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# A Review on Three-Phase, Multilevel Inverter Topology, And Various Loss Reduction Techniques

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***Abstract*— This paper explains different methods used for three phase inverters for losses calculation and reductions. It also compares two widely used modulation techniques Sinusoidal Pulse Width Modulation (SPWM) and Space Vector Modulation (SVM) with reference to the losses of a three phase two level inverter. The losses are evaluated by analytical, simulation and by loss simulator (MATLAB) by the device manufacturer. The analytical loss calculation has been carried out using datasheet parameters. Simulation has been done for R-L load. The modulation techniques are also compared in terms of harmonic spectrum, DC bus utilization and Common Mode Voltage (CMV).**

***Index Terms*—Common Mode Voltage, PWM, SPWM, SVM.**

## I. INTRODUCTION

THE PWM Voltage Source Inverter drives are widely used in industrial applications. In case of the high performance drives the inverter performance also plays a vital role. The voltage of an inverter can be controlled by various switching techniques [1]. The sinusoidal voltage is obtained by commutating the switches at a high frequency compared to the supply frequency. The higher switching frequency shifts the switching harmonics at a high frequency thereby reducing the filter requirement. The high frequency switching thus ensures a good harmonic spectrum, but at the cost of switching losses. The losses in an inverter do affect the efficiency as well as the thermal design of the switches used. These losses consist of the conduction and switching losses [2]. The conduction losses are independent of the switching technique whereas the switching losses are influenced a lot by the modulation technique used [3]. The switching losses primarily depend on the switching frequency. If the switching frequency is higher the switching losses are high but the harmonic spectrum improves. So, there is always a tradeoff between these two. Also, the switching losses are dependent on the value of the instantaneous current and hence the dc bus utilization holds a lot of importance. All these aspects are taken into account in the analysis. The most widely used modulation techniques i.e., the Sinusoidal Pulse Width Modulation (SPWM) and Space Vector Modulation (SVM) have been implemented in PSIM and the analysis is carried out with respect to the dc bus utilization, losses, harmonic spectrum and implementation complexity. Although there are two techniques by which these SVM can be implemented, direct digital technique & the carrier-based technique of which the later is used. The reference waveforms are generated and compared with the triangular wave to compute the switching instants [4-5].

## II. LOSS ANALYSIS OF A PWM INVERTER

The power schematic of a Voltage Source Inverter is shown in figure 1.

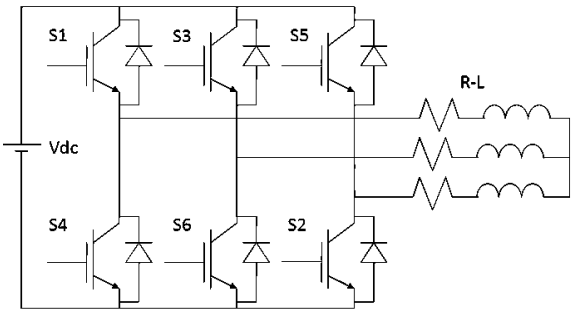


Fig.1.Schematic of a three-phase inverter

In an inverter the losses comprise of conduction loss and switching loss. “The conduction losses can be defined as the losses that occur when the switch is turned on. The total power dissipation during conduction is computed by multiplying the on-state saturation voltage by the on-state current. The switching loss can be defined as the power dissipated during turn on and turn off switching transitions” [2]. In a PWM inverter the switching losses are substantial and must be considered in thermal design. The characteristics of an ideal and practical switch are shown in figure 2. From the characteristics it is seen that in case of an ideal switch the voltage and current change instantaneously, whereas in case of a practical switch this is not the case. This area under the curve during the switching transitions causes the switching loss.

a) Ideal switch b) Practical switch

Fig.2. Characteristics of a) ideal and b) Practical switch

Hence the switching losses can be given as

$$P_{sw} = P_{on} + P_{off} \quad (1)$$

$P_{sw}$ - Switching loss of IGBT

Where $P_{on}$ and $P_{off}$ are the turn on and turn off losses [6]. The turn on and turn off losses are obtained by multiplying the turn on and turn off energies provided in the device datasheet.

$$P_{sw} = (E_{on} + E_{off}) \times f_s \qquad (2)$$

Where $E_{on}$ and $E_{off}$ are turn on and turn off energies and $f_s$ is the switching frequency.

The conduction losses include the losses of the IGBT as well as that of the freewheeling diode.

$P_{con}$ – *Total conduction loss*

$$P_{con} = P_{IGBT} + P_{FWD} \qquad (3)$$

$$P_{IGBT} = I_p \times V_{ce} \times \left(\frac{1}{8} + \frac{m_i}{3} \cos\theta\right) \qquad (4)$$

$$P_{FWD} = I_p \times V_f \times \left(\frac{1}{8} - \frac{m_i \pi}{3_\pi} \cos\theta\right) \qquad (5)$$

$P_{IGBT}$ - Conduction loss of IGBT

$P_{FWD}$ - Conduction loss of freewheeling diode

$V_{ce}$ - Saturation voltage of IGBT (from datasheet)

$I_P$ - Peak value of the load current

$V_f$ -Saturation voltage of the freewheeling diode (From datasheet)

$m_i$ - Modulation index

Cos Θ - Load power factor.

From (4) & (5), it can be inferred that the conduction loss depends on the peak current and not the switching frequency. When the IGBT is turned on the freewheeling diode gets reversed biased and the recovery current flowing through it causes the recovery loss. This is expressed as:

$$P_{rr} = \frac{1}{8} \times I_{rr} \times V_{dc} \times T_{rr} \times f_s \qquad (6)$$

$P_{rr}$ – Recovery loss

$I_{rr}$ – *Reverse recovery current (from datasheet)*

$T_{rr}$ – Reverse recovery time (from datasheet)

$V_{dc}$ – *Dc link voltage*

To calculate the losses analytically the curve tracing equations are derived by formulation the least square solution and third-degree approximation has been considered for better accuracy [7]. For the simulation purpose the IGBT datasheet CM1400DY24NF has been used and hence the equations have been computed for the same. The values of $V_{ce(sat)}, E_{sw(on)}, E_{sw(off)}, V_f, T_{rr}$ & $I_{rr}$ are calculated as a function of $I_p$. The loss for a single switch has been computed using (1-6) and the total losses are the sum of the losses for six switches.

$$\boldsymbol{V_{ce(sat)} = 0.6466 + 0.0016 I_p - 5.1494 \times 10^{-7} I_p^3 + 8.9606 \times 10^{-11} I_p^3}$$

$$\boldsymbol{E_{sw(on)} = 0.005 + 6.851 \times 10^{-5} I_p - 8.323 \times 10^{-9} \times I_p^2 + 9.32 \times 10^{-12} I_p^3}$$

$$\boldsymbol{E_{sw(off)} = 0.0082 + 1.942 \times 10^{-4} I_p - 7.55 \times 10^{-8} \times I_p^2 + 2.58 \times 10^{-11} I_p^3}$$

$$\boldsymbol{V_f = 0.7222 + 0.0017 I_p - 5.6354 \times 10^{-7} I_p^2 + 1.0667 \times 10^{-10} I_p^3}$$

Using these equations, the datasheet parameters have been computed as a function of the load current. For the simulation studies the Thermal Module in PSIM has been used which is a good tool for estimating and analyzing the power losses [8]. The basis for this is the Device Database Editor which allows the user to add new devices to the data base and manage them with ease. The devices are saved in the directory in which PSIM is installed and while simulating, these devices can be used from the database. The behavior model of the device is used in the simulation. It takes into account static characteristics like conduction voltage drop and on state resistance but not the dynamic characteristics. Based on the voltage, current and the junction temperature values from simulation, PSIM accesses the device database and calculates conduction and switching loss. The results depend upon the accuracy of the device data as well as proper scaling of the results from actual operating conditions. The device manufacturer provides the loss simulator for estimating the losses and thereby the junction temperature. In Mitsubishi devices the loss simulator available is Melcosim through which the losses have been estimated [9]. The parameters which are taken into account are current, dc link voltage, modulation index, power factor, switching frequency and supply frequency. These are the primary parameters which influence the loss. The switching method used to calculate the loss is the SPWM for the three-phase inverter.

## III. MODULATION TECHNIQUES

### 1. *Space Vector Modulation*

The space vector modulation technique offers advantages over the SPWM in terms of the dc bus utilization and the harmonic spectrum. Hence this technique is widely used in various applications. This technique is based on the eight switching combinations of the three phase two level inverter [15]. These eight switching states give rise to Space Vector diagram shown in figure 3.

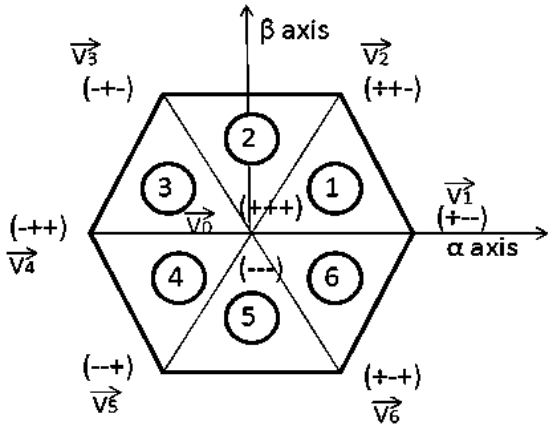


Fig.3. Space Vector diagram

The zero switching states are at the center and six active vectors form the hexagon. The six active vectors form the sectors and

switching takes place such that the nearest vectors are switched to generate the required output vector. The three-phase system is analyzed as a whole as the Clarke's transformation is applied which leads to the switching as a combined effect of all the three phases. The Volt second balance principle is used to calculate the timings where the product of the reference and sampling period equals the sum of volt multiplied by the time interval of the chosen space vectors. The maximum output voltage in the linear range is 0.707 $V_{dc}$ which is 15.5% more than SPWM. Also, by designing the zero-vector placement different switching sequences can be created, which contributes to new switching techniques.

**2. *Sinusoidal Pulse Width Modulation***

In the SPWM technique to produce the balanced three phase output voltages the triangular wave is compared with three references which are 120° apart [16]. The carrier wave frequency is higher than the reference which is at supply frequency. The frequency modulation ratio $m_f$ is defined as:

$$M_f = f_s / f_1 \quad (7)$$

$f_s$ - Frequency of the carrier
$f_1$- The supply frequency
The amplitude modulation ratio (modulation index) is defined as:

$$M_i = r_{eference} / c_{arrier} \quad (8)$$

The dc component present in the phase voltages being similar is cancelled out in the line-to-line voltages. Due to this pattern of the line-to-line voltages the harmonics are absent at the carrier frequencies and appear as sidebands of the switching frequencies and their multiples. In linear modulation range ($0<=m_i<=1$) the maximum line-to-line voltage available is 0.612 $V_{dc}$

**3. *Hybrid PWM (HPWM***

HPWM strategy, [12], is based on the clamping of one modulation signal for sometime during the non-common intervals between DSPWM and SPWM. As the modulation signals are clamped to zero for an additional time, switching frequency of the power switches is reduced and switching losses also decrease. The exact combination is chosen by a sharing variable, which can take values within the interval [0; 1] When the parameter D takes the extreme values zero or one, the HPWM becomes DSPWM or SPWM, respectively. Figure 4 shows that, when the modulation signal from SPWM crosses zero, the absolute value of the DSPWM modulation signals are exactly half the modulation index (m = amplitude of the modulation signals). This condition is used to determine the extension of the common interval directly from the instantaneous values of the modulation signals obtained from DSPWM. The modulation signals are compared with the value of x=D (m/2) to determine the additional intervals in which these signals need to be clamped to extend SPWM patterns further.

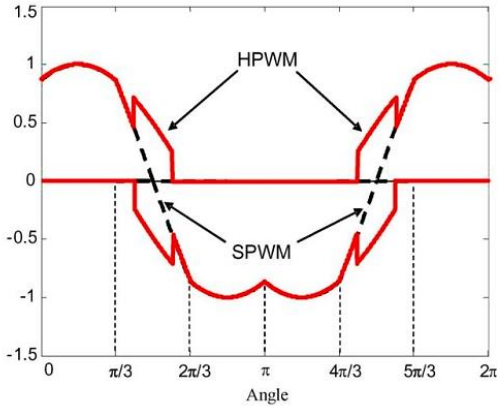


Figure 4. Modulation signal for HPWM

**CONCLUSION**

Even though the generation of SVM technique is different compared to SPWM both are regularly sampled algorithms and both create switched output waveforms to produce the result. Both the techniques have the similar switching pattern. In SPWM the nearest vectors are automatically selected whereas in SVM the switching sequence is designed by the user. The only difference in these two techniques is the placement of the zero vectors. In SPWM the sequence is automatically generated whereas in SVM it can be designed. Conventional SVM implementation centers the active space vectors in each half carrier period and splits the remaining zero space vector time equally between which is shown in figure 3. From the sequence we can see that the sequence of the space vectors reverses over a complete carrier interval which is also the case with SPWM.

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