Model predictive control for induction motor control reconfiguration after inverter faults

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ABSTRACT. *This work analyzes the use of model predictive control (MPC) for induction motor (IM) control and compares it with the standard form of the direct torque and flux control (DTFC) strategy. These two strategies are fundamentally different in operation since (i) MPC decides the current control action by on-line minimization of a cost function that uses the available inverter output voltages as optimization variables, whereas (ii) DTFC decides the current control action based on a switching table constructed using a simplified model of the IM. Emphasis is given in this work to the reconfiguration of the control action after voltage source inverter faults. We assume that the fault can be suitably detected and isolated and that the inverter* *can be reconfigured after the specific fault to continue operation, albeit with a reduced set of achievable output vectors. Based on this reduced set of vectors, we propose to reconfigure the induction motor control algorithm by (i) providing the reduced set of inverter vectors as the* reconfigured constraint set *of optimization variables for MPC or (ii) instructing DTFC to use a* reconfigured switching table*. Simulation results show that MPC with prediction horizon $N = 1$ considerably outperforms DTFC at a modest increment of computational cost. Moreover, this increment is less pronounced under fault since the number of optimization variables is reduced.*

RÉSUMÉ. *Cet article présente l'application de la commande prédictive (MPC) à la machine asynchrone (MA) et sa comparaison avec la forme standard du contrôle direct du flux et du couple (DTFC) de cette machine. Ces deux stratégies de commande ont une différence fondamentale dans leur opération vu que (i) la commande MPC décide l'action de contrôle du courant par voie de minimisation en temps réel d'une fonction de coût qu'utilisent les vecteurs de tension de l'onduleur en tant que variables d'optimisation, tandis que (ii) la commande DTFC décide l'action mentionnée sur la base d'une table de commutation construite d'après un modèle simplifié de la MA. Dans ce travail on met l'accent sur la reconfiguration de l'actionneur (l'onduleur) et de sa commande suite à l'apparition de fautes chez l'onduleur. On suppose que les fautes peuvent être détectées et isolées d'une façon convenable, et que l'onduleur continue d'être opérationnel après sa reconfiguration, même avec un ensemble réduit des vecteurs de tension. Compte tenu de cet ensemble réduit de vecteurs nous proposons de reconfigurer la loi de commande de la machine asynchrone de deux façons alternatives : (i) avec une approche MPC qu'utilise l'ensemble des nouveaux vecteurs comme variables d'optimisation et (ii) avec une approche DTC qu'utilise une nouvelle table de commutation adaptée à la reconfiguration de l'onduleur. Des résultats de simulation montrent que la performance de l'approche MPC surpasse celle de la commande DTFC n'ayant qu'un faible coût additionnel de calcul. En outre, lors de l'utilisation de l'onduleur reconfiguré, cet incrément est plus faible encore puisque le nombre des variables (vecteurs) d'optimisation est réduit.*

KEYWORDS: *model predictive control, controller reconfiguration, direct torque and flux control, induction motor, inverter faults.*

MOTS-CLÉS : *commande prédictive, reconfiguration du contrôleur, contrôle direct du flux et du couple, machine asynchrone, fautes onduleur.*

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1. Introduction

Direct torque and flux control control (DTFC) is a vector control strategy that directly controls the stator flux magnitude and the electromagnetic torque of an induction motor (IM). In this strategy, the control actions are chosen directly from a so-called *switching table*. The switching table (ST) is constructed taking into account the desired action on flux and torque (i.e., to increment or to decrement) and the position of the stator flux vector (Takahashi, Noguchi, 1986; Depenbrock, 1988). The control actions are three-phase voltages provided by a voltage source inverter (VSI), which can be represented as voltage vectors in a stationary frame of reference, the so-called *(a,b)*-plane (Leonhard, 2001). Under normal (healthy) operation, there are eight possible vectors, depending on the switch configurations, where six of them are called active vectors and two are null vectors since they produce null line voltage. The six active vectors are noted V_i, with $i = 1, ..., 6$, and depicted in Fig. 3(a).

The ST can be considered as a result of a *prediction* procedure where, using a reduced model of an IM, we predict its behavior when different voltage vectors are applied, according to the position of the stator flux. However, the selection of the appropriate vector to apply, based on this prediction and the desired action on flux and torque, follows heuristic reasoning. This suggests the possibility to improve performance by resorting to some type of optimization (Escobar *et al.*, 2003). In this work we thus propose to select the control actions by means of model predictive control (MPC) (Geyer *et al.*, 2009; Bolognani *et al.*, 2009), which minimizes an optimization criterion (cost function) based on some model outputs predicted over a time period (the *prediction horizon*) using a model of the IM. Specifically, in the current paper we utilize a cost function which weights the square of the errors between predicted flux magnitude and torque, and their respective desired references. The optimization variables used by MPC are the *(a,b)*-components of the stator voltage vector, taking into account that only a finite number of voltage vectors can be produced by the VSI.

In certain implementations of IM control, where continuous operation of the system must be ensured, the use of a fault tolerant inverter is desirable to avoid the need for parallel redundancy. There are many different fault tolerant topologies for an AC motor drive. Here we use the switch redundant topology discussed in (Welchko *et al.*, 2003), (Fu, Lipo, 1993) and (Liu *et al.*, 1993). We consider two kinds of faults that can be handled by this topology: a short-circuit fault of one switch device and an open-circuit fault. We assume that a fault detection and isolation algorithm detects which component is in faulty condition and performs the necessary actions in order to reconfigure the inverter, refer to (Fuchs, 2003) for a survey of common faults and diagnosis methods in VSI. After this reconfiguration process, the inverter can generate only four voltage vectors, according to the switch combinations available after a fault occurrence, instead of the eight voltage vectors obtained in healthy operation conditions. Based on this reduced set of vectors, we propose to reconfigure the induction motor control algorithm in the following ways depending on which strategy, MPC or DTFC, is employed:

– providing the reduced set of inverter vectors as the *reconfigured constraint set* of optimization variables for MPC, or

– instructing DTFC to use a *reconfigured switching table* proposed in (Nacusse *et al.*, 2011).

Simulation results show that MPC with prediction horizon $N = 1$ considerably outperforms DTFC at a modest increment of computational cost. Moreover, this increment in computional cost is less pronounced under fault since the number of optimization variables is reduced. In addition, the voltage vectors applied by the MPC strategy are compared with those applied by the DTFC strategy in order to analize the switching losses in the VSI.

The remainder of the paper is organized as follows. In Section 2 some concepts of the DTFC strategy are presented and the reconfigured DTFC (ReDTFC) strategy of (Nacusse *et al.*, 2011), which handles faults in the VSI, is reviewed. In Section 3 the MPC approach for IM control is presented and a reconfigured MPC (ReMPC) strategy is proposed. In Section 4, some simulation results are shown in order to demonstrate the continuous operation of the system as well as its good dynamic response. Section 5 presents conclusions and discusses future work.

2. Direct Torque and Flux Control

This section gives a brief description of the principles of the standard DTFC scheme (Takahashi, Noguchi, 1986)(Depenbrock, 1988) and presents a reconfigured DTFC strategy in order to maintain the system operability after a fault occurrence.

2.1. Classical DTFC strategy

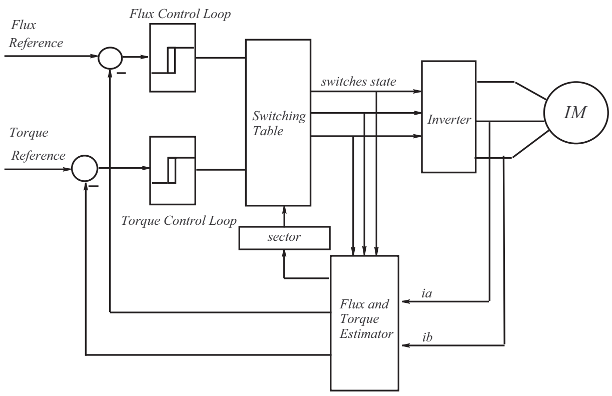


Figure 1. Schematic of stator flux based DTFC induction motor drive with VSI.

DTFC is a vector control strategy that directly controls the stator flux magnitude and the electromagnetic torque of an induction motor. The strategy consists of two control loops, associated to the stator flux magnitude and to the electromagnetic torque, respectively. Each control loop has a hysteresis comparator that indicates which control action must be performed (to increment or to decrement the magnitudes of stator flux and torque). A switching table is constructed so that, given the current flux vector position and the desired control actions, the appropriate voltage vector to be applied to the motor can be selected. The mentioned voltage vectors are a vectorial representation of the three phase voltages provided by the actuator (VSI) that feeds the machine, when the IM stator windings are star conected and the neutral is isolated.

The DTFC control strategy is based on the dynamic equations of the stator flux and electromagnetic torque. The dynamics of the stator flux vector, $\overline{\lambda_s}$, are given by

$$\dot{\overline{\lambda_s}} = \overline{V_s} - \overline{i_s} R_s, \tag{1}$$

where $\overline{V_s}$ is a voltage vector, $\overline{i_s}$ is the stator current vector and R_s is the stator resistance. The standard DTFC strategy assumes that the voltage drop on the stator resistance R_s can be neglected and hence the dynamics of the stator flux are only governed by $\overline{V_s}$. Therefore, application of a specific voltage vector $\overline{V_s}$ during a time interval ΔT yields

$$\overline{\Delta\lambda_s} = \overline{V_s}\Delta T, \tag{2}$$

which shows precisely how the voltage vector affects the stator flux. The expression of the electromagnetic torque in terms of the stator and rotor flux vectors is

$$\tau_{em} = \frac{3}{2} n_p \frac{L_m}{\sigma L_s L_r} \left|\overline{\lambda_s}\right| \left|\overline{\lambda_r}\right| \sin(\delta), \tag{3}$$

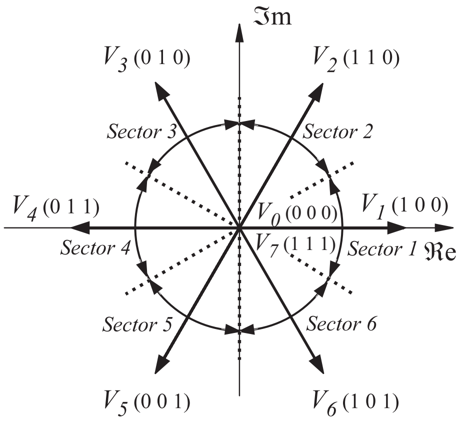
where n_p is the number of pole pairs of the induction machine, L_s and L_r are the stator and rotor inductance, L_m is the magnetization inductance, δ is the angle between rotor and stator flux vectors and σ is the total leakage factor (Leonhard, 2001). The rotor flux is known to have a dynamic response slower than that of the stator flux. Hence, provided the time period ΔT is small enough, classical DTFC assumes that the rotor flux is constant with respect to variations in the stator flux. Then, if $\left|\overline{\lambda_r}\right|$ is constant and $\left|\overline{\lambda_s}\right|$ can be kept constant, it follows from 3 that the instantaneous electromagnetic torque can be controlled by modifying the angle δ. Thus, to perform the control action, an adequate stator voltage vector must be applied to the induction motor in order to keep the stator flux magnitude constant and make the stator flux rotate to produce a desired angle difference δ.

Taking the projections of the VSI voltage vectors on a rotating reference frame with axes d and q whose d axis is aligned with the stator flux vector it is possible to know the effect of each voltage vector on the stator flux magnitude and the electromagnetic torque as given by equation (4) below [see (Bertoluzzo *et al.*, 1999) for its derivation], where λ_{dsr} is the d component of the rotor flux referred to the stator, i_{ds} and i_{qs} are the d, q components of the stator current and $\omega_{\lambda s}$ is the rotational speed of the stator flux vector with respect to the stationary reference frame. It can be seen from (4) that the d component of the voltage vector, V_{di}, influences directly the stator flux amplitude, and the q component, V_{qi}, influences the torque variation, with $i = 0, ..., 7$. Note that the stator flux vector has only d componet because it is aligned with the d axis, hence $\lambda_{qs} = 0$ and $|\lambda_{ds}| = \left|\overline{\lambda_s}\right| =: \lambda_s$.

$$\begin{aligned} \Delta\lambda_s &= \Delta T(V_{di} - R_s i_{ds}), \\ \Delta\tau_{em} &= \frac{3}{2} n_p \frac{1-\sigma}{2\sigma L_s} \lambda_{dsr} \Delta T(V_{qi} - R_s i_{qs} - \omega_{\lambda s}\lambda_s) + \frac{\tau_{em}}{\lambda_s}\Delta\lambda_s, \end{aligned} \tag{4}$$

The standard DTFC algorithm defines six sectors in the complex (a, b)-plane (stationary reference frame), where each voltage vector bisects the sector, see Fig. 3(a), (Depenbrock, 1988; Takahashi, Noguchi, 1986). Fig. 2 shows the projections of each voltage vector on the d, q rotating reference frame, (V_{di} and V_{qi}), when the d axis passes throught sector 1.

According to the sector in which the stator flux vector lies and the effects of the voltage vectors in that sector, a suitable *voltage switching table* is defined as Table 1 (Takahashi, Noguchi, 1986). In this table, a 1 in the columns of stator flux quantity or torque indicates that this magnitude needs to be increased while a 0 indicates that the quantity needs to be decreased. Depending on these desired actions, a particular voltage vector is applied when the stator flux vector lies in each of the six sectors $S1$ to $S6$.



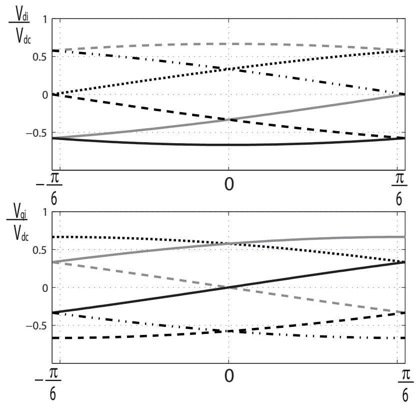


Figure 2. (a) Sector discretization in (a, b) plane. (b) Sector 1 normalized Voltage Vector Projection onto: d axis (upper), q axis (bottom). dashed grey, V1; dotted black, V2; grey, V3; black, V4; dashed black, V5; dotted dashed black, V6.

Table 1. Standard Voltage Vector Switching Table.

τ_{em}	λ_s	$S1$	$S2$	$S3$	$S4$	$S5$	$S6$
0	0	V_0	V_7	V_0	V_7	V_0	V_7
0	1	V_7	V_0	V_7	V_0	V_7	V_0
1	0	V_3	V_4	V_5	V_6	V_1	V_2
1	1	V_2	V_3	V_4	V_5	V_6	V_1

2.2. Reconfigured DTFC strategy

After the occurrence of an inverter fault (Welchko *et al.*, 2003; Fu, Lipo, 1993; Liu *et al.*, 1993), a reconfiguration procedure is started and a new inverter topology is obtained that provides only four voltage vectors; for example Fig. 4(a) shows the voltage vectors availables after a fault in the R leg. Then a new DTFC strategy, called reconfigured DTFC (ReDTFC) is necessary to deal with the new set of control actions. A ReDTFC strategy was presented in (Yznaga Blanco *et al.*, 2008) where four sectors were defined according to the four resulting voltage vectors for a fault in the leg of the VSI. Here we employ an improved ReDTFC, proposed in (Nacusse *et al.*, 2011), which uses a new discretization of (a, b) complex plane into sectors. This discretization is obtained taking the projections of the reconfigured-VSI voltage vectors on a rotating dq reference frame whose d axis is aligned with the stator flux vector, as shown in Fig. 3. The new sectors are defined between the dotted vertical lines of Fig. 3, where the influence of each voltage vector is cleary determined.

This new ReDTFC reduces the torque ripple and maintains the dynamic response achieved in (Yznaga Blanco *et al.*, 2008). Fig. 4(a) shows the new discretization using eight sectors and, based on them, a new ST is constructed as shown in Table 2.

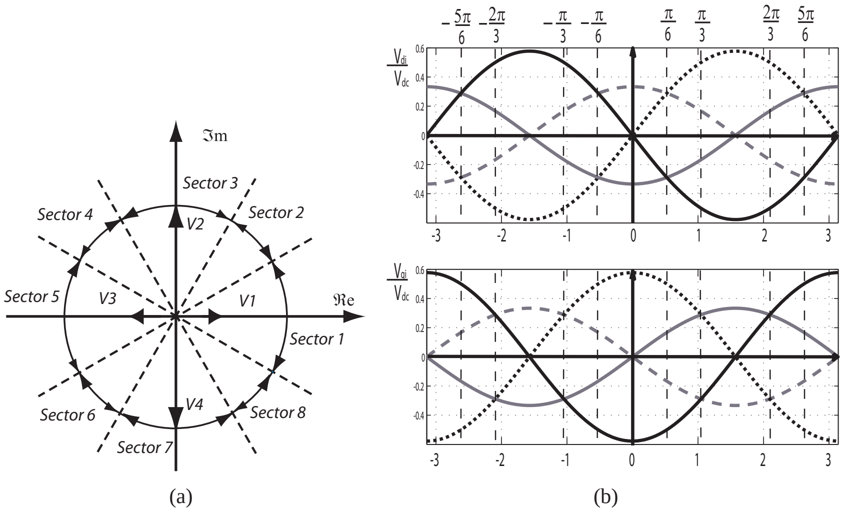


Figure 3. (a) Sector discretization in (a, b) stationary reference frame for a fault in leg R (b) Normalized Voltage Vector Projection onto: d axis (upper), q axis (bottom). dashed grey, V1; dotted black, V2; grey, V3; black, V4.

The resulting switching table works as follows: in sector 1, V_2 is applied in order to increase torque, V_1 is applied to decrease torque and increase flux, and V_3 is applied to decrease torque and flux. V_4 is never applied in sector 1 because it has a large magnitude and the torque reduction will be too drastic. In sectors 3, 5 and 7 the vectors are chosen following the same reasoning as above. For sector 2 the application of the voltage vector V_2 produces an increase in the flux magnitude and torque; the application of V_1 increases the flux magnitude and decreases torque; V_4 and V_3 produce the opposite effect, respectively. A similar reasoning is used for sectors 4, 6 and 8.

3. MPC for Induction Motor Control

Model predictive control (MPC) is a control method that, at each sampling instant, computes the control input to be applied at such instant by solving an open-loop optimal control problem. The initial state for the optimization is taken to be the current

Table 2. Reconfigured Voltage Vector Switching Table.

τ_{em}	λ_s	$S1$	$S2$	$S3$	$S4$	$S5$	$S6$	$S7$	$S8$
0	0	V_3	V_4	V_4	V_1	V_1	V_2	V_2	V_3
0	1	V_1	V_1	V_2	V_2	V_3	V_3	V_4	V_4
1	0	V_2	V_3	V_3	V_4	V_4	V_1	V_1	V_2
1	1	V_2	V_2	V_3	V_3	V_4	V_4	V_1	V_1

system state, and future states are predicted over the prediction horizon using a model of the system. The optimal control sequence resulting from the optimization is an open loop strategy comprising a set of successive control inputs to be applied over the prediction horizon. However, this is converted into a feedback strategy by applying only the first control action of this set and then repeating the whole procedure at the next sampling instant when new measurements of the system states are obtained. This technique is known as receding-horizon control. Here we propose to use an MPC strategy for IM control (Geyer *et al.*, 2009; Bolognani *et al.*, 2009; Miranda *et al.*, 2009). The full state-space model of the IM can be written as follows:

$$\dot{x}(t) = A_c(\omega(t))x(t) + B_c u(t), \tag{5}$$

$$\dot{\omega} = \mu(\lambda_{ra} i_{sb} - \lambda_{rb} i_{sa}) - \frac{b}{J}\omega - \frac{1}{J}\tau_c, \tag{6}$$

with $x = \begin{bmatrix} i_{sa} & i_{sb} & \lambda_{ra} & \lambda_{rb} \end{bmatrix}^T$, J is the moment of inertia, b is the dynamic viscosity, i_{sa}, i_{sb} and λ_{ra}, λ_{rb} are the (a, b) components of the stator current and the rotor flux, respectively, ω is the rotor speed, $u = \begin{bmatrix} V_a & V_b \end{bmatrix}^T$, V_a and V_b the (a, b) components of the applied stator voltage, and where

$$A_c(\omega) = \begin{bmatrix} -\gamma & 0 & \alpha\beta & n_p\beta\omega \\ 0 & -\gamma & -n_p\beta\omega & \alpha\beta \\ \alpha L_m & 0 & -\alpha & -n_p\omega \\ 0 & \alpha L_m & n_p\omega & -\alpha \end{bmatrix}, \quad B_c = \begin{bmatrix} \frac{1}{\sigma L_s} & 0 \\ 0 & \frac{1}{\sigma L_s} \\ 0 & 0 \\ 0 & 0 \end{bmatrix}, \tag{7}$$

with model parameters $\alpha = \frac{R_r}{L_r} = \frac{1}{T_r}$, $\beta = \frac{L_m}{\sigma L_s L_r}$, $\gamma = \frac{1}{\sigma}(\frac{1-\sigma}{T_r} + \frac{1}{T_s})$, $T_s = \frac{R_s}{L_s}$, $\sigma = 1 - \frac{L_m^2}{L_s L_r}$, $\mu = n_p \frac{L_m}{J L_r}$, where R_r is the three-phase rotoric resistance.

Let t_k, for $k = 0, 1, \ldots$ denote the sampling instants and let a subscript k on a variable denote the value of such variable at the corresponding sampling instant, e.g., $x_k = x(t_k)$. Assuming that rotor speed is known and remains approximately constant between sampling instants, an exact discrete-time model equivalent to the continuous-time equations (5) can be found as follows:

$$x_{k+1} = A_k x_k + B_k u_k, \tag{8}$$

where the matrices A_k and B_k are given by [see (Miranda *et al.*, 2009)] for further details on the online computation of these matrices)

$$A_k = e^{A_c(\omega_k)\cdot(t_{k+1}-t_k)}, \quad B_k = \int_{t_k}^{t_{k+1}} e^{A_c(\omega_k)\cdot(t_{k+1}-t)} B_c dt. \tag{9}$$

The electromagnetic torque and the squared magnitude of the stator flux are calculated at each sampling time as follows:

$$|(\lambda_s)_k|^2 = [Cx_k]^T[Cx_k], \quad (\tau_{em})_k \quad = x_k^T T x_k \tag{10}$$

where the matrices C and T are given by

$$C = \begin{bmatrix} L_s\sigma & 0 & \frac{L_m}{L_r} & 0 \\ 0 & L_s\sigma & 0 & \frac{L_m}{L_r} \end{bmatrix}, \quad T = \frac{3}{2} n_p \frac{L_m}{L_r} \begin{bmatrix} 0 & 0 & 0 & -0.5 \\ 0 & 0 & 0.5 & 0 \\ 0 & 0.5 & 0 & 0 \\ -0.5 & 0 & 0 & 0 \end{bmatrix} \tag{11}$$

The cost function for the MPC on-line minimization is

$$J_{cost} = \sum_{\ell=k}^{\ell=k+N} \Big\{ W_\tau \left[\tau_{em}(t_\ell) - \tau_{ref}(t_\ell)\right]^2 + \\ + W_\lambda \left[|\lambda_s(t_\ell)|^2 - \lambda_{ref}^2(t_\ell)\right]^2 + W_{sw}\Delta u(t_\ell) \Big\} \tag{12}$$

where N is the prediction horizon, τ_{ref} and λ_{ref} are the desired reference signals for torque and flux magnitude, respectively, and Δu equals the number of VSI leg switchings required at each sampling time known as the ‘Hamming distance’: if the control action (applied voltage vector) changes from V_i at time $t_{\ell-1}$ to V_j at time t_ℓ, with $i, j \in \{0, \ldots, 7\}$, then $\Delta u(t_\ell)$ equals $0, 1, 2$ or 3 depending on the number of VSI leg switchings required for switching from V_i to V_j. Also in (12), W_τ and W_λ are the torque and flux magnitude error weights, whereas W_{sw} is the VSI leg switching weight.

To evaluate the predicted values of torque and stator flux magnitude, $\tau_{em}(t_\ell)$ and $|\lambda_s(t_\ell)|$, for $\ell = k+1, \ldots, k+N$, the model (8)–(10) is used, where the rotor speed $\omega(t)$ is assumed to remain constant and equal to $\omega(t_k) = \omega_k$ over the prediction horizon (t_k to t_{k+N}), and the input u_ℓ, for every ℓ, is constrained (in healthy operation) to the finite set consisting of the eight voltage vectors generated by the inverter. Thus, there is a total of 8^N possible sequences of input vectors, and the same number of predicted values for the cost function (12), of which the minimum is selected. The minimizing sequence consists of N voltage vectors. The first vector of this sequence is applied and a new sequence is recalculated at the next sampling time.

3.1. Reconfigured MPC strategy

As explained previously, there are only 4 vectors after a reconfiguration of the VSI. Hence, it is possible to reconfigure the MPC control algorithm using the same cost function but constraining the input to the finite set consisting of the new, “after-fault”, voltage vectors. Notice that in this case the number of possible control input sequences over the prediction horizon is reduced to 4^N.

4. Simulation Results

In this section, simulation results are presented in order to compare the performances of MPC and DTFC and their associated reconfiguration strategies, ReMPC and ReDTFC, respectively. In particular, for the MPC strategy we consider a unity prediction horizon for the cost function (12), namely, $N = 1$. This is because our experience from (Nacusse *et al.*, 2010) is that using $N = 2$ does not improve the results obtained with $N = 1$ and the increment of computational load is significant.

The simulations were performed using Matlab/Simulink with the toolbox developed in (Felicioni *et al.*, 2002), and the power electronics components are modeled as ideal switches. A cascaded control structure for speed control is employed, adding a PI controller to compute the desired torque reference. The stator currents and the rotor speed are measured and the respective fluxes are estimated. The induction motor chosen for simulation has the following parameters: $R_r = 0.39923\Omega$, $R_s = 1.165\Omega$, $J = 0.0812Nm$, $L_s = 0.13995Hy$, $L_r = 0.13995Hy$, $L_m = 0.13421Hy$, and $n_p = 2$. The PI parameters are $P_w = 7.05$ and $I_w = 0.0282$. Four sets of weights[1] are chosen for the cost function (12), namely $W_1 = [0.008\ 0.24\ 0.001]$, $W_2 = [0.0091\ 0.089\ 0.001]$, $W_1' = [0.008\ 0.24\ 0]$ and $W_2' = [0.0091\ 0.089\ 0]$ where $W_i = [W_{\tau,i}\, W_{\lambda,i}\, W_{sw,i}]$ and $W_i' = [W_{\tau,i}\, W_{\lambda,i}\, 0]$ for $i = 1, 2$. The MPC control strategy resulting from the use of the weights W_i is denoted MPC1$_{sw}$ and that corresponding to W_i' is denoted MPC1. The switching sampling period is $T_s = 0.1ms$.

The simulation scenario is as follows. The rotor speed reference is a ramp that starts at time zero with final value $75rad/s$. At time $T = 1s$ a load torque $\tau_l = 24Nm$ is applied. At time $T = 2s$ a fault in the R leg of the fault tolerant VSI occurs.

Fig. 4 shows the resulting electromagnetic torque, which has achieved steady state conditions when the fault in the VSI occurs. The associated stator flux magnitude evolution in presence of the fault is shown in Fig. 5. The top (bottom) plots of these figures correspond to the set of weights W_1 (W_2) whereas the left (right) plots correspond to the comparison DTFC versus MPC1 (DTFC versus MPC1$_{sw}$) and their respective reconfiguration strategies. We observe that MPC1 and MPC1$_{sw}$ with weight coefficients W_1 achieve an improvement in the torque and flux ripple values with respect to the DTFC strategy, while the same strategies with weight coefficients W_2 obtain a better ripple reduction in the electromagnetic torque and the flux ripple value remains almost equal. We also observe that the reconfigured version, ReMPC1 and ReMPC1$_{sw}$, of the controller maintain their ripple reduction pattern with respect to ReDTFC. This behavior indicates that the proposed MPC strategies are suitable to

1. When the cost function contains only torque and flux magnitude error terms, the weighting matrices are chosen to balance the contribution of both error terms since the amplitude values of these errors are very different. When the term that weights the number of VSI switches is added, the above criterion cannot be maintained because the new term would dominate the control selection (thus preventing the reduction of torque and flux ripple) if its contribution to the cost value is similar to the other terms. We therefore resolve this tradeoff by selecting $W_{sw,i}$ from experience and extensive simulation tests.

operate under faulty conditions because it is possible to maintain a comparable performance without changing the controller structure.

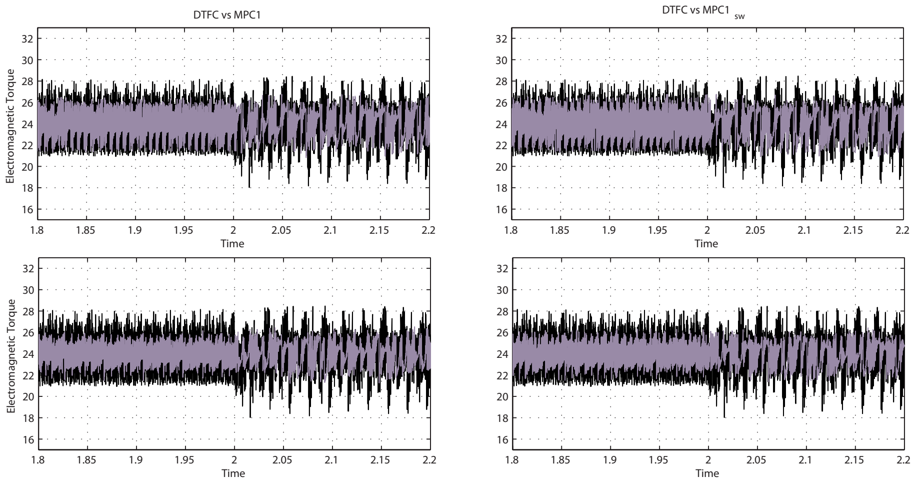


Figure 4. Electromagnetic torque for ReDTFC (in black), ReMPC1 (in grey, left plots) and ReMPC1$_{sw}$ (in grey, right plots). Simulation performed with W_1' and W_1 (top) and with W_2' and W_2 (bottom).

The voltage vectors applied during a reduced time interval are shown in Figure 6 as black dots. The grey solid line indicates the sector in which the stator flux vector lies at every time instant. Note that the stator flux vector lies in Sector 1 during most of the time interval shown. Also shown in these figures are scaled versions of the electromagnetic torque, τ_{em}, (dashed black line) and stator flux magnitude, λ_s, (dashed grey line) together with their reference signals. The top plots correspond to MPC1 and the bottom plots to MPC1$_{sw}$. The left (right) plots correspond to weight coefficients W_1 and W_1' (W_2 and W_2'). For coefficients W_1 and W_1' we see that the controller applies almost the same vectors as in DTFC (i.e. V_0, V_2 and V_3), except for a few time instants when it employs V_1 and V_4, which are not allowed in DTFC. For W_2 and W_2' the controller applies voltage vector V_1 to increment torque and flux during more than half of the time interval corresponding to Sector 1 in Figure 6, and vector V_4 to decrement both variables towards the end of that time interval. These control actions are responsible for the reduced torque and flux ripple. As observed in Fig. 2, the projection onto the d axis (top) and q axis (bottom) of the voltage vectors V_1 and V_4 has a magnitude smaller than that corresponding to V_2 and V_3. Hence, V_1 and V_4 produce a softer control action. However, switching between V_1 and V_3, and between V_2 and V_4, which occurs for MPC1, involves a greater number of inverter leg switchings and hence increase the associated commutation losses. The use of a positive weight W_{su} introduces some changes in the applied control actions but, in general, voltage vectors that are not allowed in DTFC will still be applied. When W_{su} is positive, the con-

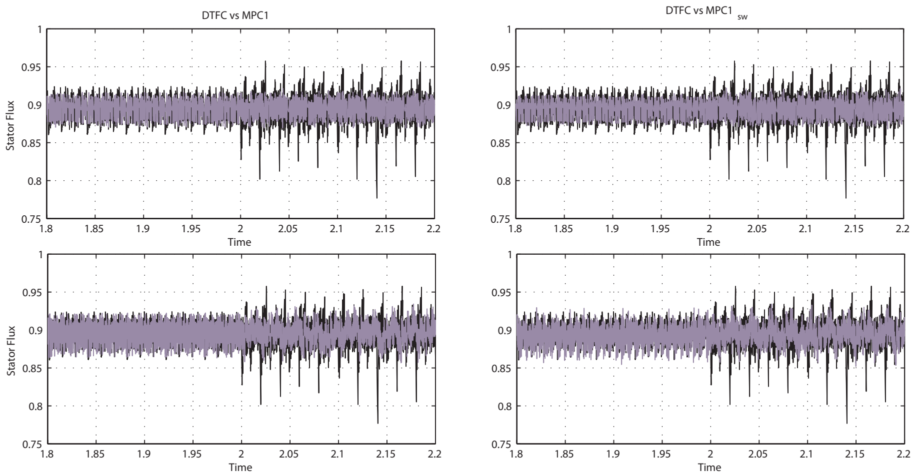
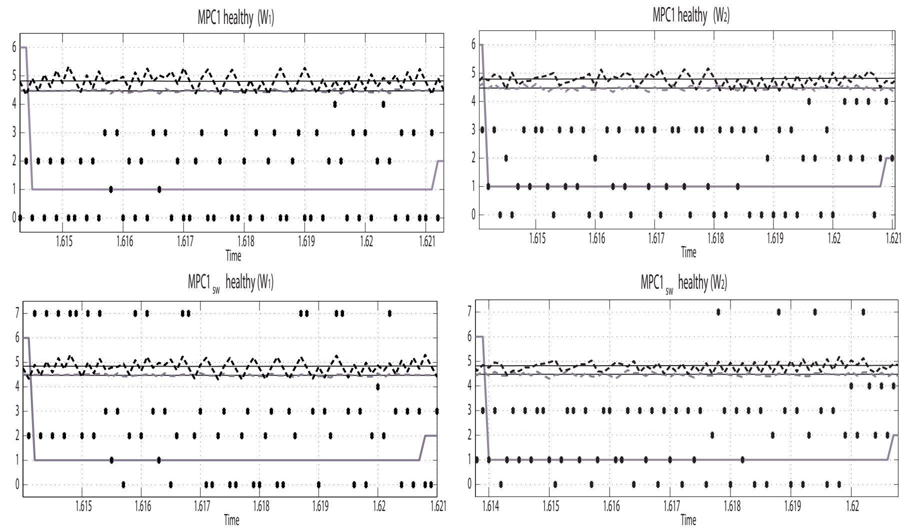


Figure 5. Stator flux magnitude for ReDTFC (in black), ReMPC1 (in grey, left plots) and ReMPC1$_{sw}$ (in grey, right plots). Simulation performed with W_1' and W_1 (top) and with W_2' and W_2 (bottom).

troller discriminates between null vectors V_0 and V_7, selecting the one which involves the fewest inverter leg switchings with respect to the previous voltage vector applied.

Similarly to Figure 6, the voltage vectors applied during faulty conditions are illustrated in Figure 7. In this case, all the ReMPC1 strategies, corresponding to weights W_1, W_1', W_2 and W_2', apply voltage vectors in a similar way because the VSI can only produce 4 different voltage vectors, instead of 8. The improvement in the ripple magnitude observed in Figure 7 when employing ReMPC1 is now mostly due to the fact that ReMPC1 employs knowledge of 5 variables in order to determine the control action, as opposed to ReDTFC which employs only 2 [see also (Nacusse *et al.*, 2010)]. Another observation in relation with the simulated torque response is that the faulty ripple amplitude is smaller than the healthy one. This is because the magnitude of the reconfigured voltage vectors is smaller than the magnitude of the original active voltage vectors: for the healthy VSI the magnitude of the voltage vectors is $\frac{2}{3}V_{DC}$ whereas for the reconfigured VSI the maximum magnitude of a voltage vector is $\frac{1}{\sqrt{3}}V_{DC}$.

Table 3 shows the number of inverter leg switchings over the whole simulation scenario, i.e. 3 sec., and the RMS torque error over 1000 points (0.1 seconds) obtained from simulation tests of ReDTFC, ReMPC1 and ReMPC1$_{sw}$ for both healthy and faulty conditions . The 1000 points belong to steady state operation condition. Note that the lowest error values correspond to ReMPC1 with W_2', but the number of inverter leg switchings is the highest, whereas ReMPC1$_{sw}$ reduces the number of switchings considerably with almost no increase in the error.



(a) (b)

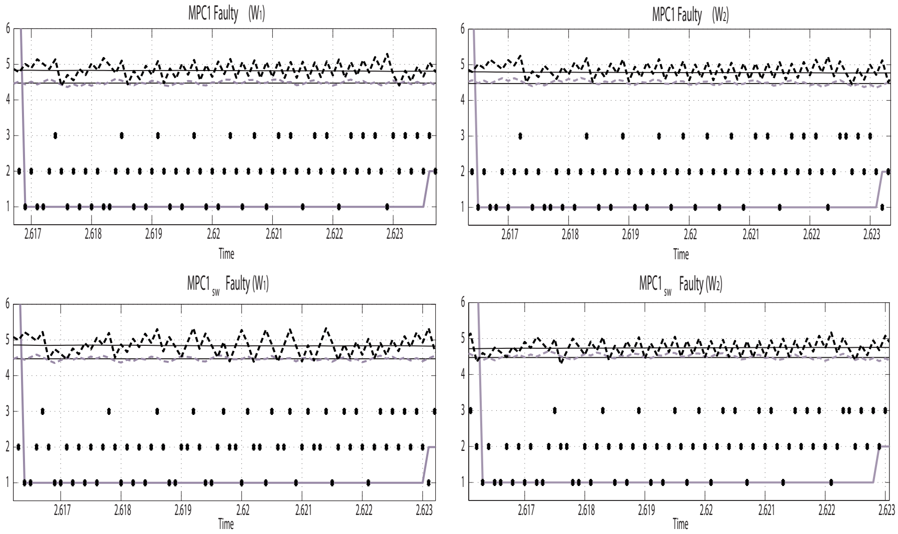
Figure 6. Sector 1 for healthy operation. (a) Simulation performed with W_1' and W_1. (b) with W_2' and W_2.

Table 3. Number of inverter leg switchings and RMS torque errors.

Strategy		Switching	Healthy RMSE	Faulty RMSE
ReDTFC		24501	1.8218	2.3875
W_1	ReMPC1	33915	1.3128	1.2606
	ReMPC1$_{sw}$	29048	1.3518	1.3439
W_2	$ReMPC1$	38540	1.0241	1.1226
	ReMPC1$_{sw}$	33128	1.0343	1.1224

5. Conclusions

We have presented a reconfigured model predictive control strategy (ReMPC) to reconfigure an induction motor control algorithm after faults in the VSI that feeds the motor. The ReMPC strategy was compared with a reconfigured DTFC strategy (ReDTFC) previously proposed. The simulation results show the achieved improvement of the ReMPC strategy with respect to the ReDTFC strategy. This improvement can be explained by the fact that, in order to select the appropriate input voltage vector, the MPC strategy benefits from knowledge of all the five state variables of the IM model, whereas DTFC employs only two variables: stator flux and electromagnetic torque. In addition, for prediction, MPC utilises a more complete model of the induction motor than that considered by the DTFC strategy. On the other hand, the mentioned improvement involves a greater number of commutations in the VSI.



(a) (b)

Figure 7. Sector 1 for faulty operation. (a) Simulation performed with W_1' and W_1. (b) with W_2' and W_2.

This increment in the switching losses has been reduced by weighting the inverter leg switchings. Future work includes the possibility to implement the proposed MPC strategy in 'explicit' form. We envisage the use of other norms in the cost function (such as 1-norms or ∞-norms) to avoid quartic functions of the state and input variables as is the case with the current choice of 2-norms used in the paper.

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