Analysis of Dual Inverter Fed Open-End Winding Induction Motor Drives

J. Prakash
M.Tech Student of GPREC, Kurnool, INDIA

ABSTRACT

In this paper, a simplified SVPWM algorithm is described. In the conventional SVPWM lookup tables are needed for the generation of space vector locations and sector identification is most time consuming task, with the zero sequence component concept, the actual times for each inverter legs are reduced directly. The simplified SVPWM algorithm has the high performance voltage generation capability compare to conventional SVPWM. As well as giving a detailed explanation of the new algorithm, this paper also presents the comparison results for the different phase sequence between the inverters. To validate the simplified algorithm, simulation studies have been carried out on open end winding induction motor and results are presented in the paper.

Keywords— Dual inverter, Open-end winding, Induction motor, Scalar approach.

I. INTRODUCTION

In recent days multi level inverters become very popular in the field of medium and high voltage drives. The main advantages of multi level inverters are low harmonic distortion in the output voltage, less switching losses, and low dv/dt stress on operating switches. The well known multi level inverters are neutral point clamp (NPC), flying capacitor (FC), cascaded H-bridge [1], [2]. In that NPC requires large number of clamping diodes, whereas FC requires more numbers of capacitors, and H-bridge requires isolated power supply for each module so system is bulky and costly. The quality of output voltage can be increased by increasing the number of levels but system becomes more complex and less reliable. For this, to increase the reliability and efficiency of the systems, in 1993 H. Stemmler and P. Guggenbach proposed three phase voltage generation by using open-end winding induction motor(OEWIM) fed by two 2-level inverters by using triangular pulse width modulation (PWM) and then its implemented by using sine PWM technique [3]. Later on E. G. shiva kumar et. al. [7] introduced space vector PWM (SVPWM) technique for dual inverter fed OEWIM. The authors have used two separate D.C sources to eliminate common mode current (CMC). Based on this principle V.T. Soamasekhar et. al. [8], Bajju et. al. [9] developed several methods to eliminate common mode voltage (CMV) by single D.C source. In this paper we introduced a sine PWM with zero sequence injected method to eliminate the CMV and reduce the complexity of identifying the sectors and switching times in conventional SVPWM. We also show the CMV for different phase shift between the two inverters.

The OEWIM drive is obtained by opening the neutral point of the star connected stator winding of the conventional three phase induction motor without changing the design of motor and feeding the motor from either end using inverters. The schematic diagram of OEWIM as follows.

Dual inverter fed open-end induction motor drives have ability to reduce the common mode voltage at the machines terminals. However the combinations of voltage space vectors of dual inverter produces zero sequences voltages [4] which in turn causes zero sequence currents [5], [6], [11]. Common mode voltage is nothing but potential difference between the star point of the load to ground. The common mode voltage mathematically can be expressed as
Here: Voo' - common mode voltage
Vao, Vbo, Vco - pole voltages of inverter-I
Va'o', Vb'o', Vc'o' - pole voltages of inverter-II

In the developed model common mode voltage and the zero sequence currents can be eliminated respectively by using simplified SVPWM technique with different modulation index values. In this paper we discuss the comparison of common mode voltages and common mode currents for different phase sequence between dual inverter configuration.

II. DUAL INVERTER FED OPEN-END WINDING INDUCTION MOTOR

The schematic diagram of dual inverter fed OEWIM is shown Fig.2. The inverters are operated with isolated power supplies with half of the DC bus voltage as compared to conventional 3-level inverter. An open-end winding induction machine, fed by two 2-level VSIs, offers several advantages when compared to a standard wye or delta connected induction machine drive. The main features of an open-end winding induction machine drive can be summarized as equal power input from both sides of each winding, thus each VSI is rated at half the machine power rating; each phase stator current can be controlled independently; possibility to have twice the effective switching frequency (depending on the modulation strategy). Dual inverter fed open-end induction motor can be operated in two modes, namely, Non-isolated mode and Isolated mode.

A. Isolated mode:

![Diagram of dual inverter fed open-end induction motor](image)

The circuit configuration is shown in Fig.2 where a standard two-level VSI is connected at each side of the machine stator winding. The VSIs are supplied by isolated DC power sources; due to this the zero sequence current cannot flow as it is denied a path for it. Vao, Vbo, Vco are the pole voltages of the inverter-I. Va'o', Vb'o', Vc'o' are the pole voltages of inverter-II. Vaa', Vbb', Vcc' are the effective phase voltages and Vaa'o', Vbb'o', Vcc'o' are effective pole voltages. Each inverter capable of generating 8 states individually, so total dual inverter can generate 64 space vectors respectively. Based on phase shift between the two inverters respective states will be operated.

An effective input DC voltage of Vdc is applied to dual inverter and is equally shared for both the inverters in symmetrical configuration. The active vector for both inverters in symmetrical configuration have magnitude of dc-link voltage is Vdc/2. Any leg of the two inverters can independently attain levels 0 or Vdc/2. The generation of pole voltages is given by

\[
\begin{align*}
V_{aoa'o}' &= V_{ao} - V_{a'o}' \\
V_{bob'o}' &= V_{bo} - V_{b'o}' \\
V_{coc'o}' &= V_{co} - V_{c'o}'
\end{align*}
\]

The effective pole voltages for symmetrical configuration are given in Table-1.

<table>
<thead>
<tr>
<th>ON switches in inverter-I</th>
<th>ON switches in inverter-II</th>
<th>Inv-I Pole voltage</th>
<th>Inv-II Pole voltage</th>
<th>Effective pole voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>S11 or S13 or S15</td>
<td>S21 or S23 or S25</td>
<td>Vdc/2</td>
<td>Vdc/2</td>
<td>Vdc/2</td>
</tr>
<tr>
<td>S11 or S13 or S15</td>
<td>S22 or S24 or S26</td>
<td>0</td>
<td>0</td>
<td>Vdc/2</td>
</tr>
<tr>
<td>S12 or S14 or S16</td>
<td>0</td>
<td>S21 or S23 or S25</td>
<td>Vdc/2</td>
<td>-Vdc/2</td>
</tr>
<tr>
<td>S12 or S14 or S16</td>
<td>0</td>
<td>S22 or S24 or S26</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

From the above table with the help of two 2-level inverters can generate the 3-level pole voltages and the phase winding can attain one of the levels, - Vdc/2, 0, Vdc/2. So it can be operated as a 3-level inverter. Based on phase shift between the inverters the respective active vectors will be operated.

III. PWM TECHNIQUES FOR DUAL INVERTER CONFIGURATION

In general PWM techniques can be implemented in either carrier comparison approach or digital
implementation approach. In digital implementation approach required pulses can be generated by space vector concept. Where as in carrier comparison approach required pulses are generated by comparing reference signals with carrier signal. In carrier comparison approach the reference or modulated signal can be generated based on the scalar approach or space vector approach.

![PWM implementation techniques](image)

Fig.3. PWM implementation techniques

There are two different PWM control techniques for dual inverter configuration. Decoupled PWM techniques and Coupled PWM techniques. In decoupled PWM technique to generate control signals two sets of independent reference signals are considered for the inverters and these are compared with one common carrier signal. Where as in coupled PWM technique one set of common reference signals are considered for both the inverters and these are compared with common level shifting carrier signals. In this paper mainly focus is given on the decoupled PWM technique.

**A. Generation of modulated signal based on Space vector approach:**

In decoupled PWM technique as both inverters independently controlled, separate modulating or reference signals are generated for both inverters. The shape of reference signals is same for both the inverters. Hence to generate those modulating signals either inverter-I or inverter-II is considered as a single unit.

The circuit model of dual inverter configuration is shown in Fig.2. S11 to S16 are the six power switches for inverter-1 and S21 to S26 are the six power switches for inverter-2 that shape the output, which are controlled by the switching the required switches. In both inverters when an upper switch is ON, i.e., it goes to 1, the corresponding lower switch is OFF, i.e., the corresponding switches go to 0. Therefore, the on and off states of the upper switches S11, S13 and S15 for inverter-I and S21,S23, S25 for inverter-II can be used to determine the output voltage. A total of eight switching states are possible for each inverter (inverter-I and inverter-II). Among these eight switching combinations six are active states and two zero states. These switching combinations can be represented in space vector plane as shown in Fig. 4. Six nonzero vectors (active states or active vectors) (V1 - V6) shape as axes of hexagonal. The angle between any adjacent two nonzero vectors is 60°. Meanwhile, two zero vectors (V7 and V0) are at the origin and apply zero voltage to the load.

![Basic switching vectors and sectors](image)

Fig.4. Basic switching vectors and sectors

SVPWM can be implemented by the following steps:

**Step 1: Determine Vd, Vq, Vref, and angle (α)**

**Step 2: Determine time duration T1, T2, T0**

**Step 3: Determine switching time of each switch**

**Step 1: Determine Vd, Vq, Vref, and angle (α)**

From Fig.4 the Vd, Vq, Vref, and angle (α) can be determined as follows:

\[
V_d = V_a - V_{bn} \cos 60 - V_{cn} \cos 60 = V_a - \frac{1}{2} \sqrt{3} V_{bn} - \frac{1}{2} V_{cn}
\]

\[
V_q = 0 + V_{bn} \cos 30 - V_{cn} \cos 30 = \frac{\sqrt{3}}{2} V_{bn} - \frac{1}{2} V_{cn}
\]

\[
|V_{ref}| = \sqrt{V_d^2 + V_q^2}
\]

\[
\alpha = \tan^{-1} \left( \frac{V_q}{V_d} \right)
\]

**Step 2: Determine time duration T1, T2, T0**

![Reference vector as a combination of adjacent vectors at sector 1.](image)

Fig.5. Reference vector as a combination of adjacent vectors at sector 1.

**Switching time duration at Sector-1**

From Fig. 5 based on volt-sec balance condition T1 and T2 can be derived as

\[
\int_{0}^{T_z} V_{ref} \, dt = \int_{0}^{T_1} V_1 \, dt + \int_{T_1}^{T_2} V_2 \, dt + \int_{T_2}^{T_z} V_0 \, dt = T_z \cdot a \cdot \frac{\sin \left( \frac{\alpha}{2} \right)}{\sin \left( \frac{\pi}{6} \right)}
\]

\[
\Rightarrow T_1 = T_z \cdot a \cdot \frac{\sin \left( \frac{\alpha}{2} \right)}{\sin \left( \frac{\pi}{6} \right)}
\]

\[
\Rightarrow T_2 = T_z \cdot a \cdot \frac{\sin \left( \frac{\alpha}{2} \right)}{\sin \left( \frac{\pi}{2} \right)}
\]

\[
\Rightarrow T_0 = T_z - (T_1 + T_2)
\]

Where \( T_z = \frac{1}{f_z} \) and \( a = \frac{|V_{ref}|}{\frac{\pi}{6} V_{dc}} \)

**Step 3: Determine switching time of each switch**

Actual switching time can be calculated by combining switching times of each switch in all the sectors. As given in Table 2.
The plots of actual switching time for positive group switches are shown in Fig. 6. These actual switching times are nothing but one set of modulating signals. In similar way second set of switching times or modulating signals can be derived for inverter-II. These two sets of modulating signals are compared with carrier signals.

![Figure 6: Plot for switching time for positive group switches](image)

For dual inverter the space vector locations of inverter-I and inverter-II as shown below

![Figure 7: Space vector locations for inverter-I and inverter-II](image)

From the space vector locations given in Fig.7 it is observed that if both inverters are operated with same switching combinations the resultant output voltage will be zero. Hence both inverters should not be operated with same switching states. (i.e. should not be operated in same sectors). But when the inverter-I is operated in sector-I it is possible to operate inverter-II in any other sector. Based on these, different switching combinations are possible for dual inverter configuration as given in Table-3.

<table>
<thead>
<tr>
<th>Sector for inverter-I</th>
<th>Sector for inverter-II</th>
<th>Switching sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>00°-11°-22°-77°</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>00°-13°-22°-77°</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>00°-13°-24°-77°</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>00°-15°-24°-77°</td>
</tr>
<tr>
<td>1</td>
<td>5</td>
<td>00°-15°-26°-77°</td>
</tr>
<tr>
<td>1</td>
<td>6</td>
<td>00°-11°-26°-77°</td>
</tr>
</tbody>
</table>

B. Generation of modulated signal based on Scalar approach (Simplified SVPWM):

The scalar based implementation of the PWM technique provides freedom for the selection of various reference signals. Hence, in order to obtain the reference signal as shown in Fig.6, a zero sequence signal can be added to the old reference signals given in (5).

Consider two sets of reference signals as given in (5) and (6)

\[ V_a = V_m \cos(\omega t) \]
\[ V_b = V_m \cos(\omega t - 2\pi/3) \]  
\[ V_c = V_m \cos(\omega t - 4\pi/3) \]  
\[ V_{aa} = V_m \cos(\omega t - X) \]
\[ V_{bb} = V_m \cos(\omega t - 2\pi/3 - X) \]  
\[ V_{cc} = V_m \cos(\omega t - 4\pi/3 - X) \]  

The mathematical expression for zero sequence signals can be considered as given in (7)

\[ V_{zs} = \frac{V_{dc}}{2} (2a_{0-1} - a_0 V_{max} + (a_0-1)V_{min}) \]  

Where

\[ V_{max} \] and \[ V_{min} \] are maximum and minimum corresponding reference signals given in (5) and (6).

It is possible to operate inverter-I and inverter-II with different switching combinations by changing the phase sequence of second set reference signals as given in Table-4.

<table>
<thead>
<tr>
<th>X(deg)</th>
<th>Sector for inverter-I</th>
<th>Sector for inverter-II</th>
<th>Switching sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>1</td>
<td>1</td>
<td>00°-11°-22°-77°</td>
</tr>
<tr>
<td>60°</td>
<td>1</td>
<td>2</td>
<td>00°-13°-22°-77°</td>
</tr>
</tbody>
</table>
By adding the zero sequence component with the old reference signals we get the new reference signals \((V_a^*, V_b^*, V_c^*)\), is given by
\[
V_i^* = V_i + V_{zs} \quad (8)
\]
\(i = a, b, c\)

The block diagram for simplified SVPWM algorithm for both the inverters as shown in Fig.8.

### IV. SIMULATION RESULTS

To validate the proposed method, simulation studies have been carried out by using Mat lab/Simlink and the induction motor is operated with the \(V/f\) control scheme. The motor parameters are as follows: Stator resistance \(R_s = 1.57\) ohm, rotor resistance \(R_r = 1.21\) ohm, stator inductance \(L_s = 0.17\) H, rotor inductance \(L_r = 0.17\) H, mutual inductance \(L_m = 0.165\) H. The simulation results of the OEWIM drive operated in isolated mode for the phase shift of 60° to 360° at the modulation index of 0.96 are shown in Figure. [9] – Figure. [14].

For the higher modulation index the waveforms are more accurate compared to lower modulation index. From Fig.9, the phase shift between the waveforms is 60°. Which means that modulating signal and pulse pattern for inverter-II will shift 60° compared to inverter-I.
Modulated signal for inv-I
Pulse pattern for inv-I
Modulated signal for inv-II
Pulse pattern for inv-II
Effective pole voltage
Effective phase voltage
Common mode voltage
Steady state currents
Fig. 11. Waveforms for 180°
Phase shift
Fig. 11. Waveforms for 240°
Phase shift
It is possible, a conventional 3-level voltage waveform can be synthesized by using the cascaded connection of the two 2-level inverters. The conventional vector control algorithm gives large ripple and varying switching frequency operation. To overcome these problems, this paper presents a simplified SVPWM algorithm, by using the zero sequence component concepts. The simplified SVPWM algorithm does not use the time-consuming process of sector and angle information. Thus, the proposed algorithm reduces the complexity involved in the conventional SVPWM algorithm and also improves the drive operation. Moreover, the system uses less number of power devices compare to conventional 3-level multi-inverter and it uses half the DC bus voltage. The simulation results show the validity of the proposed algorithm. The performance of the simplified SVPWM algorithm also more compare to conventional SVPWM.

**REFERENCES**


