TELKOMNIKA Telecommunication, Computing, Electronics and Control
Vol. 18, No. 6, December 2020, pp. 3303~3314
ISSN: 1693-6930, accredited First Grade by Kemenristekdikti, Decree No: 21/E/KPT/2018
DOI: 10.12928/TELKOMNIKA.v18i6.15342

Analysis and investigation of different advanced control strategies for high-performance induction motor drives

Nabil Farah[1], M. H. N. Talib[2], Z. Ibrahim[3], Qazwan Abdullah[4], Ömer Aydoğdu[5], Zulhani Rasin[6], Auzani Jidin[7], Jurifa Mat Lazi[8]
[1,2,3,6,7,8]Electric Vehicle Drive Laboratory, Centre for Robotics and Industrial Automation, Fakulti Kejuruteraan Elektrik, Universiti Teknikal Malaysia Melaka, Malaysia
[4,5]Faculty of Engineering and Natural Sciences, Konya Technical University, Turkey

Article Info

Article history:

Received Jan 18, 2020
Revised Jun 12, 2020
Accepted Jul 9, 2020

Keywords:

Current prediction
Flux estimation
Induction motor drives
Model predictive control
Model predictive current control
Model predictive torque control
Predictive control
Torque prediction

ABSTRACT

Induction motor (IM) drives have received a strong interest from researchers and industry particularly for high-performance AC drives through vector control method. With the advancement in power electronics and digital signal processing (DSP), high capability processors allow the implementation of advanced control techniques for motor drives such as model predictive control (MPC). In this paper, design, analysis and investigation of two different MPC techniques applied to IM drives; the model predictive torque control (MPTC) and model predictive current control (MPCC) are presented. The two techniques are designed in Matlab/Simulink environment and compared in term of operation in different operating conditions. Moreover, a comparison of these techniques with field-oriented control (FOC) and direct torque control (DTC) is conducted based on simulation studies with PI speed controller for all control techniques. Based on the analysis, the MPC techniques demonstrates a better result compared with the FOC and DTC in terms of speed, torque and current responses in transient and steady-state conditions.

Corresponding Author:

Nabil Farah,
Faculty of Electrical Engineering,
Universiti Teknikal Malaysia Melaka,
76100 Durian Tunggal, Melaka, Malaysia.
Email: nabil-farah11@hotmail.com

1. INTRODUCTION

Induction motor (IM) is an AC machine that produces mechanical energy based on electromagnetic induction. The features of ruggedness, simplicity, self-starting, maintenance-free and low cost make the IM became more prominent in industrial and domestic applications [1, 3]. Therefore, the control of IM is gaining a high level of interest among academic and industrial players [4]. The development of advanced control strategies for IM such as field oriented control (FOC) and direct torque control (DTC) has enabled them to be used in high-performance drive applications. Vector control strategies such as FOC and DTC allowed the IM to be controlled in a similar way to DC motor control with the help of phase transformation techniques [5-8]. FOC strategy works in the principle of torque and flux decoupling, where the stator currents are decomposed into d-axis and q-axis representing flux and torque component respectively. The decoupled flux and torque components are then regulated with a speed controller and fed into pulse width modulation (PWM) block to generate the switching pulses for the inverter [9-11]. FOC is characterized by achieving good steady-state behavior and faster transient response [12, 13]. On the other hand, DTC strategy works by selecting the most suitable voltage vector based on the error signs of the torque and stator flux position [14]. DTC achieves a very quick transient response, but it experiences high torque ripples during steady-state and degraded performance at lower speed operations [15-17]. For decades, FOC and DTC have been the prominent control methods for high-performance induction motor drives [18-21]. However, the advancements in technology and digital processing result in high capability processors at reduced cost. Thus, advanced control strategies can be implemented for the high-performance IM drives. Model predictive control (MPC) is one of the most recent sophisticated strategies applied for IM drives. Previously, MPC methods were limited to the slow processing applications due to the requirement of high processing capacity. Now, with the availability of low cost high capacity processors, the MPC can be applied in fast processing applications like AC motor drives applications [22-26].

Nowadays, MPC has gained a wide range of interest in the field of motor drive, due to its basic concept, easy implementation and ability to handle non-linearity issues. It is characterized by a quick transient response, less complexity and simple construction compared to FOC and DTC. MPC works based on the principle of estimating the system variables (that cannot be measured) based on the mathematical model of the system. These variables are then used with the designed cost function to select the optimum voltage vector. Unlike DTC, MPC utilizes cost function to select the optimum voltage vector instead of selecting it from a predefined switching table. Also, MPC reduces system complexity by eliminating current control loops employed in FOC. Thus, with its simple concept, quick dynamic behavior, and less system complexity, MPC has shown a strong tendency to replace the FOC and DTC for high-performance AC drives. Theoretically, MPC is classified into continuous control set MPC (CCS-MPC) and finite control set MPC (FCS-MPC). CCS-MPC usually has a complicated algorithm design and requires a modulator. In contrast the FCS-MPC does not require a modulator and easily realized for non-linearity control [27-31]. FCS-MPC can handle system non-linearity and capable of including system constraints [12]. The FCS-MPC controller also includes the inverter model and considers every possible switching vector within the cost function calculation where the optimum vector is opted as the one that minimizes the cost function. In this paper, only FCS-MPC (or MPC for short) is considered since it has proven to perform better with less complexity and has been applied to various types of applications such as power electronics converters and motor drives. Thus, this paper present the design of the two popular types of MPC known as model predictive torque control (MPTC) and model predictive current control (MPCC) [32-37]. Detail performance investigation is carried out in term of load and unload conditions comparing the four main type of high-performance drive control structures which are the MPTC, MPCC, FOC and DTC.

2. MODELLING OF INDUCTION MOTOR DRIVE SYSTEM

MPC's main concept is to estimate or predict the machine variables based on the mathematical model of the IM. Thus, it is very important to design an accurate IM model in order to obtain an effective drive system. The mathematical model of IM can be derived with the help of vector control principle, where a three-phase machine (a, b, c) can be represented by an equivalent two-phase machine (d-q). Generally, the overall IM drive system shown in Figure 1 consists of IM model, speed control, drive technique and inverter.

A three-phase voltage from the inverter is fed to the stator windings of the IM, where these voltages can be expressed by the following equations [38]:

$$V_{an} = \frac{V_{dc}}{3}\ (2S_a - S_b - S_c) \tag{1}$$

$$V_{bn} = \frac{V_{dc}}{3}\ (2S_b - S_c - S_a) \tag{2}$$

$$V_{cn} = \frac{V_{dc}}{3}\ (2S_c - S_a - S_b) \tag{3}$$

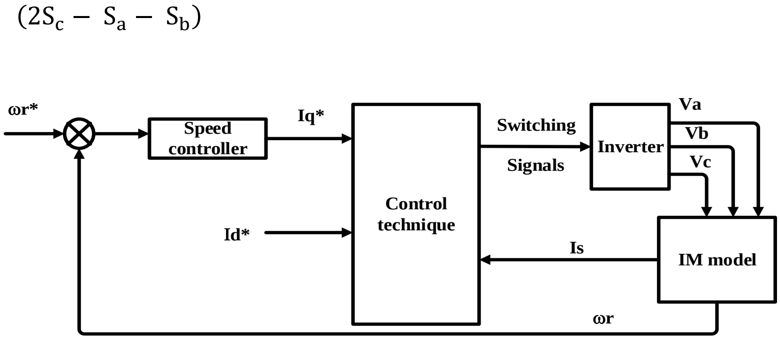


Figure 1. The block diagram of IM drive system

Using phase transformation principle, the input three-phase voltages are converted into two-phase voltages and expressed in stationary reference frame with respect to the stator as in the following equations,

$$V_{sd} = R_s I_{sd} + \frac{d\varphi_{sd}}{dt} \quad (4)$$

$$V_{sq} = \mathrm{R_s I_{sq}} + \frac{\mathrm{d}\varphi_{\mathrm{sq}}}{\mathrm{dt}} \quad (5)$$

$$\mathrm{V_{rd}} = \mathrm{R_r I_{rd}} + \frac{\mathrm{d}\varphi_{\mathrm{rd}}}{\mathrm{dt}} - \omega_{\mathrm{r}}\varphi_{\mathrm{rq}} \quad (6)$$

$$\mathrm{V_{rq}} = \mathrm{R_r I_{rq}} + \frac{\mathrm{d}\varphi_{\mathrm{rq}}}{\mathrm{dt}} + \omega_{\mathrm{r}}\varphi_{\mathrm{rd}} \quad (7)$$

and the flux equation can be expressed as:

$$\varphi_{sd} = L_s I_{sd} + L_m I_{rd} \quad (8)$$

$$\varphi_{sq} = \mathrm{L_s I_{sq} + L_m I_{rq}} \quad (9)$$

$$\varphi_{rd} = \mathrm{L_m I_{sd} + L_r I_{rd}} \quad (10)$$

$$\varphi_{rq} = \mathrm{L_m I_{sq} + L_r I_{rq}} \quad (11)$$

where V_{sd} , V_{sq} are the stator voltage, V_{rd} V_{rq} are the rotor voltages, I_{sd}, I_{sq} , I_{rd} , I_{rq} are the corresponding *d* and *q* axis of the stator and rotor currents, φ_{sd} ,φ_{sq}, φ_{rd} , φ_{rq} are the stator and rotor flux components, R_s , $\mathrm{R_r}$ are the stator and rotor resistances, L_s, L_r denotes the stator and rotor inductances, $\mathrm{L_m}$ is the mutual inductance and ω_r is the rotor rotational speed.

The above derived IM equations can be expressed in the state-space form with the choice of flux linkages or currents as the state variables. If the stator and rotor currents are chosen as the state variables, the IM equations can be presented as:

$$\begin{bmatrix} \mathrm{i_{qs}} \\ \mathrm{i_{ds}} \\ \mathrm{i_{qr}} \\ \mathrm{i_{dr}} \end{bmatrix} = \frac{1}{\sigma LsLr} \begin{bmatrix} R_s L_r & -\omega_r L_m^2 & -R_r L_m & -\omega_r L_m L_r \\ \omega_r L_m^2 & R_s L_r & \omega_r L_m L_r & -R_r L_m \\ -R_s L_m & \omega_r L_m L_s & R_r L_s & \omega_r L_r L_s \\ -\omega_r L_m L_s & -R_s L_m & -\omega_r L_r L_s & R_r L_s \end{bmatrix} \begin{bmatrix} \mathrm{i_{qs}} \\ \mathrm{i_{ds}} \\ \mathrm{i_{qr}} \\ \mathrm{i_{dr}} \end{bmatrix} + \frac{1}{\sigma LsLr} \begin{bmatrix} -L_r & 0 \\ 0 & L_r \\ L_m & 0 \\ 0 & L_m \end{bmatrix} \begin{bmatrix} v_{sd} \\ v_{sq} \end{bmatrix} \quad (12)$$

where σ is sigma and equal to $\sigma = 1 - \frac{L_m^2}{Ls\,Lr}$. Moreover, the output torque of the machine can be expressed in two forms mechanically and electrically as follow:

Mechanical torque: $T_e = J\frac{d\omega_m}{dt} + B\omega_m + T_L = \frac{J}{P}\frac{d\omega_r}{dt} + \frac{B}{P}\omega_r + T_L$ (13)

Electrical torque: $T_e = \frac{3}{2} P L_m \left(i_{sq} i_{rd} - i_{sd} i_{rq}\right)$ (14)

where J is the total moment of inertia, B is the viscous friction, T_L is the load torque, ω_r is the rotor electric angular speed in rad/s, ω_m is the motor speed in rad/s and P is the number of pole pairs.

3. MODELLING OF THE PREDICTIVE CONTROL STRATEGIES

Model predictive control (MPC) is an advanced control technique that aims to simplify the control mechanism of IM drives with non-linearity handling and drive constrains inclusion. Based on the mathematical model of the IM, MPC estimates the machine variables that can not be measured and predicts the future of these variables for every sampling step. Then, a cost function compares the predicted variables with reference variables and the voltage vector minimizing the cost function is selected as the switching vector for the next sampling interval. This paper covers two MPC types based on the control variables used. The first one is the Model predictive torque control (MPTC), where torque and flux are used as control variables of the MPC. Meanwhile the second one is the model predictive current control (MPCC), where the stator currents are used as the control variables. In this section, the theoretical principles and design processes of MPTC and MPCC are presented.

3.1. Model predictive torque control

MPTC uses stator flux and electromagnetic torque as the control variables and predicts their future values in order to use it in calculating the optimum values for actuating variables. The MPTC execution can be divided into three steps, the first step is estimating the values of stator and rotor fluxes, the second step is predicting the future values of the torque and stator flux and the final step is producing the optimum voltage vector that minimizes the cost function. MPTC estimates the stator and rotor fluxes based on the stator currents and utilizes outer speed control loop to obtain the flux and torque reference values. Mathematically, the stator flux can be estimated using the voltage equation of stator in $\alpha - \beta$ frame:

$$v_s = R_s i_s + \frac{d\varphi_s}{dt} \tag{15}$$

The flux derivative term $\frac{d\varphi_s}{dt}$ can be estimated for a sampling time of T_s using Euler forward method as:

$$\frac{dx}{dt} = \frac{x(k+1)-x(k)}{T_s} \rightarrow \frac{d\varphi_s}{dt} = \frac{\varphi_s(k+1)-\varphi_s(k)}{T_s} \tag{16}$$

Substituting in (16) into (15) yields:

$$v_s(k) = R_s i_s(k) + \frac{\varphi_s(k+1)-\varphi_s(k)}{T_s}$$

Rearranging yields:

$$\varphi_s(k) = \varphi_s(k-1) + T_s\,[R_s i_s(k) - v_s(k)] \tag{17}$$

The rotor flux can be estimated by using stator and rotor flux equations in $\alpha - \beta$ frame as:

$$\varphi_s = \mathrm{L_s i_s} + \mathrm{L_m i_r} \tag{18}$$

$$\varphi_r = \mathrm{L_m i_s} + \mathrm{L_r i_r} \tag{19}$$

Rearranging in (19) for rotor current$\mathrm{i_r}$, yields:

$$i_r = \frac{\mathrm{L_m i_s} - \varphi_r}{\mathrm{L_r}}$$

Substituting $i_r$into in (18), yields:

$$\varphi_r(k) = \varphi_s(k)\frac{\mathrm{L_r}}{\mathrm{L_m}} + \mathrm{i_s}(k)\left(\mathrm{L_m} - \frac{\mathrm{L_s L_r}}{\mathrm{L_m}}\right) \tag{20}$$

For the prediction of stator flux at$(k+1)$, the following equation can be used:

$$\varphi_s(k+1) = \varphi_s(k) + T_s\,[R_s i_s(k) - v_s(k)] \tag{21}$$

For torque prediction T at $(k+1)$, it depends on the stator flux and current predictions as:

$$T(k+1) = \frac{3}{2} P\, Im\{\varphi_s(k+1)\, i_s(k+1)\} \tag{22}$$

The stator current can be predicted based on the voltage equation as:

$$\frac{d}{dt}\begin{bmatrix}\mathrm{i_s}\\ \mathrm{i_r}\end{bmatrix} = \frac{1}{\sigma LsLr}\begin{bmatrix}-R_s Lr - j\omega_m Lm^2 & R_r Lm - j\omega_m LmLr\\ R_s Lm + j\omega_m LmLs & -R_r Ls + j\omega_m LsLr\end{bmatrix}\begin{bmatrix}\mathrm{i_s}\\ \mathrm{i_r}\end{bmatrix} + \frac{1}{\sigma LsLr}\begin{bmatrix}Lr & -Lm\\ -Lm & Lr\end{bmatrix}\begin{bmatrix}v_s\\ v_r\end{bmatrix} \tag{23}$$

$$\frac{\mathrm{di_s}}{dt} = \frac{1}{\sigma LsLr}[(-R_s Lr - j\omega_m Lm^2)\mathrm{i_s} + (R_r Lm - j\omega_m LmLr)\mathrm{i_r}] + \frac{1}{\sigma LsLr}[Lr v_s + (-Lm)v_r]$$

$$\frac{\mathrm{di_s}}{dt} = \frac{1}{\sigma LsLr}\left[-(R_s Lr - \frac{R_r Lm^2}{\mathrm{L_r}})\mathrm{i_s} - (j\omega_m Lm + \frac{R_r Lm^2}{\mathrm{L_r}})\varphi_r + Lr v_s\right] \tag{24}$$

Using Euler forward method, the stator current at instant (k+1) with sampling time T_s can be obtained as:

$$i_s(k+1) = i_s(k) + \frac{T_s}{\sigma LsLr}\left[-(R_sLr - \frac{R_rLm^2}{\mathrm{L_r}})\mathrm{i_s}(k) - (j\omega_m Lm + \frac{R_rLm^2}{\mathrm{L_r}})\varphi_r(k) + Lrv_s(k)\right] \tag{25}$$

The final step in MPTC is the calculation of the voltage vector based on the predicted values using a cost function. This cost function compares the predicted values of torque and flux with reference values of torque and flux obtained from the speed control loop. For a two-level voltage source inverter, there are eight possible switching vectors that correspond to eight prediction iterations on the cost function. From these eight iterations, the cost function will select the optimum vector producing the lowest value as the switching vector. The cost function used in MPTC can be expressed as:

$$g(i) = |T^* - T(k+1)_i| + \gamma|\varphi^* - \varphi(k+1)_i| \tag{26}$$

where, γ is the weighting factor and the basic formula to calculate it is defined as $\gamma = \frac{T^*}{\varphi^*}$ [30].

3.2. Model predictive current control

MPCC method predicts the stator currents and evaluates them with reference currents for all possible voltage vectors. From the induction motor model equations, the stator currents are expressed in (27):

$$\frac{\mathrm{di_s}}{dt} = \frac{1}{\sigma LsLr}\left[-(R_sLr - \frac{R_rLm^2}{\mathrm{L_r}})\mathrm{i_s} - (j\omega_m Lm + \frac{R_rLm^2}{\mathrm{L_r}})\varphi_r + Lrv_s\right] \tag{27}$$

Using Euler forward method, the stator current at instant (k+1) with sampling time T_s can be obtained as:

$$i_s(k+1) = i_s(k) + \frac{T_s}{\sigma LsLr}\left[-(R_sLr - \frac{R_rLm^2}{\mathrm{L_r}})\mathrm{i_s}(k) - (j\omega_m Lm + \frac{R_rLm^2}{\mathrm{L_r}})\varphi_r(k) + Lrv_s(k)\right] \tag{28}$$

These predicted currents are compared with the reference currents from the speed control loop in a designed cost function in order to select the best switching vector that minimizes the cost function. The cost function of MPCC can be written as in (29):

$$g(i) = |i_\alpha{}^* - i_\alpha(k+1)_i| + |i_\beta{}^* - i_\beta(k+1)_i| \tag{29}$$

In certain ocassion, a current protection item, I_m is added to the cost function to avoid high-current and prevent the motor from over-current operation. The formula for I_m can be expressed as in (30):

$$I_m(k+1) = \begin{cases} 0, & if\ |i_s(k+1)| \le |i_{max}| \\ & r \ge 0 \end{cases} \tag{30}$$

Thus, I_m component is to be added to the cost function where in (29) becomes as:

$$g(i) = |i_\alpha{}^* - i_\alpha(k+1)_i| + |i_\beta{}^* - i_\beta(k+1)_i| + I_m(k+1)_i$$

The MPCC control does not require a stator flux and torque estimation like the MPTC which can reduce its complexity and computational burden of the drive system. Besides, the reference torque current I_q and reference flux current I_d are obtained from the outer speed control loop. A phase transformation is required to convert the reference currents from (d-q) frame into (α-β) frame using the following equation:

$$\begin{matrix}\mathrm{I_\alpha} \\ \mathrm{I_\beta}\end{matrix} = \begin{bmatrix}\cos\theta & -\sin\theta \\ \sin\theta & \cos\theta\end{bmatrix}\begin{matrix}\mathrm{I_d} \\ \mathrm{I_q}\end{matrix} \tag{31}$$

3.3. Comparison of MPC strategies with FOC and DTC control

FOC and DTC have been the dominant control methods for the IM drives due to their effective performance and their vector control principle that allows the control of AC drives in a similar way to DC drives. In this section, a comparison of FOC and DTC with MPC techniques is presented. They are compared in terms of their structure, dynamic performance and parameters sensitivity. The block diagram of the FOC and DTC are presented in Figures 2 and 3 respectively, while the MPTC and MPCC diagrams are shown in Figures 4 and 5 respectively. Both DTC and MPC have a variable switching frequency and directly produce the switching vectors for inverter without a modulator, while the FOC has a constant switching frequency and requires a modulator for handing continuous variables [39]. In comparison to FOC, MPTC and MPCC have simplified the drive system by eliminating the inner current control loops and modulation models, thus achieving faster dynamic response. In addition, the MPTC and MPCC have better steady state performance compared to DTC because they utilize a cost function to select the most suitable switching vector instead of using heuristic switching as in DTC [40].

In terms of computational burden, FOC and DTC require a smaller computation time compared to MPTC and MPCC. For torque and current ripples, FOC produces superior performance followed by MPC and then DTC [39]. For parameters sensitivity, FOC, DTC, and MPTC have good performance under parameters change, only MPCC that has unsatisfactory performance with respect to parameters change [39]. A comparison base on simulation results is discussed in the next section.

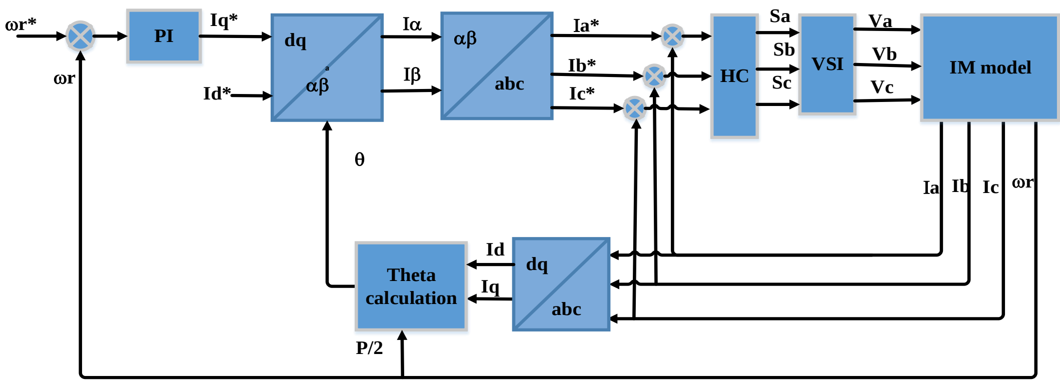


Figure 2. Field oriented control (FOC) of induction motor drives

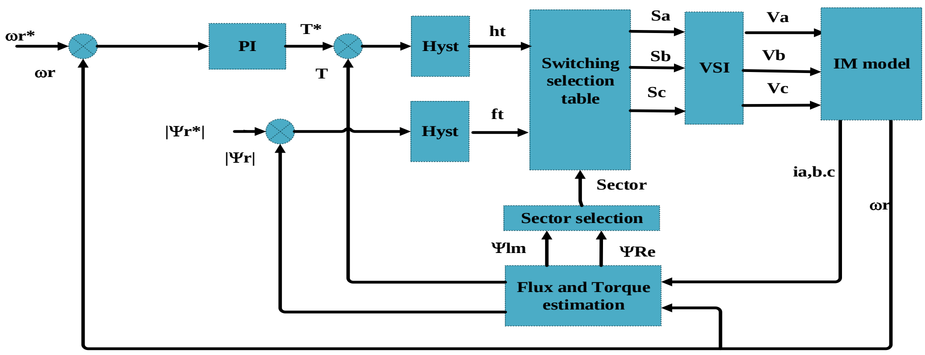


Figure 3. Direct torque control (DTC) of induction motor drives

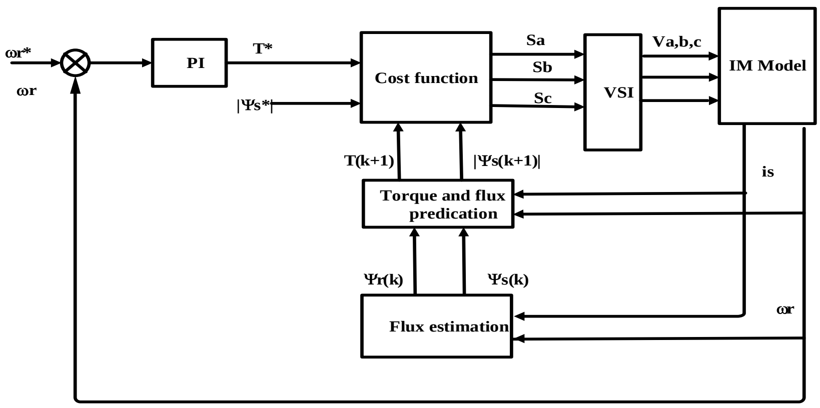


Figure 4. Model predictive torque control (MPTC) of induction motor drives

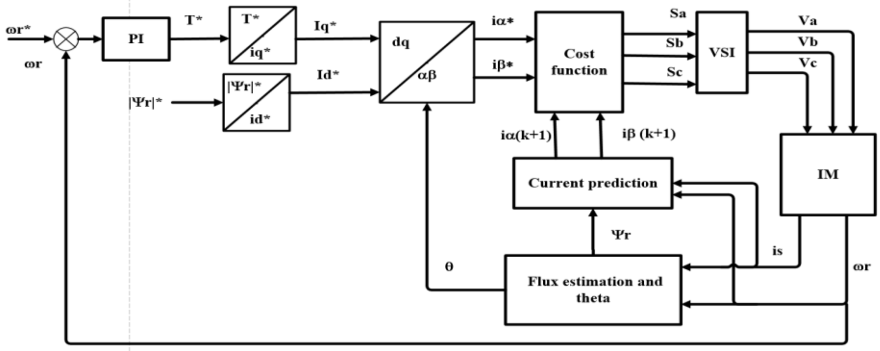


Figure 5. Model predictive current control (MPCC) of induction motor drives

4. SIMULATION RESULTS

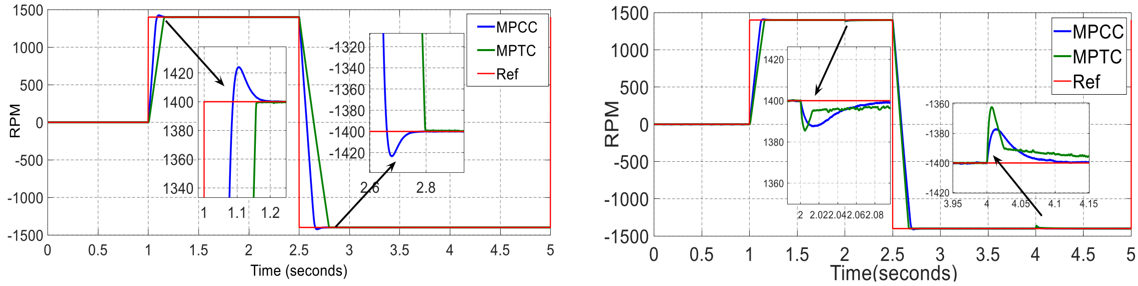
This section discusses the simulation results of the MPC methods, FOC and DTC. This includes a comparison in terms of speed performance at different speed operations, torque and currents. The results are divided into two sections where in the first section, the two MPCs' techniques are compared and analyzed between them. While in the second section, the MPCs methods are compared with the FOC and DTC methods. For a fair comparison analysis, all models are simulated with the same sampling frequency and machine parameters as in Table 1.

Table 1. Induction motor parameters

Parameter	Value
Rated Voltage	380 Vac
Poles	4
Frequency	50Hz
Rated Speed	1430 rpm
Stator Resistance	3.45 Ω
Rotor Resistance	3.6141 Ω
Stator Inductance	0.3246 H
Rotor Inductance	0.3252 H
Magnetizing Inductance	0.3117 H
Inertia	0.02 kgm^2
Viscous Friction	0.001 Nm/(rad/s)

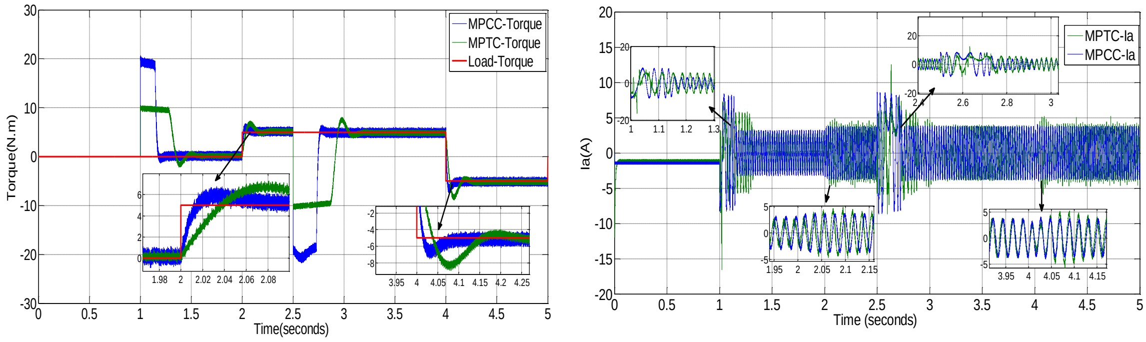
4.1. Comparison between MPCs methods (MPTC vs MPCC)

In order to verify the performance of the MPC methods for IM motor drives, a simulation model of MPTC and MPCC for IM drives have been designed in Matlab/Simulink environment. Both methods have been modeled based on the derived equations in sections 3.1 and 3.2. The speed performance of the IM drives at rated condition with MPCs methods (MPTC, MPCC) is presented in Figure 6 (a), while Figure 6 (b) shows the speed performance at load operation. In addition, the output torque and output stator currents are presented in Figures 7 (a) and (b). Based on the speed performance, it can be seen that the MPCC has better dynamic response than the MPTC, but with higher overshoot. During load disturbance, MPTC has higher speed drop than the MPCC, but it has a faster recovery time.



(a) (b)

Figure 6. Speed performance of MPCC and MPTC at rated speed 1400 rpm, (a) no-load, (b) load operation

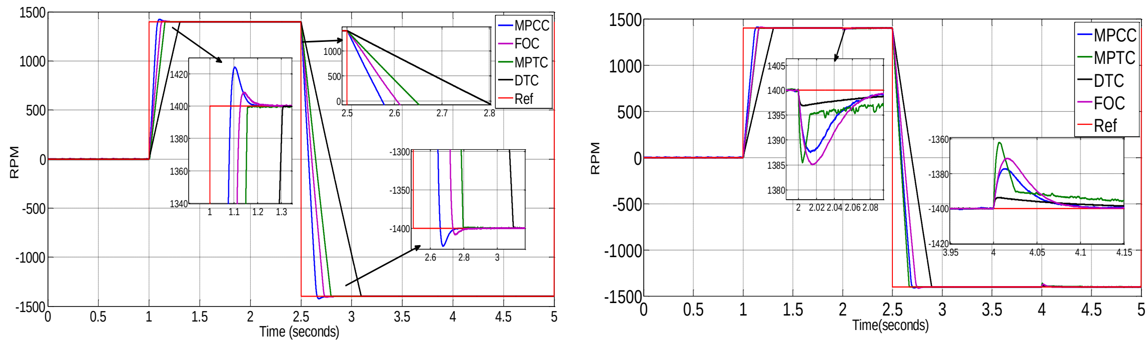


(a) (b)

Figure 7. Performance of MPTC and MPCC, (a) torque, (b) stator current (Ia)

4.2. Comparison between MPCs vs FOC and DTC

The speed performance of IM drives at rated condition with MPCs methods (MPTC and MPCC), DTC and FOC is presented in Figure 8 (a). In addition, the speed performance at loaded speed operations is shown in Figure 8 (b). Finally, the output torque and output stator currents are presented in Figures 9 and 10 respectively.



(a) (b)

Figure 8. Speed performance of MPTC, MPCC, DTC & FOC at 1400 rpm, (a) no-load,(b) load operation

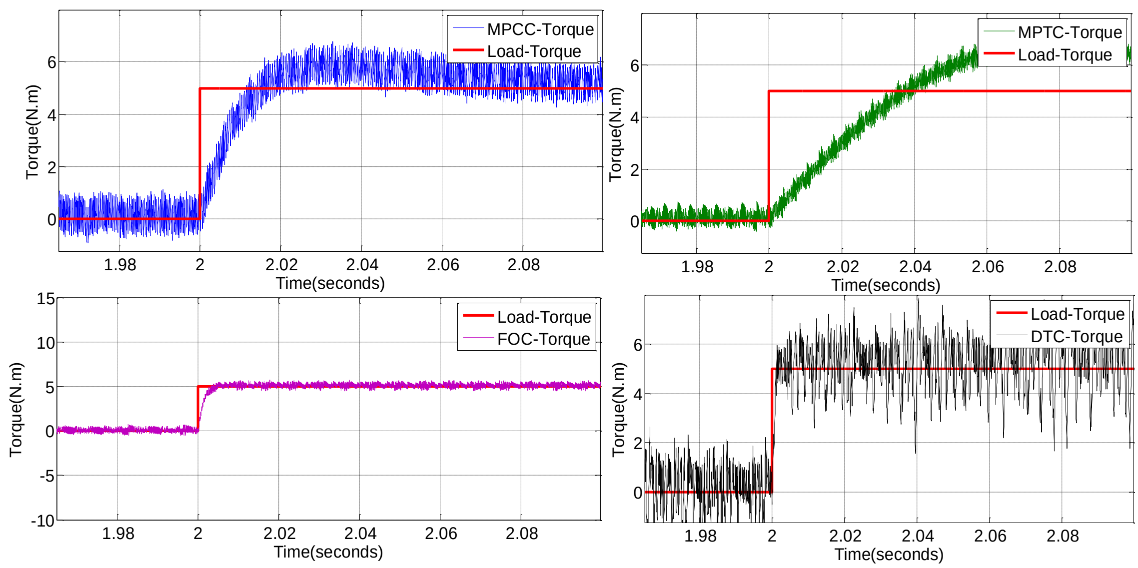


Figure 9. Torque performance of MPTC, MPCC, DTC and FOC at 1400 rpm

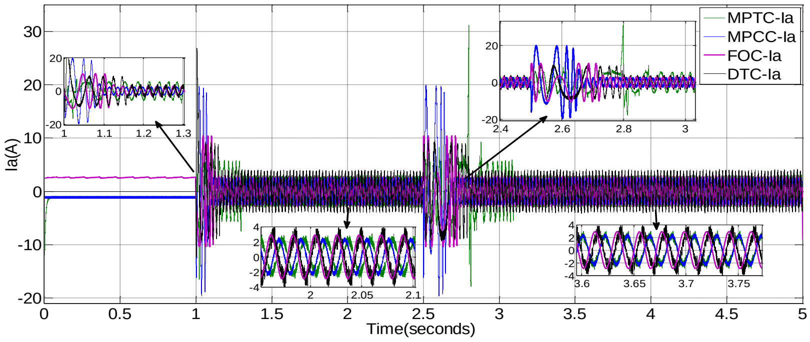


Figure 10. Stator current performance of MPTC, MPCC, DTC and FOC at 1400 rpm

In order to verify the effectiveness of the MPCs methods, numerical analysis is conducted to compute the IM drive response characteristics at rated speed (1400 rpm) such as overshoot, rise time, settling time, speed drop during load operation and how long each method takes to recover from load disturbance. Table 2 summarizes the response characteristics which shows that the MPCC has better performance in terms of overshoot, settling time, rise time and recovery time, while DTC has the smallest speed drop but has a very long recovery time. Besides, the MPCC has the highest speed drop compared with the other techniques since it has a very low response to parameters change due to the load disturbance. However, MPCC recovers quickly with the shortest recovery time of 0.151 seconds compared to other techniques. Although DTC has the smallest speed drop of 4 rpm, it recovers slowly from load disturbance in 0.224 seconds.

Table 2. Numerical comparison of MPCs and FOC &DTC at rated speed 1400 rpm

Measure	Method			
	MPCC	MPTC	FOC	DTC
Overshoot (%)	1.17	0.57	0.071	0.072
Rise Time (S)	0.062	0.098	0.133	0.265
Settling Time (S)	0.086	0.128	0.157	0.310
Speed drop (rpm)	18	14	15	4
Recovery Time (S)	0.151	0.221	0.187	0.224

5. CONCLUSION

Model predictive control (MPC) is an advanced control method that has been recently applied in high-performance IM drives due to their initiative concept and ability to handle non-linearity issues and system constraints. This paper has discussed two popular MPC methods for IM drives which are the MPTC and MPCC. The mathematical models of these techniques have been derived and developed in Matlab/Simulink. Comparison analysis of MPTC and MPCC has been conducted in terms of different speed operations, load torque rejection capability and current and torque ripples. Finally, the MPC techniques have been compared with two conventional techniques; the FOC and DTC, under same drive parameters and using PI speed controller for both techniques. Based on the analysis from the simulation results, the MPC techniques (MPTC and MPCC) have a competitive performance compared to the conventional techniques (FOC and DTC). Overall, from the all four methods, the MPCC has the best performance compared to MPTC, FOC and DTC in relation to different performance measurement such as the rise time and settling time.

ACKNOWLEDGEMENTS

The authors would like to gratefully acknowledge the funding support provided by Universiti Teknikal Malaysia Melaka (UTeM) and the Ministry of Education Malaysia under the research grant No: RACER/2019/FKE-CERIA/F00398

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BIOGRAPHIES OF AUTHORS

Nabil Farah was born in Yemen in 1990. He has received a bachelor's degree in electrical engineering (power electronics and drives) from Universiti Teknikal Malaysia Melaka in 2015. And received a master's degree in electrical engineering in the same university. Current research interest is the self-tuning fuzzy logic controller of AC Motor drives and predictive control of induction motor drives.

M. H. N. Talib was born in Malaysia, in 1976. He received his B.S. in Electrical Engineering from the Universiti Teknologi Malaysia (UTM), Johor, Malaysia, in 1999, M.S. in Electrical Engineering from the University of Nottingham, Nottingham, UK, in 2005 and PhD from the Universiti Teknikal Malaysia Melaka (UTeM), Malaysia in 2016. He is currently a senior lecturer at UTeM. His main research interests include power electronics, fuzzy logic control and motor drives.

Z. Ibrahim was born in 1966 in Malaysia. He received his B.Eng. degree from the University of Technology (UTM), Malaysia in 1989 and his PhD degree from the Liverpool John Moores University, UK in 1999. He is currently a Professor at Universiti Teknikal Malaysia Melaka (UTeM), Malaysia. His main research interests are related to power electronics, fuzzy logic control, embedded system design and electric motor drives.

Qazwan Abdullah was born in Taiz, Yemen and received his bachelor's degree in Electrical and electronic engineering from Universiti Tun Hussein Onn Malaysia (UTHM) in 2013. He also received his Master of Science in Electrical and Electronic Engineering in 2015 from the same university. Currently, he is a Ph.D. student with research interests of control system, wireless technology and microwaves.

Ömer Aydoğdu, was born in Konya, Turkey in 1973. He received the B.S., M.S. and Ph.D. degrees in electrical and electronics engineering from Selçuk University, Konya, in 1995, 1999 and 2006 recpectively. From 1996 to 2007, he was a Research Assistant with the department of Electrical and Electronics Engineering, Selçuk University, Konya, Turkey. From 2007 to 2018, he worked as an assistant professor and associate professor in the same department at Selcuk University. From 2018 to 2020, he worked as an associate professor in the department of Electrical and Electronics Engineering at Konya Technical University, Konya, Turkey. Since 2020, he has been a Professor with the same department at Konya Technical University. He is the author of a book chapter and more than 70 scientific publications. His research interests include control theory, adaptive control systems, fractional order control, fuzzy logic control and applications, Brushless DC motors and drives.

Zulhani Rasin, received his BEng (Electrical Eng.) in 2000 from University of Electro-Communications, Tokyo, Japan, his MEng (Electrical – Electronics & Communications) in 2007 from Universiti Teknologi Malaysia and his PhD in Electrical Engineering in 2015 from University of New South Wales Australia. Currently he is a senior lecturer with the Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka, and Malaysia. His research interests are in the area of grid-connected photovoltaic inverter, quasi-Z-source inverter and energy storage for electric vehicle drive system.

Auzani Jidin, (M'09 IEEE) received his B.Eng. degree, M.Eng. degree and PhD degree in Power Electronics & Drives from Universiti Teknologi Malaysia (UTM), Malaysia in 2002, 2004 and 2011, respectively. He is a lecturer in Department of Power Electronics and Drives, Faculty of Electrical Engineering at Universiti Teknikal Melaka. Malaysia (UTeM), Malaysia. His research interests include the field of power electronics, motor drive systems, FPGA and DSP applications.

Jurifa Mat Lazi received her Bachelor's degree in Electrical Engineering from Universiti Teknologi Malaysia in 2001. She then obtained his Master of Science degree in Electrical Power Engineering from University Universiti Teknologi Malaysia, in 2003. She received his Ph.D degree from University Universiti Teknikal Malaysia Melaka in 2016. She has served as an academic staff at Universiti Teknikal Malaysia Melaka (UTeM) since 2001 and she is currently a senior lecturer and Head of Industrial Training Coordinator in the Faculty of Electrical Engineering, UTeM. Her research interests include Machine Drives especially in Sensorless and PMSM drives, Power Electronics and Power System.