Abstract—This paper proposes a delay time compensation method in the model predictive control (MPC) of induction motor (IM) at high and low speed considering the selection of optimum switching vector to actuate the three-phase voltage source inverter (VSI). The proposed control method compensates the delay time to improve the performance of the system, and consequently maintain the accurate tracking of the references at different speed regions. The control scheme utilizes the discrete nature of the system, and uses the possible switching vectors of the converter in an intuitive manner. Therefore, based on minimum quality function the optimum switching vector is selected for the next sampling time actuation of the power converter. The control scheme is validated through the MATLAB simulation and experimental validation in DS1104 R&D Controller Platform. The simulation and experimental results prove the feasibility of the proposed method with encouraging performance.

Keywords— Predictive Control; Power Converter; Delay Time Compensation; Induction Motor; Torque & Flux.

I. INTRODUCTION

AC machine drives are mostly important in the industrial applications. To control the electrical drives, two types of control methods were widely used during the last two decades in the industries, such as; direct torque control (DTC) [1], [2] and field oriented control (FOC). The losses associated with the DTC can be controlled with proper utilization of space vector modulation, and imposing the predictive torque control (PTC) algorithm [3]. As the predictive control method is simple and easy to implement due to the outstanding development of the digital signal processor, this control method has been earned a great concern to research community. However, this predictive control can be applied to power electronic converter, because this control can utilize the discrete nature of power converter to predict the future behavior of the system.

Recently, many works have been investigated efficiently with the predictive control algorithm which have been proved the robustness and feasibility of the predictive control method for power converter [4].

Therefore, a predictive current control fed by voltage source inverter [5]; predictive torque and flux control of IM fed by indirect matrix converter (IMC) with unity power factor control at the input side [3]; unity power factor control at the grid side of an active front end rectifier [6], [7]; multilevel inverter fed induction motor predictive control [8]; direct matrix converter (DMC) fed predictive torque control of IM with reactive power compensation [9]; predictive current control of a three-phase four-leg inverter [10]; predictive control of bidirectional AC-DC converter [11]; torque ripple reduction of IM with predictive direct torque control method [12], and a weighting factor optimization method in the predictive control algorithm for reduction of torque ripple [13], [14] have been investigated in the recent decades. A complete review for the improvement of input current as well as total harmonic distortion (THD) analysis at the input and output side of the IMC with predictive control algorithm was investigated in [15]. Also, a comprehensive review has been presented to summarize the model predictive control (MPC) method applied to power electronics application in [16], and described the applications of MPC method on four different power electronics converters and drives.

The experimental verification is associated with a delay time of microprocessors, which deteriorates the system performance. Therefore, this paper proposes a delay time compensation method in the predictive control algorithm to increase the system performance.

This paper is organized in the following manner: the second section describes the modeling of the induction motor; the third section summarizes the proposed delay time compensated predictive control method with subsections: first order approximations for predictive variables, the importance of delay time compensations, consideration of long prediction horizons for determination of the predicted variables in the second next (k+2) sampling time instant, an
overall quality function of the MPC method, and a comprehensive predictive control scheme. In the fourth section, the simulation and experimental results are discussed to prove the feasibility of the proposed method. The last section is concluded with a comprehensive conclusion.

II. MODELING OF INDUCTION MOTOR

The power converter topology fed by induction motor (IM) is presented in Fig. 1. The three-phase system \((y_a, y_b, \text{and } y_c)\) can be represented as a two dimensional complex space vector (SV) as below:

\[
y = y_a + jy_b
\]

where, \(y_a = \frac{1}{3}(2y_a - y_b - y_c)\); \(y_b = \frac{1}{\sqrt{3}}(y_b - y_c)\) (2)

In Eq. 2, \(\alpha/\beta\)-reference frame is considered as the stationary reference frame for expected space vector. The model of the IM referred to stator is obtained as described in [17]. The fixed coordinate stator and rotor voltage equations are presented as,

\[
v_s = R_s i_s + L_s \psi_s
\]

\[
v_r = R_r i_r + L_r \psi_r - j\omega \psi_s
\]

where \(i_s\), stator current; \(i_r\), rotor current; \(R_s\), stator resistance; \(R_r\), rotor resistance; \(p\), number of pole pairs, and \(\omega\), rotor angular frequency.

The stator flux and rotor flux can be presented as below:

\[
\psi_s = L_s i_s + L_{sd} i_d, \quad \psi_r = L_r i_r + L_{rd} i_d
\]

where, \((L_s, L_r)\), self-inductances; \(L_{sd}, L_{rd}\), mutual inductance.

The developed electrical torque in the IM can be represented by stator current and stator flux as the following equation:

\[
T_e = \frac{3}{2} p (\psi_s \times i_s)
\]

III. PROPOSED PREDICTIVE CONTROL WITH DELAY TIME COMPENSATION

A. Discrete-time model predictive torque and flux control

The first order Euler’s approximations can be represented as below:

The predictive variables (stator flux and rotor flux) of the induction motor can be determined by applying the first order Euler’s approximations as following:

\[
\psi_s(k) = \psi_s(k-1) + v_r(k)T_s - R_r i_r(k)T_s
\]

\[
\psi_r(k) = i(k)(L_m - \frac{L_r}{L_m}) + \frac{L_r}{L_m}\psi_s(k)
\]

Predictive stator flux, stator current and torque in the next \((k+1)\)th sampling time instant become,

\[
\psi_s(k+1) = \psi_s(k) + v_r(k)T_s - R_r i_r(k)T_s
\]

\[
i(k+1) = (1 - \frac{T_s}{\tau_s})i(k) + \frac{T_s}{\tau_r} + \frac{1}{\tau_r} \left(\frac{k}{\tau_r} k \psi_s(k) \right)
\]

\[
T_s(k+1) = \frac{3}{2} p [\psi_s(k+1) \times i(k+1)]
\]

where, \(\tau_s = R_s + R_r k^2\); \(\tau_r = \frac{L_r}{k_s}\); \(k_s = \frac{L_m}{L_m}\); \(k_r = \frac{L_m}{L_r}\);

\[
\sigma = 1 - k, k, \text{ and } \tau_r = \sigma \tau_s / \tau_r.
\]

B. Delay time compensation

The computational time needed in the predictive control algorithm to predict the variables, and processors delay deteriorates the performance of the predictive control at the experimental investigation. To solve this delay problem, it can be considered the prediction horizon at \((k+2)^{th}\) sampling time to predict the variables which are compared with the references, and determine the quality functions. The optimum switching vector is selected corresponding to the minimum quality function, and applied it in the next \((k+1)^{th}\) sampling time actuation. As a result, one sampling time is available to compensate the time delay produced by the processor.

C. Determination of the predictive model for \((k+2)^{th}\) sampling time instant

Applying the Euler’s Approximation, similarly, for the second next \((k+2)^{th}\) sampling time instant, the predictive stator flux, stator current, and torque become as follows:

\[
\psi_s(k+2) = \psi_s(k+1) + v_r(k+1)T_s - R_r i_r(k+1)T_s
\]

\[
i(k+2) = (1 - \frac{T_s}{\tau_s})i(k+1) + \frac{T_s}{\tau_r} + \frac{1}{\tau_r} \left(\frac{k}{\tau_r} k \psi_s(k+1) + v_r(k+1)\right)
\]

\[
T_s(k+2) = \frac{3}{2} p [\psi_s(k+2) \times i(k+2)]
\]

D. Quality function

The quality function in the predictive control of IM with delay compensation is presented as below,

\[
s_{at} (k+2) = \frac{T_s(k+2)}{\tau_s} + \mu \frac{\psi_s(k+2)}{\psi_{ref}}
\]

where, \(T_s\), \(\psi_{ref}\), are the reference torque and reference flux, respectively. \(\mu\) is the weighting factor, and represent
the flux control has a priority control rather than the torque control.

E. Delay time compensated predictive control scheme

The predictive control scheme and algorithm for induction motor control are presented in Figs. 2(a) and 2(b), respectively. The predictive controller satisfies the following steps:

- First: stator voltage, \(v_s(k)\); stator current, \(i_s(k)\); and speed, \(\omega_m(k)\) of induction motor are measured in the \(k^{th}\) sampling time instant.

- Second: stator reference flux \(\psi_{ref}\) and reference speed \(\omega_{ref}\) are known values. Speed controller is used to set the reference torque \(T_{ref}\).

- Third: estimation of the stator and rotor flux.

- Fourth: predictive torque \(T_{e(k+1)}\) and predictive stator flux \(\psi_s(k+1)\) are predicted in the next sampling time period \((k+1)^{th}\) based on measured variables. And, this predictive torque and flux are used to predict the \((k+2)^{th}\) predictions of the same variables for all eight possible switching vectors.

- Fifth: the \((k+2)^{th}\) predictive values are compared with their respective references, and determine the quality functions for all the possible switching states.

- Lastly, the optimum switching vector corresponds to the minimum cost function is selected for the next sampling time actuation.

IV. SIMULATION AND EXPERIMENTAL RESULTS

The proposed control method is verified in MATLAB Simulink as well as experimental validation with DS1104 R&D Controller at different speed regions to justify the performance of the proposed control scheme. The parameters used in the simulation and experimentation are given in Table I.

A. Simulation Results

The Figs. 3 and 4 represent the results of IM control applied with model predictive control (MPC) method at high speed and low speed regions, respectively. In both simulations, the motor start at 0.01s with the reference torque of 6 Nm in Figs. 3(a) and 4(a). The predictive torque follows the reference torque with high tracking response in both verifications. In Figs. 3(a) and 4(a), when the motor obtain its reference high speed of 125 rad/s, and 37.125 rad/s, respectively, the predictive torque becomes at minimum, and follows the reference torque, accurately.

Furthermore, when the reference speeds have been changed to negative direction, the measured speeds are started to follow the reference speeds at exact time of 1.7s and 1.2s at high and low speed, respectively, with reverse high torque of 6 Nm in both the analysis. Once the motor attained its reverse high speed of -125 rad/s and -37.125 rad/s, the predictive torque becomes zero. At time of 3.5s, a load torque of 3 Nm has been applied. Consequently, the predictive controller forced the motor to develop the torque of 3 Nm to mitigate the load demand at high and low speed regions presented in Figs. 3(a) and 4(a).

Also, the predictive stator flux tracks the reference flux very well, and maintain the magnitude of 1.0 Wb throughout the simulation time in Figs. 3(a) and 4(a). The Figs. 3(b) and 4(b) show the \(\alpha\beta\)−components of the stator current of IM corresponding to reference changes in the simulations which show a very encouraging behavior with the phase displacement of 90° between the two components at forward and reverse speed regions.
Fig. 3. Simulation results (for, $\omega_m = 125$ rad/s) (a) predictive torque vs reference torque [Nm], measured speed vs reference speed [rad/s], and predictive stator flux vs reference flux [Wb]; (b) $\alpha$-components, $\alpha$-component, and $\beta$-component of stator current [A].

In forward speed, $\alpha$-component is lagged by $90^\circ$ than the $\beta$-component, but at the reverse speed, $\alpha$-component leads the $\beta$-component by $90^\circ$. Therefore, the simulation results have been proved the effectiveness of the proposed method by achieving the well tracking of references and good performances.

B. Experimental results

The Fig. 5 shows an overall laboratory experimental test setup to validate the simulation results with experimental implementation in DS1104 R&D controller platform.

In the experiment the gate signals are generated from the DS1104 R&D Controller board by compiling the control part of the simulation in the DS1104 R&D controller platform. The three phase stator currents, voltages, and speed are measured with the current sensors, voltage sensors, and speed sensors, respectively which are fed to ADC ports of DS1104 R&D controller board to complete the closed-loop of the proposed control algorithm. The experimental results of IM at high speed and low speed references are presented in the Figs. 6 and 7, respectively.

In Fig. 6(a), the reference speed is taken as 125 rad/s which is compared to measured speed to get the error signal. This error of speed acts as the input of the speed controller which generates the reference torque of 6 Nm, and the predictive torque follows the reference torque accurately, in the Fig. 6(a). Also, the predictive stator flux tracks the reference stator flux of 1.0Wb in Fig. 6(a).

The corresponding $\alpha\beta$-components of the experimental stator current at high speed of IM in Fig. 6(b) validate the simulation results. Moreover, the phase changing mode between the $\alpha\beta$-components has also been presented with zoomed when the motor changes its speed direction from forward to reverse, and at load changing moment.
Similarly, at low speed, the predictive torque, speed, and predictive flux show the rapid tracking of the reference torque, reference speed, and stator flux references, respectively, by keeping the permissible torque ripple which is presented in Fig. 7(a). Also, the corresponding $\alpha\beta$-components of experimental stator current have been shown in Fig. 7(b).

The experimental results proved that the proposed delay compensated predictive controller has been achieved the satisfactory results even at very low speed region of IM.
TABLE I: SIMULATION AND EXPERIMENTAL PARAMETERS

<table>
<thead>
<tr>
<th>Description</th>
<th>Variables</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling time</td>
<td>$T_s$</td>
<td>25 µs</td>
</tr>
<tr>
<td>DC voltage</td>
<td>$V_{dc}$</td>
<td>500 V</td>
</tr>
<tr>
<td>Supply frequency</td>
<td>$f_s$</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Reference speed</td>
<td>$\omega_{ref}$</td>
<td>12.5 rad/s and 37.175 rad/s</td>
</tr>
<tr>
<td>Nominal torque</td>
<td>$T_{nom}$</td>
<td>6 Nm</td>
</tr>
<tr>
<td>Reference Flux</td>
<td>$\Psi_{ref}$</td>
<td>1.0 Wb</td>
</tr>
<tr>
<td>Stator resistance</td>
<td>$rR$</td>
<td>21 Ω</td>
</tr>
<tr>
<td>Stator inductance</td>
<td>$L_s$</td>
<td>1.053 mH</td>
</tr>
<tr>
<td>Rotor resistance</td>
<td>$rR$</td>
<td>22.63 Ω</td>
</tr>
<tr>
<td>Rotor inductance</td>
<td>$L_r$</td>
<td>1.081 mH</td>
</tr>
<tr>
<td>Mutual Inductance</td>
<td>$L_m$</td>
<td>0.9963 mH</td>
</tr>
<tr>
<td>Number of poles</td>
<td>$P$</td>
<td>2</td>
</tr>
<tr>
<td>Moment of inertia</td>
<td>$J$</td>
<td>0.04 Kg m²</td>
</tr>
<tr>
<td>Weighting Factor</td>
<td>$\lambda$</td>
<td>$T_{nom}/\Psi_{ref}$</td>
</tr>
</tbody>
</table>

V. CONCLUSION

The simulation and experimental results show that the predictive control is a promising control tool that is robust and powerful to control the power converters and electrical machine drives. The proposed delay time compensated model predictive control method utilizes the discrete and inductive nature of the power converter and induction motor load. In this control, the long prediction horizon, i.e. the second next $(k+2)^{th}$ predictive variables are predicted, and compared with the references to determine the quality functions for all the possible eight switching vectors of the converter to overcome the inevitable control delay. The delay associated with the processors in the experiment has no effect on control performance when delay time compensation has been taken in consideration in the predictive control algorithm which results in well tracking of the reference variables at high speed, even at low speed regions of the induction motor.

REFERENCES