

Model Based Predictive Current Control of an Asynchronous Six-phase Motor Drive

R. Gregor¹, F. Barrero¹, M.J. Durán², M.R. Arahal¹ and S. Toral¹

¹ Electronic & System and Automation Engineering Departments
E.S.I.I., University of Seville

Camino de los Descubrimientos s/n, 41092 Sevilla (Spain)

Phone/Fax number:+0034 954481293, e-mails: rgregor@esi.us.es, fbarrero@esi.us.es, arahal@esi.us.es, toral@esi.us.es

² Electrical Engineering Department

E.S.I.I., University of Malaga

Pza.del Ejido s/n, 29120 Malaga (Spain)

Phone/Fax number:+0034 952132707, e-mail: mjduran@uma.es

Abstract. A new method for current control of multiphase drives is presented. The proposed control method is based on a model based predictive controller which minimises a predefined function cost. A voltage vector to minimise the current error is selected. A discrete-time model of the drive is also used to generate the control signals. Simulation and experimental results are provided. These preliminary results confirm the feasibility of the presented method for controlling an asymmetrical dual three-phase ac machine.

Keywords

Multi-phase systems, current control techniques, model based predictive control.

1. Introduction

Multiphase motor drives have been recently proposed instead of conventional three-phase ones for applications where some specific advantages (lower torque pulsations, less DC link current harmonics, higher overall system reliability, better power distribution per phase) can be better exploited [1]. Among these multiphase motor drives, symmetrical and asymmetrical dual three-phase ac machines have been used in specific applications since the late 1920s [2].

Current control in conventional and multiphase motor drives is usually based on controllers with sub harmonic voltage modulation (PWM or Space Vector) techniques [3]–[6]. Model Based Predictive Control (MBPC) is a well established control discipline with a fair number of applications in industry. The main handicap of MBPC is the use of intensive computations, which hinders its applicability to fast processes. The increase in computing power of DSPs makes MBPC plausible for controlling modern power converter and electrical drives, although linear models of the real system have been normally used. In [7] and [8] a predictive controller is designed to

control a 3-phase electrical machine. The controller optimizes a cost criterion based on reference tracking for the next sampling period, which is equivalent to a prediction and control horizon of one step. Furthermore, the model in [7] and [8] is based in a RL load allowing for a simple estimation of the Back Electromotive Force.

In this paper, the aforementioned ideas are extended in two directions. First, the MBPC technique is applied for multiphase drives considering an asymmetrical six-phase motor drive. Second, the model used takes into account the whole electrical dynamics of the machine. A discrete time model of an asymmetrical six-phase motor drive is used to predict the behaviour of the current for each different voltage vector generated by a 6-phase inverter. Then, a vector which minimises a quality function cost is selected based on the switching effort and the current error. The work shows the benefits of using a predictive controller in multiphase drives, avoiding the application of complex modulation strategies.

2. MBPC method for current regulation

Figure 1 shows the system, based on a 6-phase Inverter and the electrical machine. The possible voltage vectors generated by the inverter are also shown in Fig. 2.

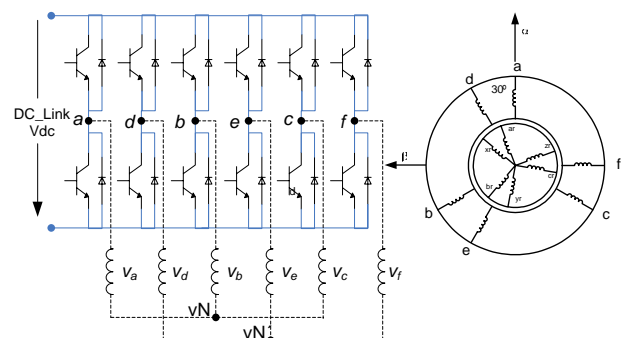


Fig. 1. Asynchronous 6-phase motor drive.

A predictive controller is composed of the following elements: predictive model, cost function and optimizer. The proposed controller uses a state–space discrete–time model of the system to predict the future value of the stator current, $i_s(k+1)$, for a sampling time T_m and each possible imposed stator voltage vector, $v_s(k)$, and it is obtained using the Vector Space Decomposition (VSD) theory [9] (notice that the two stator sets of the electrical machine is supposed to have isolated neutral points, so that no current components flow in the z_1 – z_2 subspace) as it is shown in equations (1).

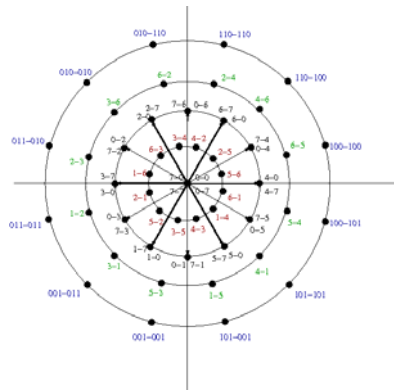


Fig. 2. Stator voltage vectors.

where p is the time derivative operator, and R_s, L_s, R_r, L_r and L_m are the electrical parameters of the machine. The torque production involves only quantities in the α – β subspace, and consequently, the model can be simplified

$$p \cdot i_{\alpha s} = c_2 \cdot (u_{\alpha s} - R_s \cdot i_{\alpha s}) + c_3 \cdot (R_r \cdot i_{\alpha r} + \omega_r \cdot i_{\beta r} \cdot L_r + \omega_r \cdot i_{\beta s} \cdot L_m) \quad (1)$$

$$p \cdot i_{\beta s} = c_2 \cdot (u_{\beta s} - R_s \cdot i_{\beta s}) + c_3 \cdot (R_r \cdot i_{\beta r} - \omega_r \cdot i_{\alpha r} \cdot L_r - \omega_r \cdot i_{\alpha s} \cdot L_m)$$

$$p \cdot i_{\alpha r} = c_3 \cdot (-u_{\alpha s} + R_s \cdot i_{\alpha s}) + c_4 \cdot (-R_r \cdot i_{\alpha r} - \omega_r \cdot i_{\beta r} \cdot L_r - \omega_r \cdot i_{\beta s} \cdot L_m)$$

$$p \cdot i_{\beta r} = c_3 \cdot (-u_{\beta s} + R_s \cdot i_{\beta s}) + c_4 \cdot (-R_r \cdot i_{\beta r} + \omega_r \cdot i_{\alpha r} \cdot L_r + \omega_r \cdot i_{\alpha s} \cdot L_m)$$

$$p \cdot i_{x s} = c_5 \cdot (u_{x s} - R_s \cdot i_{x s})$$

$$p \cdot i_{y s} = c_5 \cdot (u_{y s} - R_s \cdot i_{y s})$$

$$c_1 = L_s \cdot L_r - L_m^2; c_2 = \frac{L_r}{c_1}; c_3 = \frac{L_m}{c_1}; c_4 = \frac{L_s}{c_1}$$

$$i_{\alpha s}(k+1) = (1 - T_m \cdot c_2 \cdot R_s) \cdot i_{\alpha s}(k) + T_m \cdot c_3 \cdot \omega_r(k) \cdot i_{\beta s}(k) \cdot L_m + T_m \cdot c_2 \cdot u_{\alpha s}(k) - T_m \cdot c_3 \cdot \overline{e_{\alpha s}}(k) \quad (2)$$

$$i_{\beta s}(k+1) = (1 - T_m \cdot c_2 \cdot R_s) \cdot i_{\beta s}(k) - T_m \cdot c_3 \cdot \omega_r(k) \cdot i_{\alpha s}(k) \cdot L_m + T_m \cdot c_2 \cdot u_{\beta s}(k) - T_m \cdot c_3 \cdot \overline{e_{\beta s}}(k)$$

$$\overline{e_{\alpha s}}(k) = -R_r \cdot i_{\alpha r}(k) - L_r \cdot \omega_r(k) \cdot i_{\beta r}(k)$$

$$\overline{e_{\beta s}}(k) = -R_r \cdot i_{\beta r}(k) + L_r \cdot \omega_r(k) \cdot i_{\alpha r}(k)$$

$$g_{\alpha}(k) = -T_m \cdot c_3 \cdot \overline{e_{\alpha s}}(k) \quad (3)$$

$$g_{\beta}(k) = -T_m \cdot c_3 \cdot \overline{e_{\beta s}}(k)$$

$$h_{\alpha}(k) = (1 - T_m \cdot c_2 \cdot R_s) \cdot i_{\alpha s}(k) + T_m \cdot c_3 \cdot \omega_r(k) \cdot i_{\beta s}(k) \cdot L_m + T_m \cdot c_2 \cdot u_{\alpha s}(k)$$

$$h_{\beta}(k) = (1 - T_m \cdot c_2 \cdot R_s) \cdot i_{\beta s}(k) - T_m \cdot c_3 \cdot \omega_r(k) \cdot i_{\alpha s}(k) \cdot L_m + T_m \cdot c_2 \cdot u_{\beta s}(k)$$

and must be discretised in order to be of use for the predictive controller. A forward Euler method is used since the resulting equations will have the needed digital control form, with predicted variables depending just on past values and not on present values of variables. For the six-phase or dual three-phase electrical machine this results in equations (2).

With equations (2), and defining $g_{\alpha}(k), g_{\beta}(k), h_{\alpha}(k)$, and $h_{\beta}(k)$ as shown in equations (3), it is possible to produce a one–step prediction for the stator currents at discrete time $(k+1)$, $\hat{i}_s(k+1|k)$, given the measured past currents, $i_s(k)$, the past imposed stator voltage, $u_s(k)$, and the estimated values $\hat{g}_{\alpha}(k)$ and $\hat{g}_{\beta}(k)$, as follows:

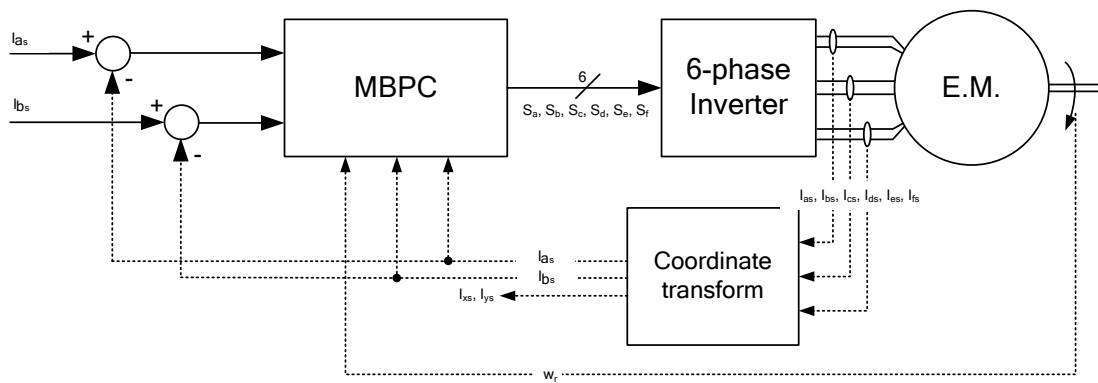
$$\hat{i}_{\alpha s}(k+1|k) = h_{\alpha}(k) + \hat{g}_{\alpha}(k) \quad (4)$$

$$\hat{i}_{\beta s}(k+1|k) = h_{\beta}(k) + \hat{g}_{\beta}(k)$$

where $\hat{g}_{\alpha}(k)$ and $\hat{g}_{\beta}(k)$ can be recursively obtained considering that their original values are zero and the following equations:

$$\hat{g}_{\alpha}(k) = \hat{g}_{\alpha}(k-1) + (i_{\alpha s}(k) - \hat{i}_{\alpha s}(k|k-1)) \quad (5)$$

$$\hat{g}_{\beta}(k) = \hat{g}_{\beta}(k-1) + (i_{\beta s}(k) - \hat{i}_{\beta s}(k|k-1))$$



```

Wait until next sampling period
Read future reference for current: i*s(k+1);
Read current and speed measurements for sample k
Produce an estimation of the g parameters
Initiate Jo to Inf
For each possible gating signal combination of indices i=1 to 49
  Produce an estimation of next stator current using model
  Evaluate J
  If J < Jo
    Jo <- J
    io <- i
  endif
endfor
Apply the stator voltage associated with index io

```

Fig. 3. MBPC method.

Consequently, the current values of the stator current are measured and used with the predictive model to generate predictions of the future stator current, one for each possible imposed stator voltage vector (49 possibilities as it is shown in the right side of Figure 1). These predictions are evaluated with a cost function J , and the vector that minimises this function is applied during the next sampling interval. The cost function is expressed in orthogonal co-ordinates in the following form:

$$J = \left(\hat{i}_s^*(k+1) - \hat{i}_s(k+1) \right) \left(\hat{i}_s^*(k+1) - \hat{i}_s(k+1) \right)^T, \quad \text{where}$$

$\hat{i}_s^*(k+1)$ is the stator reference current and t represents the transpose operator. To make things clearer, a pseudo code of the control algorithm is provided in Fig. 3, as well as a block diagram of the proposed control system.

3. Simulation Results

A Matlab/Simulink simulation environment has been designed for the dual 3-phase induction machine, and some simulations have been done to prove the effectiveness of the proposed control method. Simulation results are shown in Figures 4 and 5. In order to optimise the control action, the predictive model must be used 49 times. In this way, the cost function is extensively evaluated, and the active stator voltage vector to be applied is computed. However, simpler exploratory search strategies, considering less than 49 stator voltage vectors, can be used. For instance, the x-y stator current components are not related with electromechanical energy conversion, and they are only responsible of circulating harmonic currents. Consequently, the applied voltage vectors should contain minimum amplitude x-y components. By choosing the switching vectors that permit to have the maximum α - β amplitude, the x-y stator current components are minimized [9]. The

obtained reduction in computing time favors the real-time implementation of MBPC, although the performance characteristics can be also reduced because it is a sub-optimal solution. The proposed control method has been implemented using 49 and 13 possible stator voltage vectors, and the switching frequency of the power devices is limited to 1 and 5kHz, respectively. A step in the reference current has been applied, and transient and steady state responses are very promising. Notice that the amplitude of the x-y stator current components are slightly higher in the optimal case than in the sub-optimal one. This is due to the higher switching frequency applied (lower computing time is necessary) to power devices when using 13 possible stator voltage vectors.

4. Real-time Implementation Results

The MBPC method which requires the selection of the proper active vector is a heavy time consuming task, and the proposed algorithm has been implemented using a 32 bit floating point Texas Instruments DSP (TMS320C6711 with a clock frequency of 150 MHz and 16 Kbytes two-way set associative instruction/data cache memory) to perform a feasibility analysis. Table I shows the real-time implementation results obtained with the profiling tools included in DSP/BIOS. These results show the execution time once the algorithm has been implemented and stored in the cache memory. The predictive model must be used 49 times to evaluate the function cost, and to decide the active vector to be applied. It can be observed that evaluating the 49 possible stator voltages, the maximum switching frequency of the power devices is limited to about 1kHz. This limitation decreases reducing the number of times the predictive model is used. Considering less than 49 stator voltages,

the maximum switching frequency of the power devices arises till 5 kHz using for instance the 13 stator voltages that produce minor x-y stator current components. Notice that switching frequency data have been obtained considering a clock rate of 150 MHz, and these values can be improved using higher frequency clock rates.

TABLE I. - Real time implementation results

Number of vectors	13	25	49
Total (cycles)	26175	50152	96388
Switching frequency (kHz)	5,73	2,79	1,56

4. Conclusion

A predictive current control strategy for multiphase electrical drives has been presented. The practical implementation of the control system has been discussed in detail. Simulation results have been also obtained, showing that the proposed method controls very

effectively the current of a dual three-phase induction machine, having good dynamic and steady-state responses. Finally, although the application of a MBPC method is hinged by the fact that the computation of the control signal requires a large amount of computing time which is not available for most control systems, results that guarantee its implementation on a DSP have been also provided. Consequently, the high calculation power of existing DSPs makes the presented method an alternative to other classical methods, like SVPWM current regulation.

Acknowledgement

The authors gratefully acknowledge the Spanish Government for the economical support provided within the National Research, Development and Innovation Plan, under reference DPI2005/04438.

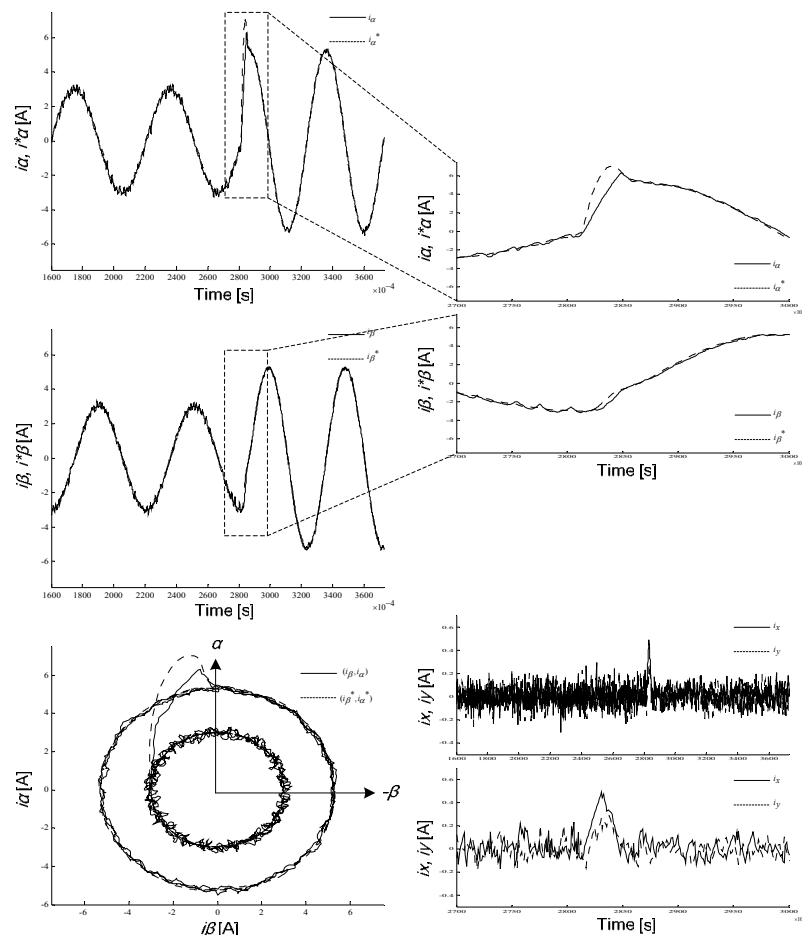


Fig. 4. Simulation results for a step in the reference current. MBPC method using the 49 possible stator voltages. The switching frequency of the power devices is limited to 1kHz.

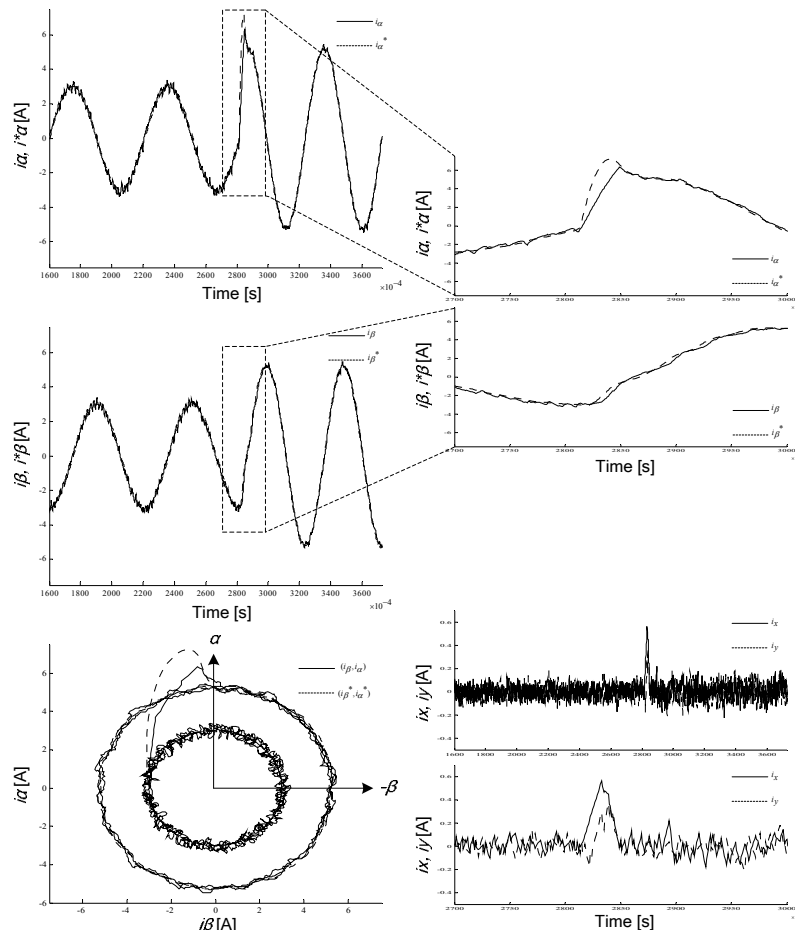


Fig. 5. Simulation results for a step in the reference current. MBPC method using the 13 possible stator voltages (those that produce minor x-y stator current components). The switching frequency of the power devices is limited to 5kHz.

References

- [1]. Levi, E.; Bojoi, R.; Profumo, F.; Toliyat, H.A.; Williamson, S.: "Multiphase Induction Motor Drives – A Technology Status Review", *Electric Power Applications, IET*, Vol. 1, Iss. 4, pp. 489-516, Jul 2007.
- [2]. Alger, P.L.; Freiburghouse, E.H.; Chase, D.D.: "Double Windings for Turbine Alternators", *Trans. AIEE*, Vol.49, pp.226-244, Jan. 1930.
- [3]. Holtz, J.: "Pulsewidth Modulation Electronic Power Conversion", *Proc. IEEE*, 1994.
- [4]. Karmierkowski, M.P.; Krishnan, R.; Blaabjerg, F.: "Control in Power Electronics", Academic Press, 2002.
- [5]. Bojoi, R.; Tenconi, A.; Griva, G.; Profumo, F.: "Vector Control of Dual-Three-Phase Induction-Motor Drives Using Two Current Sensors", *IEEE Transactions on Industry Applications*, Vol. 42, No. 5, pp. 1284-1292, Sept/Oct 2006.
- [6]. Durán, M. J.; Toral, S.; Barrero, F.; Levi, E.: "Real-Time Implementation of Multi-Dimensional Five-Phase Space Vector Pulse Width Modulation", *Electronics Letter*, Vol. 43, Issue 17, pp. 949-950, Aug 2007.
- [7]. Rodríguez, J.; Pontt, J.; Silva, C.; Salgado, M.; Rees, S.; Ammann, U.; Lezana, P.; Huerta, R.; Cortés, P.: "Predictive Control of Three-Phase Inverter", *IEE Electronics Letters*, Vol. 40, No. 9, April 2004.
- [8]. Rodríguez, J.; Pontt, J.; Silva, C.; Correa, P.; Lezana, P.; Cortés, P.; Ammann, U.: "Predictive Current Control of a Voltage Source Inverter", *IEEE Transactions on Industrial Electronics*, Vol. 54, No. 1, Feb. 2007.
- [9]. Zhao, Y.; Lipo, T.A.: "Space Vector PWM Control of Dual Three-Phase Induction Machine Using Vector Space Decomposition", *IEEE Transactions on Industry Applications*, Vol. 31, No. 5, pp. 1100-1109, Sept/Oct 1995.
- [10]. Hadiouche, D.; Baghli, L.; Rezzoug, A.: "Space-Vector PWM Techniques for Dual Three-Phase AC Machines: Analysis, Performance Evaluation, and DSP Implementation", *IEEE Transactions on Industry Applications*, Vol. 42, No. 4, Jul/Aug 2006.