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END POINT CONSTRAINTS NONLINEAR CONTINUOUS PREDICTIVE CONTROL FOR INDUCTION MOTORS

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Abstract: In this paper the optimal nonlinear predictive cascaded control structure is presented with application to induction motors, which provides global asymptotic tracking of smooth speed and flux trajectories. The controller is based on a finite horizon continuous time minimization of nonlinear predicted tracking errors. With full state measurement assumption, the robustness properties with respect to electrical parameter variations and load disturbance is presented. Finally computer simulations show the flux-speed tracking performances and the disturbance rejection capabilities of the proposed controller in the nominal and mismatched parameters case. *Copyright © 2002 IFAC*

Keywords: Nonlinear continuous-time predictive control, Cascaded structure, Robust control, Induction motors.

1. INTRODUCTION

Induction motors are widely used in industrial applications due to their low maintenance, simplicity and relatively low cost compared to other machines. However, their dynamical model is multivariable, coupled, highly non-linear and the states are not all measurable for feedback control purposes. Therefore, they are more difficult to control than DC motors.

In recent years, to increase performance of classical control, e.g. field oriented torque control (Novotny and Lipo, 1996), many control strategies have been proposed to achieve better dynamic performance and induction motors have been gradually replacing the DC motors. Among these control strategies, typical approaches include input-output linearization (Bodson, *et al*., 1994; Kim, *et al*., 1990; Kim, *et al*., 1992; Chiasson, 1993), singular perturbation methods (Djemai, *et al*., 1993) and backstepping control (Tan and Chang, 1999). R. Marino, *et al*. (1999) have proposed a speed/torque and flux tracking adaptive controller without measurements of the rotor fluxes or load torque while adapting to the changing rotor resistance. To overcome parameter variations and load disturbance, Benyahia, *et al*. (1995) and Boucher, *et al*. (1997) have proposed a cascaded generalized predictive control (GPC) combined with input-output torque-flux linearization. This paper examines the non linear continuous-time generalized predictive control approach based on a finite horizon dynamic minimization of predicted tracking errors with specified end point output constraints, to achieve torque and rotor flux amplitude tracking objectives. In the application framework of motion control (robotics, machine tool), an extension to speed control is realized with a cascaded structure. The uncertainties we accounted for are electrical parameter variations and unknown load torque, which are major concerns in motion control applications. It will be shown that some advantages of this control scheme include good tracking performance, clear physical meaning of maximum and minimum control values when saturation occurs, controller robustness with respect to electrical parameter variations and load disturbance.

The paper is organized as follows. After the mathematical model of the induction motor developed in section 2, a brief overview of the optimal nonlinear predictive control theory is presented in section 3. In section 4 we extend the previous scheme to speed control by means of a cascaded nonlinear predictive control structure. Significant simulation results are given in section 5 for the nominal and mismatched model of the induction motor with load disturbance. The paper ends up with the concluding remarks and suggestions in section 6.

2. MATHEMATICAL MODEL OF THE INDUCTION MOTOR

An induction motor is built up around three stator windings and three rotor windings. Using the Park's transformation, a two phases equivalent machine representation with two rotor windings and two stator windings is obtained. In this paper, the stator fixed α-β frame is chosen to represent the model of the machine and under the assumption of equal mutual inductance and linear magnetic circuit, the dynamics of the induction motor are given by a fifth-order model, see (Boucher, *et al*. 1997; Novotny and Lipo, 1996):

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}) + \mathbf{g}\,\mathbf{u} \qquad (1)$$

With: $\mathbf{x}=\left[i_{sa}\ i_{sb}\ f_{ra}\ f_{rb}\ W\right]^{T}$

$\mathbf{u} = \left[u_{sa}\quad u_{sb}\right]^{T}$

Where: i_{sa}, i_{sb} : stator currents,

f_{ra}, f_{rb} : rotor fluxes,

W : speed,

u_{sa}, u_{sb} : stator voltages.

Vector function $\mathbf{f}(\mathbf{x})$ and constant matrix $\mathbf{g}$ are defined as follows:

$$\mathbf{f}(\mathbf{x})=\begin{bmatrix} -g\,i_{sa}+\dfrac{k}{T_r}f_{ra}+pWkf_{rb} \\ -g\,i_{sb}+\dfrac{k}{T_r}f_{rb}-pWkf_{ra} \\ \dfrac{L_m}{T_r}i_{sa}-\dfrac{1}{T_r}f_{ra}-pWf_{rb} \\ \dfrac{L_m}{T_r}i_{sb}-\dfrac{1}{T_r}f_{rb}+pWf_{ra} \\ p\dfrac{L_m}{JT_r}\left(f_{ra}\,i_{sb}-f_{rb}\,i_{sa}\right)-\dfrac{\left(T_L+fW\right)}{J} \end{bmatrix}$$

$$\mathbf{g}=\left[g_1\quad g_2\right]=\begin{bmatrix} \dfrac{1}{s\ L_s} & 0 & 0 & 0 & 0 \\ 0 & \dfrac{1}{s\ L_s} & 0 & 0 & 0 \end{bmatrix}^{T}$$

All required parameters above have the following meanings:

$$s=1-\frac{L_m^2}{L_sL_r};\ k=\frac{L_m}{sL_sL_r};\ g=\frac{1}{sL_s}\left(R_s+R_r\frac{L_m^2}{L_r^2}\right)$$

Where: L_s, L_r are stator and rotor inductances,

L_m is the mutual inductance,

R_s, R_r are stator and rotor resistances,

$T_r = L_r/R_r$ is the rotor time constant,

p is the pole pair number,

J is the inertia of the machine,

f is the friction coefficient,

T_L is the load torque considered as an unknown disturbance.

Considering the torque and rotor flux modulus as outputs of the a.c. drive, the following equations can be derived, with y_1 as the torque and y_2 as the rotor flux norm:

$$\begin{cases} y_1=h_1(\mathbf{x})=p\dfrac{L_m}{L_r}\left(f_{ra}\,i_{sb}-f_{rb}\,i_{sa}\right) \\ y_2=h_2(\mathbf{x})=f_{ra}^{\,2}+f_{rb}^{\,2}=f_r^{\,2} \end{cases} \qquad (2)$$

3. NONLINEAR GENERALIZED PREDICTIVE CONTROL

The nonlinear continuous-time generalized predictive control is briefly described in this section. We consider the nonlinear system of the form:

$$\begin{cases} \dot{\mathbf{x}}=\mathbf{f}(\mathbf{x})+\mathbf{g}(\mathbf{x})\,\mathbf{u} \\ \mathbf{y}=\mathbf{h}(\mathbf{x}) \end{cases} \qquad (3)$$

Where $\mathbf{x}(t)\in \mathbf{X}\subset \Re^n$ is the state vector, $\mathbf{u}(t)\in \mathbf{U}\subset \Re^m$ represents the control vector. $\mathbf{y}(t)\in \Re^m$ is the output.

The functions $\mathbf{f}(\mathbf{x})$: $\Re^n \rightarrow \Re^n$, $\mathbf{g}(\mathbf{x})$: $\Re^m \rightarrow \Re^n$ and $\mathbf{h}(\mathbf{x})$: $\Re^n \rightarrow \Re^m$ are sufficiently differentiable.

The desired output trajectory is specified by a smooth function $\mathbf{y}_{ref}(t)$ for $t\in [t_0, t_f]$.

The problem consists in elaborating a control law $\mathbf{u}(\mathbf{x},t)$ that improves tracking accuracy along the interval $[t, t+T]$, where $T>0$ is a prediction horizon, such that $\mathbf{y}(t+T)$ tracks $\mathbf{y}_{ref}(t+T)$. That is, the tracking error is defined by:

$$\mathbf{e}(t+T)=\mathbf{y}(t+T)-\mathbf{y}_{ref}(t+T)$$

A simple and effective way of predicting the influence of $\mathbf{u}(t)$ on $\mathbf{y}(t+T)$ is to expand it into a r_i^{th} order Taylor series expansion, in such a way to obtain, for each component of the vectors:

$$y_i(t+T)=h_i(t)+TL_fh_i+\frac{T^2}{2!}L_f^2h_i+\ldots\ldots\ldots+\frac{T^{r_i}}{r_i!}L_f^{r_i}h_i+\frac{T^{r_i}}{r_i!}L_gL_f^{r_i}h_i\,u \quad \text{for } i=1,.,m \qquad (4)$$

Where $L_f^k h_i$ denotes the k^{th} order Lie derivative of h_i with respect to $\mathbf{f}(\mathbf{x})$. r_i is the relative degree of the output y_i, defined to be the nonnegative integer j such that the j^{th} derivative of y_i along the trajectory of equation (3) explicitly depends on $\mathbf{u}(t)$ for the first time.

The expansion of the motor outputs $\mathbf{y}(t+T)$ in a r^{th} (with r_1=1 and r_2=2) order Taylor series in compact form is:

$$\mathbf{y}(t+T)=\mathbf{y}(t)+\mathbf{V}_{\mathbf{y}}(\mathbf{x},T)+\mathbf{L}(T)\mathbf{W}(\mathbf{x})\mathbf{u}(t) \qquad (5)$$

Where:

$$\mathbf{y}(t)=\begin{vmatrix} y_1 \\ y_2 \end{vmatrix};\quad \mathbf{W}(\mathbf{x})=\begin{vmatrix} L_{g_1}h_1 & L_{g_2}h_1 \\ L_{g_1}L_fh_2 & L_{g_2}L_fh_2 \end{vmatrix}$$

$$\mathbf{L}(T)=\begin{vmatrix} T & 0 \\ 0 & \frac{T^2}{2} \end{vmatrix}\ ;\ \mathbf{V_y}(\mathbf{x},T)=\begin{vmatrix} TL_f h_1 \\ TL_f h_2 + \frac{T^2}{2} L_f^{\,2} h_2 \end{vmatrix}$$

Similarly, $\mathbf{y}_{ref}(t+T)$ may be expanded in a same r^{th} order Taylor series:

$$\mathbf{y}_{ref}(t+T)=\mathbf{y}_{ref}(t)+\mathbf{d}(t,T) \qquad (6)$$

Where:

$$\mathbf{y}_{ref}(t)=\begin{vmatrix} y_{ref_1} \\ y_{ref_2} \end{vmatrix}\ ,\ \mathbf{d}(t,T)=\begin{vmatrix} T\ \dot{y}_{ref_1} \\ T\ \dot{y}_{ref_2}+\frac{T^2}{2}\ddot{y}_{ref_2} \end{vmatrix}$$

The tracking error at the next instant $(t+T)$ is then predicted as function of the input $\mathbf{u}(t)$ by:

$$\begin{aligned}\mathbf{e}(t+T)&=\mathbf{y}(t+T)-\mathbf{y}_{ref}(t+T)=\\ &=\mathbf{e}(t)+\mathbf{V_y}(\mathbf{x},T)-\mathbf{d}(t,T)+\mathbf{L}(T)\mathbf{W}(\mathbf{x})\mathbf{u}(t)\end{aligned}$$

In order to find the current control $\mathbf{u}(t)$ that improves tracking error along the interval $[0,\ h]$, with a specified end-point constraint at $t_f=t+h$, we consider a performance index, that penalizes the tracking error and predicted control signal, of the form:

$$\begin{aligned}J&=\frac{1}{2}\left\|\mathbf{e}(t+h)\right\|^2_{\mathbf{Q}}\\ &+\frac{1}{2}\int_0^h \left\|\mathbf{e}(t+T)\right\|^2_{\mathbf{Q}_i} dT+\frac{1}{2}\int_0^{h_c}\left\|\mathbf{u}(t+T)\right\|^2_{\mathbf{R}_i} dT\end{aligned} \qquad (7)$$

$\mathbf{Q}$ and $\mathbf{Q}_i \in \Re^{2x2}$ are positive definite matrices and $\mathbf{R}_i \in \Re^{2x2}$ is a positive semi-definite matrix. h and h_c are the observation horizon of the tracking error and control signal. Assuming that the control signal is constant along the interval of integration with $h_c \ll h$, the truncated Taylor series expansion form of the predicted future input is:

$$\mathbf{u}(t+T)=\mathbf{u}(t)$$

The minimization of J with respect to $\mathbf{u}(t)$ $\partial J/\partial\mathbf{u}=0$ yields to an optimal predictive control law:

$$\begin{aligned}\mathbf{u}(t)=&-\left(\mathbf{W}(\mathbf{x})^{\mathrm{T}}\mathbf{P}(h)\mathbf{W}(\mathbf{x})+h_c\mathbf{R}_i\right)^{-1}\\ &\mathbf{W}(\mathbf{x})^{\mathrm{T}}\left(\mathbf{G}(h)\mathbf{e}(t)+\mathbf{H}(\mathbf{x},h)-\mathbf{D}(t,h)\right)\end{aligned} \qquad (8)$$

Where:

$$\mathbf{P}(h)=\mathbf{L}(h)^{\mathrm{T}}\mathbf{Q}\mathbf{L}(h)+\int_0^h \mathbf{L}(T)^{\mathrm{T}}\mathbf{Q}_i\mathbf{L}(T)dT$$

$$\mathbf{G}(h)=\mathbf{L}(h)^{\mathrm{T}}\mathbf{Q}+\int_0^h \mathbf{L}(T)^{\mathrm{T}}\mathbf{Q}_i dT$$

$$\mathbf{H}(\mathbf{x},h)=\mathbf{L}(h)^{\mathrm{T}}\mathbf{Q}\mathbf{V}_y(\mathbf{x},h)+\int_0^h \mathbf{L}(T)^{\mathrm{T}}\mathbf{Q}_i\mathbf{V}_y(\mathbf{x},T)dT$$

$$\mathbf{D}(t,h)=\mathbf{L}(h)^{\mathrm{T}}\mathbf{Q}\mathbf{d}(t,h)+\int_0^h \mathbf{L}(T)^{\mathrm{T}}\mathbf{Q}_i\mathbf{d}(t,T)\,dT$$

We notice that the previous output-tracking control law only affects the torque (y_1) and the rotor flux (y_2). In the induction machine, the aim is to control speed and flux, thus an extension to speed control is achieved, in the next section, looking at a cascaded nonlinear predictive control structure.

4. CASCADED STRUCTURE OF THE NONLINEAR CGPC

Cascaded control (Boucher, *et al*. 1996) is typically prescribed for linear systems involving time-scale separation assumption. That is, the inner loop is designed to have a faster dynamic than the outer loop. In this paper, the nonlinear continuous-time generalized predictive control scheme is extended to speed control by using the cascaded structure (fig.1). Indeed, the mechanical equation of the motor is given by:

$$\dot{W}(t)=\frac{1}{J}y_1(t)-\frac{f}{J}W(t)$$

or in the Laplace domain:

$$W(s)=\frac{1}{J\,s+f}y_1(s) \qquad (9)$$

This equation (9) allows to control the speed by acting on the torque y_1. Thus, the initial system can be decomposed into two sub-systems in a cascaded form (fig.1). The inner loop incorporates torque-flux model and the external loop is the velocity transfer function deduced from the mechanical equation given above.

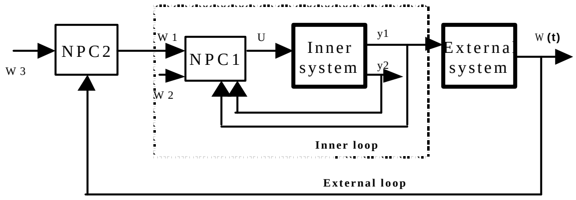

Fig.1. Cascaded control configuration

The desired reference models, chosen in continuous time, are given by:

- For the torque trajectory (y_1):

$$\frac{y_{ref\,1}(s)}{w_1(s)}=\frac{w_0}{s+w_0}$$

- For the flux trajectory (y_2):

$$\frac{y_{ref\,2}(s)}{w_2(s)}=\frac{w_f^{\,2}}{s^2+2x_f w_f s+w_f^{\,2}}$$

- For the velocity trajectory (W):

$$\frac{W_{ref}(s)}{w_3(s)}=\frac{w_v^{\,2}}{s^2+2x_v w_v s+w_v^{\,2}}$$

The control objective is the tracking of W to a desired reference W_{ref} and the tracking of y_1 and y_2 to desired reference signals y_{ref1} and y_{ref2}. The performance indexes, with end-point constraints, that penalize the tracking errors, the input control of the inner loop and the input control of the external loop at the instant $(t+T)$, are given by:

$$\begin{aligned}J_1&=\frac{1}{2}\left\|\mathbf{e}(t+h)\right\|^2_{\mathbf{Q}}\\ &+\frac{1}{2}\int_0^h \left\|\mathbf{e}(t+T)\right\|^2_{\mathbf{Q}_i} dT+\frac{1}{2}\int_0^{h_c}\left\|\mathbf{u}(t+T)\right\|^2_{\mathbf{R}_i} dT\end{aligned} \qquad (10)$$

and:

$$J_2 = \frac{1}{2}\left\|e_v(t+h)\right\|^2_{q_e} + \frac{1}{2}\int_0^{h_v} \left\|e_v(t+T)\right\|^2_{q_{ei}} dT + + \frac{1}{2}\int_0^{h_c} \left\|w_1(t+T)\right\|^2_{r_{ei}} dT \qquad (11)$$

Where: $e_v(t+T) = W(t+T) - W_{ref}(t+T)$

$$\mathbf{e}(t+T) = \mathbf{y}(t+T) - \mathbf{y}_{ref}(t+T)$$

with: $\mathbf{y}(t+T) = \begin{vmatrix} y_1(t+T) \\ y_2(t+T) \end{vmatrix}$; $\mathbf{y}_{ref}(t+T) = \begin{vmatrix} y_{ref_1}(t+T) \\ y_{ref_2}(t+T) \end{vmatrix}$

h is the flux-torque prediction horizon, h_v the speed prediction horizon and h_c the control horizon.

$\mathbf{Q}$ and $\mathbf{Q}_i$ Î Â^{2x2} are positive definite matrices, $\mathbf{R}_i$ Î Â^{2x2} is a positive semi-definite matrix, q_{ei}, q_e and r_{ei} are at least positive real.

Assuming that the torque y_1 tracks the reference signal y_{ref1}, the global prediction model of the external loop is calculated, including the torque closed loop, in the following manner:

$$W(s) = \frac{1}{Js+f} y_1(s) \approx \frac{w_0}{(Js+f)(s+w_0)} w_1(s) \qquad (12)$$

From the minimization of the performance indexes (J_1 and J_2), we obtain:

- For the external loop:

$$w_2 = f_{rnom} \qquad (13)$$

$$w_1 = -q_e \frac{\left((q_e + q_{ei}\frac{h_v}{3})\, a(h_v)\, e_v(t) + g(W,h_v) - b(W_{ref}, h_v) \right)}{(q_e + q_{ei}\frac{h_v}{5}) a^2(h_v) + r_{ei} h_c} \qquad (14)$$

Where:

$$g(W,h_v) = q_e V_v(t,h_v) a(h_v) + + q_{ei}\int_0^{h_v} V_v(t,T) a(T)\, dT$$

$$b(W_{ref}, h_v) = q_e d_v(t,h_v) a(h_v) + + q_{ei}\int_0^{h_v} d_v(t,T) a(T) dT$$

with: $a(T) = \frac{T^2 w_0}{2J}$

$$d_v(t,T) = T\,\dot{W}_{ref}(t) + \frac{T^2}{2}\ddot{W}_{ref}(t)$$

$$V_v(t,T) = \frac{Tf}{J}\left(\frac{Tf}{2J} - 1\right) W(t) + + \frac{T}{J}\left(1 - \frac{T}{J}(\frac{f}{J} + w_0)\right) y_{ref\,1}(t)$$

- For the inner loop, the control signal given in Eq.8 is:

$$\mathbf{u}(t) = -\left(\mathbf{W}(\mathbf{x})^{\mathrm{T}} \mathbf{P}(h) \mathbf{W}(\mathbf{x}) + h_c \mathbf{R}_i\right)^{-1} \mathbf{W}(\mathbf{x})^{\mathrm{T}} \left(\mathbf{G}(h)\mathbf{e}(t) + \mathbf{H}(\mathbf{x},h) - \mathbf{D}(t,h)\right) \qquad (15)$$

Tracking performance:

- For the external loop: the equation (14) with $r_{ei} = 0$, gives using the second order derivative of W the following speed tracking error dynamics:

$$(q_e + q_{ei}\frac{h_v}{5})\frac{h_v^2}{2}\ddot{e}_v(t) + (q_e + q_{ei}\frac{h_v}{4}) h_v \dot{e}_v(t) + + (q_e + q_{ei}\frac{h_v}{3}) e_v = 0$$

- For the internal loop: we assume that $\mathbf{W}(\mathbf{x})$ has a full rank. Let $\mathbf{Q} = q\ \mathbf{I}_2$, $\mathbf{Q}_i = q_i\ \mathbf{I}_2$, $\mathbf{R}_i = 0$ in the controller (15), we obtain:

$$\mathbf{u}(t) = -\mathbf{W}(\mathbf{x})^{-1} \mathbf{P}(h)^{-1} \left(\mathbf{G}(h)\mathbf{e}(t) + \mathbf{H}(\mathbf{x},h) - \mathbf{D}(t,h)\right)$$

Differentiating the output y_1 one time and the output y_2 twice and by using the above control equation, we can show that the tracking errors dynamics are:

- For the torque:

$$(q + q_i\frac{h}{3}) h\,\dot{e}_1(t) + (q + q_i\frac{h}{2}) e_1(t) = 0$$

- For the flux:

$$(q + q_i\frac{h}{5}) h^2 \ddot{e}_2(t) + 2(q + q_i\frac{h}{4}) h \dot{e}_2(t) + + 2(q + q_i\frac{h}{3}) e_2(t) = 0$$

The above dynamics equations are linear and time invariant. Thus, the proposed tracking controller design technique leads to feedback linearization and we can easily verify the asymptotic stability of the tracking errors dynamics of the overall system.

5. SIMULATION RESULTS

Computer simulations have been performed to check the behavior of the proposed controller. The plant under control is a 1.5 kW induction machine used in (Boucher *et al*., 1997) with the following parameters:

$R_r = 2.61\ \Omega$, $R_s = 4.287\ \Omega$, $L_r = 0.368$ H,
$L_s = 0.404$ H, $L_m = 0.368$ H, $J = 0.0256$ kgm^2,
$p = 2$.

The parameters values of the three reference models are chosen as follows:

$x_f = 1$, $w_f = 15$ rad/s for the flux trajectory
$x_v = 1$, $w_v = 10$ rad/s for the speed trajectory
$w_0 = 45$ rad/s for the torque trajectory.

After several trials, the control parameters are chosen as:

$\mathbf{Q} = 10^2\ \mathbf{I}_2$, $\mathbf{Q}_i = 10^3\ \mathbf{I}_2$, $\mathbf{R}_i = 10^{-3}\ \mathbf{I}_2$,
$h = 0.002$
$q_e = 1$, $q_{ei} = 10$, $r_e = 0.001$
$h_c = 0.02\ h$ $h_v = h$.

To examine the flux and the speed tracking performances, it was considered that the flux must reach the nominal value $f_{rnom} = 0.75$ Wb. The speed must reach the value $W = 100$ rad/s in the interval of time 0-2 s; $W = 150$ rad/s in the interval 2-4 s; and $W = 70$ rad/s for $t > 4$. To test the disturbance rejection, a 5 Nm unknown load torque is applied between $t = 0.8$ s and $t = 1.2$ s.

Figure 2 shows that the behavior of the actual rotor flux is very close to the flux reference. It also appears that the rotor speed fits the speed reference trajectory. The applied load torque has no effect on the flux and its effect on the speed is rapidly compensated (figure 4). Figure 3 depicts the variations of the admissible stator voltage (u_{sa}, u_{sb}) and the stator current i_s which is also admissible, within the saturations limits (Benyahia, *et al*. 1997).

In the mismatched case, the electrical parameter variations are shown in figure 5 and the simulation results are illustrated in figure 6. As seen from the figure, the flux and speed trajectories are well tracked. The above results demonstrate that the proposed controller has strong robustness properties in the presence of load disturbance and parameter variations. These results are very interesting in comparison with other already known solutions tested on the same benchmark. It is also possible to show that the controller is not very sensitive to the tuning parameters.

6. CONCLUSIONS

In this paper, we have shown that the non-linear continuous-time generalized predictive controller, used in cascaded structure, with end-point constraints, can be successfully applied to the control of induction machines. Based on simulation results, we have demonstrated that the proposed control law achieves speed and flux amplitude tracking objectives even with disturbance, thus presents sufficient robustness in case of electrical parameter variations. These results obtained with the particular trajectories used in motion control are very attractive in this field of applications. The non-linear continuous-time generalized predictive control is developed under the assumption that the full state vector is measurable. This assumption will be avoided in the future with an extension of the non-linear continuous-time generalized predictive control with state observer.

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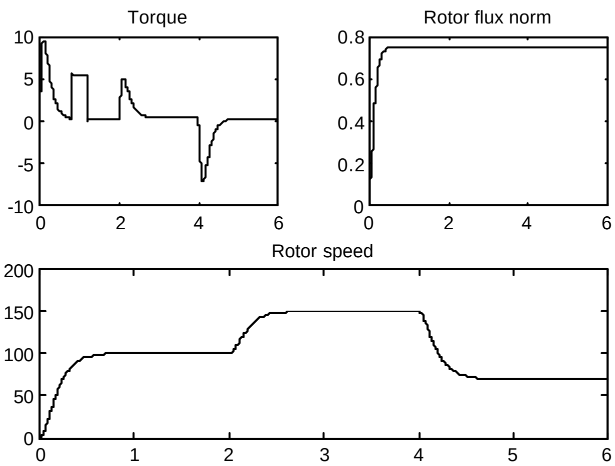

Fig.2. Rotor torque, rotor flux and speed tracking performance

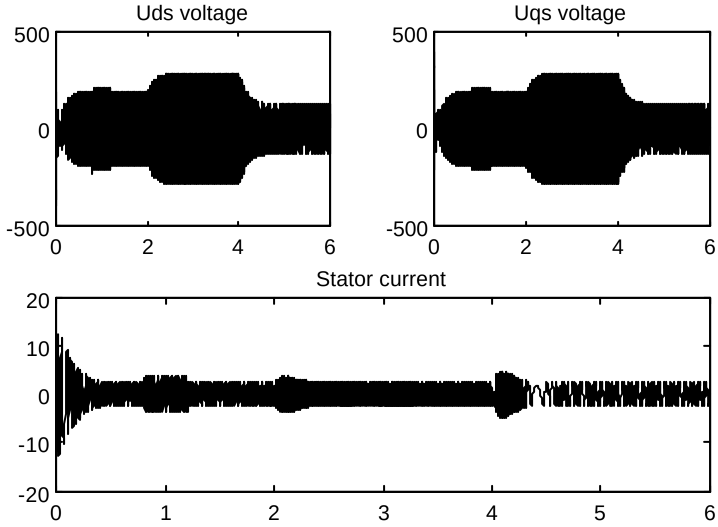

Fig.3. Stator voltage (u_{sa} , u_{sb}) and stator current i_s

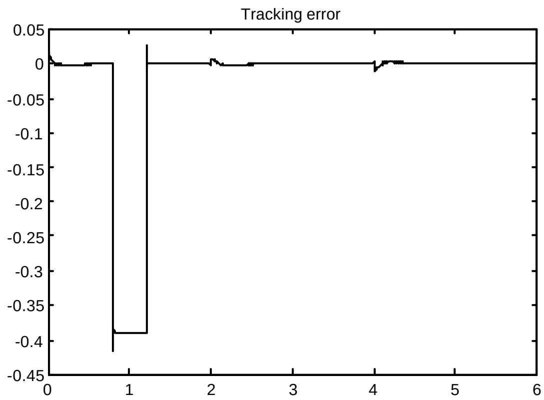

Fig.4. Speed error tracking

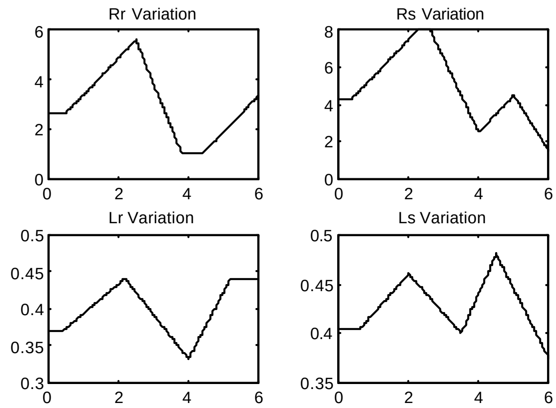

Fig.5. Electrical parameter variations

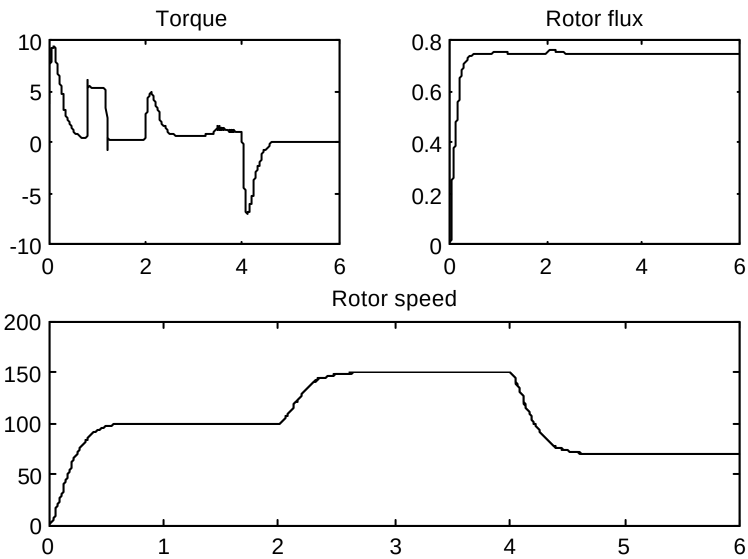

Fig. 6. Rotor torque, rotor flux and speed tracking performance in the mismatched case