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# Predictive control of an induction machine drive system for field-weakening regime

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***Abstract.*** *In this paper is studied the model predictive control (MPC) of an induction machine (IM) drive for wakening applications. The control structure is implemented in Matlab software. The predictive control law is based on finite set combinations imposed by the two-level inverter topology. The study developed for field-wakening regime shows that the speed tracking objective remains stable despite stator resistance variation. Also, the load torque disturbance rejection is efficiently done to evaluate un unrated parameter. Thus, the operation of the IM drive with MPC law is robust on the sensitivity of parameters of the model.*

***Keywords****: induction machine (IM), model predictive control (MPC), Matlab software, speed response, load torque rejection.*

## 1. Introduction

In recent years, induction machine (IM) has become the most popular solution for medium and high power fields applications. Having a simple, robustness, and cheap structure, IM is largely used in industrial and residential applications for a large variety of electrical drives: electrical traction, motion system, electrical propulsion, special applications.

The IM drives powered directly from electrical grid, have a limited area of applications, usually in pumps, mils and some domestic areas that does not require high performances. More advanced features aroused once with IM drives supplied by power invertors [1] together with field oriented control (FOC). Thus, the magnitude and frequency of voltage are independently controlled which make the possibility to obtain new benefits on IM drive operation [2]: large range of speed and torque, field-weakening, constant torque mode operation, constant torque regime and constant power mode.

Although the classical PI linear controllers become a certainty in the IM industrial application, there are also several limitations [1-3]: non-optimal control law, difficulties in constraints imposing and low robustness on the variation of plant parameters.

To overcome the above-mentioned drawbacks, a high-performance strategy based on IM model is developed. The model predictive control (MPC) has the ability to improve the classical results. There are two types of MPC methods, with continuous set control (CSC) and finite set control (FSC). The MPC – CSC starting for large industrial plant [4-5] and requires advanced mathematical algorithm and wide amount of hardware resources. In the recent years, the increasing of the computational effort make possible the MPC – CSC control law implementation of the IM drive [6-7]. However, the MPC – CSC strategy requires a frequency modulator for command synthesis. A last iteration is the MPC strategy with finite set control (FSC) which gives an optimal control obtained by an optimal switching states combinations of the electronic power inverter of the IM drive system [8-9]. In the rest of the paper, the MPC strategy discussed is MPC – FSC, being simply replaced by MPC.

In the paper is proposed a MPC control of an IM drive for field-weakening applications. For this aim, when the mechanical speed exceeds the base speed, the magnetic flux reference will decrease. The MPC control used for controlling flux and speed has a multivariable structure being developed for state-space representation. A case study developed in Matlab software will illustrate the effectives of the presented study.

The rest of the paper is organized as follows. In the second section is presented the IM model in a stationary system reference frame. The MPC strategy for IM cascade structure is developed in the third section. A case study approached in Matlab software simulation environment is discussed in section four. Finally, in section fourth are summarized the main benefits of the study of the paper.

## 2. IM mathematical modelling

The IM control model represented in a fixed system reference frame $(\alpha, \beta)$ is obtained by starting from stator and rotor voltages equations, respectively, as follows [8]:

$$u_{s\alpha} = R_s i_{s\alpha} + \frac{d\psi_{s\alpha}}{dt}, \tag{1}$$

$$u_{s\beta} = R_s i_{s\beta} + \frac{d\psi_{s\beta}}{dt}, \tag{2}$$

$$0 = R_r i_{r\alpha} + \frac{d\psi_{r\alpha}}{dt} + p_b \omega \psi_{s\beta}, \tag{3}$$

$$0 = R_r i_{r\beta} + \frac{d\psi_{r\beta}}{dt} - p_b \omega \psi_{s\alpha} \quad, \tag{4}$$

where the involved magnetic flux is:

$$\psi_{s\alpha} = L_s i_{s\alpha} + L_m L_{r\alpha} \quad, \tag{5}$$

$$\psi_{s\beta} = L_s i_{s\beta} + L_m L_{r\beta} \quad, \tag{6}$$

$$\psi_{r\alpha} = L_r i_{r\alpha} + L_m L_{r\alpha} \quad, \tag{7}$$

$$\psi_{r\beta} = L_r i_{r\beta} + L_m L_{r\beta} \quad. \tag{8}$$

The motion equation is described by:

$$\tau - \tau_1 = J \frac{d\omega}{dt} \quad, \tag{9}$$

with the electromagnetic torque relationship:

$$\tau = \frac{3}{2} p_b (\psi_{s\alpha} i_{s\beta} - \psi_{s\beta} i_{s\alpha}) \quad. \tag{10}$$

In Eq. (1) – (10), the quantities involved has the next significance: $(u/i/\psi)_{\alpha/\beta}$ are the stator/rotor components of voltage, current and magnetic flux space vectors, $(R_s, R_r)$ denotes the stator and rotor resistances, $(L_s, L_r, L_m)$ are stator, rotor and magnetizing inductance, respectively, $\omega$ is the rotor speed, $\tau_1$ represents the load torque, $J$ is the rotor inertia, $p_b$ is the number of magnetic stator pairs of poles.

Some important remarks may be done about this model.

By using the forward Euler discretization method, a first-order linear approximation method is obtained for a generic quantity x(t) as follows:

$$\left.\frac{dx(t)}{dt}\right|_{x=x[k+1]} = \frac{x[k+1]-x[k]}{T_e} \quad, \tag{11}$$

where $T_e$ is the sampling time period.

Taking into account the approximation (11) of the first derivative, from (1) – (8) are obtained the discrete flux equations:

$$\left.\begin{bmatrix} \hat{\psi}_{s\alpha}(k) \\ \hat{\psi}_{s\beta}(k) \end{bmatrix}\right| = \begin{bmatrix} \hat{\psi}_{s\alpha}(k-1) \\ \hat{\psi}_{s\beta}(k-1) \end{bmatrix} + T_e \left.\begin{bmatrix} u_{s\alpha}(k) \\ u_{s\beta}(k) \end{bmatrix}\right| - R_s T_e \left.\begin{bmatrix} i_{s\alpha}(k) \\ i_{s\beta}(k) \end{bmatrix}\right| \quad, \tag{12}$$

$$\left.\begin{bmatrix} \hat{\psi}_{r\alpha}(k) \\ \hat{\psi}_{r\beta}(k) \end{bmatrix}\right| = \frac{L_r}{L_m} \begin{bmatrix} \hat{\psi}_{s\alpha}(k-1) \\ \hat{\psi}_{s\beta}(k-1) \end{bmatrix} + \left.\begin{bmatrix} i_{s\alpha}(k) \\ i_{s\beta}(k) \end{bmatrix}\right| + \left( L_m - \frac{L_s L_r}{L_m} \right) \quad, \tag{13}$$

that were used for magnetic flux estimation.

Further, by applying (11) to (1) – (8) there are obtained the flux and current predictions in the discrete state-space representation:

$$\begin{bmatrix} \psi_{s\alpha}^{p}(k+1) \\ \psi_{s\beta}^{p}(k+1) \end{bmatrix} = \begin{bmatrix} \hat{\psi}_{s\alpha}(k) \\ \hat{\psi}_{s\beta}(k) \end{bmatrix} + T_e \begin{bmatrix} u_{s\alpha}(k) \\ u_{s\beta}(k) \end{bmatrix} - R_s T_e \begin{bmatrix} i_{s\alpha}(k) \\ i_{s\beta}(k) \end{bmatrix}, \qquad (14)$$

$$\begin{bmatrix} i_{s\alpha}^{p}(k+1) \\ i_{s\beta}^{p}(k+1) \end{bmatrix} = \left(1 + \frac{T_s}{T_t}\right) \begin{bmatrix} i_{s\alpha}(k) \\ i_{s\beta}(k) \end{bmatrix} + \frac{T_s}{T_t + T_s} \left\{ \frac{1}{R_t} \begin{bmatrix} \frac{k_r}{T_r} \begin{bmatrix} \hat{\psi}_{s\alpha}(k) \\ \hat{\psi}_{s\beta}(k) \end{bmatrix} \\ + k_r \omega \begin{bmatrix} \hat{\psi}_{s\alpha}(k) \\ -\hat{\psi}_{s\beta}(k) \end{bmatrix} + \begin{bmatrix} u_{s\alpha}(k) \\ u_{s\beta}(k) \end{bmatrix} \end{bmatrix} \right\}, \qquad (15)$$

where the used group of constants are:

$$T_s = \frac{L_s}{R_s}; T_r = \frac{L_r}{R_r}; k_s = \frac{L_m}{L_s}; k_r = \frac{L_m}{L_r}$$

$$T_t = \left(1 - \frac{L_s}{L_r}\right)\frac{L_s}{R_t}; R_t = R_s + R_r k_r^2 . \qquad (16)$$

Finally, based on previous flux and current prediction (15) – (16), there is obtained the one-step-ahead prediction of electromagnetic torque:

$$\tau^{p}(k+1) = \frac{3}{2} p_b (\psi_{s\alpha}^{p} i_{s\beta}^{p} - \psi_{s\beta}^{p} i_{s\alpha}^{p}) . \qquad (17)$$

## 3. Predictive control of IM

In the operation of IM drive, the power electronic inverter has an important role, ensuring the derived voltages required for meeting the high performances.

A typical power inverter structure with two voltage levels is depicted in Fig. 1. The command on the same leg of inverter is negated through an inverter.

The scope of the MPC algorithm is to find a direct command, without a frequency modulator, which is included in the finite set of all possible combinations of the switching states of the power inverter.

A common method using power inverter modeling is based on switching functions, that are associated to each phase and leg of the inverter:

$$\mathbf{S}_a = \begin{cases} 1, & if \quad S_1 \equiv on \quad and \quad S_4 \equiv off \\ 0, & if \quad S_1 \equiv off \quad and \quad S_4 \equiv on \end{cases}, \qquad (18)$$

$$\mathbf{S}_b = \begin{cases} 1, & if \quad S_2 \equiv on \quad and \quad S_5 \equiv off \\ 0, & if \quad S_2 \equiv off \quad and \quad S_5 \equiv on \end{cases}, \tag{19}$$

$$\mathbf{S}_c = \begin{cases} 1, & if \quad S_3 \equiv on \quad and \quad S_6 \equiv off \\ 0, & if \quad S_3 \equiv off \quad and \quad S_6 \equiv onf \end{cases}, \tag{20}$$

where $\{\mathbf{S}_a, \mathbf{S}_b, \mathbf{S}_c\}$ are the set switching state corresponding to each phase, while $S_i, i = 1,6$ is the state corresponding to each electronic device of power electronic inverter.

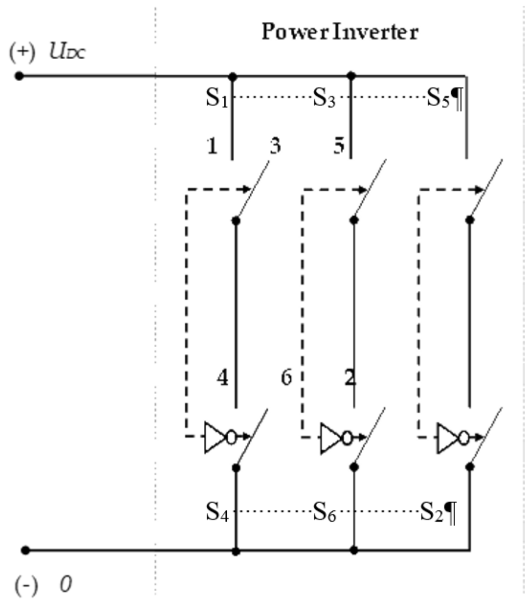


**Figure 1.** The two-level power inverter topology.

Based on the switching function of legs of the inverter, a space vector switching function may be defined:

$$\mathbf{S} = \frac{2}{3}(S_a + \mathbf{a}S_b + \mathbf{a}^2 S_c), \tag{21}$$

where $\mathbf{a} = -1/2 + j\sqrt{3}/2$ is the rotational operator used for the three-phase coordinate representation.

The output voltage of the power inverter results as a function of DC link voltage $U_{DC}$:

$$u_{s,anc} = U_{DS}\mathbf{S}, \tag{22}$$

where $U_{DS}$ is the Direct Current link voltage.

The MPC control law is formulated as an optimization problem which found the best switching function combination [8]:

$$\min_{\mathbf{S}} g(\mathbf{S})$$
$$s.t.: \; g = \left\| \tau^{ref} - \tau^{p}(k+1) \right\| + \delta_{\psi} \left\| \psi_{s}^{ref} - \psi_{s,\alpha\beta}^{p}(k+1) \right\|, \tag{23}$$

where $\delta_{\psi}$ is the flux weight factor.

The stator magnetic flux reference is selected to have a constant value or to decreasing, depending on the mechanical speed range:

$$\psi_{s}^{ref} = \begin{cases} \psi_{sN}, & \|\omega\| \le \omega_{n} \\ \psi_{sN} \dfrac{\omega_{n}}{\|\omega\|}, & \|\omega\| > \omega_{n} \end{cases}. \tag{24}$$

The block scheme of the IM cascade MPC structure is depicted in Fig. 2. The IM is supplied by a power electronic inverter from Fig. 1.

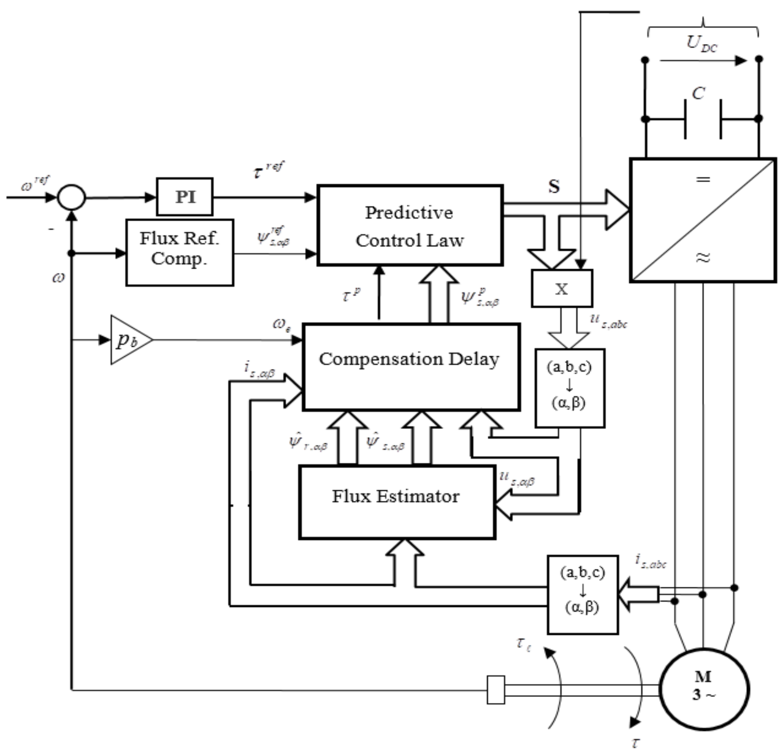


**Figure 2.** The two-level power inverter topology.

The inner loop of the cascade structure is designed for controlling both magnetic flux and electromagnetic torque by a MPC space-state multivariable controller according to (23).

To obtain a fast speed response, the outer loop is designed via a classical PI controller by classical pole placement method [3].

The structure is developed in the coordinates $(\alpha, \beta)$, and for ensuring the compatibility of $\alpha\beta$ model with the natural *abc* model, there are used coordinates transformations as it is shown in Fig. 2.

At last, the MPC law requires the knowledge of DC-link voltage $U_{DC}$ of the power inverter that is considered constant on the entire operation domain.

### 4. Simulation results

In the previous section has been established the IM control law for a cascade structure. To prove the performances above mentioned in MPC IM control structure, it is considered a case study for an IM with the parameters given by Table 1.

**Table 1.** IM model parameters

| No. | Quantity | Symbol | Value | Unit |
|---|---|---|---|---|
| 1. | Stator resistance | $R_s$ | 1.2 | Ω |
| 2. | Rotor resistance | $R_r$ | 1 | Ω |
| 3. | Stator inductance | $L_s$ | 175e-3 | H |
| 4. | Rotor inductance | $L_r$ | 175e-3 | H |
| 5. | Magnetizing inductance | $L_r$ | 175e-3 | H |
| 6. | Rotor inertia | $J$ | 0.063 | kg·m$^2$ |

The discretizing process of the MPC algorithm is accomplished with the time sampling period $T_s = 4e-5$.

A speed stairs-steps profile of speed reference is adopted, with operation, at starting for 1 second in no-weakening regime, and then for 1 second in weakening regime, and finally return for 1 second in no-weakening, as depicted in Fig. 3. The study considers the results obtained for the rated value of stator resistance $R_s$ and for a stator resistance value equal to $R_s \cdot 1.2$ which can often appear in practice. It can be easily observed from Fig. 3 that, for rated conditions, the MPC control presents acceptable speed response. In the case of stator resistance variation, the setting time of speed is increased and, supplementary appear unwanted variations. For the IM drive, it is applied a step load torque $\tau_l = 2Nm$. Compared with electromagnetic torque obtained in rated conditions, in case of stator resistance variation, the electromagnetic torque presents a slow fluctuation and an unwanted dynamic component, as illustrated in Fig. 4. Overall, we can appreciate that MPC control law remains robust on speed response despite unwanted electromagnetic torque variations. However, the rejection of the load torque disturbance is efficiently done.

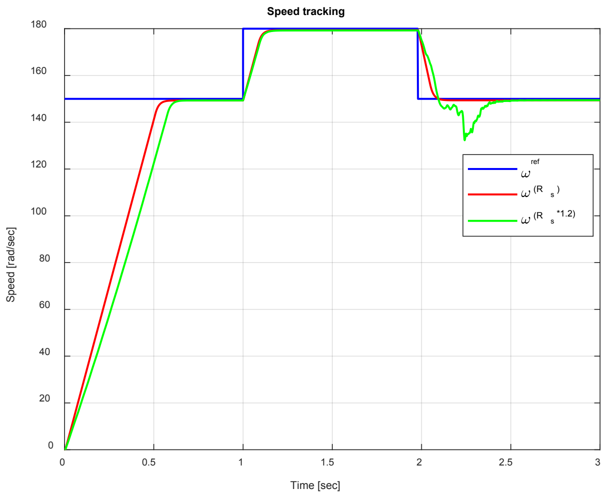


**Figure 3.** Speed responses of IM drive.

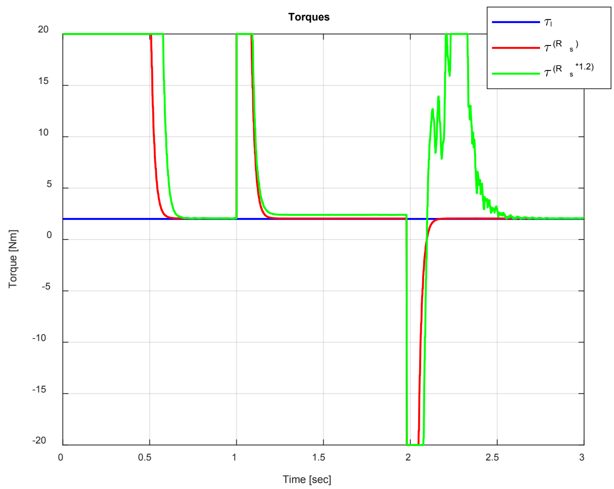


**Figure 4.** Load and electromagnetic torques.

The stator phase currents are depicted in Fig. 5. It is clearly that, in steady-state regime, they are insignificant. In dynamic regime there are increased peak values as a consequence of stator resistance modifications.

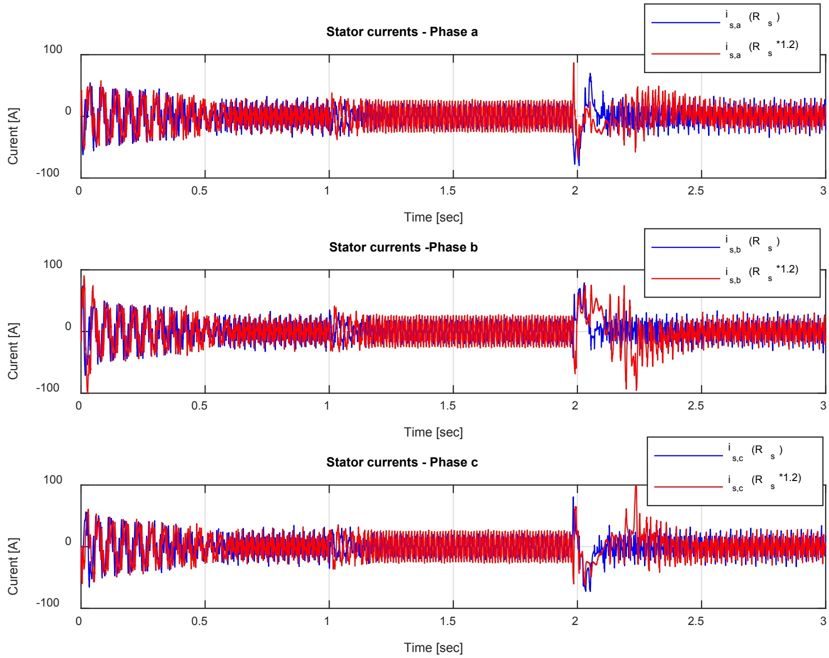


**Figure 5.** Stator phase currents.

## 5. Conclusions

The MPC control strategy is a high-performance control law that ensures reliable results for advanced IM drives. Compared with the classical linear controller PI, the MPC law presents an optimal law implemented without modulator of frequency, the power electronic inverter being taking into account for designing the optimal control law.

High speed tracking results and load torque disturbance rejection of IM has been proven by simulation in both field-wakening regime and up to rated speed situations.

A robust feature of the MPC law has been also shown at stator resistance variation, and it is important to highlight that the operation remains stable in this case that occurs in practical situation. The speed and phase currents present acceptable differences, which show the robust feature of the MPC advance control strategy.

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