IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE)
e-ISSN: 2278-1676, p-ISSN: 2320-3331, Volume 17, Issue 6 Ser. I (Nov. – Dec. 2022), PP 42-49
www.iosrjournals.org

Intriguing issues on 2-level inverter system design

Obute K.C.[1] Abonyi S. O[1], Olufalahan Oduyemi[2], Mbeledogu E.C.[1]

1. *Department of Electrical Engineering, Nnamdi Azikiwe University, Awka, Anambra State, Nigeria*
2. *Department of Engineering and Technology, Sotuh East Missouri State University, Cape Giradeau, Missouri!MO63701, USA*

Corresponding Author: Obute Kingsley Chibueze. Department of Electrical Engineering, Nnamdi Azikiwe University, Awka, Anambra State, Nigeria

Abstract
*Majority of the appliances around us use alternating current (AC) power while the Photo Voltaic (PV) modules produce Direct current (DC) power. Therefore, the conversion of DC power to AC power is required before it can be used for running such appliances. In a general note, the power inverter is an electronic device or circuitry that changes direct current (DC) to alternating current (AC). This conversion can be achieved either by transistor or by Silicon Controlled Rectifiers (SCRs) [1]. The input voltage, output voltage and frequency, and overall power handling capacity depend on the design of the specific device or circuitry. For low and medium power outputs, transistorized inverters are suitable but for high power output, silicon controlled rectifiers (SCRs) should be used. Strictly speaking, inverters can be broadly classified into single (one) level inverter and multi (more than one) level inverter. Multilevel inverter as compared to single level inverters has advantages, as they can operate on several voltage levels with minimum harmonic distortion. Though in our recent inverter topology, the multilevel began with the three level inverters,s the conventional, two level inverter has many limitations for high voltage and power application. It produces an output parameters (voltage or current) with level either zero or +ve/-ve, which is inferior to that of a multilevel counterpart with smoother output voltage with **n** number of possible values. In contrary to the multilevel inverter, the 2-level inverter counterpart produces output parameter with larger harmonics, but on the other hand, it has less component and easy to control. In high power application the 2-level inverter however has some limitations in operating at high frequency, due to switching losses and constraints of device rating [2].*

Key words: *Photo-voltaic, 2-level inverter, Harmonic control.*

Date of Submission: 15-11-2022 Date of Acceptance: 01-12-2022

I. Introduction

From the late nineteenth century through the middle of the twentieth century, DC-to-AC power conversion was accomplished using rotary converters or motor-generator set (M-G sets). In the early twentieth century, vacuum tubes and gas filled tubes began to be used as switches in inverter circuits. The most used type of tube was the thyratron.

The origins of electromechanical inverters explain the source of the term inverter. Early AC-to DC converters used an asynchronous or synchronous AC motor direct-connected to a generator, so that the generator's commutator reversed its connections at exactly the right moments to produce DC. A later development is the synchronous converter, in which the motor and generator windings are combined into one armature, with slip rings at one end and a commutator at the other and only one field frame.The result with either is AC-in, DC-out. With an M-G set, the DC can be considered to be separately generated from the AC; with a synchronous converter in a certain sense it can be considered to be "mechanically rectified AC". Given the right auxiliary and control equipment an M-G set or rotary converter can be "run backwards;" converting DC to AC. Hence an inverter is an inverted converter [3].

II. Inverter Circuit description

Let us see how an inverter generates AC supply from the DC supply. Fig 1 shows a basic circuit which can produce AC supply from a DC supply from the battery. In this circuit a power source, a switch and a transformer is being used. When the switch is closed, current starts to rise in the circuit. This will make the transformer to generate an electromotive force (EMF), opposing the E.M.F of the battery (Lenz law). If the resistance of the transformer is assumed very small that it can be neglected, then the current will rise at a constant rate.

This rise will depend on the inductance of the transformer, the greater the inductance, the more time will be required to produce the current required to balance the EMF of the battery.

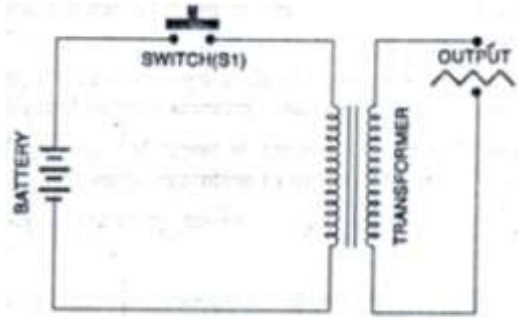

Fig 1: Basic circuit for producing AC from DC [4].

From fig 1, if the switch is opened before the current in the transformer grows fully, the current in the circuit will start to fall. This will make the transformer to generate reverse EMF. Once the circuit current reaches zero, the switch(S_1) is once again closed and this whole process will start to repeat itself.
Hence, by producing open and close cycle of switch in the circuit one can produce an alternating current (AC) output from a direct current (DC) source (battery).
Assuming the switch is kept in close or open condition for a long time, then there will not be any current in the secondary but, if the switch is opened and closed at a constant rate then the changes in the primary of the transformer will induce output at the secondary of the transformer which will be a square wave of frequency.

More-still, the circuit used in real inverters can be understood by observing the circuit of fig 2 below

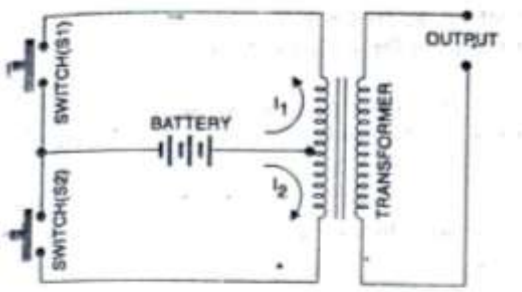

Fig 2 – Circuit shows the principle of operation of inverter

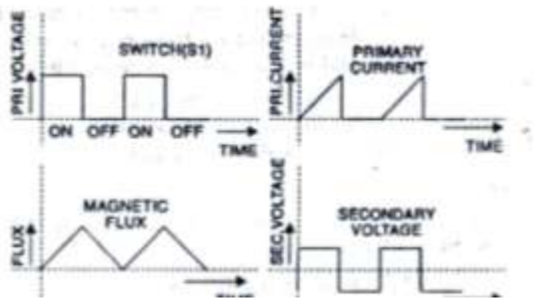

Fig. 3 - Formation of frequency at the secondary winding

The transformer used in the circuit of fig 2 has a centre tapping, which divides the primary into two equal sections. This center tapping is connected to the positive terminal of the battery.
Two ends of the primary are connected to the negative terminal of the battery through switches S_1 and S_2, which are turned on/off alternatively to generate voltage in the primary coil.
When the switch S_1 is closed and S_2 is opened, the current (I_1) flow in first part of primary winding and the e.m.f_1 is induced in the secondary winding.
Conversely, when the switch (S_2) is closed and S_1 is opened the current (I_2) flows in the second part of the primary winding and the e.m.f_2 of opposite polarity to e.m.f_1 is induced in the secondary winding.
If the S_1 and S_2 are alternately opened and closed at constant rate then the output from the secondary winding is a square wave of the frequency of operation of the switches (S_1 and S_2) [4].
This is the basic working principle of inverter. In practical inverters, transistors are used for the switching operations as in fig. 4.

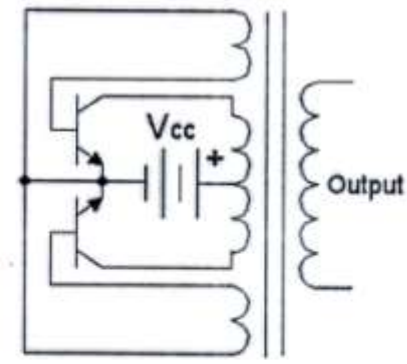

Fig 4 – Automatic equivalent auto-switching devices implemented with two transistors and split winding transformer in place of the mechanical switches

As they become available with adequate power ratings, transistors and various other types of semiconductor switches have been incorporated into inverter circuit designs. Certain ratings, especially for large systems (many kilowatts) use thyristors (SCR). SCRs provide large power handling capability in a semiconductor device, and can readily be controlled over a variable firing range.

More-still, the insulated Gate Bipolar Transistor (IGBT), a majority-carries device with high input impedance and large bipolar current-carrying capability, has been viewed by many designers as a device with MOS input characteristics and bipolar output characteristics that is a voltage-controlled bipolar device.

To make use of the advantages of both power MOSFET and BJT, the IGBT has been introduced. It is a functional integration of power MOSFET and BJT devices in monolithic form [2].

III. Inverter Input Voltage

A typical 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. Example include;

i) 12V DC, for smaller consumer and commercial inverters that typically run from a rechargeable 12V lead acid battery or automotive electrical outlet

ii) 24V, 36V, and 48V DC, which are common standards for home energy system.

iii) 200V to 400V DC, when power is from photo voltaic solar panels.

iv) 300V to 450v DC, when power is from electric vehicle battery packs in vehicle to –grid system.

IV. Inverter Output Voltage Power and Waveform

The AC output voltage of a power inverter is often regulated to be the 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.

More-still 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 ranges from 150 to 3000 watts. However not all inverter applications are primarily concerned with power delivery, in some cases the frequency and or wave form properties are used by the follow-on circuit or devices.A perfect AC power output should have sinusoidalbehavior, meaning that the AC current and voltage should be pure sure wave. In practice, converting D.C. power into square wave AC power output is much simpler as compared to converting a DC power into perfect sure wave AC power output. On the other hand, the AC power with square wave is considered low quality AC power while the AC power with sine wave is consider high quality ac power.

The quality of the AC power affects the performance and life of the appliances which use this AC power.

Commercially, inverters are available with the following types of output waveforms viz;

i) Square wave

ii) Modified square wave

iii) Pure sinusoidal wave

The two recently dominant commercialized wave forms of inventers of our time are modified sine wave and sine wave.

There are two basic designs for producing household plug-in voltage from a lower-voltage DC source, the first of which uses a switching boost converter to produce a higher voltage DC and then converts to AC.

The second method converts DC to AC at battery level and uses a line frequency transformer to create the output voltage [4].

V. The two level inverter topology

The input voltage, output voltage and frequency, and the overall power handing capability of any inverter depend on the design of its circuitry. The inverter does not produce any power; rather the power is provided by the DC source. Power inverter can be entirely electronic or a combination of mechanical effects of rotary apparatus and electronic circuitry. Static inverters (the one of our interest) do not use moving parts in the conversion process.

In its strict sense, the multilevel inversion of inverter with **n** number of levels supposedly has **n** number of possible output values.

In 2-level inverter topology, the output voltage of two possible values is formed using two voltage levels.

The inverter which produce an output voltage or current with levels either zero or positive/negative voltage or current is known as **two level inverter**. Two-level inversion can be employed in two ways, ie producing a square wave output, or producing a pulse width modulated (PWM) output (which when filtered produces a good approximation of a sinusoidal wave form. In high power and high voltage application, the two level inverters have some limitations in operating at high frequency mainly due to switching losses and constraints of device rating. When the switches of the 2-level inverters are arranged in series, their voltage withstanding capabilities are inferior to those of 3-level inverter system, also their output sinusoidal voltage wave forms are inferior when compared with those of multi-level inverter counterparts. This is due to the fact that their output voltages are formed using two voltage levels only.

Owing to the unique structure of 2-level inverter, high voltages with moderately low-harmonics can only be reached with the use of transformers or series-connected synchronized switching devices. With the help of these devices, the harmonic content of the output voltage waveform decreases appreciably.

VI. The 2 – Level Inverter Analysis and Design

This forms the backbone of our task there are many different power circuit topologies and control strategies used in inverter designs and analysis. Different design/analytical approaches address various issues that many be more or less important depending on the way that the inverter is intended to be used.

The issue of wave form quality can be addressed in many ways. Capacitors and inductors can be used to filter the waveform. If the design includes a transformer, filtering can be applied to the primary or the secondary side of the transformer or to both sides. Low-pass filters are applied to allow the fundamental component of the waveform to pass to the output while limiting the passage of the harmonic components. If the inverter is designed to provide power at a fixed frequency, a resonant filter can be used. For an adjustable frequency inverter, the filter must be tuned to a frequency that is above the maximum fundamental frequency.

Sofar, most loads contain inductance, feedback rectifiers or antiparallel diodes are often connected across each semiconductor switch to provide a path for the peak inductive load current when the switch is turned off. The antiparallel diodes are somewhat similar to the “freewheeling diodes” used in AC/DC converter circuits.

Following the schematic diagrams of fig (5/6) below, a detailed description of the analysis of 2-level inverter is achieved.

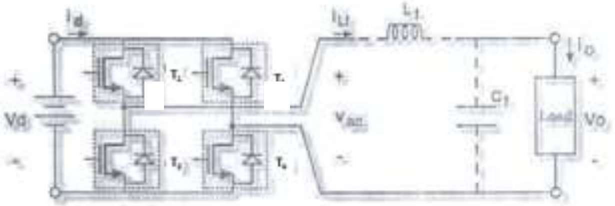

Fig 5

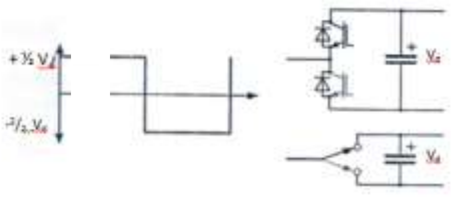

Fig 6

The Single Phase two-level inverter
with possible LC Filter

In this analysis, a d.c. supply is connected to the input of an inverter. To achieve this, active switches (transistors) are necessary as well as a simple control circuit to gate (ie turn on) the switches.

As in fig 5, the inverter, contains a full-bridge (ie four) switch structure and with the gating control, a "two – level output (ie positive **+v_d** or negative **– v_d**) is produced. However, the two-level inversion can be employed in two ways, ie, producing square wave output, or producing a pulse width modulated output. More-still, in fig 5, the switches **T_1, $T_2$$T_3$,$T_4$**are MOSFET n-channel transistors, with "back connected" diodes as part of its internal construction. The back-connected diodes are employed in the circuit if the inductor (L_f) is incorporated in the filtering section of the inverter.

VII. The Circuit Analysis

To have a comprehensive grasp of how the transistor of the inverter can be controlled, let us suppose that transistors**T_1** and **T_4**are turned on for half a cycle, making **V_{ac} = V_d,** then transistor **T_2** and **T_3**are turned on, while **T_1** and **T_4** are off, making **V_{ac}** = - **V_d** for the second half cycle. The bridge voltage is a square wave. It must be noted that the controller determines the frequency of the square wave; example, 50Hz (as used in Nigeria) As **V_{ac}** is either positive or negative, square wave inversion is considered "two-level inversion". In some applications, this is all that is needed, and the bridge output is connected directly to the load. More often a "smoother" ac voltage is needed, so either an inductor or an inductor-capacitor filter is used. However, the possible LC filter would have to be quite large for both the inductor and capacitor, and worse yet, the output wave form would still not be sinusoidal, ie just a square wave with smoothed corners. (see fig 5).

This is partly because there is a limit on how large the L and C filter components can be. If too large, the output ac voltage, V_0 will become too attenuated, not to mention the cost of employing large L and/or C filter components.

The size and cost of the LC filter can be reduced, so as to obtain a more sinusoidal output voltage, by assuring that the transistors in the bridge are turned on and off more frequently.

For the two-level inversion (ie, at any time one pair of diagonal transistor is on), if the controller can vary the time for which each pair of transistor is on, then it is possible to control the average output voltage. It must be recalled that; in steady-state **V_{ac}**, avg = **V_o**, avg. If we slowly change the on time of say transistor **T_1, T_4** being simultaneously on with **T_1** and the LC low-pass filter is used to filter out the high frequency ac component of **V_{ac}**, then it is possible to obtain a low frequency sinusoidal voltage for **V_o**.

Under theorical description, as the transistor switching frequency goes to infinity, the V_o waveform becomes perfectly sinusoidal. This type of operation of a converter, where the on time of the transistors is changing slowly, to control the desired average output voltage, is called "**quasi-static operation**". This implies that over two or three transistor switching periods, we can take the transistor duty-ratio to be almost constant. The average output voltage over one switching period is known as "**local average**".

However, finally, in this two level inversion topology, there are two frequencies of interest; viz; the transistor switching frequency, which is always constant at a value of several kHz and the output sinusoidal power frequency, which is determined by the controller. Example 50Hz in Europe and some African countries like Nigeria and 60Hz for North America etc.

VIII. The Circuit Design

The performance index of every system is a function of the effectiveness of its design. The cost of inverter is majorly affected by the size of DC – link capacitor, transistor and the filtering component. These are all dependent on the effectiveness of the design values.

IX. Determination of the size of the Dc-Link capacitor

Owing to the fact that the cost of DC- link capacitor is remarkable, the sizing should be done carefully. Significant optimization should be carried-out to choose most suitable amount and size of capacitors. The size of the DC – link capacitance is determined from the ripple of a rectifier output voltage.

However, the minimum size of the capacitance can be calculated from [5];

$C_{min} = 2P_L\left[\left(V_{max}^2 - V_{min}^2\right)F_r\right]^{-1}$ farads …1

Where P_L = Load power, V_{max} = Maximum applied voltage, V_{min} = Minimum applied voltage, F_r= rectifier output frequency

The tolerance of the capacitance of the Dc – link capacitor is of utmost necessity when determining its actual size. This has to be done because the capacitance will decrease during the lifetime.

When the actual size of the capacitor is determined the need for serial or parallel connections has to be considered. If there is need for serial connections, the voltage requirement for one capacitors can be calculated as follow [6]

$V_{cap} = (V_{applied} \text{ x } Tolerance_{max})[Tolerance_{max} + (n-1)\ Tolerance_{min}]^{-1}$volts ..2

Where n – Number of capacitors in series.

For the two-level inverter, when the voltage and capacitance tolerance requirements are met, the D.C. link capacitance will be created with serial and parallel capacitances.

X. Determining the Power loss

In efficiency point of view, the power losses of inverters are averaged over the whole period of the output voltage. The losses are calculated on assumption that sinusoidal pulse width modulation (PWM) is used

Most of the power loss incurred in 2-level inverters occurs, in the switches (transistors), but there is also some power loss in the DC – link capacitor.

Therefore, the total power loss(P_T) is;

$P_T = 3P_{cond}\ 3P_{sw} + P_{cap}$

$= 3[P_{cond} + P_{cap} + 3^{-1}\ P_{cap}]$ …3

Where P_{cond} = Conduction loss in each phase, P_{sw} = Switching loss of each phase

P_{cap} = Power loss in the DC – link capacitor

XI. Analysis of the respective power loss

For a two-level inverter;

(i) Conduction losses

The conduction losses in the transistors can be calculated below [6]

$$P_{cond}\,T_1 = ½\left[\frac{V_{CEO}}{\pi}\,\hat{i} + \frac{\hat{r_f}}{4}\,\hat{i}^2\right] + M\cos\theta\left[\frac{V_{CEO}}{8}\,\hat{i} + \frac{\hat{r_f}}{3\pi}\,\hat{i}^2\right] \quad \ldots 4$$

Where V_{CEO} = collector – emitter voltage with zero current,

M = Modulation index, r_f = forward resistance, $\hat{i}$ = output peak current.

and θ = Phase shift, which expresses how the current divides between the transistors and diodes.

The conduction losses in the diodes are calculated with equation;

$$P_{cond\,D}1 = ½\left[\frac{V_{f0}}{\pi}\,\hat{i} + \frac{\hat{r_{fd}}}{4}\,\hat{i}^2\right] - M\cos\theta\left[\frac{V_{f0}}{8}\,\hat{i} + \frac{r_{fd}}{3\pi}\,\hat{i}^2\right] \quad \ldots 5$$

where V_{f0} = forward voltage drop at zero, current and r_{fd} = forward resistance of the diode.

(ii) Switching loses

The transistor switching loses can be calculated as below; [6]

$$P_{on} + P_{off} = \frac{1}{\pi}\cdot F_s\,[E_{on}(\hat{i}) + E_{off}(\hat{i})] \quad \ldots 6$$

Where E_{on} = On-energy, E_{off} = Off-energy and F_s = Switching frequency.

The switching energy are dependent on junction temperature and DC – link voltage.All these parameters are chosen in the module datasheet

(iii) **Losses in the DC – link capacitor**

The DC – link capacitor losses can be determined by the ESR value of capacitance and the current through the capacitor. The ESR value is got from datasheet while the current can be evaluated with the help of charge and discharge times of the capacitor.When the charge and discharge currents are evaluated, the current through the capacitor can be estimated from the charge and discharge current

$$I_{RMS} = \sqrt{I^2_{CRMS} + I^2_{DCRMS}} \quad \ldots 7$$

Where I_{CRMS} = value of the charge current, I_{DCRMS} = value of discharge current

Whenthe configuration of DC – link capacitance is taken into account, the total losses of capacitors are then evaluated.

XII. The Output wave form

Pure sine waves is ideal for almost all AC loads, and is considered as the best quality power. Any deviation from sinusoidal is said to introduce harmonics thereby degrading the quality of AC power. The extent of degradation of AC power or the quality of AC power is measured using the term **Total Harmonic**

Distortion (THD)

Unfortunately, the output wave form of a two-level inverter topology is not sinusoidal. It is characterized by a square wave with smoothed corners as in fig 2.3 below.

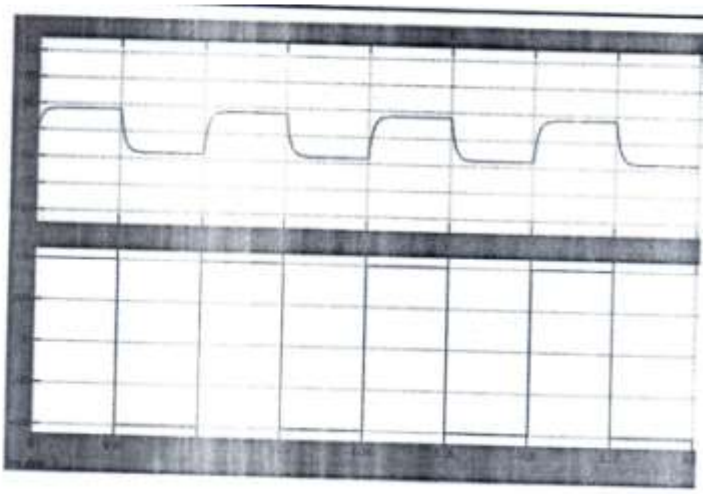

Fig 7 –The output wave form of a two-level inverter

The AC power with square wave is considered low quality A.C. power while the A.C. power with sine wave is considered high quality AC power. The quality of the A.C. power affect the performance and longevity of the appliances which use it.

An improvement of the of the two level inverter topology is the multilevel inverter topology with the following characteristic;

i) Has a better and improved Total Harmonic Distortion. This is because the output voltage and current is much more sinusoidal. The multilevel inverters offer better sinusoidal voltage wave form than 2-level inverters due to the fact that output voltage can be formed using more than two voltage levels. When several voltage levels are used, the dv/dt of (change in voltage with respect to time) of the output voltage is smaller thus the stress in cables and motors is smaller.

ii) Unlike in two-level inverter in which the efficiency of the whole system is dominated by the rectifier losses in high loads, in multilevel inverters the efficiency at full load is better. This means better energy capture of the system. Better efficiency at rated power means smaller heat sink and better reliability

iii) Conduction losses are also lower because of low forward-voltage drop.

iv) Multilevel inverter can operate at both fundamental switching frequency and high switching frequency PWM.It should be noted that lower switching frequency implies lower switching loss and conversely higher efficiency.

Fortunately, the two-level inverter has one importance advantage over the multilevel inverter counterpart, one particular advantage is the fewer number of power semiconductor switches required. Hence the two level inverter configuration is cheaper than the multilevel counterpart [6].

XIII. Harmonic Control and obtaining desired Wave form in 2-level inverter System

The voltage source inverter used in the active filter makes the harmonic control possible. This inverter uses a d.c capacitor as the supply and can switch as a high frequency to generate a signal which will cancel the harmonics from the nonlinear load.

The current wave form for cancelling harmonics is achieved with the voltage source inverter and an interface signal. The desired wave form is obtained by accurately controlling the switches in the inverter. Control of the current wave shape is limited by the switching frequency of the inverter and by the available driving voltage across the interface reactor. The driving voltage across the interface reactor determines the maximum di/dt that can be achieved by the power filter [5]

References

[1]. P.C. Sen-Power Electronics. Published by Tata Mc Grew-Hill Education Private limited. 7 west Pate/Negar, New Delhi 110008 and Printed at India Binding House, Noida 201301 (1987). Page 726, 736).

[2]. Tejaswini Honade, Sonali Udapure etc-Comparative study between two and three level converter for Electric Application-International Journal of Advances in Engineering and Technology (IJAET) April 2016. ISSN22311963.

[3]. Power inverter-Wikipedia page 11

[4]. K.B. Bhatia-Practical AC and DC motor winding (2nd edition 2016) Published by A.K. Jain for standard publisher distributors 1705-B, Naisarak, Delhi-11006.

[5]. Piyus Mohanty and Saransh Sahoo-Analysis of two level and three level inverters. A project report submitted to the department of Electrical Engineering, National Institute of Technology, Rourkela.

[6]. Mika Ikonen, Ossilaakkonen etc-Two-level and three-level converter comparison in wind power Application. Department of Electrical Engineering Lapeenranta University of Technology P.O Box 20, FI-53851 Lappeentanta, Finland.

Authors Profile

Dr. Obute Kingsley Chibueze is a lecturer in the department of Electrical Engineering, Nnamdi Azikiwe Univeristy, Awka, Anambra State, Nigeria. He is a prolific writer with many journals and texts published to his credits. He has specific interest in Electric Machines. He is a Member of Nigeria Society of Engineers (NSE) and is registered with council for the Regulation of Engineering in Nigeria (COREN)

Engr. Dr. Sylvester Emeka Abonyi hails from Opi, Nsukka Local Government Area of Enugu State. He attended Opi Boys Secondary School Opi, where he sat for Senor Secondary School Certificate in 1986. He studied Physics/ Chemistry at federal College of Education Eha-Amufu, Enugu State and graduated with Distinction in 1993 and later went to the university and studied Electromechanical Technology and graduated in 2000 with Second Class Honor (Upper Division) at Nnamdi Azikiwe University Awka, Anambra State, Nigeria. He received his master of Technology Degree from the same University in 2004. Dr. Abonyi holds a Doctor of Philosophy in Electrical Engineering from University of Nigeria Nsukka, Enugu State Nigeria. He is currently a Senior lecturer in the Department of ElectricalEngineering,Nnamdi Azikiwe University Awka. He is a member of Council for Regulation of Engineering in Nigeria, Nigerian Society of Engineers, Nigerian Association of Technologist in Engineering, Solar Energy Society of Nigeria and host of others. Email ID: s.abonyi@unizik.edu.ng

Prof. Olifolahan Oduyemi is currently an Associate Professor of Facilities and Construction Project Management at the Southeast Missouri State University, Cape Girardeau, Missouri, USA. He had his bachelors degree in Estate Management from Federal University of Technology, Akure, Ondo State Nigeria in 2008, his Masters degree in Property Management and Investment from Edinburgh Napier University, Scotland, UK in 2011, a PhD in Facilities Management from University of Derby, UK in 2015 and a Masters in Business Administration (MBA) from Southeast Missouri State University, Cape Girardeau Missouri, USA in 2019

Engr Emeka Chukwuma Mbeledogu is a graduate from the Department of Electrical Engineering Nnamdi Azikiwe University Awka, Nigeria. He is a member of many professional bodies:- NSE, NIEEE, COREN. He is currently a staff in the Department of Electrical Engineering Nnamdi Azikiwe University Awka, Nigeria.

Obute Kingsley Chibueze, et. al. "Intriguing issues on 2-level inverter system design." *IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE)*, 17(6), 2022, pp. 42-49.