Abstract – This paper deals with the performance analysis of three phase induction motor drive fed by a PWM voltage source inverter. The PWM method, which involves the modulation of conventional sinusoidal reference signal and a triangular carrier is used here to produce pulse width modulated output only for under modulation index. This paper work deals mainly with the performance analysis of three phase induction motor fed by PWM voltage source inverter in terms of phase current of inverter, rotor and stator current, speed, electromagnetic torque developed and total harmonic distortion in line and phase voltage of inverter for under modulation range i.e., ma<1. For the implementation of the proposed drive the MATLAB/SIMLINK environment has been used. Two types of the switching techniques are available for the production of the balanced three phase output voltage i.e. either unipolar scheme or bipolar scheme but only unipolar scheme has been used as it offers several advantages. The performance of the inverter has been carried out by using the parameter total harmonic distortion. The impact of the modulation index on the performance of the inverter has been done in terms of the waveforms for inverter phase voltage, line voltage, line current, stator current, rotor current, rotor speed and electromagnetic torque developed by the motor.

Keywords – Induction motor drive, Modulation Index, Matlab, PWM, Switching, Simulink, THD, Unipolar Switching

I. INTRODUCTION

DC-AC inverters are electronic devices used to produce AC power from low voltage DC energy (from a battery or solar panel). This makes them very suitable for when required to use AC power tools or appliances but the usual AC mains power is not available. Examples include operating appliances in caravans and mobile homes, and also running audio, video and computing equipment in remote areas. Most inverters do their job by performing two main functions: first they convert the incoming DC into AC, and then they set up the resulting AC to mains voltage level using a transformer. And the goal of the designer is to have the inverter perform these functions as efficiently as possible. So that as much as possible of the energy drawn from the battery or solar panel is converted into mains voltage AC, and as little as possible is wasted as heat [1].

Three-phase inverters are used for variable-frequency drive applications. A basic three-phase inverter consists of three single-phase inverter switches each connected to one of the three load terminals [2].

II. THREE PHASE SPWM INDUCTION MOTOR DRIVE

Figure 1 shows a three-phase inverter, which is the most commonly used topology in today’s motor drives. The circuit is basically an extension of the bridge style single-phase inverter, by an additional leg. The control strategy is similar to the control of the single phase inverter. The odd triplen harmonics (3rd, 9th, 15th, etc.) of the reference waveform for each leg are eliminated from the line-to-line output voltage. The even-numbered harmonics are canceled as well if the waveforms are pure AC, which is usually the case [3, 4].

The standard three-phase VSI topology as shown in Fig. 1, the switches of any leg of the inverter (S1 and S4, S3 and S6, or S5 and S2) cannot be switched on simultaneously because this would result in a short circuit across the dc link voltage supply [5]. Similarly, in order to avoid undefined states in the VSI, and thus
undefined ac output line voltages, the switches of any leg of the inverter cannot be switched off simultaneously as this will result in voltages that will depend upon the respective line current polarity.

Fig. 1 : Topology of a three-phase inverter

Three phase voltage-fed PWM inverters are recently showing growing popularity for multi-megawatt industrial drive applications. The main reasons for this popularity are easy sharing of large voltage between the series devices and the improvement of the harmonic quality at the output as compared to a two level inverter. In the lower end of power, GTO devices are being replaced by IGBTs because of their rapid evolution in voltage and current ratings and higher switching frequency. The Space Vector Pulse Width Modulation of a three level inverter provides the additional advantage of superior harmonic quality and larger under-modulation range that extends the modulation factor to 90.7% from the traditional value of 78.5% in Sinusoidal Pulse Width Modulation [7].

Fig. 2 : Three phase pwm inverter fed induction motor

In most variable speed drives pulse width modulation (PWM) voltage source inverters are used. Usually machine design tools only consider the fundamental harmonic of the stator voltage when calculating the losses. These losses are caused by harmonics of the voltage and the current due to the PWM. A number of algorithms for PWM voltage generation are available. Some well known techniques are unipolar voltage switching and bipolar voltage switching, harmonic elimination and space vector PWM. In fact there are many more techniques in which the basic principles of the ones mentioned are used with some modifications. Different PWM algorithms cause different voltage harmonics. These voltage harmonics give rise to current harmonics due to the machine impedance. The voltage harmonics cause additional core losses whereas the current harmonics cause additional losses in the stator and rotor winding of the machine [8, 9].

It is the first and foremost requirement that the output of three phase inverter should be purely sinusoidal. However the waveforms of the practical inverter are non-sinusoidal and contain certain harmonics. These harmonics are generated by the semiconductor devices used in implementing three phase inverter is in the generation of harmonics. The power electronics devices when used in practical circuits like converter/controller circuits generate harmonics in the output voltage supply. The harmonics generate undesirable effects in power supply circuits like generation of humming noises, derating of the machines and torque pulsations which make the operation of the machine pulsating [10]. The following are the important parameters which measure the quality of the inverter output voltage are

1. Harmonic Factor
2. Total Harmonic Distortion
3. Distortion Factor
4. Lowest order Harmonic

III. TECHNIQUES USED TO IMPLEMENT INVERTER

Formerly 180° conduction mode full bridge type inverter were used so as to produce three phase output voltage waveform. The output voltage is available in the form of discrete pulses displaced from each other by an angle of 120°. However the harmonics contents are more. Inverter gain is less and the output voltage regulation is poor [11]. To satisfy the constant voltage and frequency requirement is also difficult.

So as to fulfill above mentioned requirements, the most efficient technique used to implement the three phase inverter is the Pulse Width Modulation Technique. The inverter so fabricated is called PWM Inverter. In this technique, the width of each pulse is
varied on per half cycle basis. This variation of the pulse width in each half cycle enables us to control output voltage in an efficient manner and eliminate the particular harmonic component from output voltage waveform. The commonly used PWM techniques used for implementing three phase inverter are

1. Single Pulse width modulation
2. Multiple Pulse Width Modulation
3. Sinusoidal pulse Width Modulation

By using the number of pulses and modulating the width of these pulses in each half cycle rather than using a single pulse, the harmonic contents can be further reduced. This analogy can be implemented by using Multiple Pulse Width Modulation and Sinusoidal pulse Width Modulation techniques [12, 13].

IV. MATLAB/SIMULATION BASED ANALYSIS
THREE PHASE SINUOSOIDAL PULSE WIDTH MODULATED INVERTER (SPWM)

Simulation is done on a three phase induction motor fed by a PWM inverter developed in Matlab/Simulink environment. The figure 3 shows the Simulink diagram of the developed model. For the simulation purpose, the tool box used is the Sim-power system tool box. The basic circuit of the proposed scheme consists of a three phase induction motor as wound rotor type having ratings as 3HP, 220V, 50 Hz. The three phase induction motor drive is fed by a three phase PWM VSI inverter. The modulation technique used for the generation of three phase balanced output from the inverter is the sinusoidal pulse width modulation technique.

Voltage source pulse width modulated inverter is made up of six IGBTs switches in a bridge form and fed by a dc voltage source of 300 V. IGBT switches has been used because of the number of advantages offered them for switching purpose. Three phase output is taken from the of three arms of bridge circuit designated as a, b, c, which is connected to the three phases a, b, c, on the stator side of three phase induction motor.

The harmonics present in the output voltage and the load current has also been measured. The evolution of the harmonic contents has been carried out by its THD and the harmonics spectrum has been extracted using the FFT analysis. Scope 1 and 3 measure the RMS and THD of the phase ‘a’ current. Similarly scope 2 and 4 shows the RMS value and THD of line voltage VAB.

V. GENERATION OF GATING PULSES

The gating pulses for the six IGBTS of three legs are generated. The generation of these pulses is carried out by Sinusoidal Pulse Width Modulation technique. A number of algorithms for PWM voltage generation are available. Some well-known techniques are unipolar voltage switching and bipolar voltage switching. In this work the unipolar switching scheme has been used.

VI. SIMULATION RESULTS OF THE SPWM FED INDUCTION MOTOR DRIVE

Results are obtained by simulating the circuit. Here we analyze the inverter and motor performance for under modulation range i.e. for the value of m < 1. Amplitude Modulation index is defined as the ratio of control signal amplitude and carrier signal amplitude i.e. $m = A_c / A_r$. The number of pulses per half cycle depends upon the value of the frequency modulation index m defined by the relation $m = f / (2f)$.
where
\[ f_c = \text{frequency of the carrier signal} \]
and \( f = \text{frequency of the modulating signal} \)

6.1. For modulation index \( m_a = 0.7 \) (under modulation):

First of all the inverter is operated in the under modulation range i.e. the value of \( m_a = 0.7 \) is maintained.

Figure 7 shows the waveform of line voltage \( V_{ab} \). Similar waveforms can be obtained for the other line voltages \( V_{bc} \) and \( V_{ca} \). Form the waveform it is clear that the output waveform is pulse width modulated wave and the frequency of the output voltage wave is 50 Hz and its amplitude is 220V for the value of the dc input voltage of 300V.

Fig. 5: Generation of firing pulses supplied to the IGBT of the three phase Inverter for \( m_a = 0.7 \)

The figure 5 shows the six pulses generated as the output of the firing circuit. The generated pulses are applied to the gate circuit of the six IGBTs which in turn produce the balanced pulse width modulated three phase output voltages.

Fig. 6: Phase ‘a’ current waveform for \( m_a = 0.7 \)

Figure 6 shows the waveform for the phase “a” current. Form the waveform it is clear that the part of the waveform present before the time 0.33 sec is the transient part and after that it acquires it steady state value of x amperes.

Fig. 7: Waveform of line voltage \( V_{ab} \) for \( m_a = 0.7 \)

The variation of rotor and stator current i.e. \( I_r \) and \( I_s \) of phase ‘a’ of motor with respect to time is shown in fig 8 the rotor current has transient time of 0.3 Sec and stator current has 0.35 Sec.

Fig. 8: Waveforms of rotor and stator current of phase ‘a’ three phase induction motor for \( m_a = 0.7 \)

Fig. 9: Waveform for the developed electromagnetic torque in n-m

Fig. 10:THD in phase voltage ‘a’ for \( m_a = 0.7 \)
Fig. 11: THD in line voltage $V_{ab}$ for $m_a=0.7$

The figures 10 and the figure 11 show the frequency spectrum of the phase voltage and the line voltage. The value of the THD for line voltage is 83.73% while for the phase voltage it is 133.37%. The value of the fundamental component of the line voltage is 181.2 V while for the phase it is 87.25 V for the dc input voltage of 300 V for the value of the $M_a = 0.7$. From the waveforms it is clear that the dominant harmonic is the third harmonic. Similarly from the simulation of circuit for modulation index $M_a=0.7$ the total harmonic distortion in line current is $I_a=0.5111$ and its rms value is $I_a = 8.679$ A.

6.2. For Modulation Index $M_a=0.8$:

For modulation index $m_a = 0.8$, the waveform of phase current $I_a$ and line voltage $V_{ab}$ of inverter is shown in fig 12 and 13. Observed that the phase current $I_a$ has transient time 0.5sec which is greater as compared to the transient time obtained when $m_a = 0.7$. It indicates that the response of the motor becomes sluggish as time value of $M_a$ is increased.

Fig. 12: Phase ‘a’ current waveform for $m_a=0.8$

Fig. 13: Waveform of line voltage $v_{ab}$ for $m_a=0.8$

Fig. 14: Waveforms of rotor $I_r$ and stator current $I_s$ of phase ‘a’ three phase induction motor for $m=0.8$

From the waveform of rotor and stator current of phase ‘a’ of motor observed that the transient time is increased to 0.45 Sec for $m_a = 0.8$.

Fig. 15: THD in phase voltage $V_a$ for $m_a=0.8$
Figures 15 and the figure 16 show the frequency spectrum of the phase voltage and the line voltage for modulation index $m_a=0.8$. The value of the THD for line voltage is 72.72% while for the phase voltage it is 103.63%. The value of the fundamental component of the line voltage is 196.4 V while for the phase it is 105.4 V for the dc input voltage of 300 V. and from the simulated circuit the value of total harmonic distortion in line current $I_a$ is 0.4032 and its RMS value is 9.453.

6.3. For modulation index $m_a=0.9$:

Now the results are obtained for the value of modulation index $m_a=0.9$

Observe that the transient period of phase current $I_a$, rotor current $I_r$ and stator current $I_s$ of motor is increased when the modulation index increased to 0.9. Transient time of phase current $i_a$ increased to 7.8 sec while that for motor rotor and stator current is 0.9 sec and 0.75 sec.

The frequency spectrum of three phase inverter line voltage and phase voltage is shown in figure 20 and 21. The value of THD in line voltage is 68.64% while in phase voltage is 94.03%. Whereas the value of fundamental component is increased to 196.2 in line voltage.
voltage and 111.8 in phase voltage for the modulation index $m_a=0.9$. The RMS value of phase current $i_a$ obtained by simulating the circuit is 9.712 and THD in $i_a$ comes to be 0.2731.

VII. COMPARISON OF LINE AND PHASE VOLTAGE FOR DIFFERENT MODULATION INDEX

<table>
<thead>
<tr>
<th>No.</th>
<th>$m_a$</th>
<th>Line Voltage</th>
<th>Phase Voltage</th>
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<tbody>
<tr>
<td>1</td>
<td>0.7</td>
<td>83.74</td>
<td>191.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fundamental</td>
<td>THD %</td>
</tr>
<tr>
<td>2</td>
<td>0.8</td>
<td>72.72</td>
<td>196.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>103.63</td>
<td>105.4</td>
</tr>
<tr>
<td>3</td>
<td>0.9</td>
<td>68.64</td>
<td>196.2</td>
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<tr>
<td></td>
<td></td>
<td>94.03</td>
<td>111.8</td>
</tr>
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</table>

VIII. CONCLUSIONS

The paper presents performance analysis of three phase induction motor fed by PWM voltage source inverter in under modulation range. For this purpose the MATLAB/SIMULINK approach has been used for the implementation of the proposed drive. The three phase inverter has been implemented using the unipolar scheme as compared to bipolar switching scheme. The harmonic contents of the former are less as compared to later. The switching devices used are the power IGBTs. For generation of switching pulses the sinusoidal pulse width modulation algorithm has been used which produces three phase balanced output. The three phase balanced output is then used to drive an induction motor. The performance analysis of the inverter has been done using the parameter total harmonic distortion implemented with the help of FFT block. The THS has been calculated for the phase current, phase voltage and line voltage. The analysis has been carried under modulation range. The effect of modulation index on the motor performance in terms of the rotor current waveform, stator current, line voltage, phase voltage, and phase current waveform has been carried out. Its impact on the on the performance on the motor in terms of the transients and steady state response has been presented. The main advantage of this approach is that it shows the performance of the motor as well as of the voltage source three phase inverter for the entire range of under modulation index. There is appreciable improvement in THD in inverter line and phase voltage as the modulation index is increased and close to unity. From the analysis we conclude that as the modulation index increased.

The transient time of the phase current of inverter output increased and become more with the increment in modulation index.

The motor speed is zero initially and increased to the final value as the time increased. Initially the electromagnetic torque developed by the motor is highly oscillatory and after the transient time it settles down to the value which is equals to the load torque.

Total harmonic distortion THD in line and phase voltage decreases as the value of modulation index increased. The value of fundamental component in line and phase voltage is increased with the increase in modulation index.

IX. REFERENCES


