections to follow:

3.3.1 Inductor design for the proposed Dual Buck Inverter

A dual buck converter or Step-Down Inverter can also be called as a switch mode regulator. Popularity of a switch mode regulator is due to its fairly high efficiency and compact size and a switch mode regulator is used in place of linear voltage regulator at relatively high output.

Fig. 3.7 shows the four topological stages in one output current cycle for the proposed inverter. Note that the point N is the dc link negative terminal, and the point E is the load negative terminal. The four operation modes are briefly described as follows.

During the positive half cycle of output current S1, and S4 are commutating at the PWM switching frequency. When S1 and S4 are on and the other switches and diodes are OFF, the inductor current is charging, as shown in Fig. 3.7(a).

Under the condition that the inductance values of L1 and L4 are identical, the inductor voltage can be found as

$$V_{L1} = V_{L4} = 0.5(V_{DC} - V_{AC}) \qquad (3.10)$$

And the output voltage VAC is calculated by

$$V_{AC} = V_{DC} M \sin(\omega t) \qquad (3.11)$$

where,

VDC = DC link voltage
M = Modulation index
= Angular frequency of output.

From (3.10) and (3.11), the ground potential VEN1 in the charging interval during positive half cycle can be expressed as

$$V_{EN1} = 0.5V_{dc}(1 - M\sin(\omega t)) \qquad (3.12)$$

In the freewheeling interval during the positive half cycle shown in Fig. 3.7 (b), the S1 and S4 simultaneously turn OFF and D2 and D3 are ON. The voltages of the inductor L1 and L4 are given as

$$V_{L1} = V_{L4} = 0.5(-V_{AC}) \qquad (3.13)$$

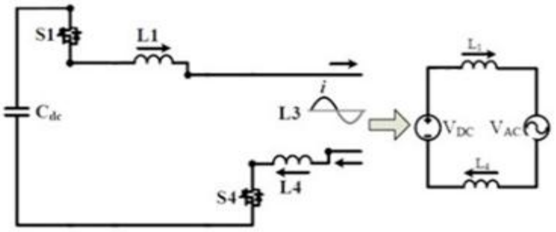
Under the condition that the S1 and S4 share the DC link voltage when they are simultaneously turned OFF, the voltage stress of S4 can be found as

$$V_{S_4} = 0.5V_{DC} \qquad (3.14)$$

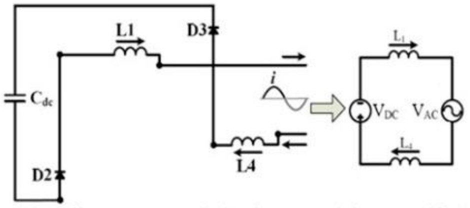
From (3.11), (3.13) and (3.14), the ground potential VEN2 in the freewheeling interval during positive grid half cycle can be expressed as

$$V_{EN2} = 0.5V_{DC}(1 - M\sin(wt)) \qquad (3.15)$$

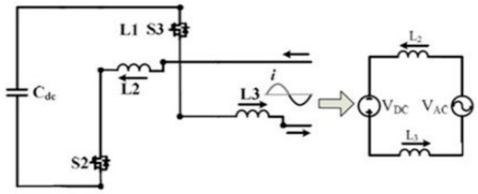
Based on the fact that (3.15) is identical to (3.12), the PWM switching frequency voltage of the ground potential is avoided. The operation modes similarly change during the negative half cycle.



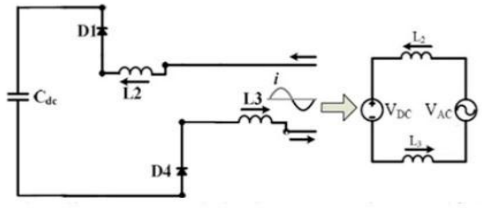
(a)Charging interval during positive half cycle



(b)Freewheeling interval during positive half cycle



(c)Charging interval during negative half cycle



(d)Freewheeling interval during negative half cycle.

Fig. 3.7: Topological operating stages of the proposed inverter

From Fig. 3.7 (a)-(d), it can be seen that the body diodes of the MOSFETs are naturally inactive. As a result, MOSFETs can be employed as all the active switches and high ground leakage current can be avoided [5].

The output inductance can be calculated based on the design criterion that the maximum magnitude of the peak-peak current ripple is less than approximately 20% - 40% of the rated output current Irated.

The peak-peak inductor current ripple is

$$\Delta i_{peak-peak} = \frac{(V_{DC} - V_{AC})D}{(L_1 + L_4)f_s} \qquad (3.16)$$

The maximum peak-peak ripple of the inductor current in the whole output cycle is calculated by

$$\Delta i_{peak-peak} = \frac{(V_{DC} - V_{AC})D}{(L_1 + L_4)f_s} \leq (20{\sim}40)\% \cdot I_{rated} \qquad (3.17)$$

In the proposed inverter, the output inductance then can be calculated as

$$(L_1 + L_4) \geq \frac{(V_{DC} - V_{AC})D}{f_s(20{\sim}40)\% \cdot I_{rated}}$$

$$L_{out} \geq \frac{V_{AC}(V_{DC} - V_{AC})}{\Delta I_L \times f_s \times V_{DC}} \qquad (3.18)$$

The operating parameters of the proposed Dual Buck Inverter are assumed as:

Output Power = 2500W

VDC = 200V

VAC = 120V

Minimum switching frequency, fs = 4000Hz

$$P = V \times I \qquad (3.19)$$

$$I_{out} = \frac{P}{V} = \frac{2500}{120} = 20.83A$$

ΔI_L = Inductor ripple current is 20% – 40% of rated output current I_{rated}

$$\Delta I_L = \frac{40}{100} \times 20.83 = 8.33A$$

$$L_{out} \geq \frac{V_{AC}(V_{DC} - V_{AC})}{\Delta I_L \times f_s \times V_{DC}}$$

$$L_{out} \geq \frac{120(200 - 120)}{8.33 \times 4000 \times 200} = 1440.6\mu H$$

As Lout = L1+L4 there are two inductors in series in a Dual Buck Full-Bridge Inverter the inductor values should be half of the value calculated above for each, since there are two current paths L1 = L4 is one path and L2 = L3 in the other path.

$$L_1 = L_2 = L_3 = L_4 = \frac{1440.6\ \mu H}{2} = 720.3\mu H$$

So, inductors L1, L2, L3 and L4 for buck circuit are selected approximately equal to .

3.3.2 DC link capacitor design

The DC link capacitor is calculated assuming a maximum peak value of 15% for the second order harmonic in the DC bus when the converter operates with rate power.

So the minimum DC link capacitor size is given by the equation:

$$C_{dc} = \frac{P_{OUT}}{2 \times \omega \times V_{dc} \times \Delta V_{ripple}} \qquad (3.20)$$

where,

Cdc = DC link capacitor

= The peak value of the second order harmonic in DC link

The rated DC link voltage

$$\omega = 2\pi f$$

POUT = Power output.

$$C_{dc} = \frac{2500W}{2 \times 2\pi \times 50 \times 200 \times (0.15 \times 2000)} = 663.14\mu F$$

3.3.3 Design of LCL filter

The value of C and L of LCL filter is calculated using the condition to be satisfied by cut-off frequency in a low pass filter,

$$Z_0 = X_C = \frac{1}{2\pi f_c C}$$

where,

Z0 = Characteristic impedance fc = Cut-Off Frequency.

At resonant frequency, (taking resonant frequency)

$$\omega L = \frac{1}{\omega C} \qquad (3.21)$$

$$\omega^2 = \frac{1}{LC} \qquad (3.22)$$

In the proposed design, the cut-off frequency, fc= 2000Hz and characteristic impedance is assumed as 30Ω. Therefore, the values of C and L are calculated using

$$C_f = \frac{1}{2\pi f_c R} = \frac{1}{2\pi \times 2000 \times 30} = 2.65\mu F$$

$$L_f = \frac{R}{2\pi f_c} = \frac{30}{2\pi \times 2000} = 2.38mH$$

After designing the Dual Buck Inverter and filter circuit, switching control strategies are required to fire the switches used in the Dual Buck Inverter. Selection of switching devices among various power electronic devices used for switching and various Pulse Width Modulation switching technologies applied to the inverter are available and some of those are discussed in the next section.

3.4 Switching control strategies of the inverter power stages

Different switching techniques have been mentioned to control the Voltage Source Inverter (VSI) power stage. There are three major output current control technique for VSI which include PWM inverter, Square Wave Inverter and Single-Phase Inverters with Voltage Cancelation method.

The DC-AC inverters usually operate on PWM technique. The PWM is very advanced and very useful technique in which width of the gate pulses are controlled by various mechanisms. PWM inverter is used to keep the output voltage of the inverter at the rated voltage irrespective of the output load. With PWM, inverters usually switch between different circuit topology, which means that inverter is non-linear, specifically piecewise smooth system.

In addition to this, the control strategies used in the inverter are also similar to those in DC-DC converter. Both Current–Mode control and Voltage-Mode control are employed in practical applications. PWM is a technique which is characterized by the generation of constant amplitude pulse with modulating the pulse duration by modulating the duty cycle.

The PWM inverter has been main choice in the power electronic for decades, because of its circuit simplicity and strong control scheme, depending on switching performance and good characteristics features, SPWM will be used.

As mentioned advantageous of using PWM include low power consumption, high energy efficient up to 90%, high power handling capacity, no temperature variation and aging caused drifting are degradation in linearity and SPWM is easy to implement and control. SPWM techniques are characterized by constant amplitude pulse width different duty cycle for each period [10].

3.4.1 Sinusoidal pulse width modulation (SPWM)

Inverters that use PWM switching techniques have a DC input voltage that is usually constant in magnitude. There are many different ways that pulse width modulation can be implemented to shape the output to be AC power. A common technique called Sinusoidal PWM will be explained. In order to output a sinusoidal waveform at a specific frequency a sinusoidal control signal at the specific frequency is compared with a triangular waveform. The inverter then uses the frequency of the triangle wave as the switching frequency. This is usually kept constant. The triangle waveform, Vtri is at switching frequency fs this frequency controls the speed at which the inverter switches are turned OFF and ON. The control signal, Vcontrol is used to modulate the switch duty ratio and has a frequency f1. This is the fundamental frequency of the inverter voltage output. Since the output of the inverter is affected by the switching frequency it will contain harmonics at the switching frequency. This comparison of waveforms produces the SPWM signals to turn ON/OFF switches.

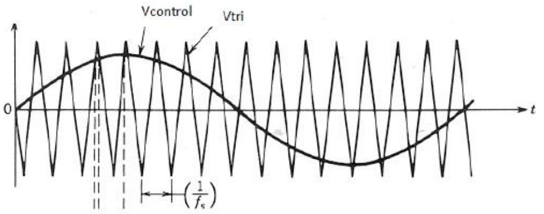


Fig. 3.8: Comparison of desired frequency and triangular waveform

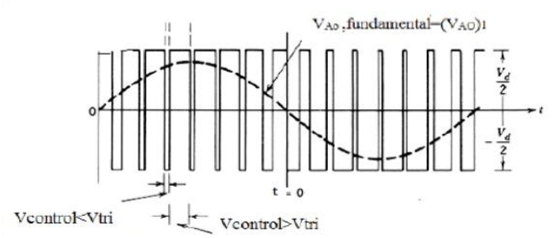


Fig. 3.9: Description of PWM gating pattern

3.4.2 SPWM with bipolar voltage switching

The basic idea to produce PWM Bipolar voltage switching signal is shown in Fig. 3.10. It comprises of a comparator used to compare between the reference voltage waveform, Vr with the triangular carrier signal Vc and produces the bipolar switching signal.

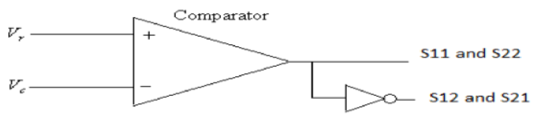


Fig. 3.10: Block schematic of Bipolar PWM generator

In this scheme the diagonally opposite transistors S11, S21, and S12, S22 are turned ON or turned OFF at the same time. The output of leg A is equal and opposite to the output of leg B. The output voltage is determined by comparing the control signal Vr and the triangular signal Vc as shown in Fig. 3.11 to get the switching pulses for the devices, and the switching pattern and output waveform is as follows.

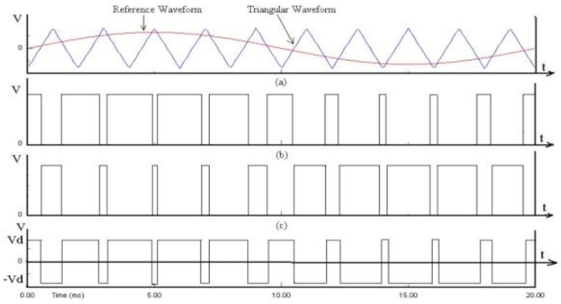


Fig. 3.11: SPWM with Bipolar voltage switching waveforms.

(a) Comparison between reference waveform and triangular waveform

(b) Gating pulses for S1 and S4 (c) Gating pulses for S2 and S3 (d) Output waveform

3.4.3 SPWM with unipolar voltage switching

The basic idea to produce SPWM with unipolar voltage switching is shown in Fig. 3.12. The different between the SPWM with bipolar voltage switching generators is that generator uses another comparator to compare between the inverse difference waveform with the triangle voltage.

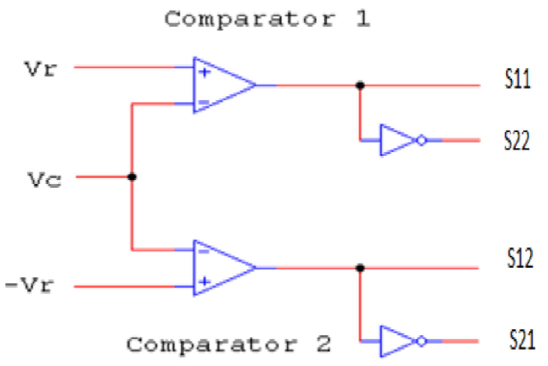


Fig. 3.12: Block schematic of Unipolar PWM generator

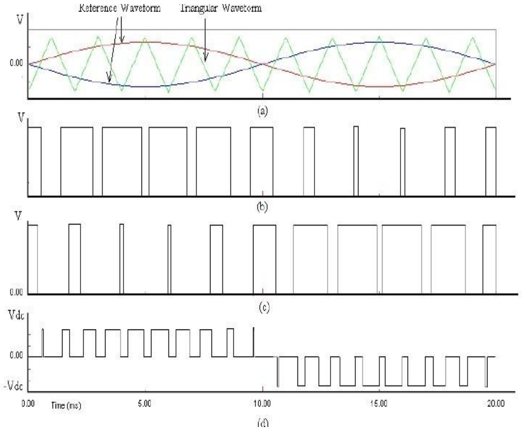


Fig. 3.13: SPWM with Unipolar voltage switching waveforms

(a)Comparison between reference waveform and triangular waveform
(b)Gating pulses for S1 and S4 (c) Gating pulses for S2 and S3 (d) Output waveform

The switching pattern and outuput waveforms is shown in Fig. 3.13, when the switching occurs the output voltage changes between zero and Vd or zero and -Vd voltage levels. This is why it is called SPWM with unipolar voltage switching.

In SPWM the effective switching frequency is seen by the load is doubled and the voltage pulse amplitude is halved. Due to this, the harmonic content of the output voltage waveform is reduced compared to bipolar switching. In unipolar voltage switching scheme the amplitude of the significant harmonics and its side bands is much lower for all modulation indices thus making filtering easier and with its size being significantly smaller.

The SPWM unipolar voltage switching has the advantage of effectively doubling the switching frequency as for as output harmonics are concerned, comparing to bipolar voltage switching scheme. Also the voltage jumps in the output voltage at each switching are redued to Vd as compared to twice –Vd in bipolar voltage switching [4].

In unipolar voltage switching output has three states Vd, zero and -Vd; due to the presence of zero state in the output it provides a path for ground leakage current. But in case of bipolar voltage switching output has only two states Vd and –Vd; due to the absence of zero state in the bipolar PWM method there is no path for ground leakage current. Since the proposed inverter is used for PV application Bipolar PWM switching method is suitable. Inverters require Power Electronic devices for switching purpose and selection of switching devices for the proposed inverter is discussed in the next section.

3.5 Selection of switching devices

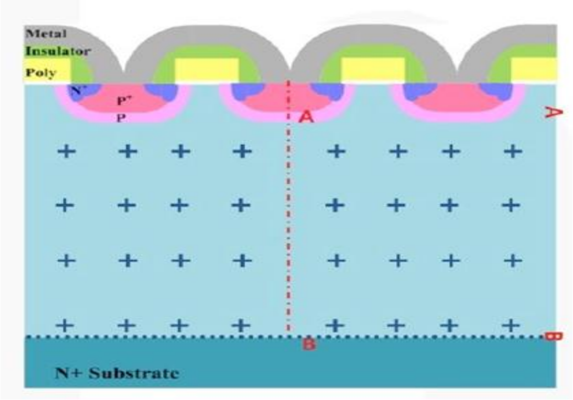
Two main types of switches are used in power electronics. One is the Metal Oxide Semiconductor Field Effect Transistor (MOSFET), which is designed to handle relatively large voltage and currents. Other is Insulated Gate Bipolar Transistor (IGBT). Each has its own advantages and there is high degree of overlap in the specifications of the two.

IGBTs are generally used in very high voltage applications, usually above 200V, generally above 600V. They do not have the high frequency switching capability of MOSFETs and used at frequency lower than 29 kHz. They can handle high currents, are able to output greater than 5kW and have very good thermal operating ability and able to operate above 1000Celcius. One of the major drawback of IGBTs in their unavoidable current tail when they turn OFF. Essentially, when the IGBT turns OFF the gate current of transistor cannot dissipate immediately, which causes loss of power each tail this occurs. IGBTs tend to be used in high power applications, such as UPS of power higher than 5kW, welding and low power lighting.

MOSFETs have a much higher switching frequency capability than IGBTs and can be switched at frequency higher than 200kHz they do not have as much capability for high voltage and high current application and also used at voltage lower than 250V less than 500W. MOSFET do not have current tail power loss which make more efficient than IGBTs. Both MOSFETs and IGBTs have power losses due to ramp up and ramp signal when the turning ON and turning OFF.

Super Junction Power MOSFET

The RDS(ON) × QG, Figure of Merit (FOM) is generally considered the single most important indicator of MOSFET performance in Switching-Mode Power Supplies (SMPS). Therefore, several new technologies have been developed to improve the RDS(ON) × QG FOM. Fig. 3.14 shows vertical structure and electric field profile of a Planar MOSFET and a Super-Junction MOSFET. Breakdown voltage of the Planar MOSFET is determined by drift doping and its thickness. The slope of electric field distribution is proportional to drift doping. Therefore, thick and lightly doped epi is needed to support higher breakdown voltage.



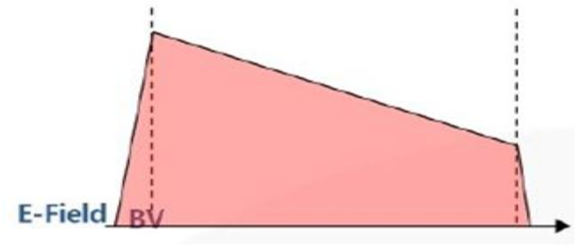


Fig. 3.14: Verticl structure and electric field profile of Planar Power MOSFET

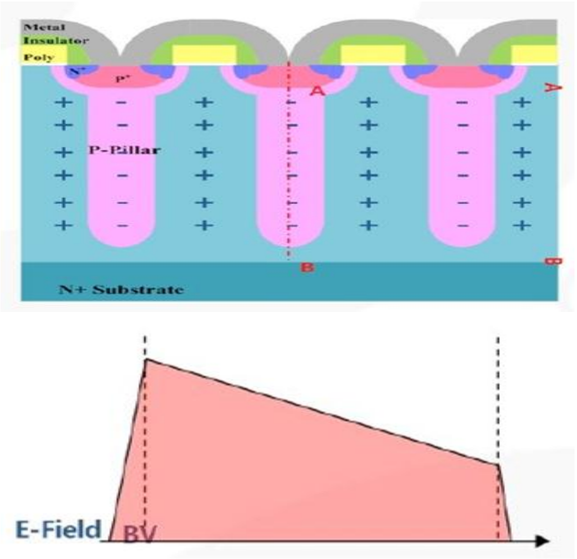


Fig. 3.15: Vertical structure and electric field profile of Super-Junction Power MOSFET.

The major contribution to On-Resistance of high-voltage MOSFET comes from the drift region: The On-Resistance exponentially increases with the light doping and thick drift layer for higher breakdown voltage. In high-voltage MOSFET technologies, the most remarkable achievement for On-Resistance reduction is Super-Junction technology shown in Fig. 3.16.

Super-Junction technology has deep p-type pillar like structure in the body in contrast to the well like structure of conventional planar technology.

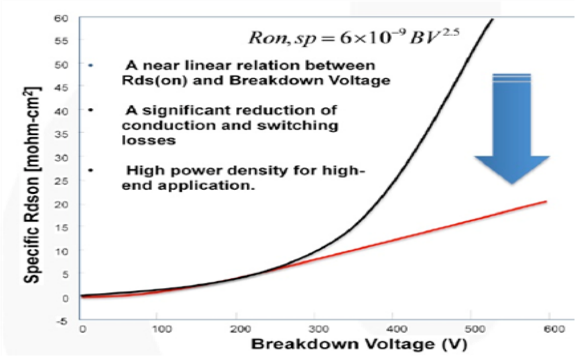


Fig. 3.16: Specific RDS(ON) of Planar MOSFET or Super-Junction MOSFET as a function of breakdown voltage.

The effect of the pillars is to confine the electric field in the lightly doped epi region. Thanks to this p-type pillar, the resistance of n-type epi can be dramatically reduced compared to the conventional planar technology, while maintaining same level of breakdown voltage [6].

This new technology broke silicon limits in terms of On-Resistance and achieves only one-third specific On-Resistance per unit area compared to planar processes. This technology also achieved unique nonlinear parasitic capacitance characteristics and therefore enabled reduced switching power losses. Therefore, in this simulation MOSFET is used as High frequency

IV. IMPLEMENTATION AND SIMULATION RESULTS

4.1 Introduction

Simulation is carried using MATLAB/SIMULINK R2014a version, based on the calculation shown in the previous chapter for Dual Buck Inverter implementation and simulation results are shown in this chapter. Dual Buck Full-Bridge Inverter operating parameters are listed in the Table 4.1.

Table 4.1: Operating parameter for a Dual Buck Inverter

Symbol	Actual Meaning	Value
Vin	Given DC input voltage	200V
Vout	Desired RMS output voltage	120V
Fs	Minimum switching frequency of the converter	4000Hz
IL	Maximum inductor current	20.83A
ΔIL	Estimated inductor ripple (40% Maximum inductor current)	8.33A
ΔVout	Desired output voltage ripple (1.5% of the output voltage)	1.8V

4.2 Traditional Bipolar PWM Method

The implementation of the Dual Buck Full-Bridge Inverter with Traditional Bipolar PWM (TBPWM) method is shown in Fig 4.1.

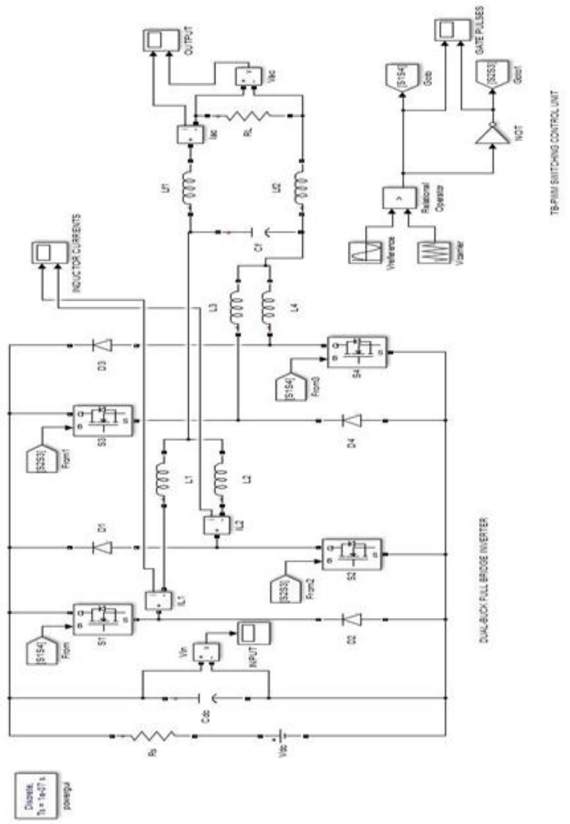


Fig. 4.1: Simulation model of Traditional Bipolar PWM (TB-PWM) method.

By simulating the model shown in Fig. 4.1 the voltage, current and gate pulses characteristic waveforms are obtained and are shown in Fig.4.2 to Fig. 4.5.

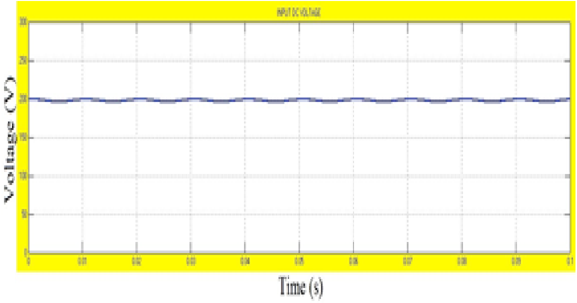


Fig. 4.2: Input DC voltage (Voltage across DC link capacitor).

Fig. 4.2 shows the voltage across the DC link capacitor and it is the input voltage to the Dual Buck Full-Bridge Inverter. The DC link capacitor provides almost constant input voltage to the inverter. Since the inverter used is Voltage Source Inverter type, the voltage should be maintained constant at the input.

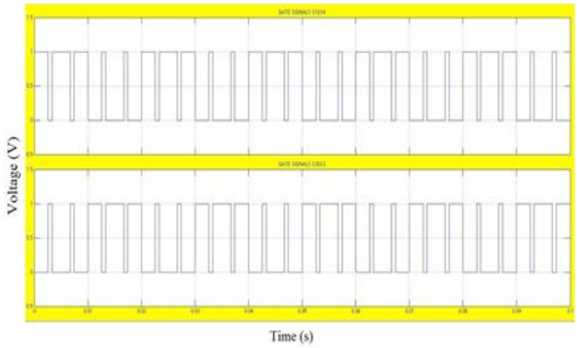


Fig. 4.3: Switching pulses of TB-PWM method.

Fig. 4.3 shows the gate switching pulses obtained from Traditional Bipolar PWM (TB-PWM) method. As seen from the graph it is concluded that complementary switching pulses are generated. These switching pulses are given to the gate terminal of the power MOSFET's to fire the switching devices used in the inverter. Due to complementary switching of the MOSFET's circulation current is exist in the circuit. Circulation current in the circuit is seen from the inductor current shown in Fig. 4.4.

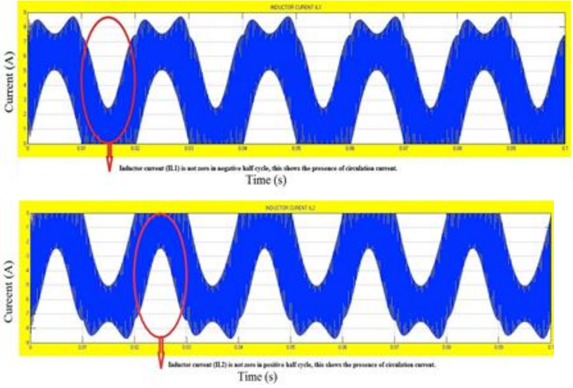


Fig. 4.4: Inductors' current under TB-PWM method.

As shown in the Fig. 4.4 the current is measured through the inductor L1, which in the positive current path of the circuit the current was expected to be positive in positive half cycle and zero in negative half cycle. And current through the inductor L2, which in the negative current path of the circuit, the current is expected to be negative in negative half cycle and zero in positive half cycle. But under the traditional bipolar PWM method, switching is shown in the Fig. 4.3 and from the Fig. 4.4 it is seen that current is not zero through inductor L1 in the negative half cycle and current is not zero through inductor L2 in the positive half cycle respectively. This shows the presence of circulation current in the circuit.

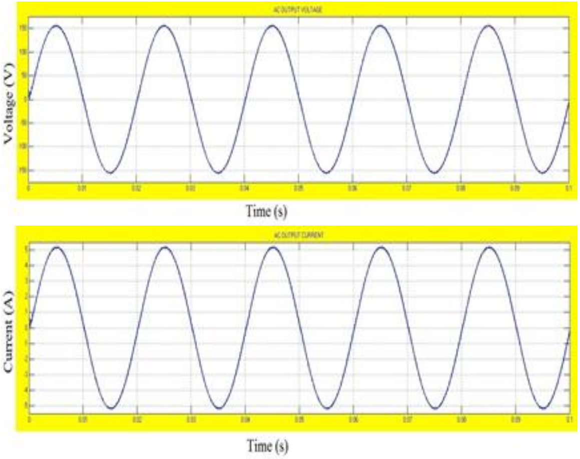


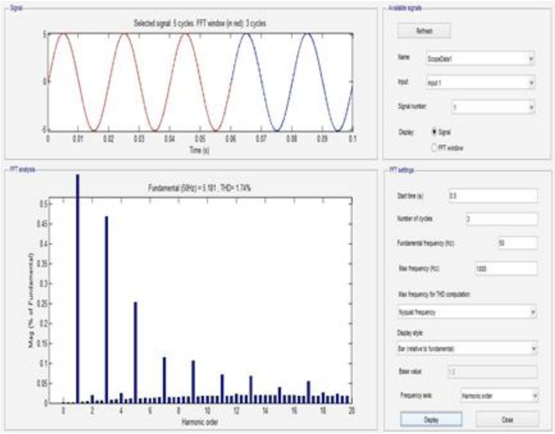
Fig. 4.5: AC output voltage and AC output current under TB-PWM method.

Fig. 4.5 shows the AC output voltage and AC output current measured across the resistive load. As seen from the AC output current waveform, almost a sinusoidal AC output is obtained and it has no zero crossing distortion. But this method is suffered from the problem of circulation current in the circuit.

FFT Analysis of Output AC Current under TB-PWM Method

Harmonics or harmonic frequencies of a periodic voltage or current are frequency components in the signal that are at integral multiples of the frequency of the main signal. This is the basic outcome that Fourier analysis of a periodic signal shows. Harmonic distortion is the distortion of the signal due to its harmonics. A voltage or current that is purely sinusoidal has no harmonic distortion because it is signal consisting of single frequency.

In order to find the harmonic distortion present in the AC output current or voltage, FFT analysis of the AC output current is carried out in MATLAB/Simulink which is shown in Fig. 4.6.



Fundamental (50Hz) = 5.181 , THD= 1.74%

Name: ScopeData1
Input: input 1
Signal number: 1
Display: ● Signal ○ FFT window
Start time (s): 0.0
Number of cycles: 3
Fundamental frequency (Hz): 50
Max frequency (Hz): 1000
Max frequency for THD computation: Nyquist frequency
Display style: Bar (relative to fundamental)
Base value: 1.0
Frequency axis: Harmonic order

Fig. 4.6: FFT analysis of AC output current under TB-PWM method.

From Fig. 4.6, it is observed that the total harmonic distortion is 1.74%. Though the output current and voltage are obtained as per the design and there is no zero crossing distortion in the AC output current as shown in Fig. 4.5, the Dual Buck Inverter is affected by circulation current in the circuit. In order to overcome the circulation current in the circuit, Improved Bipolar PWM switching method is adopted for the same Dual Buck Inverter. The discussions in this regard are presented in the next section.

4.3 Improved Bipolar PWM Method

The implementation of the Dual Buck Full-Bridge Inverter with Improved Bipolar PWM (IBPWM) method is shown in Fig. 4.7.

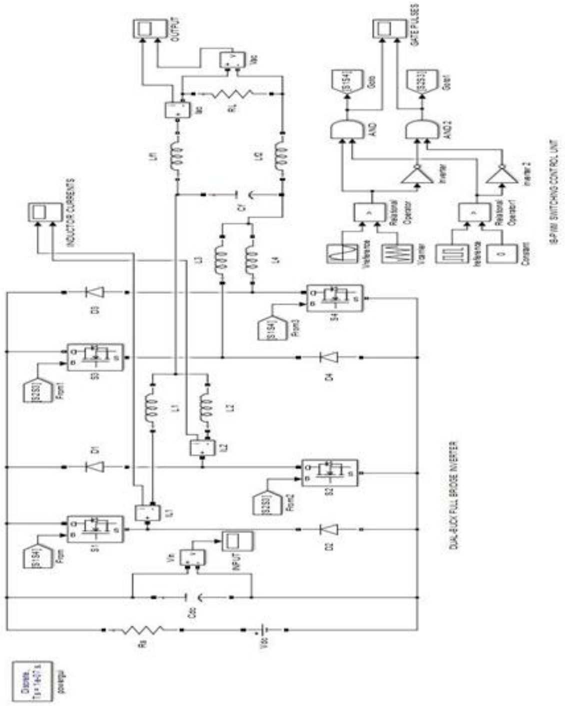


Fig. 4.7: Simulation model of Improved Bipolar PWM (IB-PWM) method.

By simulating the model shown in Fig. 4.7, the voltage, current and gate pulses characteristic waveforms are obtained and are shown in Fig.4.8 to Fig. 4.11.

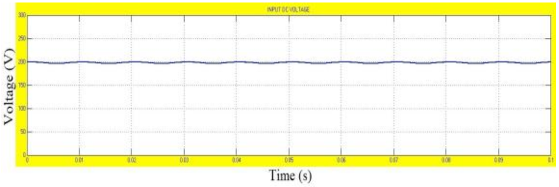


Fig. 4.8: Input DC voltage (Voltage across DC link capacitor).

Fig. 4.2 shows the voltage across the DC link capacitor and it is the input voltage to the Dual Buck Full-Bridge Inverter. The DC link capacitor provides almost constant input voltage to the inverter. Since the inverter used is Voltage Source Inverter type, the voltage should be maintained constant at the input.

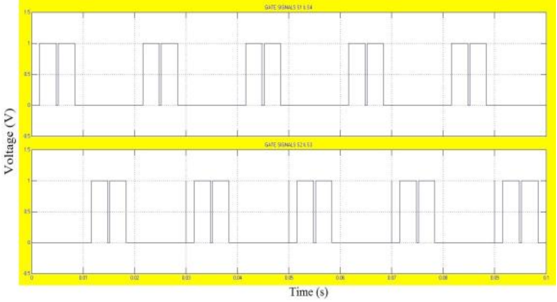


Fig. 4.9: Switching pulses of IB-PWM method.

Fig. 4.9 shows the gate switching pulses obtained from the Improved Bipolar PWM (IB-PWM) switching method. Gate switching pulses are required to fire the switching devices used in the inverter. In this switching method complementary switching of the switching MOSFET's is eliminated. So the positive half cycle of AC output current driving the load caused by switching the devices S1+S4. And the negative half cycle of the AC output current driving the load caused by switching the devices S2+S3.

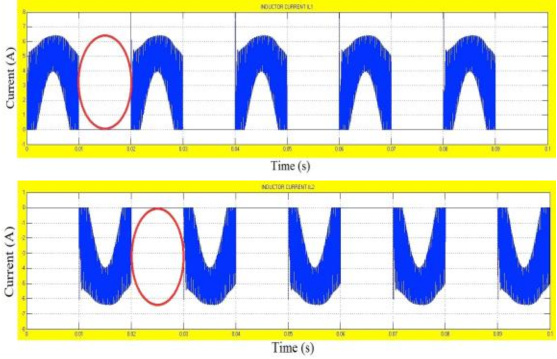


Fig. 4.10: Inductors' current under IB-PWM method.

As seen from the Fig. 4.10 under Improved Bipolar PWM method, current through the inductor L1 as shown in the simulation result is positive in the positive half cycle and zero in the negative half cycle. Similarly, current through the Inductor L2 is negative in the negative half cycle and zero in the positive half cycle this shows the elimination of the circulation current. So this method overcomes the problem of circulation current. But this method introduces a current distortion at zero crossing.

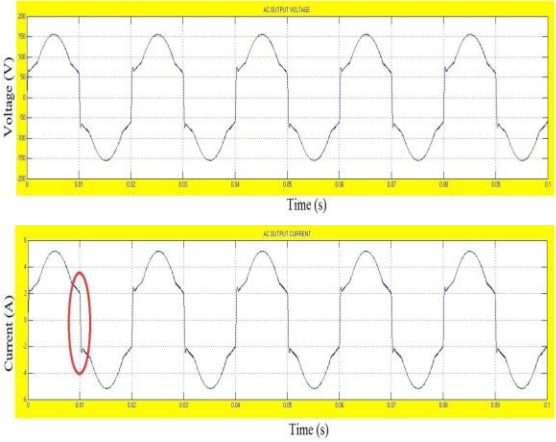
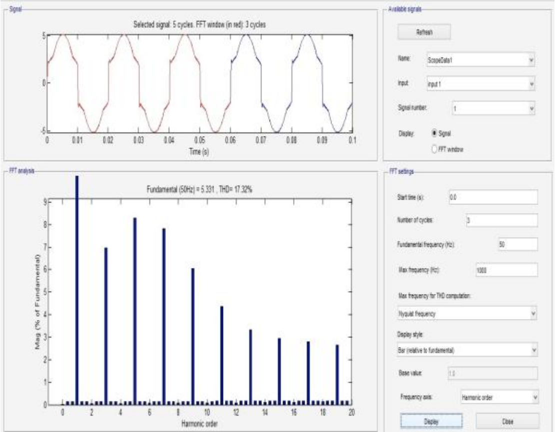


Fig. 4.11: AC output voltage and AC output current under IB-PWM method.

Fig. 4.11 shows the AC output voltage and AC output current under Improved Bipolar PWM method. Though the problem of circulation current in the circuit is eliminated, this method is suffering from a current distortion at zero crossing. From Fig. 4.11 it is observed that there is a distortion at zero crossing D is approaching 50%. Therefore, the current ripple at zero crossing point is not zero. The same analysis applies to the negative half cycle current. When the positive half cycle current connects with the negative half cycle current, it will create a jump. The current jump at zero crossing will reflect on a voltage jump on the output. At zero crossing region, D is almost 0.5 and the output will be distorted at zero crossing.

FFT Analysis of Output AC Current under IB-PWM Method

In order to find the harmonic distortion present in the AC output current or voltage, FFT analysis of the AC output current is carried out in MATLAB/Simulink which is shown in Fig. 4.12.



Name: ScopeData1
Input: input 1
Signal number: 1
Display: ● Signal ○ FFT window
Start time (s): 0.0
Number of cycles: 3
Fundamental frequency (Hz): 50
Max frequency (Hz): 1000
Max frequency for THD computation: Nyquist frequency
Display style: Bar (relative to fundamental)
Base value: 1.0
Frequency axis: Harmonic order

Fig. 4.12: FFT analysis of AC output current under IB-PWM method

From Fig. 4.12 it is observed that the total harmonic distortion is 17.32%. Even though circulation current is eliminated, due to the presence of current distortion at zero crossing of the waveform and it is more, the total harmonic distortion is increase from 1.74% of TB-PWM method to 17.32% in IB-PWM method.

This zero crossing distortion has to be minimized in order to obtained distortion free, high quality output AC current with no circulating current in the circuit and also to reduce total harmonic distortion to a low value. This is done by employing a New PWM method. The proposed New PWM method eliminates the circulation current, minimizes the current distortion at zero crossing of the waveform and reduces the total harmonic distortion. The discussions in this regard are presented in the next section.

4.4 Proposed New PWM Method

The implementation of the Dual Buck Full-Bridge Inverter with New PWM (IB-PWM) method is shown in Fig. 4.13.

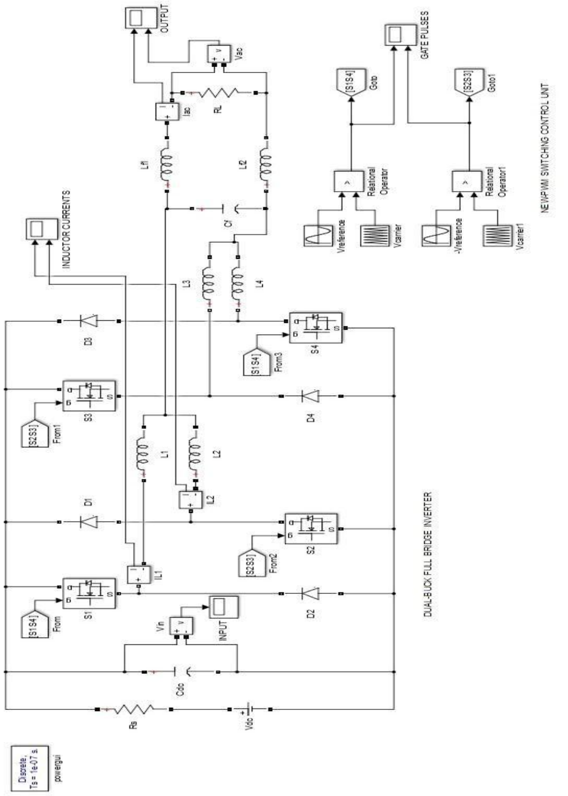


Fig. 4.13: Simulation model of New PWM method.

By simulating the model shown in Fig. 4.13, the voltage, current and gate pulses characteristic waveforms are obtained and are shown in Fig.4.14 to Fig. 4.17.

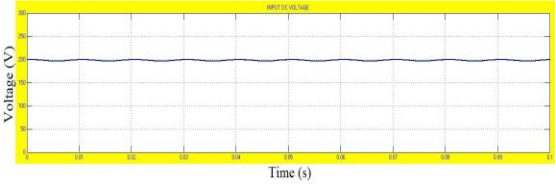


Fig. 4.14 shows the voltage across the DC link capacitor and it is the input voltage to the Dual Buck Full-Bridge Inverter. The DC link capacitor provides almost constant input voltage to the inverter. Since the inverter used is Voltage Source Inverter type, the voltage should be maintained constant at the input.

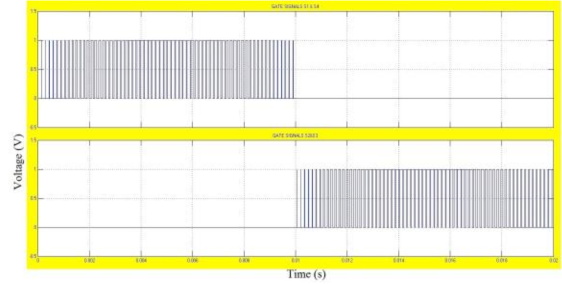


Fig. 4.15: Switching pulses of New PWM method.

Fig. 4.15 shows the gate switching pulses obtained from the New PWM switching method. Gate switching pulses are required to fire the switching devices used in the inverter. In this switching method complementary switching of the switching MOSFET's is eliminated. So the positive half cycle of AC output current driving the load caused by switching the devices S1+S4. And the negative half cycle of the AC output current driving the load caused by switching the devices S2+S3. In this method, Discontinuous Conduction Mode (DCM) is reduced.

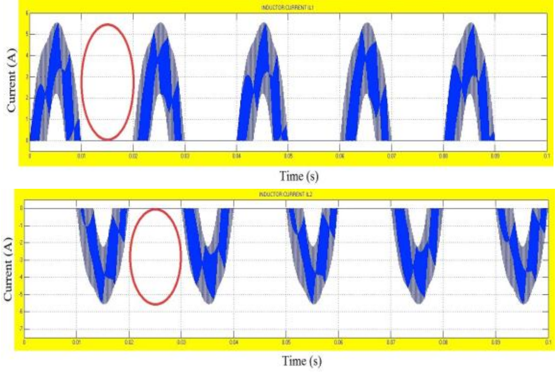


Fig. 4.16: Inductors' current under New PWM method.

As seen from the Fig. 4.16, under New PWM method, current through the inductor L1 is positive in the positive half cycle and zero in the negative half cycle. Similarly, current through the Inductor L2 is negative in the negative half cycle and zero in the positive half cycle, Hence, it is concluded that circulation current is eliminated.

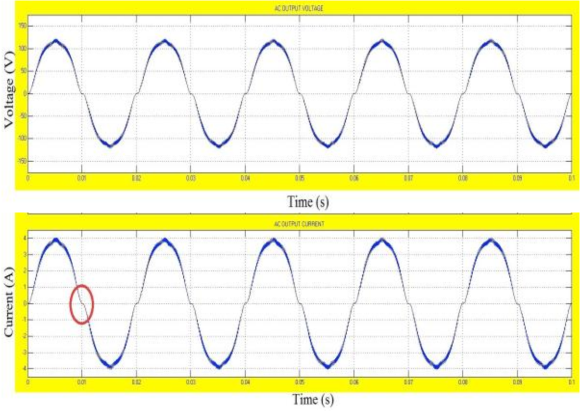


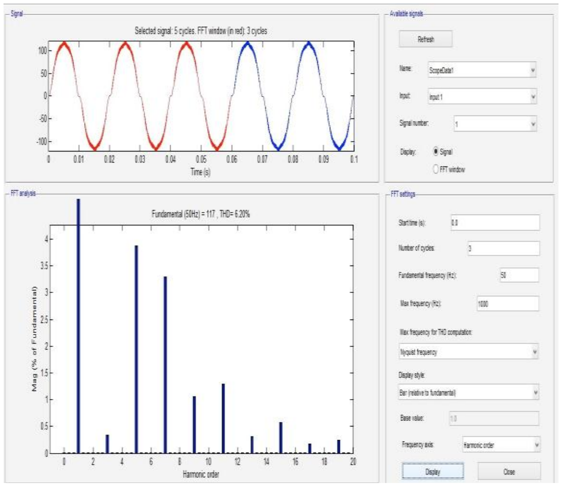
Fig. 4.17: AC output voltage and AC output current under New PWM method

As shown in Fig. 4.17 by employing a New PWM modulation method DCM is reduced and hence current distortion at zero crossing is minimized. It is clear from the results that there is no circulation current in the circuit and zero crossing distortion in the AC output current and both are is minimized in the proposed New PWM method.

New PWM method combines the advantage of traditional bipolar PWM method and improved bipolar method. In this method, the circulation current is eliminated (which increases the efficiency) and zero crossing distortion is also minimized.

FFT Analysis of Output AC Current under New PWM Method

In order to find the harmonic distortion present in the AC output current, FFT analysis of the AC output current is carried out in MATLAB/Simulink. Results obtained in this regard are shown in Fig. 4.18.



Name: ScopeData1
Input: input 1
Signal number: 1
Display: ● Signal ○ FFT window
Start time (s): 0.0
Number of cycles: 3
Fundamental frequency (Hz): 50
Max frequency (Hz): 1000
Max frequency for THD computation: Nyquist frequency
Display style: Bar (relative to fundamental)
Base value: 1.0
Frequency axis: Harmonic order

Fig. 4.18: FFT analysis of AC output current under New PWM method.

From Fig. 4.18 it is observed that because of elimination of circulating current and minimization in zero crossing distortion, the total harmonic distortion is reduced from 17.32% of Improved Bipolar method to 6.20% in this New PWM method.

4.5 THD analysis of the inverter topologies

The power quality of distribution systems has a drastic effect on power regulation and consumption. Power sources act as non linear loads, drawing a distorted waveform that contains harmonics. These harmonics can cause problems ranging from telephone transmission interference to degradation of conductors and insulating material in motors and transformers. Therefore, it is important to gauge the total effect of these harmonics.

Total harmonics distortion is the summation of all harmonic components of the voltage or current waveform compared against the fundamental component of the voltage or current wave. THD calculations can be obtained from the MATLAB\SIMULINK. The switching pattern that is used in this project for all of the inverter is Sinusoidal PWM technique. In this method the switching angles for switches should be calculated in such a way that the dominant harmonics are eliminated [7]. Theoretically %THD can be calculated by the formula given below

$$\%THD = \frac{\sqrt{V_1^2+V_2^2+V_3^2+V_4^2+\dots\dots+V_n^2}}{V_1} \times 100$$

where,

V1 = Fundamental voltage magnitude
V2 = Magnitude of 2nd harmonic
V3 = Magnitude of 3rd harmonic
Vn = Magnitude of nth harmonic

Table 4.2: Comparison of Total Harmonic Distortion in AC Output Current under TB-PWM, IB-PWM and New PWM Methods.

Methods	TotaL Harmonic Distortion
TB-PWM Method	1.74%
IB-PWM method	17.32%
New PWM method	6.20%

The Table 4.2 shows the Total harmonic distortion in the AC output current obtained under TBPWM, IB-PWM and New PWM method. It is observed that under TB-PWM method THD is 1.74%. But, this method suffers from the problem of circulating current, which is the major drawback of the inverter.

In Bipolar PWM method, the problem of circulating current is eliminated. But, due to the presence of current distortion at zero crossing, the total harmonic distortion is increased to 17.32%. In New PWM method, both the circulation current and zero crossing distortion are eliminated. Hence, total THD is reduced to 6.2%.

4.6 Summary

The present chapter explains the implementation and simulation of the Dual Buck Full-Bridge Inverter with different bipolar PWM switching techniques. Also, the results obtained from simulation work are analyzed. Total harmonic distortion present in the AC output current under different bipolar PWM methods is calculated. Few important conclusions drawn out of the present project work and scope for the future work are stated in the next chapter.

V. CONCLUSION AND SUGGESTIONS

5.1 Conclusions

The Dual Buck Full-Bridge Inverter with different switching models are successfully developed. The simulation of the Dual Buck Inverter model in MATLAB/SIMULINK software is successfully completed. The set objectives in the present work are successfully met.

This project has introduced a dual buck inverter, which reduces 'Circulating current' and 'Distortion at zero crossing'. Performance studies involving SIMULINK model of Dual Buck Full-Bridge Inverter are made. Simulation results obtained with different bipolar PWM switching techniques are discussed. Comparative studies of the AC output current THD values assessed are also performed.

Few important conclusions that are drawn out of the present project work are as follows:

- Dual Buck Full-Bridge Inverter involving Traditional Bipolar PWM scheme will have circulating current, but no current distortion at zero crossing. Total THD of AC output current is 1.74%. Even though THD is small, this method is observed to suffer from a circulating current in the circuit. This is the major disadvantage of the Traditional Bipolar PWM scheme.
- Dual Buck Full-Bridge Inverter topology with Improved Bipolar PWM does not have circulating current, but has significant current distortion at zero crossing. Due to the presence of current distortion at zero crossing, THD is increased to 17.34%. This disadvantage is overcome by a new PWM method.
- With proposed New PWM method for Dual Buck Full-Bridge Inverter operation, the circulating current is eliminated and zero crossing distortion stands significantly reduced. From the results obtained, it is observed that Total Harmonic Distortion is reduced to 6.47%.

5.2 Suggestions for future work

In the present work, the Simulink models of Dual Buck Full-Bridge Inverter with different PWM switching methods are developed and the results obtained are analyzed. It is suggested that Fuzzy logic controller may be employed for relative comparison of the controller performances. There is a scope for Hardware implementation of proposed Dual Buck Inverter. The experimental studies on hardware equivalence of the proposed Dual Buck Full-Bridge Inverter and PWM schemes, may lead to interesting insight into the operation. This work can be extended to build three-phase version of Dual Buck Full-Bridge inverter. Though the harmonics are reduced substantially in this project, scope for further reduction by employing current controller and a feedback system is foreseen.

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