Predictive Torque Control - A solution for mono inverter-dual parallel PMSM system
Ngoc Linh Nguyen, Maurice Fadel, Ana-Maria Llor

To cite this version:
Ngoc Linh Nguyen, Maurice Fadel, Ana-Maria Llor. Predictive Torque Control - A solution for mono inverter-dual parallel PMSM system. 2011 IEEE 20th International Symposium on Industrial Electronics (ISIE), Jun 2011, Gdansk, Poland. pp.697-702, 10.1109/ISIE.2011.5984242 . hal-03542238

HAL Id: hal-03542238
https://ut3-toulouseinp.hal.science/hal-03542238
Submitted on 25 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.
Abstract—The objective of this paper is to present a Predictive Torque Control (PTC) algorithm for controlling system composed by two Permanent Magnet Synchronous Motors (PMSM) operating in parallel, fed by a single power inverter. In this system, it is expected that both motors will get the same speed even if they have different conditions of load torque. The principle of PTC algorithm is considered as follows: a model of the system is used to predict the system behavior under a set of configurations of a power inverter, a cost function is built from the predicted values and their references and an optimal algorithm will be solved to find the best configuration to apply to the system in the next time step. Simulation results in Matlab/Simulink indicated that the algorithm (PTC) is well adapted for the synchronism of this system over a wide range of operations.

I. INTRODUCTION

Permanent magnet synchronous machines (PMSM) become more and more popular in industrial motor drive applications such as cars, ships and aircrafts where weight and volume are very important problems. Unlike DC motors, PMSM do not have to face with mechanical problems caused by brush system. Besides, since the rotor flux is produced by magnets, the rotors are not wound as in induction machines. The weight of the rotor and the heat losses will be decreased remarkably. Nowadays, more and more systems use several permanent magnet synchronous machines operating together. A classical system with multi-inverter and multi-machine comprises a three-phase inverter for each machine to be controlled. This structure results in a fully independent operation of each machine because the three-phase voltage systems are generated by different inverters. However, the number of power electronic components is then increased, and the system will be heavy and bulky. Another approach consist in using only one three-phase inverter to supply several permanent magnet synchronous machines. According to this structure, the number of power electronic components is clearly reduced and the volume and the size of the system also decrease consequently. Some studies have been done concerning control problems of these systems in [4] [5]. In [4], two synchronous machines are controlled simultaneously. The quadrature current of each motor, which is proportional to the motor torque, is controlled, while the direct current, which relates to the energy optimization problem, is uncontrolled. Consequently, the power losses are increased. Ref. [5] uses master-slave structure to operate the system.

II. PRINCIPLE OF PREDICTIVE TORQUE CONTROL FOR ONE MACHINE

The proposed control method can be classified as Model based Predictive Control (MPC) and is represented in the PMSM control system (Fig. 1). A model which can represent the real system with adequate accuracy is very important. The rotor position of the two motors is always compared. The motor with the higher load is set as the master one and the rest one is assigned as the slave and is fed by the same voltage as the master. According to this solution, the parameters of two machines must be identical or very close to get the best performances.

In this paper, a predictive controller based on the principle of direct torque control is proposed in order to control the drive system which presented in Fig.3. Two machines are controlled simultaneously by the same control signal obtained from solving a cost function. This method demonstrates the use of predictive control algorithm with variable switching frequency. Therefore, the complexities of modulation techniques can be eliminated, since only one vector is applied in a switching period.

In the first part of this paper, the principle of predictive torque control (PTC) will be presented. The second part will consider the structure of mono inverter dual parallel PMSM system, controlled by the predictive torque controller. The third part shows several simulation results which are stimulated under Matlab/Simulink environment to verify the system performance.
Only a limited number of possible voltage vectors can be generated by an inverter, correlative with the number of configurations (with a two-level inverter is 8). The values of the predicted parameters and their references are considered in a cost function. To select the appropriate voltage vector to be applied to the system, an optimal problem must be solved. The voltage vector that minimizes the cost function is then selected.

1. Model of the Permanent Magnet Synchronous Motor

In this paper, the considered PMSM is non-salient machine. Therefore, the two inductances \( L_d \) and \( L_q \) are equal: \( L_d = L_q = L \). Assume that the magnetic saturation is neglected, the back electromagnetic force is supposed sinusoidal and the eddy current, magnetic hysteresis losses and the cogging torque are very small and then also neglected. The electrical and mechanical equations of a PMSM in \((dq)\) rotor flux reference frame are expressed as follows:

\[
\begin{align*}
\dot{\psi}_d &= L_d \dot{i}_d + \omega_c \psi_q - \omega \psi_d \\
\dot{\psi}_q &= L_q \dot{i}_q + \omega_c \psi_d - \omega \psi_q \quad (1)
\end{align*}
\]

with \( \psi_d = L_i d + \psi_f \quad (2) \)

\[ \psi_q = L_i q \quad (4) \]

where \( u_d, u_q, L_d, \psi_d \) and \( \psi_q \) are respectively \((dq)\) frame stator voltages, currents, inductances and flux-linkages, \( \psi_f \) is the flux generated by the permanent magnet, \( R_s \) is the stator resistance, \( \omega_c = p \omega_r \) (where \( \omega_r \) is the rotor speed), \( p \) is the number of poles pair.

The electromagnetic torque is given by (5)

\[ T_e = p \left( \psi_d i_q - \psi_q i_d \right) = p \psi_f i_q \quad (5) \]

And the mechanical equations of the PMSM are in (6) (7)

\[ T_e - T_L = J \frac{\omega_r}{dt} + f \omega_r \quad (6) \]

\[ \frac{d\theta_r}{dt} = \omega_r \quad (7) \]

where \( J \) is rotor inertia, \( f \) is viscous friction coefficient, \( T_L \) is the load torque and \( \theta_r \) is the rotor position.

With a sampling time \( T_s \) small enough, it can be considered that the stator currents vary linearly and the mechanical parameters including speed and rotor position are constant in one sampling period. In this case, the discrete-time model of a permanent magnet synchronous machine can be obtained as in (8).

\[
\begin{bmatrix}
i_d(k + 1) \\
i_q(k + 1)
\end{bmatrix} = \begin{bmatrix}
1 - T_s R_s & T_s \omega_r(k) \\
-T_s \omega_r(k) & 1 - T_s \frac{R_s}{L}
\end{bmatrix}
\begin{bmatrix}
i_d(k) \\
i_q(k)
\end{bmatrix}
+ \begin{bmatrix}
\frac{T_s}{L} & 0 \\
0 & \frac{T_s}{L}
\end{bmatrix}
\begin{bmatrix}
\psi_d(k) \\
\psi_q(k)
\end{bmatrix} + \frac{0}{T_s} \begin{bmatrix}
\omega_r(k) \\
\psi_f
\end{bmatrix} \quad (8)
\]

The predictive values of torque and flux will be calculated from the discrete-time model by (9) and (10)

\[
\begin{align*}
\psi_f (k + 1) &= \sqrt{\psi_d^2 (k + 1) + \psi_q^2 (k + 1)} \\
\psi_f (k + 1) &= \sqrt{\left(L_i d (k + 1) + \psi_f \right)^2 + \left(L_i q (k) + 1 \right)^2}) \quad (10)
\end{align*}
\]

2. Model of the three-phase two-level inverter

In this study, a three-phase two-level inverter is used to fed the PMSM and is expressed in Fig. 2. The phase-to-neutral voltages can be expressed as functions of inverter’s leg states as in [3]

\[
\begin{align*}
\begin{bmatrix}
u_{AN}(k) \\
u_{BN}(k) \\
u_{CN}(k)
\end{bmatrix} &= \begin{bmatrix}
E/3 & 2 & -1 & -1 \\
-1 & 2 & -1 & -1 \\
-1 & -1 & 2 & -1
\end{bmatrix}
\begin{bmatrix}
s_A(k) \\
s_B(k) \\
s_C(k)
\end{bmatrix}
\end{align*}
\]

where \( s_X (X = A, B, \text{or } C) \) is represented for two states of each inverter phase.

\[ s_X = \begin{cases}
0 & \Leftrightarrow \ u_{XN} = 0 \\
1 & \Leftrightarrow \ u_{XN} = E
\end{cases} \quad (12)\]

Stator voltages expressed in the \((\alpha\beta)\) stator reference frame are calculated by using a matrix transformation (13)

\[
\begin{bmatrix}
u_{\alpha}(k) \\
u_{\beta}(k)
\end{bmatrix} = \sqrt{2} \begin{bmatrix}
1 & -1/2 & -1/2 \\
n/2 & 1/2 & 1/2
\end{bmatrix}
\begin{bmatrix}
u_{AN}(k) \\
u_{BN}(k) \\
u_{CN}(k)
\end{bmatrix} \quad (13)
\]

Finally, stator voltages expressed in the \((dq)\) rotor flux reference frame can be obtained as follows:
### TABLE I

**The Configurations of a Three-Phase Two-Level Inverter**

<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>s_a</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>s_b</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>s_c</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>

\[
\begin{bmatrix}
  u_d(k) \\
  u_q(k)
\end{bmatrix} = R(k) \begin{bmatrix}
  u_a(k) \\
  u_B(k)
\end{bmatrix} \\
= \sqrt{3} R(k) \begin{bmatrix}
  \cos \theta_e(k) & \sin \theta_e(k) \\
  -\sin \theta_e(k) & \cos \theta_e(k)
\end{bmatrix} \begin{bmatrix}
  s_A(k) \\
  s_B(k) \\
  s_C(k)
\end{bmatrix}
\]

where

\[
R(k) = \begin{bmatrix}
  1 & -1/2 & -1/2 \\
  \sqrt{3}/2 & -\sqrt{3}/2 & 0
\end{bmatrix}
\]

\[
\theta_e(k) = \text{the electrical angular position of the rotor}.
\]

There are 8 possible inverter configurations (see Table I). Since configurations 0 and 7 are identical zero voltages, the case i = 0 will not be considered.

### 3. Cost Function definition

For the proposed control method, the predicted variables are the electrical torque \( T_e \) and stator flux \( \Psi_s \) on the next sampling interval. These predicted variables, indicated by the superscript \( "p" \), and, together with their reference values, will be considered in the cost function. In this paper, the cost function is composed of the square root of square error of the predicted torque and square error of the predicted flux magnitude, resulting in

\[
g = \sqrt{\left(T_{eref} - T_p^p\right)^2 + A \left(\Psi_{sref} - \Psi_p^p\right)^2}
\]

where \( A \) is a weighting factor. Here, the use of \( A \) is necessary in order to balance the coefficient between the torque and the flux criteria.

### 4. Selection of the optimal voltage vector

In the proposed predictive algorithm, (9) and (10) are used for each of seven possible voltage vectors, giving seven different predicted torque and flux values. The voltage vector, which gives the predicted torque and flux values closest to the reference values, will be applied to the system at the next sampling instant. In other words, the selected vector will be the one that minimizes the cost function (16).

The electric torque reference will be generated from a PI controller. Here, the RST structure is used. All the parameters of the controller are calculated from the nominal values of the machine by pole placement method. The anti-windup problem is also considered in the regulator. The limitation of the torque reference is set equal to 1.5 times the nominal torque. There is no need to estimate the load torque, since the electric torque reference is considered directly in the predictive controller, as show in Fig.1. However, it is necessary to guarantee the limit value of the load torque. This value should be smaller than the maximum torque which can be generated from the machine. The stator flux-linkage reference can be obtained based on the criterion of maximum torque per unit current (keep \( i_d \approx 0 \)). From that, it can be obtained:

\[
\Psi_s = \sqrt{\left(L i_d + \Psi_f\right)^2 + L^2 i_q^2} \approx \sqrt{\Psi^2_f + L^2 i_q^2}
\]

From (5), the stator current which produces a torque can be calculated.

\[
i_q = \frac{T_c}{p \Psi_f} \Rightarrow i_{qref} = \frac{T_{eref}}{p \Psi_f}
\]

Finally, the equation for the reference value of flux is obtained in (19).

\[
\Psi_{sref} = \sqrt{\Psi^2_f + L^2 \left(\frac{T_{eref}}{p \Psi_f}\right)^2}
\]

### 5. Effect of the weight factor \( A \)

In this method, instead of controlling the two current components \( i_d,i_q \), two criteria are considered: torque and flux linkage, with an adjustable parameter \( A \). From the equations above:

\[T_e = p \Psi_f i_q \text{ and } \Psi_s = \sqrt{\left(L i_d + \Psi_f\right)^2 + L^2 i_q^2}\]

At the nominal values: \( \frac{T_{erate}}{\Psi_{strate}} \approx 300 = A \)

Therefore, \( A \) is chosen equal to 300. The aim of adjusting the value of \( A \) is to control strictly the d-axis current. When \( A \) is increased, the current \( i_d \) is kept around zero, the power losses \( R_s i_d^2 \) are reduced.

### III. Mono Inverter – Dual Parallel PMSM

The structure of this system is shown in Fig. (3). Two motors are connected in parallel and are powered by a single inverter; therefore, the voltage applied to each phase of the motors is the same.
The discrete-time models of the two motors in the \((dq)\) rotor flux reference frame are presented as follows:

\[
\begin{bmatrix}
    i_d^{1,2}(k+1) \\
    i_q^{1,2}(k+1)
\end{bmatrix} =
\begin{bmatrix}
    1 - T_s \frac{R_s}{L} & T_s \omega_e^{1,2}(k) \\
    -T_s \omega_e^{1,2}(k) & 1 - T_s \frac{R_s}{L}
\end{bmatrix}
\begin{bmatrix}
    i_d^{1,2}(k) \\
    i_q^{1,2}(k)
\end{bmatrix} +
\begin{bmatrix}
    \frac{T_s}{L} & 0 \\
    0 & \frac{T_s}{L}
\end{bmatrix}
\begin{bmatrix}
    u_d^{1,2}(k) \\
    u_q^{1,2}(k)
\end{bmatrix} +
\begin{bmatrix}
    0 \\
    T_s
\end{bmatrix}
\Psi_f
\]

(20)

Because the same voltages are applied to the two motors, the \((dq)\) voltages can be calculated as in equations (21):

\[
\begin{bmatrix}
    u_d^{1,2}(k) \\
    u_q^{1,2}(k)
\end{bmatrix} =
\begin{bmatrix}
    \cos \theta_e^{1,2}(k) & \sin \theta_e^{1,2}(k) \\
    -\sin \theta_e^{1,2}(k) & \cos \theta_e^{1,2}(k)
\end{bmatrix}
\begin{bmatrix}
    u_d(k) \\
    u_q(k)
\end{bmatrix}
\]

(21)

where \(\theta_{e1}, \theta_{e2}\) are the electrical angular positions of rotor of each motor. In this paper, it is considered that all the values of \(\theta_{e1}, \theta_{e2}\) can be measurable.

The predicted values of torque and flux of each motor consequently can be obtained through

\[
T_{e1}^{1,2}(k+1) = p \Psi_f L_{d1}^{1,2}(k+1)
\]

(22)

\[
\Psi_s^{1,2}(k+1) = \sqrt{(L_{d1}^{1,2}(k+1) + \Psi_f)^2 + (L_{q1}^{1,2}(k+1))^2}
\]

(23)

The cost function is built as in (16):

\[
g = \sqrt{(T_{ref1} - T_{el1})^2 + A(\Psi_{sref1} - \Psi_{s1})^2} + \sqrt{(T_{ref2} - T_{el2})^2 + A(\Psi_{sref2} - \Psi_{s2})^2}
\]

(24)

IV. SIMULATION RESULTS

All simulations in this paper have been carried out with Matlab/Simulink to verify the performance of the proposed predictive method for the mono inverter-dual parallel PMSM system. Parameter of the simulated system are give in Table 2.

<table>
<thead>
<tr>
<th>TABLE 2</th>
<th>PARAMETER USING IN SIMULATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC voltage (V)</td>
<td>360</td>
</tr>
<tr>
<td>Rated torque (Nm)</td>
<td>5</td>
</tr>
<tr>
<td>Rated speed (rpm)</td>
<td>3000</td>
</tr>
<tr>
<td>(R_s) (Ω)</td>
<td>2.06</td>
</tr>
<tr>
<td>(L) (H)</td>
<td>9.15 \times 10^{-3}</td>
</tr>
<tr>
<td>(\Psi_f) (Wb)</td>
<td>0.29</td>
</tr>
<tr>
<td>Number of pole pairs ((p))</td>
<td>3</td>
</tr>
<tr>
<td>Inertia (kg m^2)</td>
<td>7.2 \times 10^{-4}</td>
</tr>
<tr>
<td>Sampling time (Ts)</td>
<td>1 \mu s</td>
</tr>
</tbody>
</table>

In this simulation, the sampling time is chosen equal to 1 \mu s to be sure that the stator currents vary linearly and the mechanical parameters including speed and rotor position are constant in one sampling period. In a real application, the switching frequency will not be constant, since the optimal switching vector will be applied during a variable time, until a new optimal vector will be given by the cost function. For a real implementation, a limitation of the switching frequency around 20 kHz must be assured.

A. Predictive torque control for one PMSM fed by a single inverter

The simulation is tested at the first time with one machine in several set points of speed. In Fig.4, the set point of speed is changed from \(\omega_{ref} = 10 \times \pi \text{ (rad s}^{-1})\) to \(70/3 \times \pi \text{ (rad s}^{-1})\) while the load torque is kept constant at \(T_{load} = 5 \text{ (Nm)}\).

Fig. 4. Response of system when change the speed

In the next simulation, the value of load torque is changed from \(T_{load} = 3 \text{ (Nm)}\) to 5\(\text{ (Nm)}\) at \(t = 0.15 \text{ (s)}\). The speed of the motor is set at \(\omega_{ref} = 70/3 \times \pi \text{ (rad s}^{-1})\). The results are shown in Fig.5 and Fig.6.

Fig. 5. The torque response when change the load
For the system including only one machine, the proposed method showed its feasibility. Optimal problem always finds the best solution. Although there is a small ripple for the torque, it is kept close to the reference value (<5%). The speed of the motor always gets to the set point even if the load torque or the set point is changed. The overshoot is almost zero, the response time is very fast (approximate 0.02s compared with natural response of the motor 0.1s). The system is robust to the variations load torque.

B. Predictive torque control for a dual parallel PMSM power by a single inverter

The predictive torque control algorithm continues to be verified for this system: one inverter powers two parallel PMSM.

Two motors are reversed from $\omega_{ref} = \frac{100}{3} \times \pi \text{rad.s}^{-1}$ to $-\frac{100}{3} \times \pi \text{rad.s}^{-1}$ at the time $t = 0.4 \text{s}$ and kept stand still from the time $t = 0.8 \text{s}$. The load torque in the two motors is different: for motor 1 is set equal to the rated torque (5Nm), while the load torque applied to motor 2 varies between two values $T_{load1} = 4 \text{(Nm)}$ and $T_{load2} = 6 \text{(Nm)}$.

The Fig.7 shows the speed response of the system. At the steady state, the speeds of two motors get to the set point. The overshoot is nearly zero; there is a small ripple (<5%). When there is the change in the load, there is also a difference between the speeds of two motors. However, the controller still keeps the system stable, the synchronism is re-established after a short time (~0.1s).

According to Fig.8, the torque response is not the same as the case of one machine. The torques generated from two machines does not oscillate around the reference values from the PI regulators. The difference can be explained because the optimal problem must satisfy simultaneously both machines with both criteria about torque and flux. Therefore, the expressions $(T_{ref1} - T_{e1})^2$ and $(T_{ref2} - T_{e2})^2$ can not be zero at the same time. The controller just keeps the cost function at the minimum value.
The A-phase current of two motors is presented in the Fig. 9. At the steady state of the nominal speed, the current has the sine wave form with the frequency of 50Hz. When two motors are kept at standstill, the current of each phase is constant.

V. CONCLUSION

Simulation results have shown that it is possible to control a system including two PMSM in parallel powered by an inverter using predictive torque control algorithm. The systems can response timely to load variations and the speed set point. The principle of this control technique is very simple; however, the effect is very impressive. Besides, with this method it is easy to consider a different criterion without changes in the control structure, just adding these criteria into the cost function.

Because of the dependence on the model used for prediction, the robustness of the control method needs to be considered for errors in the values of inductance and resistance in the PMSM model. Moreover, using the information about speed and position in the model is always a disadvantage and a challenge for an engineer. Therefore, to eliminate completely the speed and position sensor, the next step of this study is designing an observer. Besides, in order to improve the response of the system, a load observer should be studied. Estimating exactly all the above parameters, a multi-parallel PMSM single inverter sensorless control system can be consequently obtained.

REFERENCES