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Achieving High-Quality Performance in AC Machines with a Very Simple Model Predictive Control Strategy

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Abstract—This paper presents a new and very simple strategy for torque and flux control of AC machines. The method is based on Model Predictive Control and uses one cost function for the torque and a separate cost function for the flux. This strategy introduces a drastic simplification, achieving a very fast dynamic behavior in the controlled machines. Experimental results obtained with an induction machine confirm the drive's very good performance.

Index Terms—Predictive Control, Drives, Power Electronics

1. INTRODUCTION

The control of electrical machines has been one of the most classical and challenging problems of electrical engineering. With the explosive development observed in electromobility in the last decade, the control of electrical machines is of highest interest for industry today. Two strategies are widely accepted as standard solutions for high performance AC drives: Field Oriented Control (FOC) and Direct Torque Control (DTC). FOC was invented in 1972 [1], [2] and DTC was invented in 1986 [3], [4]. these strategies were developed more than 30 years ago, at a time where modern microprocessors were not available. Microprocessors have since been used to improve the performance of these strategies without introducing significant changes in the basic concepts of the theories. However, the tremendous calculation power available today at high speeds and reduced costs makes it possible to develop different control strategies. In effect, Model Predictive Control is one of these modern control strategies that use microprocessors' calculation power differently in the field of power electronics [5]–[15]. Up to now, the Finite Control Set Model Predictive Control (FCS-MPC) of torque and flux of AC machines has been done mainly using a single cost function with a weighting factor to give more importance to one of these control objectives [16]–[18]. The calculation of the weighting factor has been one of this control strategy's important challenges. In most cases, the weighting factor is obtained by a trial and error process that is not easy or elegant, nor is it acceptable for many users [13]– [15], [19]–[23]. This paper presents a new strategy for predictive torque and flux control of AC machines that does not use weighting factors. This strategy is called Sequential Model Predictive Control (SMPC), and it uses a sequential structure with a single cost function for each control objective in the system. The first stage controls the torque, and the second stage is dedicated to controlling the flux. The resulting strategy solves in a very simple and logical way, all the problems and difficulties related to the calculation of the weighting factors. The following sections of the paper will present the mathematical models for the machine and the inverter, the prediction equations, the control strategy and the experimental results obtained with an induction machine.

2. MATHEMATICAL MODELS

The inverter used in this work is the 2-level Voltage Source Inverter (2L-VSI). Fig. 1 shows the power circuit of the 2LVSI. This inverter is the simplest and most mature power inverter technology; it has only two power switches for each output leg that work complementarily, but it generates a large harmonic content. However, as the focus of this work is the control strategy, this simple inverter is used. Fig. 2 shows the possible voltage vectors generated by the 2L-VSI. There are eight possible voltage vectors described in

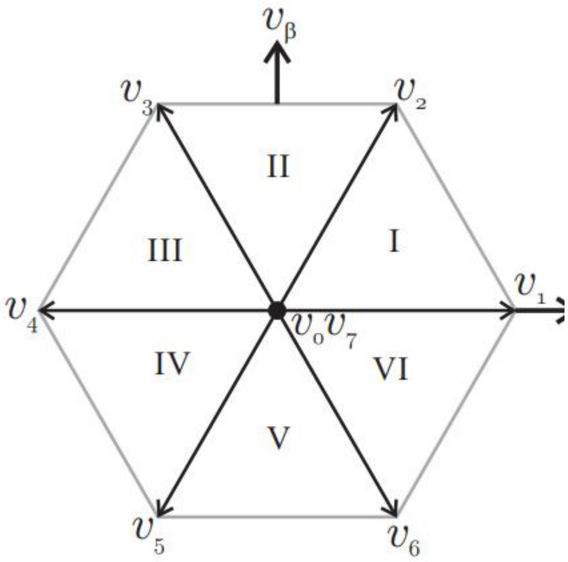

Fig. 2: Vectors of the 3-phase 2L-VSI.

TABLE I: Possible switching states of 3 phase 2L-VSI

	Switching State			Voltage Vector	
	S_A	S_B	S_C	v_α	v_β
v_0	0	0	0	0	0
v_1	1	0	0	$2V_{DC}/3$	0
v_2	1	1	0	$V_{DC}/3$	$\sqrt{3}V_{DC}/3$
v_3	0	1	0	$-V_{DC}/3$	$\sqrt{3}V_{DC}/3$
v_4	0	1	1	$-2V_{DC}/3$	0
v_5	0	0	1	$-V_{DC}/3$	$-\sqrt{3}V_{DC}/3$
v_6	1	0	1	$V_{DC}/3$	$-\sqrt{3}V_{DC}/3$
v_7	1	1	1	0	0

Table I, and vectors v0 and v7 are the null voltage vectors (vα = 0; vβ = 0). The mathematical equations that describe the 2L-VSI are:

$$v_a = S_a \frac{V_{DC}}{2}$$
$$v_b = S_b \frac{V_{DC}}{2}$$
$$v_c = S_c \frac{V_{DC}}{2}$$

The voltage in α − β frame can be written as:

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \frac{2}{3} V_{DC} \begin{bmatrix} 1 & -0.5 & -0.5 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix}$$

Model of the Induction Machine

To generate the mathematical model of the induction machine (IM) the stator flux Ψs and stator current is are taken as state variables. The dynamic equations of IM can be expressed in stationary frame as follow

$$\begin{aligned} \mathbf{v_s} &= R_s \mathbf{i_s} + \frac{\mathrm{d}\boldsymbol{\Psi}_\mathbf{s}}{\mathrm{d}t} \\ 0 &= R_r \mathbf{i_r} + \frac{\mathrm{d}\boldsymbol{\Psi}_\mathbf{r}}{\mathrm{d}t} - j\frac{\omega}{p}\boldsymbol{\Psi}_\mathbf{r} \\ \boldsymbol{\Psi}_\mathbf{s} &= L_s \mathbf{i_s} + L_m \mathbf{i_r} \\ \boldsymbol{\Psi}_\mathbf{r} &= L_m \mathbf{i_s} + L_r \mathbf{i_r} \\ T &= \frac{3}{2} p |\boldsymbol{\Psi}_\mathbf{s} \otimes \mathbf{i_s}| \\ J\frac{\mathrm{d}\omega}{\mathrm{d}t} &= T - T_L \end{aligned}$$

where vs is the voltage vector, ω denotes the rotor angular speed, p is the pair of poles, and Rs and Rr are the stator and rotor resistance, respectively. Ls, Lr and Lm are the stator, rotor and mutual inductance, respectively. Finally, T and TL are the electrical torque and load torque, respectively.

3. EQUATIONS FOR PREDICTION

For prediction of torque and flux [8], [14], [20], estimation of the stator flux Ψs and the rotor flux Ψr are required at the present sampling time k. The rotor flux can be calculated using the equivalent equation of the rotor dynamics of an IM in rotating reference frame aligned with the rotor winding, which gives:

$$\mathbf{\Psi_r} + \tau_r \frac{d\mathbf{\Psi_r}}{dt} = L_m \mathbf{i_s}$$

where τr = Lr/Rr is the rotor time constant. Using the backward-Euler discretization and considering Ts as the sampling time, the discrete-time equation for the rotor flux estimation is as follows:

$$\mathbf{\Psi_r}^k = L_m \frac{T_s}{\tau_r}\mathbf{i_s}^{k-1} + \left(1-\frac{T_s}{\tau_r}\right)\mathbf{\Psi_r}^{k-1}$$

The stator flux can be estimated by the equation:

$$\mathbf{\Psi_s}^k = \frac{L_m}{L_r}\mathbf{\Psi_r}^k + \left(1-\frac{L_m^2}{L_s L_r}\right)\mathbf{i_s}^k$$

Now, the stator flux prediction is obtained by the forwardEuler discretization:

$$\mathbf{\Psi_s}^{k+1} = \mathbf{\Psi_s}^k + T_s\mathbf{v_s}^k - T_s R_s\mathbf{i_s}^k$$

The stator current prediction is also obtained by the forwardEuler discretization:

$$\mathbf{i_s}^{k+1} = C_1\mathbf{i_s}^k + C_2\mathbf{\Psi_s}^k + \frac{T_s}{L_\sigma}\mathbf{v_s}^k$$

Finally, the torque prediction depends on the stator flux and stator current predictions and can be written as follow:

$$T^{k+1} = \frac{3}{2}p|\mathbf{\Psi_s}^{k+1} \otimes \mathbf{i}_\mathbf{s}^{\mathbf{k+1}}|$$

4. THE CONTROL STRATEGY

The proposed control strategy, called Sequential Model Predictive Control (SMPC), uses a cascade structure to control more than one control objective. The strategy uses a sequence of cost functions to control each control objective. Instead of using a single cost function with several control objectives related by a weighting factor, the problem is solved by using different cost functions, each of which is dedicated to controlling a single control objective. It should be noted that in the implementation of the predictive control strategy, the delay in the application of the optimal vector must be considered because the measurement, the data processing, and the optimization algorithm are not instantaneous. To compensate for this delay, the control variables should be predicted for the future instant k +2. This delay compensation strategy is well documented in [26]. The block diagram of the SMPC strategy is presented in Figure 3. The error between the reference speed (ω ∗) and the measured speed (ω) is introduced to a Proportional-Integral (PI) controller, which delivers the reference Torque (T ∗) to be generated by the machine. The cost function for the torque control (g1) is given by:

$$T^{k+2} = \frac{3}{2}p|\mathbf{\Psi_s}^{k+2} \otimes \mathbf{i}_\mathbf{s}^{\mathbf{k+2}}|$$

This cost function is represented by block 2 of the block diagram in Fig. 3. In addition, g1 is calculated for all seven different voltage vectors generated by the inverter. The two voltage vectors that generate the smallest values for g1 (that is, the smallest error) are selected for the next control step, which corresponds to the minimization of the flux error. This action is performed by the cost function g2, which corresponds to the flux error, defined by

$$\mathbf{\Psi_s}^{k+2} = \mathbf{\Psi_s}^{k+1} + T_s\mathbf{v_s}^{k+1} - T_s R_s \mathbf{i_s}^{k+1}$$

This cost function is evaluated for each of the two voltage vectors selected by the previous step of torque control. This operation is represented by block 3 in Fig. 3. Finally, the voltage vector that minimizes g2 is selected and delivered to the load.

TABLE II: Test bench parameters

Parameter	Value
DC link voltage V_{DC}	582V
R_s	2.68Ω
R_r	2.13Ω
L_m	275.1mH
L_s	283.4mH
L_r	283.4mH
p	1
ω_{nom}	2772.0RPM
T_{nom}	7.5 Nm
J	0.005kg/m^2

The test-bench consists of two 2.2 kW squirrel-cage induction motors, the load side and main motors. The load side machine is driven by a Danfoss VLT FC-302 3.0 kW inverter. The main motor is driven by a modified SERVOSTAR620 14 kVA inverter that provides full control of the IGBT gates. A self-made 1.4 GHz real-time computer system is used. The rotor position is measured by a 1024-point per revolution incremental encoder. The sampling frequency is 16kHz. The average switching frequency is around 3.3kHz. Table II shows the parameters of the test bench and Fig. 5 shows the equipment used in the laboratory

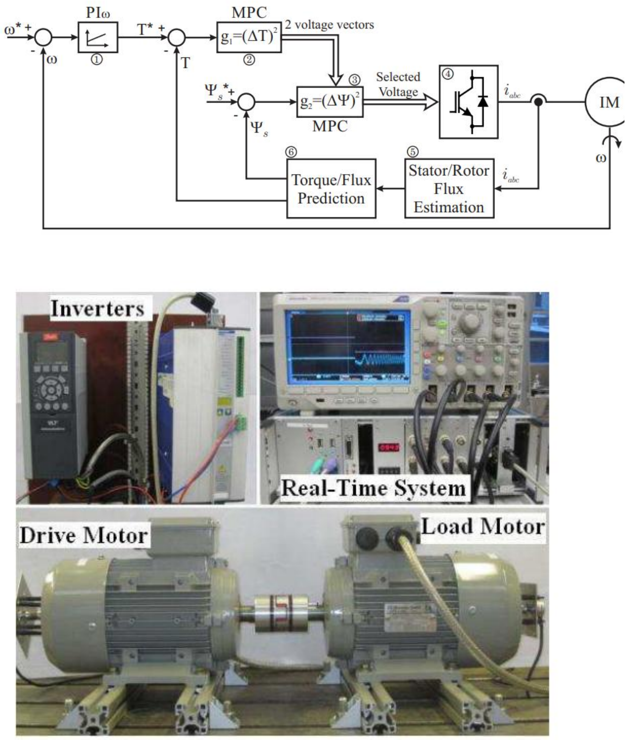

Fig. 2: Experimental test bench.

A relevant report can be seen in [27] as well. But, this is not our major goal in this paper, therefore, we could not deal this with more details. Fig. 8 shows the transient behavior of the torque in greater detail. The variables included in this figure are: reference torque (T∗), torque (T) and stator current (iα). It can be observed that the torque reaches the reference in less than 1 ms. However, a PI controller could be adjusted so that the transient response is as fast as possible. The design procedure for this purpose is the magnitude optimum method.

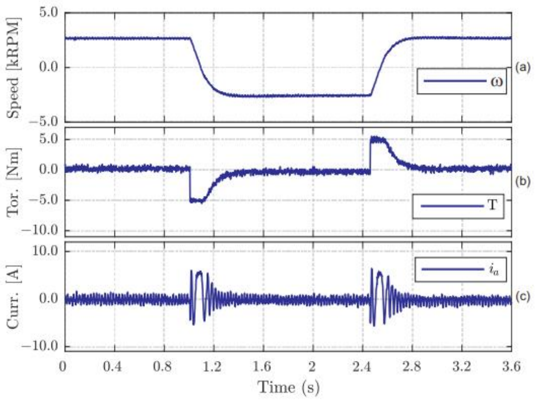

Fig. 3: Experimental results for speed reversal of ±2772 RPM: (a) Rotor speed (ω); (b) Torque (T); (c) Stator current (ia).

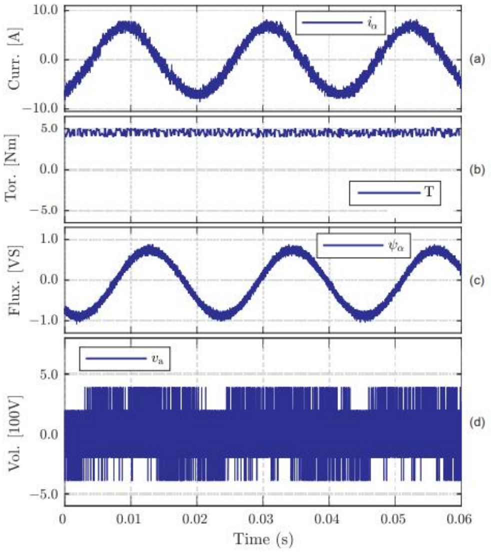

Fig. 4: Experimental results for steady state: (a) Stator current (iα); (b) Torque (T); (c) Stator Flux (ψα); (d) Stator voltage (va).

The position of the stator flux in the complex plane must be identified by the control to select the right direction of the lookup table. None of these important and necessary features are needed or considered using our proposed strategy, making it much simpler than DTC. Fig. 9 shows the block diagram of DTC and the standard MPC. It is possible to see that DTC is different from MPC schemes (standard or proposed), and as the standard MPC uses only one cost function with a weighting factor, also it

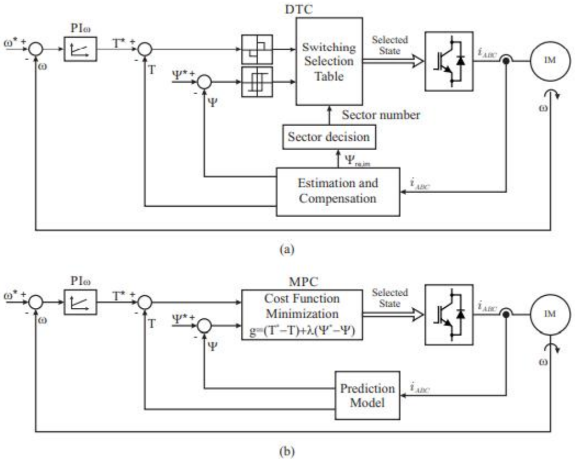

Fig. 5: Block diagram of: (a) DTC; (b) Standard MPC.

5. CONCLUSIONS

This paper has presented a new and very simple strategy for high performance control of an induction machine called Sequential Model Predictive Control (SMPC). The method uses the approach of Model Predictive Control and is based on the fundamental equations of the machine and of the inverter. SMPC calculates the variables of the system in a sequential way using a single cost function for each control objective. Moreover, this work demonstrates that it is not necessary to use weighting factors to control torque and flux when using predictive control. Experimental results confirm that the strategy effectively controls torque and flux. This simple strategy eliminates the problem of calculating any weighting factor. MPC is conceptually different from established strategies for high performance control of AC machines. It uses the capabilities of modern microprocessors and the discrete analysis of the system to be controlled (inverter and machine) in a simple way. Finally, these results confirm that this strategy is a very attractive and promising alternative for high performance AC drives.

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