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Modulated Multi-Level Fundamental Frequency Inverter for Three-Phase Photovoltaic Application

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Abstract: - A fundamental frequency modulated multi level inverter scheme is introduced (best suited for a three phase stand alone photovoltaic (PV) system). The system consists of four series connected PV arrays, a five level diode clamped multi level inverter (DCMLI) generating fundamental modulation staircase three phase voltages, with three phase induction motor as a load. A five-level diode clamped multilevel inverter (DCMLI) fundamental frequency switching strategy is proposed by selecting the switching angles such that the lower order harmonics are eliminated. In this study a harmonic elimination technique is presented that allows one to control a multilevel inverter in such that it is an efficient low total harmonic distortion (THD) inverter that can be used to interface distributed dc energy sources with a main ac grid or as an interface to a motor drive powered by fuel cells, batteries, or ultra-capacitors.

Keywords*-Total Harmonic Distortion; Diode clamped multilevel inverter; Photovoltaic; Staricase Three Phase voltage;Grid*

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I. INTRODUCTION

When a power grid is not available (or not available at reasonable cost) a standalone photovoltaic cell can be used to generate the needed electric energy. A photovoltaic array is a linked collection of photovoltaic modules, which are in turn made of multiple interconnected solar cells. The cells convert solar energy into direct current via the photovoltaic effect. The power that one module can produce is seldom enough to meet requirements of a home or a business, so the modules are linked together to form an array. There are numerous PV power systems ranging from 100W to several mega watts. As the PV cells generate DC, power conditioning system is also required, in order to suit the frequency and voltage level to the load required and allow the parallel connection. In addition, a PV system must present some features related to the safety, efficiency, and power quality. Most PV arrays use an inverter to convert the DC power produced by the modules into alternating current that can plug into the existing infrastructure to power lights, motors, and other loads.

Solar energy is one of the favorable renewable energy resources and the multi level inverter has been proven to be one of the important enabling technologies in PV utilization. Multilevel voltage source inverters offer several advantages compared to their conventional counterparts. By synthesizing the ac output terminal voltage from several levels of voltages, staircase waveforms can be produced, which approach the sinusoidal waveform with low harmonic distortions thus reducing filter requirements. The need of several sources on the dc side of the inverter makes multilevel technology attractive for photovoltaic applications. For a multilevel inverter, switching angles at fundamental frequency are obtained by solving the selective harmonic elimination equations in such a way that the fundamental voltage is obtained as desired and certain lower order harmonics are eliminated. As these equations are nonlinear transcendental in nature for a particular modulation index. The figure 1 below shows the block diagram representation of a DCLMI.

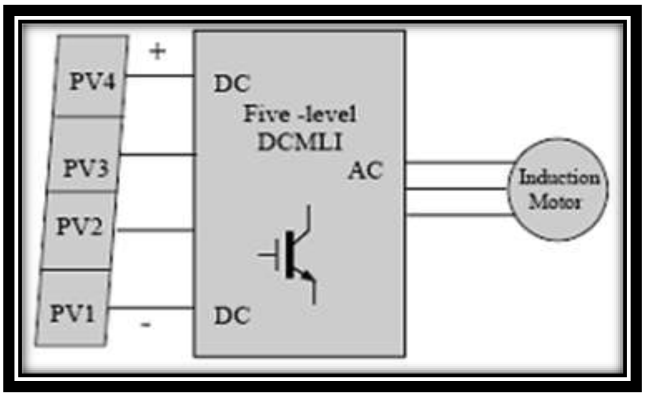

Fig.1.The DCMLI block diagram for a standalone PV power system configuration

II. HARMONICS IN ELECTRICAL SYSTEMS

One of the biggest problems in power quality aspects is the harmonic contents in the electrical system. A harmonic is a signal or wave whose frequency is an integral (whole numbers) multiple of the frequency of some reference signal or wave (In general the reference will be nothing but the fundamental frequency i.e. the frequency of the fundamental component).

Fundamental frequency is the frequency at which most of the energy is contained or at which the signal is defined to occur if the signal is displayed on an oscilloscope. The wave form will appear to repeat at a rate corresponding to '*f* 'Hz. Nearly all signals contain energy at harmonic frequency in addition to the energy at fundamental frequency. If all the energy in a signal is contained at fundamental frequency then that signal is a perfect sine wave. If the signal is not a perfect sine wave then some energy will be contained in the harmonics. Some wave forms contain large amount of energy at harmonic frequencies. E.g.: square, triangular, saw tooth waves.

III. MULTI LEVEL INVERTERS

The elementary concept of a multilevel inverter to achieve higher power is to use a series of power semiconductor switches with several lower voltage dc sources to perform the power conversion by synthesizing a staircase voltage waveform. Capacitors, batteries, and renewable energy voltage sources can be used as the multiple dc voltage sources. The commutation of the power switches aggregate these multiple dc sources in order to achieve high voltage at the output; however, the rated voltage of the power semiconductor switches depends only upon the rating of the dc voltage sources to which they are connected. So the general function of the multilevel inverters is to synthesize a sinusoidal voltage out of several levels of dc voltages. The multilevel inverter can therefore be described as a voltage synthesizer in which the high output voltage is synthesized from many discrete smaller voltage levels.

IV. APPLICATIONS OF MULTILEVEL INVERTERS

1. The most attractive application of this technology is in the medium-to-high-voltage range, and includes motor drives, power distribution, and power conditioning applications.
2. Many multilevel inverter applications focus on utility interface for renewable energy systems, flexible AC transmission system (FACTS), and traction drive systems.
3. Another application for multilevel inverters is distributed power systems. Multilevel inverters can be implemented using distributed energy resources such as photovoltaic and fuel cells, and then be connected to an AC power grid.
4. Multilevel inverter can be used as a reactive power compensator. For example, a multilevel inverter being used as a reactive power compensator could be placed in parallel with a load connected to an AC system. This is because a reactive power compensator can help to improve the power factor of a load.
5. Multilevel diode-clamped inverter can also be used as an interface between a high-voltage dc transmission line and an ac transmission line.
6. Multilevel inverters can solve problems with some present bi-level PWM adjustable-speed drives (ASDs).

V. PROBLEM

ASDs usually employ a front-end diode rectifier and a inverter with PWM-controlled switching devices to convert the DC voltage to variable frequency and variable voltage for motor speed control. Motor damage and failure have been reported by industry as a result of some ASD inverters' high-voltage change rates (*dv*/*dt*), which produce a common-mode voltage across the motor windings. High-frequency switching can exacerbate the problem because of the numerous times this common mode voltage is impressed upon the motor each cycle. The main problems are reported as "motor bearing failure" and "motor winding insulation breakdown" because of circulating currents, dielectric stresses, voltage surge, and corona discharge. The failure of some ASDs is because the voltage change rate (*dv* / *dt*) sometimes can be high enough to induce corona discharge between the winding layers.

With the development of modern power electronic devices, these can switch at higher frequency and higher voltages, which can generate broadband electromagnetic interference (EMI). Although the high-frequency switching can increase the motor running efficiency and is well above the acoustic noise level, the (*dv*/*dt*) associated dielectric stresses between insulated winding turns are also greatly increased.

VI. SOLUTION

The multilevel inverter is one of the more promising techniques for mitigating the aforementioned problems. Multilevel inverters utilize several DC voltages to synthesize a desired AC voltage. For this reason, multilevel inverters can reduce (*dv*/*dt*) to conquer the motor failure problem and EMI problem. Multilevel inverters also have emerged as the solution for working with higher voltage levels. Multilevel inverters include an array of power semiconductors and capacitor voltage sources, which generate output voltages with stepped waveforms. The commutation of the switches permits the addition of the capacitor voltages, which reach high voltage at the output, while the power semiconductors must withstand only reduced voltages.

VII. FIVE LEVEL DIODE CLAMPED MULTI LEVEL INVERTER

In general an m-level diode clamped inverter typically consists of (m-1) capacitors**,** and produces an m-level output phase voltage and a (2m-1) level output line voltage. Therefore, for a 5-level inverter

1. The number of capacitors required are (5-1) =4.
2. It produces a 5-level output phase voltage and a 9-level output line voltage.

In the figure 2, the voltage drop across the capacitors C_1, C_2, C_3, C_4, C_5 is V_{DC},

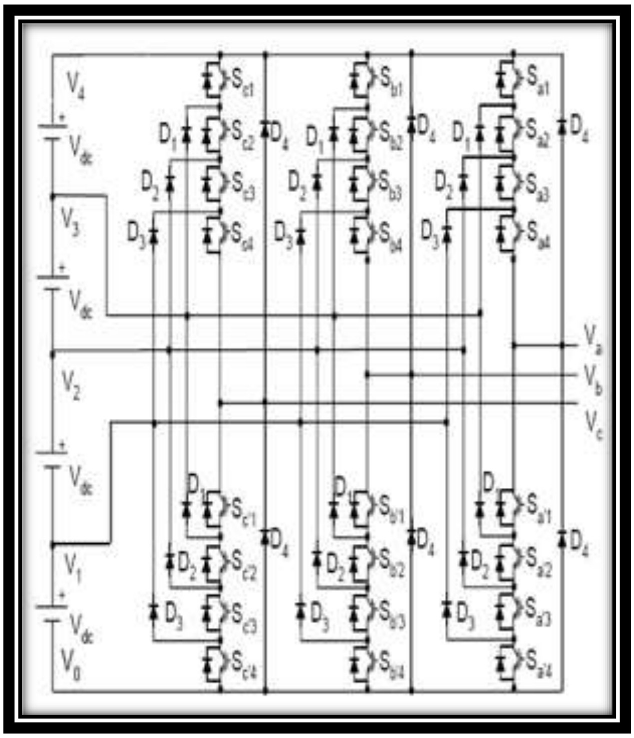

Fig.2. Three Phase five level diode clamped multi level inverter.

it implies that $(V_1 - V_0)$=$(V_2 - V_1) = (V_3 - V_2) = (V_4 - V_3) = V_{DC}$). V_0 is the reference voltage (V_0=0).Each phase has four complementary switch pairs such that turning on one of the switches of the pair require that the other complementary switch be turned off. The complementary switch pairs for phase leg *a* are (*Sa1*, *Sa'1*), (*Sa2*, *Sa'2*), (*Sa3*, *Sa'3*), and (*Sa4*, *Sa'4*). Table 1 lists the output voltage levels possible for one phase of the inverter with the negative dc rail voltage V_0 as a reference. State condition 1 means the switch is on, and 0 means the switch is off. At any instant only 4 switches will be turned on in each leg. For an output voltage of Vo, switches *Sa'1,Sa'2,Sa'3,Sa'4* should be turned on, for an output voltage of V_1 switches *Sa4,Sa'1,Sa'2,Sa'3,* should be turned on. Similarly for V_2, V_3, V_4 switches will be turned on as per table1.

Voltage V_{a0}	Switch State							
	S_{a1}	S_{a2}	S_{a3}	S_{a4}	$S_{a'1}$	$S_{a'2}$	$S_{a'3}$	$S_{a'4}$
$V_4 = 4Vdc$	1	1	1	1	0	0	0	0
$V_3 = 3Vdc$	0	1	1	1	1	0	0	0
$V_2 = 2Vdc$	0	0	1	1	1	1	0	0
$V_1 = Vdc$	0	0	0	1	1	1	1	0
$V_0 = 0$	0	0	0	0	1	1	1	1

Table.1. DCMLI output voltage levels and switching states

VIII. MULTILEVEL MODULATION CONTROL METHODS

The harmonic orders and magnitudes depend on the inverter type and the method of control. The harmonic spectra depend on the switching frequency and the control method. The modulation methods used in multilevel inverters can be classified according to switching frequency. In general there are two types of modulation control .They are

1. Low switching frequency control
2. High switching frequency control

The popular methods for low switching frequency methods are

1) Space vector modulation (SVM) method and
2) Selective harmonic elimination (SHE) or Fundamental switching frequency method

The popular methods for high switching frequency methods are

1) Classic carrier based sinusoidal PWM (SPWM) and
2) Space vector PWM.

The classic carrier-based sinusoidal PWM (SPWM) that uses the phase-shifting technique to increase the effective switching frequency. Therefore, the harmonics in the load voltage can be reduced. Methods that work with high switching frequencies have many commutations for the power semiconductors in one cycle of the fundamental output voltage. The modulation technique for multilevel inverters is a key issue for multilevel inverter control. The traditional pulse width modulation (PWM), space vector PWM, and space vector control methods do not completely eliminate specified harmonics. In addition, space vector PWM and space vector control method cannot be applied to multilevel inverters with unequal DC voltages. The carrier phase shifting method for traditional PWM method also requires equal DC voltages.

Basic modulation techniques that are used in multilevel power conversion applications include multi-disposition PWM, stepped sine wave and switching angle optimization. These techniques enable harmonic elimination by predetermination of the switching angles. This is determined according to a previously calculated and stored pulse width modulated technique is seriously limited as the number of levels increases because of the increased complexity and the reduced accuracy of the non linear solutions. Most of these methods use high frequency switching because it is the most effective at achieving the requirements.

IX. FUNDAMENTAL FREQUENCY MODULATION

An important issue in multilevel inverter design is that the output voltage waveform should be near sinusoidal and the lower order harmonics must be eliminated. For many power inverter applications, it is desirable for the inverter to output a desired waveform with minimum distortion. For example, a DC-AC inverter is desired to output a purely sinusoidal waveform. But for the practical inverters, they can just output a series of rectangular waves. The key issues for the control of the inverters are to get the modulation methods to control the output rectangular waves to synthesize the desired waveforms. Therefore, a modulation control method needs to generate desired fundamental frequency voltage and eliminate other higher order harmonics as much as possible.

A key concern in the fundamental switching scheme is to determine the switching angles in order to produce the fundamental voltage and not generate specific higher order harmonics.

Fundamental frequency switching control

A five level DCMLI fundamental frequency switching strategy is proposed by selecting the switching angles such that the lower order harmonics are eliminated. The simplest way to control a multi level inverter is to use a fundamental frequency switching control where the switching devices generate a staircase waveform that tracks a sinusoidal waveform. The fundamental switching frequency method popularly known as selective harmonic elimination method is based on the harmonic elimination theory. The output voltage of the diode clamped inverter is a quarter-wave symmetric stepped voltage waveform. The output voltage will have fundamental and the associated harmonics. These harmonics produces additional heating, when the output voltage of the inverter is fed to the induction motor. Therefore it is preferred to reduce the harmonic in the output. In general, the most significant low-frequency harmonics are chosen for elimination by properly selecting switching angles among different level inverters, and high frequency harmonic components can be readily removed by using additional filter circuits. The conducting angles $\theta_1, \theta_2, \theta_3 \ldots \theta_s$ (where s is the total number of sources) can be chosen such that the voltage total harmonic distortion is a minimum. Normally, these angles are chosen so as to cancel the predominant lower frequency harmonics. The 5^{th}, 7^{th}, 9^{th} etc…..harmonics can be eliminated with the appropriate choice of the conducting angles. To keep the number of eliminated harmonics at a constant level, all switching angles must satisfy the following condition or the THD level increases dramatically.

$$0 < \theta_1 < \theta_2 < \theta_3 < \cdots \theta_s$$

However, if the switching angles do not satisfy the condition, this method no longer exists. To minimize harmonic distortion and to achieve adjustable amplitude of the fundamental component, up to **(s-1)** harmonic contents can be removed from the voltage waveform.

X. Computational Problems

The major difficulty for selective harmonic elimination methods, including the fundamental switching frequency method, is to solve the transcendental equations for switching angles. The transcendental equations characterizing the harmonic content can be converted into polynomial equations. Elimination theory has been employed to determine the switching angles to eliminate specific harmonics, such as the 5th, 7th, 11th, and the 13th. However, as the number of DC voltages or the number of switching angle increase, the degrees of the polynomials in these equations are large, and one reaches the limitations of the capability of contemporary computer algebra software tools (e.g., Mathematic or Maple) to solve the system of polynomial equations.

XI. FOURIER SERIES

A periodic function $f(t)$ can be represented by an infinite sum of sine or cosine functions that are harmonically related.Thus, given f(t) is periodic (e.g. square wave, triangular wave, half rectified wave, etc.), then f(t) can be represented as follows:

$$f(t) = \sum_{k=0}^{\infty} [\, a_k \cos(kw_o\, t) + \, b_k(\sin kw_o\, t) \quad (1)$$

Where k is the integer sequence 0, 1, 2, 3 $a_k, and\ b_k$ called the Fourier coefficients that are calculated from $f(t)$.

$w_o = \frac{2\pi}{T}$ is the fundamental frequency of the periodic function $f(t)$ with period T, and kw_o is known as the k^{th} harmonic of $f(t)$

$a_k, and\ b_k$ can be found as follows:

$$a_k = \frac{2}{T}\int_{t_0}^{t_o+T} f(t)\cos(kw_o t)\, dt \qquad (2)$$

$$b_k = \frac{2}{T}\int_{t_0}^{t_o+T} f(t)\sin(kw_o t)\, dt \qquad (3)$$

Quarter-wave symmetry

A periodic function possesses quarter - wave symmetry if:

1. It has half - wave symmetry, and

2. It has symmetry about the midpoint of the positive and the negative half cycles.

If a periodic function is even, and has quarter-wave symmetry, the Fourier coefficients are:

$a_k = 0$ (4) for k even, because of the half wave symmetry;

$b_k = 0$ (5) for all k, because $f(t)$ is even.

$a_k = \frac{8}{T}\int_0^{\frac{T}{4}} f(t)\cos(kw_o t)\,dt$ (6) for k odd;

If a periodic function is odd, and has quarter-wave symmetry, the Fourier coefficients are:

$a_k = 0$ (7) for all k, because $f(t)$ is odd.

$b_k = 0$ **(8)** for k even, because of the half wave symmetry.

$b_k = \frac{8}{T}\int_0^{\frac{T}{4}} f(t)\sin(kw_o t)\,dt$ (9) for k odd.A multilevel inverter as shown in fig 3, can produce a quarter-wave symmetric voltage waveform by several DC voltages.

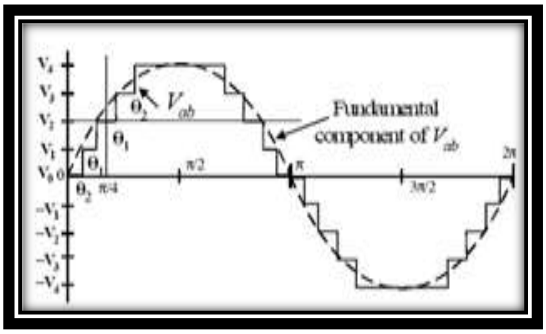

Fig.3. Line voltage waveform for a five-level DCMLI

After applying Fourier theory to the output voltage waveform of multilevel inverters, which is odd quarter-wave symmetric, we can find the Fourier expression of the multilevel output voltage,

$$V(t) = \sum_{k=1,3,5\ldots}^{\infty} \frac{4\sqrt{2}V_{DC}}{k\pi}(\cos(k\theta_1) + \cos(k\theta_2) + \cdots \cos(k\theta_s))\sin(kw_o\,t) \qquad (10)$$

Where s is the number of dc sources, and V_{DC} is the level of each dc voltage. The Fourier series theory and Harmonics Elimination theory will be used to derive the transcendental equations for the fundamental frequency switching method for multilevel inverters.

XII. Calculations:

By looking at the waveform (Fig 10) we can see that the two unknowns are (θ_1, θ_2)**.** Now our aim is to solve for (θ_1, θ_2). Let's go step by step to find out (θ_1, θ_2)**.**

The problem of finding out the solution (θ_1, θ_2) can be divided into 6 steps:

1st step: Finding out the equation for the output line voltage waveform (Fig.3.) using Fourier analysis

***2nd Step*:** Analysis of the harmonics those are present in the waveform $V(t)$

***3rd Step*:** Elimination of the lower order odd harmonics those are present in the waveform $V(t)$

***4th Step*:** Derivation of the harmonic equations. Since we have two unknowns (θ_1, θ_2), we should get two equations.

***5th Step*:** Converting the above two transcendental equations into polynomial equations.

***6th Step*:** The transcendental harmonic equations that have been changed into polynomial equations in the variables $x_1, x_2, x_3, x_4, x_5 \ldots..$ will be solved using one of the iterative techniques namely Newton-Raphson method**.**

Solving the following equations according to the above mentioned steps we get,

$$V(t) = \sum_{k=1,3,5\ldots}^{\infty} \frac{4\sqrt{2}V_{DC}}{k\pi}(\cos(k\theta_1) + \cos(k\theta_2) + \cdots \cos(k\theta_s))\sin(kw_o\,t) \qquad (A)$$

Where s is the number of dc sources, and V_{DC} is the level of each dc voltage.

f(t) = V(t) =

$$\begin{cases} V_o = 0 & 0 \le \theta < \left(\frac{\pi}{4} - \theta_2\right) \\ V_1 = V_{DC} & \left(\frac{\pi}{4} - \theta_2\right) \le \theta < \left(\frac{\pi}{4} - \theta_1\right) \\ V_2 = 2V_{DC} & \left(\frac{\pi}{4} - \theta_1\right) \le \theta < \left(\frac{\pi}{4} + \theta_1\right) \\ V_3 = 3V_{DC} & \left(\frac{\pi}{4} + \theta_1\right) \le \theta < \left(\frac{\pi}{4} + \theta_2\right) \\ V_4 = 4V_{DC} & \left(\frac{\pi}{4} + \theta_2\right) \le \theta < \frac{\pi}{2} \end{cases} \qquad (B)$$

Substituting the values of $f(t)$, in the following equation we get,

$b_k = \frac{4}{\pi}\int_0^{\frac{\pi}{2}} f(t)\sin(k\theta)\,d\theta$ (C) For k odd;

$= \frac{4}{\pi}\{\int_0^{\left(\frac{\pi}{4}-\theta_2\right)} V_o \sin(k\theta)d\theta +$

π4−θ2π4−θ1V1sin(kθ)dθ+ π4−θ1π4+θ1V2sin(kθ)dθ+

$\int_{\left(\frac{\pi}{4}+\theta_1\right)}^{\left(\frac{\pi}{4}+\theta_2\right)} V_3\sin(k\theta)d\theta + \int_{\left(\frac{\pi}{4}+\theta_2\right)}^{\frac{\pi}{2}} V_4\sin(k\theta)d\theta\}$

$$= \frac{4V_{DC}}{\pi}\left(\int_{\left(\frac{\pi}{4}-\theta_2\right)}^{\left(\frac{\pi}{4}-\theta_1\right)} \sin(k\theta)d\theta + \int_{\left(\frac{\pi}{4}-\theta_1\right)}^{\left(\frac{\pi}{4}+\theta_1\right)} 2\sin(k\theta)d\theta + \int_{\left(\frac{\pi}{4}+\theta_1\right)}^{\left(\frac{\pi}{4}+\theta_2\right)} 3\sin(k\theta)d\theta + \int_{\left(\frac{\pi}{4}+\theta_2\right)}^{\frac{\pi}{2}} 4\sin(k\theta)d\theta\right) \qquad (D)$$

We know that

$$\int_a^b \sin k\theta = \frac{1}{k}(\cos a - \cos b) \qquad \text{(E)}$$

Simplifying equation (3), with the help of equation (4), we get

$$b_k = \frac{4V_{DC}}{k\pi}\Big(\cos k\left(\frac{\pi}{4}-\theta_1\right) + cosk\left(\frac{\pi}{4}+\theta_1\right) + cosk\left(\frac{\pi}{4}-\theta_2\right) + cosk\left(\frac{\pi}{4}+\theta_2\right) + \cdots + \cos k\left(\frac{\pi}{4}-\theta_s\right) + cosk(\pi/4 + \theta_s)\Big) \qquad \text{(F)}$$

We know that $\cos(A+B) + \cos(A-B) = 2\cos A \cos B$

Therefore

$$\cos k\left(\frac{\pi}{4}-\theta_1\right) + cosk\left(\frac{\pi}{4}+\theta_1\right) = 2\cos\left(\frac{k\pi}{4}\right)\cos(k\theta_1)$$

$$\cos k\left(\frac{\pi}{4}-\theta_2\right) + cosk\left(\frac{\pi}{4}+\theta_2\right) = 2\cos\left(\frac{k\pi}{4}\right)\cos(k\theta_2) \qquad \text{(G)}$$

$$\cos k\left(\frac{\pi}{4}-\theta_s\right) + cosk\left(\frac{\pi}{4}+\theta_s\right) = 2\cos\left(\frac{k\pi}{4}\right)\cos(k\theta_s)$$

Substituting the above equations in equation (F), we get

$$b_k = \frac{4V_{DC}}{k\pi}\Big(2\cos\left(\frac{k\pi}{4}\right)\cos(k\theta_1) + 2\cos\left(\frac{k\pi}{4}\right)\cos(k\theta_2) + \cdots + 2\cos\left(\frac{k\pi}{4}\right)\cos(k\theta_s)\Big)$$

$$b_k = \frac{8V_{DC}}{k\pi}\cos\left(\frac{k\pi}{4}\right)\big(\cos(k\theta_1) + \cos(k\theta_2) + \cdots + \cos(k\theta_s)\big)$$

$$b_k = \frac{8V_{DC}}{k\pi}\cos\left(\frac{k\pi}{4}\right)\big(\cos(k\theta_1) + \cos(k\theta_2) + \ldots + \cos(k\theta_s)\big) \ for\ k\ odd \qquad \text{(H)}$$

$$we\ know\ that\ f(t) = \sum_{k=0}^{\infty}[\,a_k\cos(kw_o\,t) + b_k(\sin kw_o\,t)$$

$$\boldsymbol{f(t) = V(t)} = \sum_{k=1,3,5\ldots}^{\infty} \frac{8V_{DC}}{k\pi}\cos\left(\frac{k\pi}{4}\right)(\cos(k\theta_1) + \cos(k\theta_2) + \cdots \cos(k\theta_s)(\sin kw_o\,t))$$

We can see that for $k\ odd$,

$$V(t) = \sum_{k=1,3,5\ldots}^{\infty} \frac{4\sqrt{2}V_{DC}}{k\pi}(\cos(k\theta_1) + \cos(k\theta_2) + \cdots \cos(k\theta_s)(\sin kw_o\,t))$$

And

$$b_k = \frac{4\sqrt{2}V_{DC}}{k\pi}\big(\cos(k\theta_1) + \cos(k\theta_2) \ldots + \cos(k\theta_s)\big) \quad for\ k\ odd$$

Since we have two unknowns (θ_1, θ_2), we should get two equations.

The first harmonic equation for 5-level DCMLI is nothing but

$$(\cos\theta_1 + \cos\theta_2) = m \qquad \text{(I)}$$

Based on the harmonic elimination theory, if one wants to eliminate the n^{th} harmonic, then

$$\cos(n\theta_1) + \cos(n\theta_2) + \cos(n\theta_3) + \ldots + \cos(n\theta_s) = 0$$

If we want to eliminate the 5^{th} harmonic

$$\cos(5\theta_1) + \cos(5\theta_2) = 0 \qquad \text{(J)}$$

So the two harmonic equations required to solve (θ_1, θ_2) are

$$(\cos\theta_1 + \cos\theta_2) = m$$

$$\cos(5\theta_1) + \cos(5\theta_2) = 0$$

Solving (I) & (J) along with equations (A) to (H) and by following steps (1) to (6) we get (θ_1, θ_2) to be

$$(\theta_1, \theta_2) = (83.624^0, 47.627^0)$$

XIII. SIMULATION RESULTS

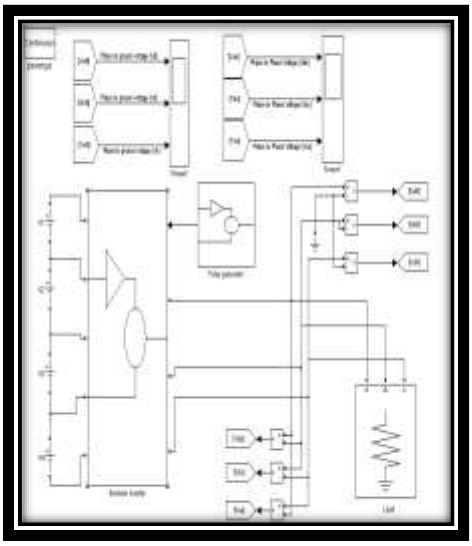

Fig.4 Block Diagram Of Simulation (R Load)

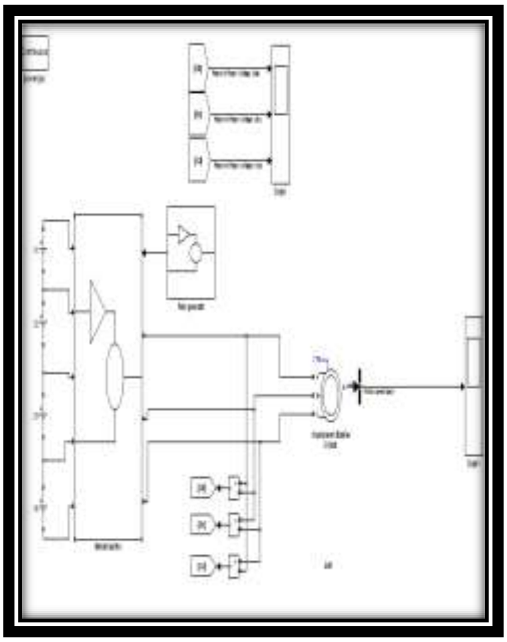

Fig.5. Block Diagram Of Simulation (Induction Motor Load)

ISSN: 2349-7947
24 – 32

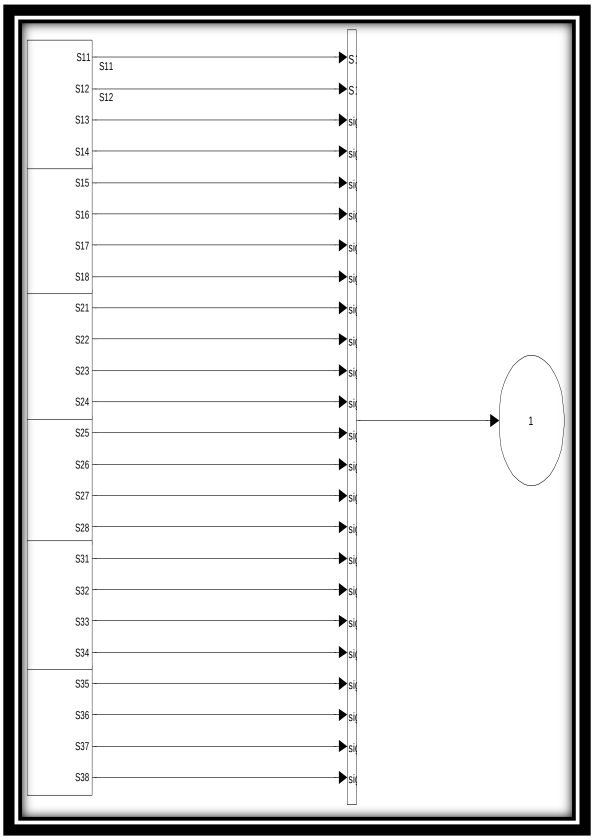

Fig.6. Pulse Generator

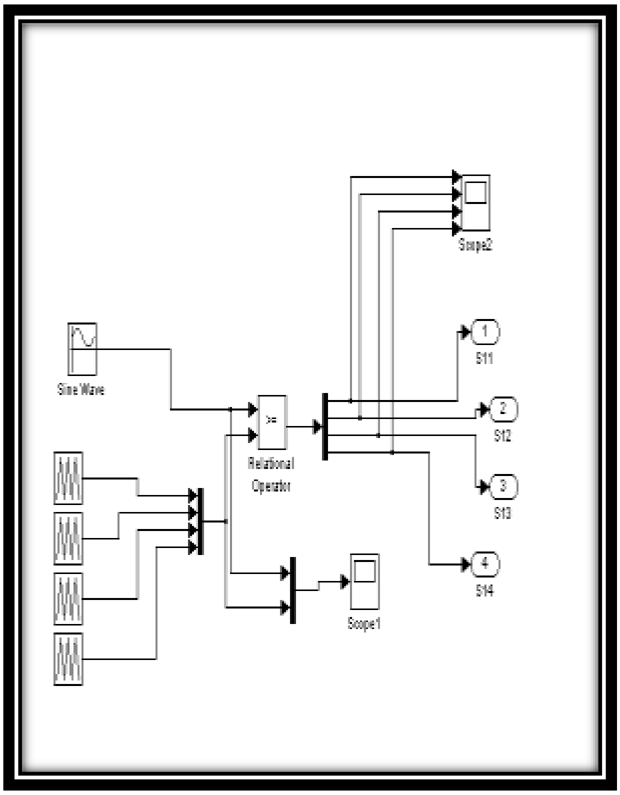

Fig.7. Circuit diagram for generating gate pulses to $S_{11}, S_{12}, S_{13}, S_{14}$

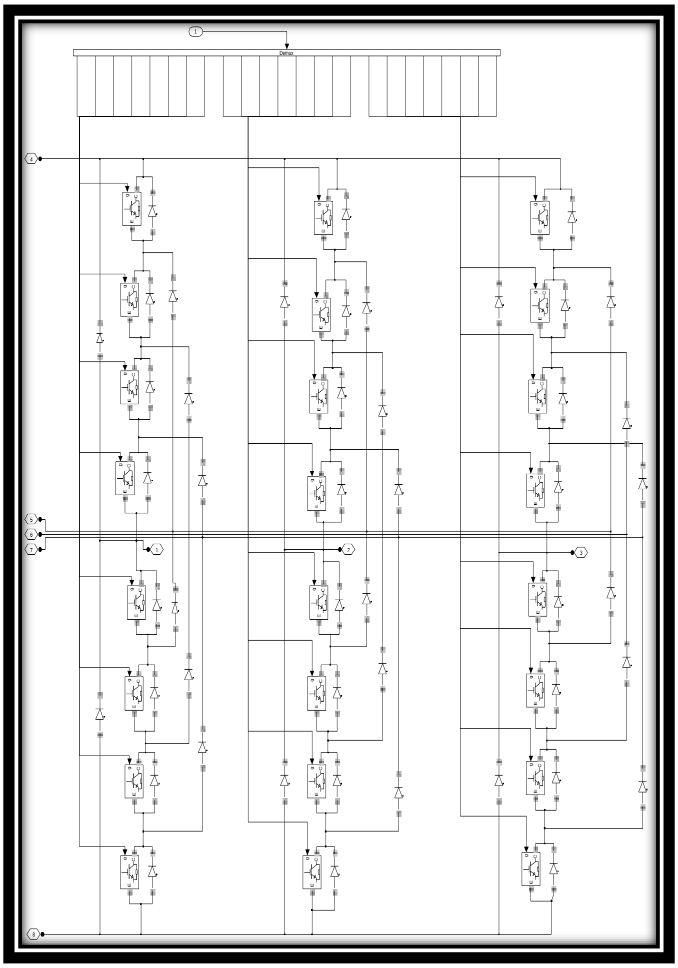

Fig.8. Five Level Inverter (DCLMI That Was Used In Simulation)

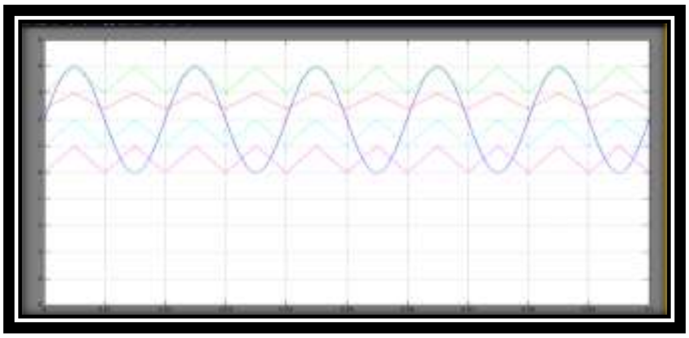

Fig.9. Output Waveform of Scope 1

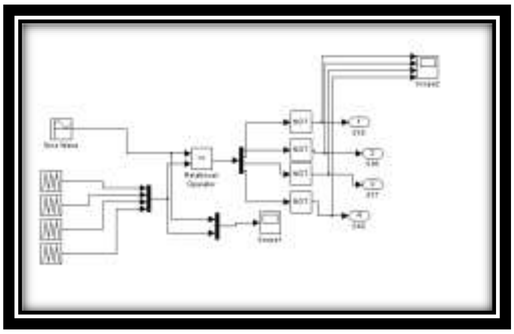

Fig.10. Circuit diagram for generating gate pulses to $S_{15}, S_{16}, S_{17}, S_{18}$

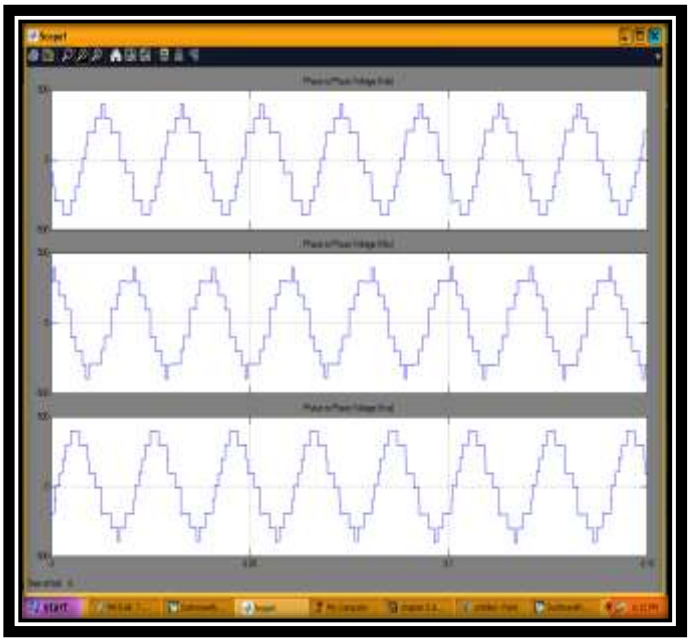

Fig.11. Phase voltages for a five level diode clamped multilevel inverter (V_a, V_b, V_c)

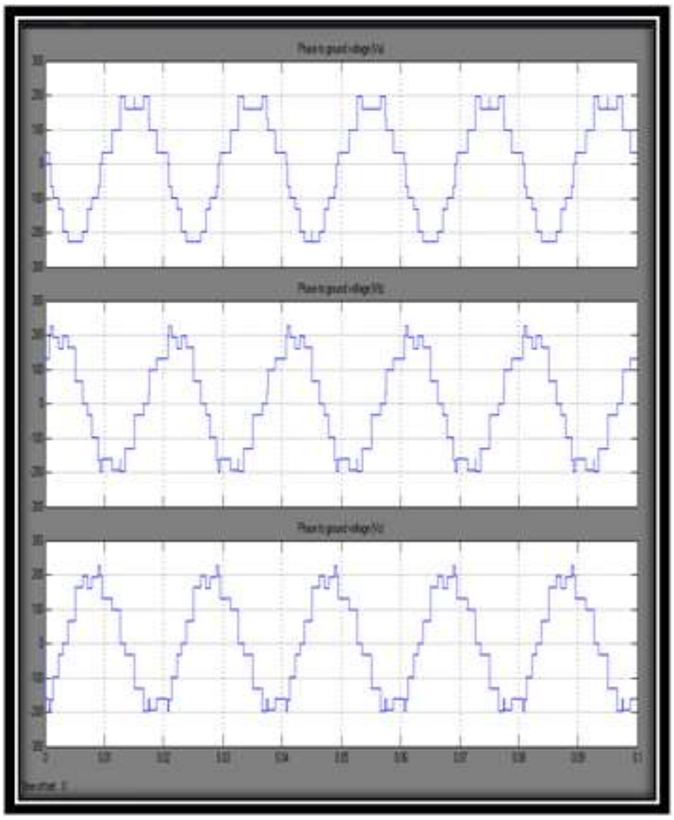

Fig.12. Line voltages for a five level diode clamped multilevel inverter (V_{ab}, V_{bc}, V_{ca})

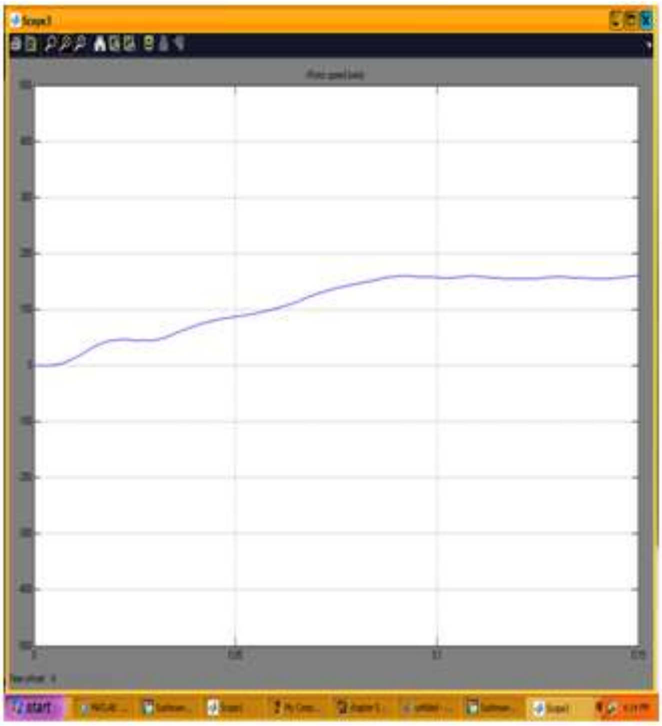

Fig.13 Rotor Speed

XIV. CONCLUSION

This study has successfully developed a new Fundamental frequency switching scheme for a three-phase stand-alone PV generation system. The effectiveness of the five-level diode clamped multilevel inverter control scheme for the three-phase stand-alone PV generation system was verified by simulation results. According to the experimental results, the maximum conversion efficiency of the multilevel inverter is about 96.5%, which is comparatively higher than conventional high frequency PWM-based inverters. Moreover, the ac output voltage of the multilevel inverter is a near-sinusoidal waveform, and the corresponding THD values of load current under different loads are generally less than 5%, which satisfies the harmonic standards for most applications.

The developed PV-based power generation system belongs to a stand-alone power generation approach, maximum-power-point-tracking and modified the fundamental frequency switching algorithms can be applied to form a grid connected generation framework. The application presented in this paper is applicable to rural areas where there is no grid connection to the utility network.

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