Comparison of different solutions in predictive control for two PMSM in parallel
Maurice Fadel, Ana-Maria Llor

To cite this version:

Maurice Fadel, Ana-Maria Llor. Comparison of different solutions in predictive control for two PMSM in parallel. 19th World Congress of the International Federation of Automatic Control (IFAC) 2014, Aug 2014, Le Cap, South Africa. pp.11962-11967, 10.3182/20140824-6-ZA-1003.02249. hal-03543643

HAL Id: hal-03543643
https://ut3-toulouseinp.hal.science/hal-03543643
Submitted on 26 Jan 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L’archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.
Comparison of different solutions in predictive control for two PMSM in parallel

MAURICE FADEL 1,2, ANA LLOR 1,2

1 Laboratoire PLasma et Conversion d'Energie - LAPLACE
UMR 5213, CNRS, INPT, UPS : 2 rue Camichel BP7122 - 31071 Toulouse Cedex7, France
2 CNRS; LAPLACE; F-31062 Toulouse, France.

Abstract: The operation of two PMSM in parallel on the same inverter requires taking account of information from the two machines to ensure the stability of the system. Today there are several solutions that address this issue. But about energy efficiency improvement it is important to develop new algorithms. The classical approach is based on a master-slave procedure where the current is controlled only in a master machine and the slave machine is simply connected in parallel. This solution guaranteed stability but losses are not minimal. The predictive control applied to this configuration helps to ensure the stability of the device and gives the possibility to reduce joules losses. In this way 3 predictive control laws are proposed by setting appropriate criteria. The results are compared in terms of dynamic performance and losses. The first law uses the concept of master-slave machine, the second is defined with criteria taking into account in the same way the two machines, and the third uses the concept of virtual vector which gives rise to an implementation of SV-PWM. The results are compared in terms of dynamic performance and losses. The algorithms are tested on an experimental low-power bench.

Keywords: PMSM; Finite Control State-Model Predictive Control; SV-PWM; Dual Machine

I. INTRODUCTION

Today the Permanent Magnet Synchronous Machine (PMSM) is a high performance actuator used both for its dynamic performances and for its energy performance [21]. Therefore, this machine is preferentially used in the field of aeronautics. Overall, for embedded systems, it appears today other specific needs for actuators working in cooperation, i.e. when 2 or more actuators are combined to achieve the same objective. This is the case, for example, of the flaps on the aircraft wings to do a synchronized development of flight surfaces, even when both load torques are different. This is also the case for braking applications, using different actuators distributed and synchronized to a common goal. So, as soon as it concerns the association of several actuators for a same function, it seems reasonable to limit the number of static converters embedded, in order to reduce the weight and volume of the system. This is the context of our work, which considers two PMSM supplied from the same three-phase voltage inverter.

The intensive use of the synchronous machine as an actuator is also related to the autopilot operation, ensuring a rigid link between the rotation frequency and speed [21]. This procedure uses a position encoder and ensures the stability of the machine by the cost function to minimize the criterion. The control law is defined at each moment the machine which will be controlled (Master machine), while the second is just connected in parallel (Slave). If the stability is guaranteed, then it can be interesting to consider the question of energy efficiency and performance of this solution. Indeed, when a single machine is considered, the degrees of freedom of the power inverter allow imposing any desired torque by reducing the consumed current [16]. It is difficult to maintain this property when the inverter feeds two machines, and losses can become important. The deal is therefore to search control laws ensuring the stability of the two machines in order to reduce the energy consumption. The solution is found with a compromise, because supply voltages provided by the power inverter cannot be optimal for both machines at the same time. In this work we will work with a particular control type, which is the Finite Control Set-Model Predictive Control (FCS-MPC). The predictive control is based on a prediction model providing the currents evolution on the d-q axes, for all possible combinations of the inverter switches [10]. The best combination, evaluated using a criterion, is then retained and applied during the next sampling period. The criterion constitutes an arbitration to choose one alternative among all candidate solutions. It is on the criterion choice where we have focused our efforts, by comparing different possibilities, taking into account this particular system containing two machines. Here, we use non-salient poles machines, for which the losses are minimal when the current on the d axis is zero. Three control laws (CL) will be evaluated and compared:

- CL1: from stability considerations, the master machine is chosen and the best control solution is evaluated with a criterion based on the sum of the squares of d-q current errors for the master machine. Only one machine is evaluated in the cost function (master machine).

- CL2: only one criterion is used for both machines, the criterion contains the sum of the squares of both, d-axis and q-axis current errors.

- CL3: the approach start like CL2 method but the selected vector is used as a basis to consider, in a region close to it, a finite number of virtual vectors which will be evaluated by the cost function to minimize the criterion. The control law solution is applied via a SV-PWM technique.

These three control laws are then compared in terms of quality of response and Joule losses, for one reference profile type. The quality of the response is evaluated through the squared error of d-q axes currents.

II. FCS-MPC FOR ONE PMSM

The FCS-MPC was introduced several years ago, she adapted very well to conversion devices energy as static converters [13], [19]. We consider here the PMSM powered by a three phase inverter represented in figure 1. In this paper we consider a non-salient pole PMSM through an application of speed control.
A two-level three-phase inverter has a finite number of possible configurations. The 8 different control states of the inverter are represented in TABLE I. Configurations 0 and 7 are identical in terms of output voltage, so onwards only the combination 7 will be evaluated.

<table>
<thead>
<tr>
<th>i</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>sA</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>sB</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>sC</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

**TABLE I: INVERTER CONFIGURATIONS**

To select the most appropriate vector, an optimal control problem must be solved after definition of a criterion of satisfaction. The voltage vector minimizing this criterion should then be chosen to be applied. The predictive model must be the most accurate possible to predict the future behavior of the system when applying a control combination of the inverter [7].

### A. Model of PMSM (Permanent Magnet Synchronous Machine)

Considering that the magnetic circuit operates in linear regime, the electromotive force is sinusoidal and the magnetic losses and the cogging torque are negligible. Equations of the electrical machine in the d-q frame are expressed as follows:

\[ u_d = R_i i_d + \frac{d\psi_d}{dt} - \omega_e \psi_q \]  \hspace{1cm} (1)

\[ u_q = R_i i_q + \frac{d\psi_q}{dt} + \omega_e \psi_d \]  \hspace{1cm} (2)

Where \( u_d, u_q, i_d, i_q, L, \psi_f \) and \( \psi_d \) represent, respectively, the voltages and stator currents, synchronous inductance and flux in the d-q axes. \( \psi_f \) is the flux generated by the permanent magnets, \( R_i \) the stator resistance, \( \omega_e = n_p \omega_h \) (where \( \omega_h \) is the rotor speed) and \( n_p \) the number of pole pairs. The electromagnetic torque is given by equation (5), and the speed by equation (6).

\[ T_e = \frac{3}{2} n_p (\psi_d i_q - \psi_q i_d) = \frac{3}{2} n_p \psi_f i_q \]  \hspace{1cm} (5)

\[ \frac{d\Theta}{dt} = \omega_r \]  \hspace{1cm} (7)

Where \( J \) represents the inertia of the rotor, \( f \) the coefficient of viscous friction, \( T_l \) the load torque and \( \Theta \) the rotor position. With a low switching period we can consider that during that period the speed remains constant. In this case, the discrete model of the synchronous machine can be expressed as presented in equation (8), where \( T_s \) represents a sampling time:

\[ \begin{bmatrix} i_d(k+1) \\ i_q(k+1) \end{bmatrix} = \begin{bmatrix} 1 - T_s \frac{R_i}{L} & T_s \omega_e(k) \\ -T_s \omega_e(k) & 1 - T_s \frac{R_i}{L} \end{bmatrix} \begin{bmatrix} i_d(k) \\ i_q(k) \end{bmatrix} + \begin{bmatrix} \frac{T_s}{L} & 0 \\ 0 & \frac{T_s}{L} \end{bmatrix} \begin{bmatrix} u_d(k) \\ u_q(k) \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{\omega_e(k)}{L} \end{bmatrix} \psi_f \]  \hspace{1cm} (8)

Thus the prediction of the electromagnetic torque can be achieved by the model (9):

\[ T_e(k+1) = \frac{3}{2} n_p \psi_f i_q(k+1) \]  \hspace{1cm} (9)

### B. Three-phase inverter model

A 2-level 3-phase inverter is used to feed the machine. The mathematical model is given by equation (10).

\[ \begin{bmatrix} u_{AN}(k) \\ u_{BN}(k) \\ u_{CN}(k) \end{bmatrix} = \frac{E}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} S_A(k) \\ S_B(k) \\ S_C(k) \end{bmatrix} \]  \hspace{1cm} (10)

where \( S_x (x = A, B, C) \) represents the switches states.

\[ S_x = 0 \Leftrightarrow u_{xN} = 0 \quad S_x = 1 \Leftrightarrow u_{xN} = E \]  \hspace{1cm} (11)

In fixed \((\alpha, \beta)\) reference frame, stator voltages are represented by equation (12), while in \((d,q)\) reference, they are represented by equation (13):

\[ \begin{bmatrix} u_{\alpha}(k) \\ u_{\beta}(k) \end{bmatrix} = \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 \end{bmatrix} \begin{bmatrix} u_{AN}(k) \\ u_{BN}(k) \\ u_{CN}(k) \end{bmatrix} \]  \hspace{1cm} (12)

\[ \begin{bmatrix} u_d(k) \\ u_q(k) \end{bmatrix} = R(k) \begin{bmatrix} u_{\alpha}(k) \\ u_{\beta}(k) \end{bmatrix} = \frac{2}{3} \text{ER}(k) \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} S_A(k) \\ S_B(k) \\ S_C(k) \end{bmatrix} \]  \hspace{1cm} (13)

Where \( R(k) \) represents the rotation matrix between \((\alpha, \beta)\) to \((d,q)\) frames.

We can define a cost function from the predicted currents on d-q axes. These predictions are marked by the exponent “\(p\)” and, with the values of references, we can write the cost function. Note that, since it is a non-salient pole machine, we impose \( i_{dref} = 0 \). The choice of the control configuration \( s_x (X = A, B, C) \) minimizing the cost function (14) allows imposing the torque while minimizing losses, because the current on the axis \( d \) will be the minimum. In addition, this control ensures the stability of the synchronous machine [10].

\[ g = \sqrt{(i_{qref} - i_{q}^p)^2 + (i_{d}^p)^2} \]  \hspace{1cm} (14)

III. TWO PMSM CONNECTED IN PARALLEL TO ONE INVERTER

The structure is represented in figure 2. There are 2 speed loops, one for each of the machines with a common reference speed \( \omega_{ref} = \omega_{r1} = \omega_{r2} \) since the machines must turn at the same speed. Two PI speed regulators provide the reference torque for each machine, which also depend on the load torque. The control configuration applied to the inverter is unique and built
taking into account the data of the two machines to obtain the desired speed, while ensuring the stability of the whole system.

Fig. 2: Mono inverter dual parallel PMSM

There are 2 speed loops, one for each of the machines with a common reference speed \( \omega_{\text{ref}} = \omega_{r1} = \omega_{r2} \) since the machines must turn at the same speed. Two PI speed regulators provide the reference torque for each machine, which also depend on the load torque. The control configuration applied to the inverter is unique and built taking into account the data of the two machines to obtain the desired speed, while ensuring the stability of the whole system.

The voltages at the terminals of the two machines are identical in the \((\alpha, \beta)\) reference frame and the currents prediction in the machines is given by the following relationships:

\[
\begin{bmatrix}
    i_{d1}^{\text{L2}}(k+1) \\
    i_{q1}^{\text{L2}}(k+1)
\end{bmatrix} = \begin{bmatrix}
    1 - T_e \frac{\Delta t}{\tau_c} & T_e \omega_{r1}^{\text{L2}}(k) \\
    -T_e \omega_{r1}^{\text{L2}}(k) & 1 - T_e \frac{\Delta t}{\tau_c}
\end{bmatrix} \begin{bmatrix}
    i_{d1}^{\text{L2}}(k) \\
    i_{q1}^{\text{L2}}(k)
\end{bmatrix} + \begin{bmatrix}
    0 & \frac{2}{\tau_c} \\
    \frac{2}{\tau_c} & 0
\end{bmatrix} \begin{bmatrix}
    u_{d1}^{\text{L2}}(k) \\
    u_{q1}^{\text{L2}}(k)
\end{bmatrix}
\]

The voltages at the terminals of the machines in the \((d,q)\) reference can be calculated by (16):

\[
\begin{bmatrix}
    u_{d1}^{\text{L2}}(k) \\
    u_{q1}^{\text{L2}}(k)
\end{bmatrix} = \begin{bmatrix}
    \cos \theta_{1}^{\text{L2}}(k) & \sin \theta_{1}^{\text{L2}}(k) \\
    -\sin \theta_{1}^{\text{L2}}(k) & \cos \theta_{1}^{\text{L2}}(k)
\end{bmatrix} \begin{bmatrix}
    u_{d1}(k) \\
    u_{q1}(k)
\end{bmatrix}
\]

Where \( \theta_{1}^{\text{L2}}(k) \) represent the electrical angles associated with the positions of the rotor machines. Here, we consider that these two informations are measurable and delivered by position sensors. Depending on the chosen control law, the cost function is calculated differently.

CL1:

For this control law, first master and slave machines must be identified. To ensure the stability of the system, it is necessary to control the machine with the highest mechanical load angle. So, to determine the master machine, the electrical positions \( \psi_{\text{ref}} , E_2 \) must be compared. The machine that has the smallest value of this angle will be the master machine. Then, for this master machine, the best control vector is obtained by analyzing the following cost function for all the possible inverter configurations.

\[
g = \sqrt{(i_{\text{qref}} - i_{q1}^{\text{p}})^2 + (i_{d1}^{\text{p}})^2}
\]

For this control law the two machines are considered at the same level and the cost function is evaluated by considering currents on the \( d \) and \( q \) axis:

\[
g = \sqrt{(i_{\text{qref}} - i_{q1}^{\text{p}})^2 + (i_{d1}^{\text{p}})^2 + (i_{\text{qref}} - i_{q2}^{\text{p}})^2 + (i_{d2}^{\text{p}})^2}
\]

CL3:

Finally, the selected cost function is the same as in CL2 (eq.19). In addition, the obtained control vector serves as a base to look for a better virtual voltage vector, situated in one of the two adjacent sectors of this base solution, which will lead to a lower value of the cost function [16]. That implies using virtual vectors, which will be defined in a finite number, in order to reduce the computational cost of the algorithm. These virtual vectors are characterized by spaced angular positions of \( \Delta \alpha=10^\circ \), and step amplitudes of \( \Delta V=10 \text{ V} \) from 0 to \( V_{\text{max}} \) (Figure 3).
vector must be reconstructed from two real control vectors of the converter. In order to make comparisons of the simulation results, the sampling frequency is set to 20 kHz for all the methods, which will correspond to the modulation frequency for method CL3. Better results are expected for control laws working at constant switching frequency, since the others (CL1 to CL2) should be evaluated at higher frequencies (≈ 50 kHz) in order to obtain equivalent precision.

![Block scheme of CL3](image)

**IV. TEST PROCEDURE**

The different control laws will be compared under particular load torque (figure 5) profiles. The comparison is based in two indicators, evaluated over the complete time horizon. The first is used to evaluate the dynamic performance of the control (19) and the second to characterize losses by Joule effect (20), only in the machines. Power converter losses are not considered since only the energy efficiency in the PMSM is studied.

![Reference profile of speed](image)

For the losses by Joule effect (20), it is considered only the losses penalties due to the d component of current ($Loss_{s_D}$).

<table>
<thead>
<tr>
<th>$R_s$</th>
<th>2.06(Ω)</th>
<th>$T_s$</th>
<th>$5 \times 10^{-2}(s)$ (20kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{cd}$ = $L_{sq}$ = $L$</td>
<td>$9.15 \times 10^{-3}(H)$</td>
<td>$T_{rms_{res}}$</td>
<td>$5 , N \cdot m$</td>
</tr>
<tr>
<td>$\psi_p$</td>
<td>0.29(Wb)</td>
<td>$V_{DC}$</td>
<td>540 V</td>
</tr>
<tr>
<td>Numbers of pole pairs ($n_p$)</td>
<td>3</td>
<td>Inertia (J)</td>
<td>$7.2 \times 10^{-4}(kg \cdot m^2)$</td>
</tr>
</tbody>
</table>

**TABLE II: PARAMETERS FOR PMSM.**

**V. EXPERIMENTATION PROCESS:**

The experimental test bench, shown in Fig. 6 includes a system with two PMSM (PMSM1 and PMSM2) plugged in parallel to the same inverter. Each motors (800 w) is coupled to its own linear actuator ball screw driven (axis 1 and axis 2) and drives its own slide (slide 1 and slide 2). A third machine (load motor) produces a controlled torque $T_{Ld}$ and drives a third slide. This slide is rigidly connected to the slide 1, so that the torque variation – $T_{Ld}$ is applied to PMSM1. In this system, other load torques applied to the motors are because of the axis frictions (static, Coulomb, viscous and Stribeck friction). Simplified load torque equations are given in (7).

$$
T_{L1} = T_{01} + f_1 \Omega_1 - T_{Ld}
$$

$$
T_{L2} = T_{02} + f_2 \Omega_2
$$

For the losses by Joule effect (20), it is considered only the losses penalties due to the d component of current ($Loss_{s_D}$).

![Experimental setup](image)

**Fig. 6: Experimental setup**

First two control laws (CL1, CL2) will lead to variable-frequency operation in power switches, only the sampled time is constant $T_s$ (20 kHz) which does not set the switching frequency. The last control law (CL3) are based in a SVM - PWM modulation at constant switching frequency of 20 kHz.

Experimental results for the different proposed control methods (CL1 to CL3) are showed next, (Figure 7 to 12). For each control law, are showed:

**Fig. 7: Speed Rotation (rd/s) – CL1**
From these experimental results, we can conclude that model predictive control is an interesting and powerful solution for the management of the synchronous machines in parallel on the same inverter. The observed behavior depends strongly on the selected cost function.

Table III summarizes the results of the 3 control laws giving the numerical values of the indicators. We find that the law of command LC3 guarantees a very good control of the speeds for both machines (the ISE indicator is minimal).

**VI. CONCLUSION:**

Setting two synchronous machines in parallel connected to the same inverter reduces the embedded electronics, and so weight and volume are also reduced. However this power structure shows a stability problem as well as low efficiency of the energy conversion. For this purpose, the predictive control offers various solutions, with control laws acting on predetermined indicators. Three different control laws have been tested, minimizing different cost functions in order to improve the energy efficiency. The voltage inverter gives, at each moment, a voltage (amplitude and phase) which may not be optimal for each of the machines and therefore this opens the way for the optimization. In this sense, a control law based using a finite number of virtual vectors, allows the system reaching a minimum of the cost function lower than with classical algorithms. This method still allows to reduce the value of the criterion in choosing a higher number of virtual vectors which will increase the calculation time. This solution has the characteristics of a PWM command and the dynamic performance of the predictive control. This is a good compromise for our system. Studies should continue to take into account losses in the inverter.

**Reference:**


