A Matlab Simulation and Comparison of PWM Strategies as Applied to Variable Frequency Induction Motor Drive

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Abstract - A Matlab simulation and comparison of the performance of a variable frequency induction motor drive for the basic Sinusoidal Pulse Width Modulation (SPWM), Modified Sinusoidal Pulse Width Modulation (MSPWM), Selective Harmonic Injection Pulse Width Modulation (SHIPWM) and Selective Harmonic Elimination Pulse Width Modulation (SHEPWM) is presented. The complete system taken for simulation is a three-phase, AC-DC-AC voltage source inverter based variable frequency squirrel cage induction motor drive employing PWM techniques for inverter control. All the components of the system are modeled as functionally decoupled Matlab-Simulink blocks, so that any modifications for a new configuration of the system can be readily incorporated.

I. INTRODUCTION

The field of modeling and simulation of industrial drives has acquired much importance in recent years, because of the valuable predictions given and cost effective experimentation admitted. Naturally modeling of variable frequency induction motor drives becomes a necessity and a good number of literatures have been reported on the same.

The principle behind the simulation of symmetrical induction machinery is reported by P.C.Krause and H.C.Thomas in 1965. They discussed the various reference frames for modeling the induction motor dynamics. Analysis and simplified representation of a Rectifier-Inverter induction motor drive is first presented by P.C.Krause and T.A.Lipo in 1969. The comparison of computer and test results of a static AC drive system is reported by P.C.Krause & L.T.Woloszky. However a systematic computer aided analysis and design approach for static voltage source inverter using switching function concept was reported by Phoivas.D.Ziogas etal in 1985. This paper heralded a new way of simulating a drive system functionally. A simplified functional simulation model for a variable frequency SPWM drive system using Matlab simulink was reported by Byoung-Kuk Lee and Mehradad Ehsani in 2001. This paper claimed about the simplification in the static power circuits modeling and the solution for the convergence and long run time problems faced with the Pspice counterpart. While this paper demonstrated only the Sinusoidal Pulse width modulation as applied to the inverters, need arises to simulate other PWM strategies using the same technique.


The present paper aims at simulating the complete performance of the variable frequency induction motor drive employing four PWM techniques viz, the basic SPWM, MSPWM, SHIPWM, SHEPWM and operating on a constant torque load. The Matlab simulink is used as the simulation tool where each of the system components are modeled as separate blocks thus imparting modularity to the model.

II. PROBLEM FORMULATION

While developing a variable frequency induction motor drive, problems pertaining to design and troubleshooting of the system were encountered. It also became necessary to assess the performance of the drive when subjected to any given PWM strategy. Hence it was decided to simulate the complete model functionally. The system considered for simulation consists of

- The 3-phase squirrel cage induction motor, which drives the mechanical load.
- The three phase transistorized bridge inverter to convert the DC to variable voltage, variable frequency AC to be fed to the induction motor.
- A PWM controller for controlling the voltage and the frequency of the inverter output.
- Uncontrolled diode bridge rectifier with filter to convert the three-phase AC to an almost perfect DC to be supplied for the inverter.

III. THE SIMULINK MODEL

The Matlab Simulink was chosen to implement the block diagram model described above because of the functional decoupling of blocks that is possible with Simulink. The detailed explanation of deducing the Simulink model from the above block diagram is described below.

A. The Induction Motor Model

The synchronously rotating reference frame state model of the induction machine’s electromechanical dynamics [8] is
given by the matrix equation (1).

\[
\begin{bmatrix}
- \frac{2 \pi}{P} & V_{dr} \\
\end{bmatrix}
\begin{bmatrix}
L_s & 0 & 0 & 0 \\
0 & L_m & 0 & 0 \\
0 & 0 & L_m & 0 \\
0 & 0 & 0 & L_s \\
\end{bmatrix}
\begin{bmatrix}
-i_{ds} \\
-i_{qs} \\
i_{fr} \\
\end{bmatrix}
= \begin{bmatrix}
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0 \\
\end{bmatrix}
\begin{bmatrix}
-X_r & -X_s & 0 & -X_m \\
X_r & -X_s & 0 & -X_m \\
0 & -X_m & -R_r & -S_X_r \\
0 & -X_m & -S_X_r & -R_r \\
\end{bmatrix}
\begin{bmatrix}
i_{ds} \\
i_{qs} \\
i_{fr} \\
\end{bmatrix}
\begin{bmatrix}
R_s & R_r & 0 & 0 \\
0 & 0 & -3P & 0 \\
0 & 0 & 0 & 2P \\
-\frac{2}{2} L_m I_{dr} & \frac{3}{2} P I_{dr} & 0 & 0 & +2F \\
0 & 0 & 0 & 0 & 0 \\
\end{bmatrix}
\begin{bmatrix}
V_{ds} \\
V_{qs} \\
V_{fr} \\
0 \\
\end{bmatrix}
\]

(1)

Where
\[\begin{align*}
V_{ds} &= \text{Direct axis stator voltage} \\
V_{qr} &= \text{Quadrature axis rotor voltage} \\
L_s &= \text{Stator inductance} \\
L_m &= \text{Magnetizing inductance} \\
V_{fr} &= \text{Direct axis rotor voltage} \\
S &= \text{Operating slip} \\
o_{eo} &= \text{Synchronous speed elec. rad/sec} \\
o_{ex} &= \text{Rotor speed elec. rad/sec} \\
R_s &= \text{Stator resistance} \\
R_r &= \text{Rotor resistance referred to stator} \\
J &= \text{Motor moment of inertia} \\
P &= \text{No. of poles} \\
i_{ds} &= \text{Direct axis stator current} \\
i_{fr} &= \text{Direct axis rotor current} \\
i_{qr} &= \text{Quadrature axis rotor current} \\
S &= \text{Friction factor} \\
i_{qs} &= \text{Quadrature axis stator current} \\
\alpha_1 &= 10.55 \text{ degrees}, \alpha_2 = 16.09 \text{ degrees}, \alpha_3 = 30.91 \text{ degrees}, \alpha_4 = 32.87 \text{ degrees} \\
\end{align*}\]

With the given initial conditions and the input values the above model can be easily solved by the Simulink to obtain the dynamic electromechanical responses.

### B. The Inverter Model

If the switching functions of a standard three-phase bridge inverter's three arms are named as SF\(_a\), SF\(_b\) and SF\(_c\) respectively, then the voltages \(V_a, V_b, V_c\) with respect to the DC midpoint is given by [5] as revealed by (2).

\[\begin{align*}
V_{ao} &= \frac{V_d}{2} \cdot SF_a \\
V_{bo} &= \frac{V_d}{2} \cdot SF_b \\
V_{co} &= \frac{V_d}{2} \cdot SF_c
\end{align*}\]

where \(SF_a = PWM_1 - PWM_4\), \(SF_b = PWM_2 - PWM_6\), \(SF_c = PWM_3 - PWM_5\)

Where the subscript denotes the PWM control voltage for the corresponding switch.

The inverter is modeled as a single block in Simulink with switching functions and the DC - link voltage as the input and the corresponding inverter line-to-line voltages as the output.

#### C. The Inverter Control Model

Presently four PWM strategies are simulated, so that the load performance for each one of the techniques could be studied effectively. They are described as follows.

#### i. The Sinusoidal Pulse Width Modulation (SPWM)

This type of modulation is implemented by comparing a sinusoidal modulating signal \(v_m(\omega t) = V_m \sin \omega t\) with a triangular carrier signal of maximum height \(V_c\) [8]. The natural intersection of \(v_m(\omega t)\) and \(v_c(\omega t)\) determine both the onset and duration of the modulated pulses.

#### ii. The Modified Sinusoidal Pulse Width Modulation (MSPWM)

The SPWM technique can be modified so that the carrier wave is applied during the first and last 60 degree intervals per half cycle (e.g., 0 to 60 degrees and 120 to 180 degrees). The fundamental component is increased and its harmonic characteristics are improved by this technique.

#### iii. The Selective Harmonic Injection Pulse Width Modulation (SHIPWM)

The modulating signal is generated by injecting selected harmonics to the sine wave (Rashid 1998). For a third harmonic injection, the reference wave, \(V_r\) is given by

\[V_r = 1.15 \sin \omega t + 0.19 \sin 3\omega t\]  

(3)

The fundamental component is approximately 15% more than that of a normal sinusoidal PWM.

#### iv. The Selective Harmonic Elimination Pulse Width Modulation (SHEPWM)

The switching angles of a PWM waveform can be calculated in order that waveform possesses a fundamental component of a desired magnitude while, simultaneously, optimizing a certain performance criterion.

It is logical to suppress the 5,7,11 and 13\(^{th}\) order harmonics, which results in \(\alpha_1 = 10.55 \text{ degrees}, \alpha_2 = 16.09 \text{ degrees}, \alpha_3 = 30.91 \text{ degrees}, \alpha_4 = 32.87 \text{ degrees} (Sheperd 1998)\).

All the PWM strategies are implemented as a block with the set voltage and frequency (required in the output of the inverter) as the input and all the three switching functions as output.

The set voltage is determined from the set-frequency via a V / F controller which generates the voltage command from the frequency command.
D. The Rectifier and filter model

The circuit of the three-phase, six-pulse full bridge diode rectifier with the filter capacitor of the DC side of the rectifier as given by [11] is modeled in Simulink as a single block with the frequency as input and filtered DC voltage as the output. This block in turn consists of two blocks, one generating the switching functions and the other generating the DC output voltage.

The capacitor filter is modeled as a transfer function with gain

\[
\text{Capacitor TF} = \frac{1}{0.35S+1} \quad (6)
\]

The Coefficients of the denominator is chosen so as to give the optimal settling time and the ripple factor for the pulsating DC output.

IV. PERFORMANCE STUDY

The simulation results lay a firm platform for the study of the system performance under various PWM strategies. The main simulation results worked out are

1. The line Voltage output of the inverter Vs Time for Phase A
2. Stator line Current Vs Time for Phase A
3. RMS value of the fundamental component of inverter output voltage for Phase A at steady state
4. Total Harmonic Distortion value of inverter output voltage for Phase A at steady state
5. RMS value of the fundamental component of stator line current for Phase A at steady state
6. Total Harmonic Distortion value of stator line current for Phase A at steady state
7. Displacement Power Factor and Power Factor of the induction machine

All these performance parameters of the system are studied for the SPWM scheme at rated operating conditions and compared with other PWM strategies. All the aforesaid results are presented below.

A. For SPWM scheme at rated frequency 50 Hz

B. For SHPWM scheme at rated frequency 50 Hz

C. For MSPWM scheme at rated frequency 50 Hz

D. For SHEPWM scheme at rated frequency 50 Hz

Fig. 1 Voltage and Current Vs Time at steady state

Fig. 2 Voltage and Current Vs Time at steady state

Fig. 3 Voltage and Current Vs Time for two cycles of the fundamental frequency at steady state

Fig. 4 Voltage and Current Vs Time for one cycle of the fundamental frequency at steady state
TABLE I
PERFORMANCE COMPARISON AT RATED FREQUENCY

<table>
<thead>
<tr>
<th>S. No</th>
<th>Performance Specification</th>
<th>S PWM</th>
<th>SHI PWM</th>
<th>SHE PWM</th>
<th>MS PWM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$V_{ab}$ – Fundamental RMS (volts)</td>
<td>361</td>
<td>411.5</td>
<td>427</td>
<td>376</td>
</tr>
<tr>
<td>2</td>
<td>$V_{ab}$ - THD</td>
<td>0.7</td>
<td>0.5</td>
<td>0.55</td>
<td>0.33</td>
</tr>
<tr>
<td>3</td>
<td>$I_{ab}$ – Fundamental RMS (amps)</td>
<td>4.56</td>
<td>4.56</td>
<td>4.56</td>
<td>4.6</td>
</tr>
<tr>
<td>4</td>
<td>$I_{ab}$ - THD</td>
<td>0.09</td>
<td>0.08</td>
<td>0.135</td>
<td>0.05</td>
</tr>
<tr>
<td>5</td>
<td>Motor DPF</td>
<td>0.97</td>
<td>0.94</td>
<td>0.93</td>
<td>0.96</td>
</tr>
<tr>
<td>6</td>
<td>Motor PF</td>
<td>0.96</td>
<td>0.93</td>
<td>0.92</td>
<td>0.96</td>
</tr>
</tbody>
</table>

V. CONCLUSION

In this paper a complete simulation of a variable frequency induction motor drive under four existing PWM strategies are presented. These results find potential application in drive industries where it can be used to predict the drive behaviour in field test with the appropriate choice of PWM technique. Also the model can be easily modified suiting to any motor and load parameters or any new control technique because any modification requires the replacement of corresponding blocks only. The future work pertaining to inclusion of saturation effects, space harmonics, unbalanced operating conditions, incorporating the real power switches model also could be done.

VI. REFERENCES