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Comparison of Weighted Total Harmonic Distortion of Various PWM Techniques employed in Multi-level Inverters

Nithil Babu N[1]

UG Student, Dept. of EE, National Institute of Technology Calicut,Kerala, India[1]

ABSTRACT: The role played DC to AC inverters in the present industrial and domestic applications is immense. Every drive applications need an inverter in some way or other. But the harmonic content and power utilization of an inverter may produce problems in grid. Harmonic distortion in line current and change in power factor really make a bad impact on the network. Another characteristic, which affect efficiency is the losses, mainly switching loss and conduction losses. Switching losses are of great concern, as high frequency switching are done in inverters. To minimize this, various methods have been introduced and many have proven to be good enough. Multi-level inverters, producing staircase waveform has been invented by Nabae in earlier 80's, starting with Three Level Neutral Point Clamped inverter. Many other topologies are also invented like Diode-Clamped, Flying Capacitor & Cascaded structure. Many techniques has also been introduced to vary the gain of these inverters and the most popular one is Pulse Width Modulation. In this literature, a study of various PWM techniques on diode-clamped multi-level inverters will be studied comparing them with respect to harmonics produced in output, mainly considering Three Level NPC Inverter.

KEYWORDS: Weighted Total Harmonic Distortion, WTHD, PWM, Space Vector PWM, Three level NPC Inverters

I.INTRODUCTION

AC fed systems are preferred over DC fed ones in many applications as the former is advantageous due to many reasons. Using unidirectional flow, charges can be stored in capacitors. So the usage of this direct supply to produce AC provides us with great help whenever AC can't be obtained directly. But the production of a Sinusoidal AC from a constant supply is indeed a challenging area as far as harmonic content and losses in the switches are concerned. The power electronics device which converts DC power to AC power at required output voltage and frequency level is known as inverter. Based on the nature of input source, inverters can be classified into:

a. Voltage Source Inverters(VSI)
b. Current Source Inverters(CSI)

In case of Voltage Source Inverter, the input to the inverter is provided by ripple free dc voltage source and the independently controlled ac output is a voltage waveform, whereas in Current Source Inverter, the voltage source is first converted into a current source and then used to supply the power to the inverter. On the basis of connections of semiconductor devices, inverters are classified as

a. Bridge inverters
b. Series inverters
c. Parallel inverters

The most important performance characteristic of an inverter is the harmonic content in its output. Almost all the electrical appliances and instruments are frequency sensitive. The frequency response of some may be entirely different from operating frequency at other frequencies. Ideally, the output of an inverter should be a pure sinusoidal alternating wave with only one harmonic content. But the exact replication and production of a sine wave with power frequency is impossible as no change in amplitude can be produced instantaneously. Rather a waveform of similar variation with a

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limited amount of appreciable harmonics can be produced using certain techniques. The higher order harmonics won't do any useful work in many applications like drives. These have to be filtered out after shifting the harmonics far from the fundamental so that filtering requirements are less. In this literature survey, the main aim is to find a method which yields minimum harmonic content in the output, so that filtering requirements can be reduced.

II.MULTI-LEVEL INVERTERS

The elementary concept of a multilevel converter is to achieve higher power using a series of power semiconductor switches with several lower voltage dc sources to perform the power conversion by synthesizing a staircase voltage waveform thereby reducing harmonic distortion. The level of an inverter is dependent on the number of different pole voltages. The basic inverter model is the Two-level inverter or conventional inverter. The inverters which produces two levels of pole voltages are known as two level inverters.In high-power and high-voltage applications these two-level inverters however have some limitations in operating at high frequency mainly due to switching losses, high harmonic content and constraints of device rating. Increasing the number of voltage levels in the inverter without requiring higher rating on individual devices can increase power rating and quality of AC waveform. A multilevel converter has several advantages over a conventional two-level converter and important of them are:

a. Higher power rating
b. Low harmonic distortion in line currents
c. Low $\frac{dv}{dt}$ stress on switches
d. Low EMC problems
e. Lower Common-mode voltages

A Multi-level inverter will have more than two levels of pole voltages and it starts from three. A multi-stage inverter is being utilized for multipurpose applications, such as active power filters, static VAR compensators and machine drives for sinusoidal and trapezoidal current applications. They also have certain disadvantages. One particular disadvantage is the greater number of power semiconductor switches needed. Although lower voltage rated switches, each requires a related gate drive circuit which causes the overall system to be more expensive and complex.There are three main types of transformer-less inverter topologies. They are:

a. Diode clamped Multilevel Inverter (DCMLI)
b. Flying capacitor Multilevel Inverter (FCMLI)
c. Cascaded H-bridge Multilevel Inverter (CMLI)

III.PULSE WIDTH MODULATION

When ac loads are fed through inverters it required that the output voltage of desired magnitude and frequency be achieved. In many industrial applications, output voltage control of the inverters is necessary for the following reasons:

a. Due to variations in DC input voltage
b. To regulate voltage of inverters

A variable output voltage can be obtained by varying the input dc voltage and maintaining the gain of the inverter constant. On the other hand, if the dc input voltage is fixed and it is not controllable, a variable output voltage can be obtained by varying the gain of the inverter, which is normally accomplished by pulse-width-modulation (PWM) control within the inverter. Pulse modulation is basically a sampling of the input reference analog signal. Various pulse modulation schemes are: (a) Pulse Amplitude Modulation, (b) Pulse Width Modulation, (c) Pulse Position Modulation and (d) Pulse Code Modulation. The most efficient method of controlling output voltage is to incorporate Pulse Width Modulation (PWM) control within inverters. In this method, a fixed DC voltage is supplied to inverter and a controlled AC output voltage is obtained by adjusting on-off period of inverter switching devices. A number of Pulse width modulation (PWM) schemes are used to obtain variable voltage and frequency supply. PWM signals are pulse trains with fixed frequency and magnitude and variable pulse width. There is one pulse of fixed magnitude in every PWM period. However, the width of the pulses changes from pulse to pulse according to a modulating signal. The frequency

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of a PWM signal must be higher than the fundamental frequency, frequency of modulating signal, in order to make energy delivered depends mostly on the modulating signal.With respect to the quality of output, lower order harmonics can be eliminated or minimized along with its output voltage control using this method. As higher order harmonics can be filtered easily, the filtering requirements are minimized. The main disadvantage of this method is that SCRs are expensive as they must possess low turn-on and turn-off times. There are many PWM techniques to control the output by varying gain of inverter. The commonly used methods are:

a. Single Pulse Width Modulation
b. Multiple Pulse Width Modulation
c. Sinusoidal Pulse Width Modulation
d. Phase-displacement Control
e. Space Vector Pulse Width Modulation
f. Discontinuous Pulse Width Modulation
g. Selective Harmonic Elimination PWM
h. Virtual Vector PWM

The above various techniques differ from each other with respect to the quality of the output waveform, mainly harmonic content and utilization of input voltage. In this literature, the difference in the aspect of harmonic content is analyzed and an attempt has been made to find most suitable method.

IV.SVPWM & DPWM

Space Vector Pulse Width Modulation (SVPWM) method is an advanced, computation intensive PWM method and possibly the best among all the PWM techniques for drive applications. The SVPWM is an alternative method for the determination of switching pulse width and their position. The major advantage of SVPWM stem from the fact that, there is a degree of freedom of space vector placement in a switching cycle. This feature improves the harmonic performance of this method. This method has been finding widespread application in recent years because of the easier digital realization and better dc bus utilization and they are also applicable in Vector control, Direct Torque control and v/f control.The concept of space vector can easily be understood from revolving magnetic field produced by three phase windings, displaced by 120°. Revolving magnetic field itself can be considered as a space vector. It can be shown that revolving magnetic field will have an amplitude 1.5 times that of the amplitude of phase sine voltages and frequency being same. But a revolving magnetic field can also be produced by an equivalent two phase windings, displaced by 90° from each other. In balanced system, three phase quantities sum up to zero. So one variable can always be represented by other two variables. Hence system can be represented by only two independent quantities, i.e. a plane. SVPWM is based on the fact that there are only two independent variables in a three-phase voltage system. So orthogonal coordinates can be used to represent the 3-phase voltage in the phasor diagram. If α and β are the two stationary orthogonal coordinate axes, the three-phase voltage vector may be represented as:

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix}\begin{bmatrix} V_{A0} \\ V_{B0} \\ V_{C0} \end{bmatrix}$$

and space is defined as:

$$\overline{v_s^*} = \frac{2}{3}\left(v_a + \overline{a}v_b + \overline{a^2}v_c\right)$$

where V_{A0}, V_{B0} and V_{C0} are the three Pole voltages and $\overline{a} = \exp(j2\pi/3)$. So the number of space vectors in an inverter depends upon three pole voltages and hence level of the inverter. For an n–level inverter, the number of unique voltage levels in each pole is 'n'. So the total number of space vectors or states will be n×n×n or n^3. In Space vector domain, the reference is a rotating vector with angular speed corresponding to the fundamental frequency, which represents three phase sinusoidal voltage. The aim of SVPWM is to approximate this reference vector using the

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available states of the inverter. So we sample the reference vector at each switching period, and is represented using suitable states such that they are nearest to the sample at any specific point of time. This point clearly shows the less harmonic content produced using Space vector modulation.

The distinct feature of space vector PWM is the freedom of explicit pulse placement in half of the carrier cycle. By using this degree of freedom alternative space vector PWM strategy can be formulated in which the active vectors in two successive half switching period are moved to join together, and zero space vector consequently vanishes. This results in a new method called as Discontinuous Space vector PWM. Due to this manipulation one branch of the inverter remain unmodulated during one switching interval. Switching takes place in two branches and one branch is either tied to the positive dc bus or negative dc bus. The number of switching is thus reduced to 2/3 compared to the continuous SVPWM, hence, the switching losses are reduced significantly. There are six different schemes of DPWM, depending on the variation in the placement of the zero space vectors.

a. T0 = 0 (DPWMMAX)
b. T7 = 0 (DPWMMIN)
c. 0° Discontinuous modulation (DPWM 0)
d. 30° Discontinuous modulation (DPWM 1)
e. 60° Discontinuous modulation (DPWM 2)
f. 90° Discontinuous modulation (DPWM 3)

V. THD & WTHD

Grid operator imposes harmonic limit on the line current and power factor control to maintain quality feeding to grid. Harmonic distortion in current is dependent on distortion in Voltage and impedance. In order to reduce harmonic in current, generated by voltage source inverter should be less for a given impedance. Hence this study is of prime importance. Traditionally quality of output voltage is measured by THD, which reflects energy of the waveform harmonic content and is defined as

$$THD = \frac{1}{V_1}\left(\sum_{n-2,3..}^{\infty} V^2{}_n\right)^{1/2}$$

where V_1 is RMS value of fundamental component voltage and V_n is RMS value of the nth harmonic component.Presence of inductance in a transformer or filter damps out higher order current harmonics quickly as compared to lower order. This indicates that higher order harmonics are not sever as lower one. However THD does not consider severity of lower order harmonics and treat all harmonic equally. In this regard another measuring index is proposed in addition to THD is Weighted Total Harmonic Distortion (WTHD). This index gives a better measure of harmonic pollution by using the order of each harmonic component as its weight factor. Further index considers the severity of lower order of current harmonics and WTHD is defined by.

$$WTHD = \frac{1}{V_1}\left[\sum_{n=2,3..}^{\infty}\left(\frac{V_n}{n}\right)^2\right]^{1/2}$$

Now the WTHD from a VSI is calculated for various PWM methods discussed above. For uniformity, a normalisation is done in the calculation of WTHD and is given by:

$$NWTHD = \frac{\sqrt{\sum_{n=2}^{\infty}\left(\frac{V_{n,LL}}{n}\right)^2}}{V_{1,LL}} \cdot M = \frac{2\sqrt{2}}{\sqrt{3}} \cdot \frac{\sqrt{\sum_{n=2}^{\infty}\left(\frac{V_{n,LL}}{n}\right)^2}}{V_{dc}}$$

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VI. RESULT AND DISCUSSION

The study is conducted on a three level neutral clamped DC-AC Inverter on Matlab-Simulink, comparing the output harmonic content of SVPWM, DPWM and VVPWM.

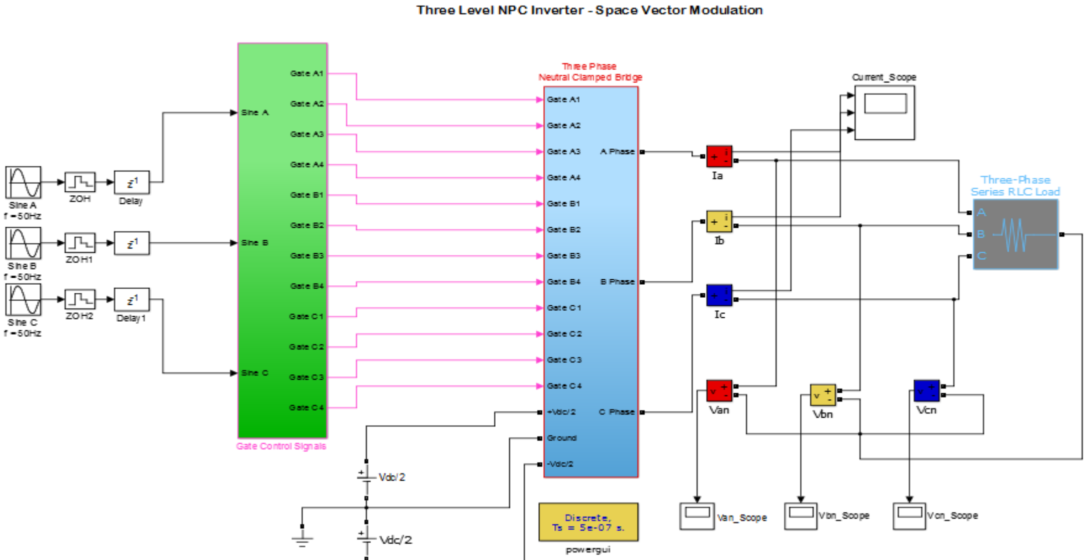

Fig. 1 Three level NPC Inverter in Matlab-Simulink

In the fig 1, the complete system of a DC-AC inverter is shown, with various subsystems - Gate Control Signals subsystem and three phase neutral clamped bridge subsystem.

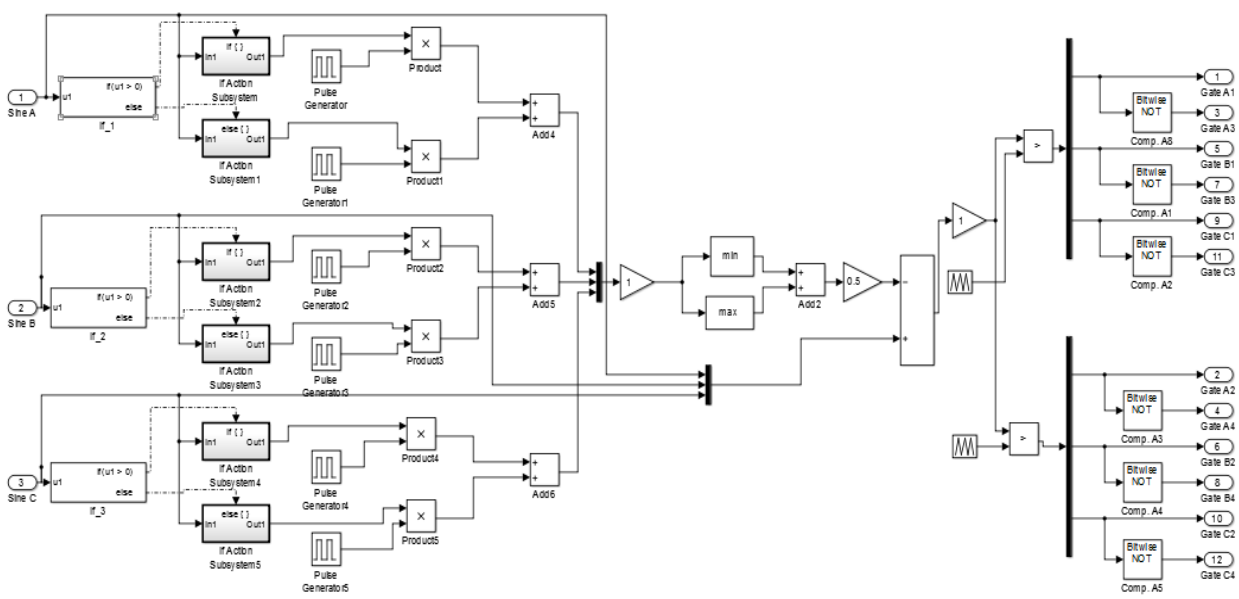

Fig. 2 Subsystem to obtain Gating signals

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In the fig 2, the subsystem made for generation of gate signals is expanded and shown. This is one of the main block made for the simulation as this produces the gate signals required for all switches in the three phase neutral clamped bridge subsystem. The method implemented through this subsystem is SVPWM, various steps of which are shown in figure.

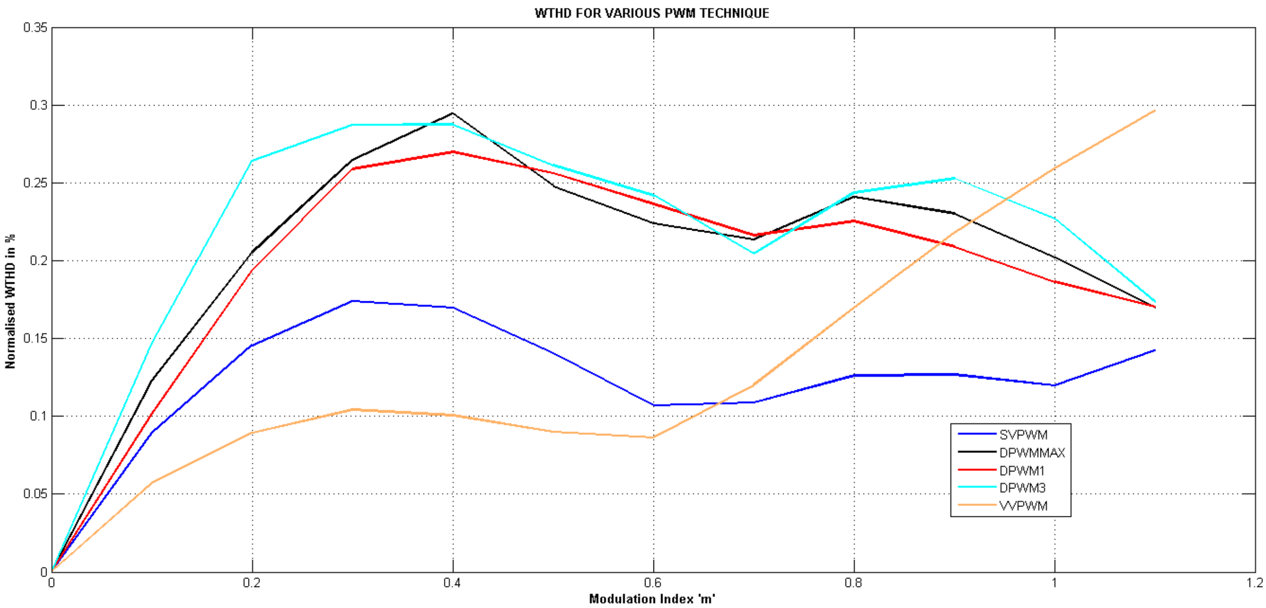

Fig .3 Normalised WTHD Vs Modulation Index 'm'

Harmonic Analysis is done in Matlab for various PWM techniques like SVPWM, DPWM1, DPWM3, DPWMMAX and VVPWM for various modulation indices. The result is plotted in the form of a graph is shown in fig 3. The same model can be used for simulating various PWM techniques, with only difference has to be made in Gate Control signals subsystem.

VII.CONCLUSION

It is observed that Space vector Modulation has better quality in terms of Harmonic content. WTHD of SVPWM is decreasing with modulation index after some point. Discontinuous PWM methods are showing relatively less switching losses, but it has very high value of harmonic distortion. In fact, they are much higher than that of SVPWM. The harmonic content in output using VVPWM largely increases after one particular modulation index, making it a poor technique in this context. However, considering switching loss DPWM has the most advantage. But the most efficient method in context of harmonics is Space Vector Pulse width modulation.

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