Improving The Performance of the DTC Saturated Model of the Induction Motor in Case of Two Level and Three Level VSI using GA and PSO algorithms

Mohamed .M. Ismail

Abstract—The problem of controlling the p-model induction motor with magnetic saturation is considered in this proposed research. Direct Torque Control (DTC) of induction motor has been developed since three decades. Furthermore many techniques have been proposed to improve the performance of the induction machines that using the DTC drives in industry. However, all the previous models are based on the linear model of the machine for approximation. However linear model is not the exact model and there is no guarantee that the induction motor will work outside the saturation region of the flux, especially in large rating of induction machines. In this paper, two types of voltage source inverters are used in the simulations and the performance of the induction machine response in the two cases are studied using MATLAB SIMULINK, one is based on torque control while the other is based on speed control technique, GA and PSO are used for improvement of the performance of the speed control for the two and three level inverters.

Index Terms— Direct Torque Control (DTC), Magnetically Saturated Induction Motors, Two and Three Level Inverter, GA and PSO.

I. INTRODUCTION

In the middle of 1980 direct torque control was developed by Takahashi and Depenbrock [1] as an alternative to field oriented control to overcome its problems [2]. Many techniques are used for implementation of DTC as in [3] and [4]. The DTC model used for simulation is illustrated using Matlab/Simulink for linear model of induction motor in [5]. In a Direct Torque Controlled (DTC) induction motor drive supplied by a voltage source inverter, the scheme as the name indicates, it is possible to control directly the stator flux linkage (or rotor flux or the magnetization flux) and the electromagnetic torque by the selection of an optimum inverter voltage vector through a pre designed inverter gate pulses look-up tables. The stator flux and electromagnetic torque are controlled in a closed loop by using flux and torque hysteresis comparators [6].

Then, the selection of the optimum voltage vector of a voltage source inverter is to restrict the flux and torque errors within their respective flux and torque hysteresis comparators bands. To obtain fast torque response. Many researches have developed different types of inverters [7-17], the two level and the three level inverters are usually used but none of the previous work explain the difference between the two techniques. The common assumption made in the development of these control laws is the linearity of the magnetic circuit of the machine. This assumption is usually justified by including the flux magnitude in the outputs to be regulated by the controller and keeping this magnitude regulated at a value far from the saturation region as presented in [18-19]. However there are no guarantees that the flux magnitude remains in the linear magnetic region during machine transients. Moreover, in many variable torque applications, it is desirable to operate the machine in the magnetic saturation region to allow the machine to develop higher torque as explained in [20-21]. Saturation effects are also known to be pronounced in drives operating in the field weakening region, or in drives that operate with optimally varying flux levels in a specified sense [22]. However, the operation of the motor at various magnetization levels makes the nominal inductance a bad approximation. Recently, researchers have been attracted to induction motor control with magnetic saturation. Feedback input-output linearization schemes for induction motors with magnetic saturation were proposed in a fixed stator frame [23] and in a synchronously rotating frame [24]. In [23] the control signal is the stator voltage, while in [24] it is the stator current. Both articles treat the T-model of an induction motor. Unfortunately, due to the complicated nature of the T-model, drastic simplifications are required to facilitate the use of this model in nonlinear control synthesis. The major drawback in [23] (also present in the optimal flux reference selection of [24]) is the assumption that the stator and rotor leakage parameters $\sigma_s$ and $\sigma_r$, as defined in [25], are equal and constant. This assumption has the indirect effect of neglecting any cross-saturation effect that might appear in the dynamics of the motor. On the other hand, the model in [24] is obtained by firstly simplifying the motor equations assuming a linear magnetic circuit and then including a mutual inductance that varies with mutual current. This approach does not include derivatives of the saturation function that should appear in a complete model [26]. A similar modeling approach can also be found in [27] for incorporating magnetic saturation in the passivity-based control design methodology of [28]. It is worth pointing out
that, in [27] similar to [24], where stator currents are used as the control signal. All the work presented so far is based on a T-Model of the induction motor, contrary to the π-Model proposed in [20]. The π-Model differs from the conventional T-Model in that it is more closely related to the physical structure of the machine. Where its derivation is primarily based on the stator-tooth pair magnetic circuit. Even though the work in [20] is based on a wound rotor motor, it is shown in the same paper how the modeling approach can be applied to a squirrel cage motor. It is not difficult to show that both models are equivalent when a linear magnetic circuit is assumed. This equivalence does not hold when main flux saturation is included. In the published work [52], it was shown that considering magnetic saturation explicitly in nonlinear control synthesis is of foremost importance especially when the machine is voltage actuated. Because the π-model was experimentally found in [20] to be better suited to capture the nonlinear magnetic effects. In this proposed research, the induction motor with magnetic saturation is considered with the DTC model. This consideration assumes no simplifying assumptions are used in the development of the model. This paper is completely different from the previous work given in [29], such that the saturated π-model of the induction motor is used. The simulations are performed using MATLAB for clarifying the performance of the saturated model of induction motor in case of the two level and three level VSI DTC , in addition to the motor performance in case of torque control and speed control techniques. We are using intelligent artificial techniques for PI auto tuning parameters during the motor operation, while many researches are done before in the field of adaptation of PID parameters as in [30-36].

II. INDUCTION MOTOR MODEL

The main results of induction motor control under magnetic saturation in this article, will be based on the π-model. The π-model for the complete motor, at zero speed, is shown in Figure (1). The two phase electrical equations for an induction machine in an arbitrary frame rotating with speed (\(\omega_0\)) are given by:

\[
\begin{align*}
V_s &= R_s I_s + \frac{d\psi_s}{dt} + \omega_0 J_2 \psi_s \\
0 &= R_r I_r + \frac{d\psi_r}{dt} + (\omega_0 - \omega) J_2 \psi_r
\end{align*}
\]

(1)

Such that \(V_s\) is the stator phase voltage vector, \(I_s\) is the stator phase current vector, \(I_r\) is the rotor phase current vector, \(p\) is the number of pole pairs, \(\omega\) is the rotor speed, \(R_s\) is the stator phase resistance, \(R_r\) is the rotor phase resistance, \(\psi_s\) and \(\psi_r\) are the stator and rotor flux linkage vector s respectively.

Equation (1) holds whether the induction motor magnetic circuit is considered linear or saturated and \(J_2\) is the \(2 \times 2\) rotating matrix defined by:

\[
J_2 = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}
\]

(2)

The mechanical equation can be expressed as:

\[
J \frac{d\omega}{dt} + b \omega = T - T_L
\]

(3)

Where \(J\) is the motor inertia, \(b\) is the viscous damping, \(T_L\) is the load torque and \(T\) is the generated torque. The relationship between the currents and the fluxes for the π model at d-q frame rotating with speed (\(\omega_0\)) are given by:

\[
\begin{bmatrix} I_s \\ I_r \end{bmatrix} = \begin{bmatrix} G_s & \psi_s \\ G_r & \psi_r \end{bmatrix} \begin{bmatrix} \psi_s \psi_r \end{bmatrix} + \begin{bmatrix} g_{s2} & -g_{s2} \\ -g_{r2} & g_{r2} \end{bmatrix} \begin{bmatrix} \psi_s \psi_r \end{bmatrix}
\]

(4)

Where \(g_l\) is defined as:

\[
g_l = \frac{1}{L_l}
\]

(5)

where \(G_s\) and \(G_r\) are the stator and rotor vector-valued nonlinear functions and defined as:

\[
G_s(x) = G_s \left[ \begin{bmatrix} \psi_s \psi_s \end{bmatrix} \right] = \begin{bmatrix} 1 \psi_s \psi_s \end{bmatrix} = I_m \psi_s \psi_s
\]

(6)

Where; \(I_m\) and \(\Psi_m\) are the mutual current and flux vector, respectively, and subscript (x) can be (s) for stator and (r) for rotor. The relationship between the currents and the fluxes for the π model can be compactly written as:

\[
\begin{bmatrix} I_s \\ I_r \end{bmatrix} = \begin{bmatrix} g_s & \psi_s \\ g_r & \psi_r \end{bmatrix} \begin{bmatrix} \psi_s \psi_s \end{bmatrix} + \begin{bmatrix} g_{s2} & -g_{s2} \\ -g_{r2} & g_{r2} \end{bmatrix} \begin{bmatrix} \psi_s \psi_r \end{bmatrix}
\]

(7)

Where; \(I_2\) is the \(2 \times 2\) identity matrix, \(g_l\) is defined as the reciprocal of the leakage inductance(\(L_l\)), \(g_s\) and \(g_r\) are the stator and rotor vector-valued nonlinear saturation functions. The scalar saturation functions \(g_s(x)\) and \(g_r(x)\) have to be identified experimentally for each motor as shown in the next section.
Finally, the generated torque (T) and p is the poles number is given by:

\[ T = P J_2(\psi_s^*) \]

(8)

III. TWO LEVEL DTC VSI MODEL

A voltage source inverter (VSI) is used to convert a fixed DC voltage to three phase AC voltage. The circuit diagram for a two-level voltage source inverter for power applications is shown in Fig. 2.

![Two Level Inverter Diagram](image)

The inverter is composed of six groups of active switches, S1 to S6. Depending on the DC operating voltage of the inverter, each switch is an IGBT switching device. The operating status of the switches in the two-level inverter in Fig. 2 can be represented by switching states. As indicated in Table 1, switching state ‘1’ denotes that the upper switch in an inverter leg is on and the inverter terminal voltage \( V_{an}, V_{bn}, V_{cn} \) is positive (+Vd) while ‘0’ indicates that the inverter terminal voltage is zero due to the conduction of the lower switch. There are eight possible combinations of switching states in the two-level inverter as listed in Table 2.

<table>
<thead>
<tr>
<th>Switching State</th>
<th>Leg A</th>
<th>Leg B</th>
<th>Leg C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>On</td>
<td>Off</td>
<td>Vd</td>
</tr>
<tr>
<td>0</td>
<td>Off</td>
<td>On</td>
<td>0</td>
</tr>
</tbody>
</table>

![Switching State Table](image)

Table 1 Definition of Switching States

The representation of rotating vector in complex plane is shown in Fig 3.

\[ \bar{V}_{ref} = V_{\alpha} + jV_{\beta} = \frac{2}{3}(V_{a} + aV_{b} + a^{-2}V_{c}) \]

(9)

Such that

\[ a = e^{j2\pi/3} \]

\[ |\bar{V}_{ref}| = \sqrt{V_{\alpha}^2 + V_{\beta}^2} \quad \alpha = \tan^{-1}\left(\frac{V_{\beta}}{V_{\alpha}}\right) \]

\[ V_{\alpha} + jV_{\beta} = \frac{2}{3}\left(V_a + e^{j\frac{2\pi}{3}}V_b + e^{-j\frac{2\pi}{3}}V_c\right) \]

(10)

Equating real and imaginary parts:
IV. THREE LEVEL DTC VSI MODEL

The circuit diagram for a three-level voltage source inverter for power applications is shown in Fig. 4.

![Image of a three-level inverter circuit diagram](image)

Figure (4): Three Level Inverter

Switching states that are shown in Fig. 4 can represent the operating status of the switches in the three-level inverter. When switching state is ‘1’, it is indicated that upper two switches in leg A connected and the inverter terminal voltage \(V_{az}\), which means the voltage for terminal A with respect to the neutral point \(Z\), is \(+E\), whereas ‘-1’ denotes that the lower two switches are on, which means \(V_{az} = -E\). When switching state ‘0’, it indicates that the inner two switches S2 and S3 are connected and \(V_{az} = 0\) through the clamping diode, depending on the direction of the load current \(I_a\). Table 3 shows switching status for leg A. Leg B and leg C have the same concept.

<table>
<thead>
<tr>
<th>Switching State</th>
<th>Device Switching Status (Phase A)</th>
<th>Inverter Terminal Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>On</td>
<td>(E)</td>
</tr>
<tr>
<td>S2</td>
<td>On</td>
<td>(E)</td>
</tr>
<tr>
<td>S3</td>
<td>Off</td>
<td>(0)</td>
</tr>
<tr>
<td>S4</td>
<td>Off</td>
<td>(-E)</td>
</tr>
</tbody>
</table>

Switching states in the three-level inverter as listed in Table 4

![Image of a space vector diagram](image)

Figure 5: Space vector diagram of the three-level inverter

![Image of sectors and regions](image)

Figure 6: Division of sectors and regions for three-level inverter

Table 4 Switching States, and On-State Switches for three level inverter

<table>
<thead>
<tr>
<th>Space Vector</th>
<th>Switching State</th>
<th>Vector Classification</th>
<th>Vector Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>(V_a)</td>
<td>[1 1 1]</td>
<td>[1 -1 -1]</td>
<td>[0 0 0]</td>
</tr>
<tr>
<td>(V_1)</td>
<td></td>
<td></td>
<td>(\frac{1}{3}V_a)</td>
</tr>
<tr>
<td>(V_2)</td>
<td></td>
<td></td>
<td>(\frac{1}{3}V_a)</td>
</tr>
<tr>
<td>(V_3)</td>
<td></td>
<td></td>
<td>(\frac{1}{3}V_a)</td>
</tr>
<tr>
<td>(V_4)</td>
<td></td>
<td></td>
<td>(\frac{1}{3}V_a)</td>
</tr>
<tr>
<td>(V_5)</td>
<td></td>
<td></td>
<td>(\frac{1}{3}V_a)</td>
</tr>
<tr>
<td>(V_6)</td>
<td></td>
<td></td>
<td>(\frac{1}{3}V_a)</td>
</tr>
<tr>
<td>(V_7)</td>
<td></td>
<td></td>
<td>(\frac{1}{3}V_a)</td>
</tr>
<tr>
<td>(V_8)</td>
<td></td>
<td></td>
<td>(\frac{1}{3}V_a)</td>
</tr>
<tr>
<td>(V_9)</td>
<td></td>
<td></td>
<td>(\frac{1}{3}V_a)</td>
</tr>
<tr>
<td>(V_{10})</td>
<td></td>
<td></td>
<td>(\frac{1}{3}V_a)</td>
</tr>
<tr>
<td>(V_{11})</td>
<td></td>
<td></td>
<td>(\frac{1}{3}V_a)</td>
</tr>
<tr>
<td>(V_{12})</td>
<td></td>
<td></td>
<td>(\frac{1}{3}V_a)</td>
</tr>
<tr>
<td>(V_{13})</td>
<td></td>
<td></td>
<td>(\frac{1}{3}V_a)</td>
</tr>
<tr>
<td>(V_{14})</td>
<td></td>
<td></td>
<td>(\frac{1}{3}V_a)</td>
</tr>
</tbody>
</table>

The representation of rotating vector in complex plane is shown in Fig 5 and 6.
V. DTC TORQUE CONTROL AND SPEED CONTROL

The block diagram of the DTC for torque control technique can be simply represented in figure 7, while by adding PI controller as shown in figure 8, The new technique become speed control DTC.

VI. ADAPTATION USING GENETIC ALGORITHM

Genetic Algorithms (GA) are a stochastic global search method that mimics the process of natural evolution, due to space limitations, The summary of the process will be described in figure 9, more details can be found in [32-35]

VII. ADAPTATION USING PSO ALGORITHM

Optimization techniques using analogy of swarming principle have been adopted to solve a variety of engineering problems in the past decade, due to space limitations, the summary of the process will be described in figure 10 More details can be obtained in [37-40]

VIII. SIMULATIONS

The motor parameters that will be used in matlab simulink simulations are included in table 5

Table 5: Motor Parameters

<table>
<thead>
<tr>
<th>parameters</th>
<th>( \pi )- model</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_s )</td>
<td>( s )</td>
<td>( \Omega )</td>
</tr>
<tr>
<td>( R_r )</td>
<td>( s )</td>
<td>( \Omega )</td>
</tr>
<tr>
<td>( L_{ds} )</td>
<td>N/A</td>
<td>( H )</td>
</tr>
<tr>
<td>( L_{qr} )</td>
<td>N/A</td>
<td>( H )</td>
</tr>
<tr>
<td>( L_q )</td>
<td>0.062</td>
<td>( H )</td>
</tr>
<tr>
<td>( J )</td>
<td>0.06</td>
<td>Kgm ( ^2 )</td>
</tr>
<tr>
<td>( b )</td>
<td>0.04</td>
<td>Nm/( \text{rad/s} )</td>
</tr>
</tbody>
</table>

a- Simulations for torque control

Simulations are performed for the two and three level inverter, the torque and flux reference are varied during the operation. The motor performance are obtained in figures 11 to 14

Figure 7 DTC Torque Control

Figure 8 DTC Speed Control

Figure 9 Genetic Algorithm Process Flow chart

Figure 10 PSO Process Flow chart

Figure 11 Motor induced torque for 2 and 3 level VSI in Torque control operation
Simulations for speed control

Simulations are performed for the two and three level inverter, the speed and flux reference are varied during the operation, the controller PI gains are tuned by using zigeler Nichols method [41] ( $K_p = 34.345$ and $K_i = 2.567$ ) . The motor performance are obtained in figures 15 to 18.

From the simulation results in the two cases of torque control and speed control, the motor performance in the three level inverter is more better than in the two level inverter such that...
the torque ripple in the three level inverter is decreased in both simulations.

c- Simulations in case of speed control by using GA and PSO for PI parameters tuning

Repeating the above simulation but by using GA and PSO for PI parameters tuning instead of zigeler Nichols method

In this paper, we are defining the parameters to be used in the GA optimization as followings: sys_overshoot=max(yout)-1 , alpha=10;beta=10. The fitness function (to be minimized) is defined as 
\[ F=(de/dt)*beta+sys_overshoot*alpha \]
, The yout is the speed , e is the speed error and alpha and beta are constants the no of variables is two (Kp , KI) , the population type is double vector , population size is 30 , the initial range of variable is [0.5 0.5] For the reproduction , the elite count is 2 and the crossover friction is 0.8 , the mutation function is Gaussian , the crossover function is scattered , the stopping rules is the no of generation is 100 , and the stall time limit is 300 sec,. while the parameters to be used in the PSO optimization are selected as followings: The fitness function is the same as in GA , There will be two variables (r1,r2) with two constants c1 = c2 = 0.8 , the weighting constant (w = 0.9) and the size of swarm ( number of birds) N = 50 , max no of bird step is 30 , the motor speed response is indicated in figures 19 to 22.

From simulation results , we find that using GA for optimal PI tuning parameters give better performance for two and three level inverters than PSO technique.

**IX. Conclusion**

In this paper, we are studying the saturated model of the induction motor performance in case of the two level and three level VSI DTC for torque and speed control. The performance of the saturated model of induction motor in case of speed control DTC is improved by using GA and PSO, simulations are performed using matlab to demonstrate the validation of the proposed techniques. From the simulation, we can find that GA technique give better performance than PSO.

**REFERENCES**
