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Sensitivity of predictive controllers to parameter variation in five-phase induction motor drives

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ABSTRACT

Model predictive control techniques have been recently proposed as a viable control alternative for power converters and electrical drives. The good current tracking, flexible control design or reduced switching losses are some of the benefits that explain the recently increased attention on finite-control-set model predictive control. The performance of the predictive model of the drive, which is the core of the predictive control, highly depends on the parameters of the real system. In this context, most research works assume good agreement between electrical parameters of the predictive model and the real machine, on the basis of nominal values. Nevertheless, this is far from being a real assumption, where non-modeled variables (i.e. the temperature, the magnetic saturation or the deep-bar effect) produce a detuning effect between the real system and its model, which can harm the control performance. The influence of parameter variations on the predictive control has barely been investigated in recent research works, where only conventional three-phase power converter configurations and permanent magnet drives have been taken into account. However, there is a lack of knowledge when different technologies like induction machines or multiphase drives are considered. It is worth highlighting the interest of the industry in induction motors as a mature technology or in multiphase drives as a promising alternative in applications where high overall system reliability and reduction in the total power per phase are required. This paper attempts to fill this gap by examining the impact of parameters mismatch on the finite-control-set predictive control performance of a five-phase induction motor drive, one of the multiphase electromechanical conversion systems with greatest impact in the research community. An exhaustive experimental sensitivity analysis of the close loop system performance based on more than three hundred trials in a test bench is presented.

1. Introduction

The research interest in Model Predictive Control (MPC) has appeared in recent times highly influenced by the development of modern microprocessors, whose high computational power has favored the implementation of complex and time-consuming controllers in power converters and electrical drives (Kouro, Perez, Rodriguez, Llor, & Young, 2015). In this area of application, Finite-Control-Set MPC (FCS-MPC) is the most used predictive technique and appears as a promising alternative to conventional Field Oriented Control (FOC) and its principal competitor, the Direct Torque Control (DTC), due to its simplicity and flexibility to incorporate different control objectives, as well as the exhibited excellent dynamic performance (Lim, Rahim, Hew, & Levi, 2013; Rodriguez et al., 2013; Wang, Zhang, Davari, Rodríguez, & Kennel, 2014). Its extension to multiphase drives has been satisfactorily assessed in recent research works providing fast torque response and better transient performance than conventional FOC (Lim, Levi, Jones, Rahim, & Hew, 2014) and an improvement in the torque controllability with lower torque ripple comparing to the DTC (Riveros et al., 2013), since more than two system variables can be controlled at the same time.

The FCS-MPC technique is an optimization based control method, which selects at every sampling time the optimal control action (a switching state of the power converter among a finite number of

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possibilities) that minimizes a predefined cost function. The main challenge of FCS-MPC in real applications is the required computational burden of the optimization process, which is particularly critical in novel technologies based on multilevel converters (Vatani, Bahrani, Saeedifard, & Hovd, 2015) or multiphase drives (Arahal, Barrero, Toral, Duran, & Gregor, 2009; Martín, Arahal, Barrero, & Durán, 2016a). On the other hand, predictive controllers are, by definition, a model based control technique and its formulation relies on the knowledge of a model of the real system. When applied to the control of electrical drives, the model depends on the electrical parameters of the electrical machine, which are usually estimated using off-line techniques, such as the ones described in Chai, Wang, and Rogers (2013),Riveros et al. (2012) and Yepes et al. (2012) . However, their values usually change during the normal operation of the drive due to thermal, saturation or deep-bar effects, among others. It is well known that parameter detuning can have an important effect on the drive performance, and in Martín, Arahal, Barrero, and Durn (2016b) and Young, Perez, Rodriguez, and Abu-Rub (2014) it is shown that the operating point and the model design can highly affect the performance of the system. For this reason, it is important to evaluate the parameter sensitivity of predictive controller in order to guarantee its usefulness under different operating points and conditions.

The effect of parameters mismatch in MPC has been assessed in recent research works. Thus, parameter uncertainty in a three-phase permanent magnet synchronous machine fed by a Voltage Source Inverter (VSI) is analyzed in Morel, Lin-Shi, Retif, Allard, and Buttay (2009), Siami, Khaburi, Abbaszadeh, and Rodrguez (2016) and Zhang, Hou, and Mei (2016) for different MPC control schemes. Simulation and experimental results conclude that machine inductance variations are related to current ripple, whereas resistance and flux linkage variations affect to steady state errors and dynamic responses. Resistance and inductance of the predictive model of a three-phase active front end drive are detuned in Kwak, Moon, and Park (2014) when it is controlled by a finite-control-set predictive controller, and an experimental analysis of the controlled system reports that inductance variations produce high current ripples and steady state errors, being negligible the effects if resistances are disturbed. A sensitivity analysis in three-phase inverters is also shown in Young, Perez, and Rodriguez (2016), where it is stated that the steady state performance of the FCS-MPC is degraded when parameters are incorrect, being the load resistance in relation with steady state errors whereas changes in the load inductance increase the current ripple. All in all, previous works present a wide analysis of the predictive control dependence on the electrical parameters of the system model for different conventional power converters and drives. There is however a lack of knowledge regarding FCS-MPC applied to multiphase drives, which represent an interesting research field (Levi, Barrero, & Duran, 2016) and promising industry technology (Jung, Yoo, Sul, Choi, & Choi, 2012; Liu, Huang, Yu, Wen, & Zhong, 2014). The model of multiphase machines involves more electrical parameters and the phase currents are decomposed into more subspaces due to the higher number of degrees of freedom, making more difficult the sensitive analysis with respect to the three-phase case.

The purpose of this paper is therefore the experimental investigation of the parameter detuning impact on the performance of a controlled five-phase induction machine (IM), one of the most interesting multiphase drives (Barrero & Duran, 2016; Levi, 2016). The FCS-MPC method is used to control the stator currents, and an outer PI control loop regulates the machine speed. This speed controller is based on a conventional Indirect Rotor Field Oriented Control (IRFOC) where the usual four inner PI current regulators are replaced by the FCS-MPC current control. Each electrical parameter of the machine will be individually tested for several operating points in order to identify the system variables principally affected by each parameter. The rest of the paper is organized as follows. The model of the five-phase IM drive is presented in Section 2. Then, the general control scheme, which is composed by a FCS-MPC based current controller and an outer speed control, is shown in Section 3. Section 4 presents the principles for the sensitivity analysis and the obtained experimental results are shown in Section 5. Conclusions are summarized in the last section.

2. Modeling of the multiphase system

A five-phase IM with distributed windings equally displaced ($\vartheta = 2\pi/5$) and fed by a five-phase two-level VSI constitutes the system under study. A schematic layout of the drive is presented in Fig. 1, where the VSI gating signals are represented by $(S_a, \dots, S_e)$ together with their complementary values $(\bar{S}_a, \dots, \bar{S}_e)$. The modeling of the five-phase machine and the VSI are presented in the following subsections.

2.1. Five-phase IM model

During the modeling process, some simplifications are normally made in the machine equations to facilitate the real-time implementation of the control technique. Thus, the following standard assumptions are made: uniform air gap, symmetrical distributed windings, sinusoidal MMF distribution, and negligible core losses and magnetic saturation. Following the Vector Space Decomposition (VSD) approach and taking into account the previous simplifications, the machine model can be represented in state space matrix form in two orthogonal subspaces (Levi, Bojoi, Profumo, Toliyat, & Williamson, 2007) as follows

$$\frac{d\boldsymbol{x}(t)}{dt} = \boldsymbol{A}(\omega_r(t))\,\boldsymbol{x}(t) + \boldsymbol{B}\,\boldsymbol{v}(t)$$
$$\boldsymbol{y}(t) = \boldsymbol{C}\,\boldsymbol{x}(t) \quad (1)$$

where the $\alpha-\beta$ and $x-y$ stator currents and the $\alpha-\beta$ rotor flux are selected as state variables $\boldsymbol{x} = (i_{s\alpha}, i_{s\beta}, i_{sx}, i_{sy}, \psi_{r\alpha}, \psi_{r\beta})^T$, the input signals are the applied stator voltages $\boldsymbol{v} = (v_{s\alpha}, v_{s\beta}, v_{sx}, v_{sy})^T$, and the output signals are the stator currents $\boldsymbol{y} = (i_{s\alpha}, i_{s\beta}, i_{sx}, i_{sy})^T$. The $\alpha-\beta$ subspace corresponds to the fundamental flux and the generated electrical torque, while the $x-y$ subspace is related to the losses. A zero sequence current component in the z-axis also exists, but it does not flow due to the star-winding connection in the machine. In (1) matrices $\boldsymbol{A}$ and $\boldsymbol{B}$ depend on the rotor electric speed ω_r and the electrical machine parameters as it will be shown in the next two equations. The electrical parameters of the machine are the stator and rotor resistances R_s and R_r, stator and rotor inductances L_s and L_r, stator and rotor leakage inductances L_{ls} and L_{lr} and mutual inductance L_m.

$$\boldsymbol{A} = \begin{pmatrix} a_1 & 0 & 0 & 0 & a_2 & \omega_r a_3 \\ 0 & a_1 & 0 & 0 & -\omega_r a_3 & a_2 \\ 0 & 0 & -\frac{R_s}{L_{ls}} & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{R_s}{L_{ls}} & 0 & 0 \\ \frac{L_m R_r}{L_r} & 0 & 0 & 0 & -\frac{R_r}{L_r} & -\omega_r \\ 0 & \frac{L_m R_r}{L_r} & 0 & 0 & \omega_r & -\frac{R_r}{L_r} \end{pmatrix}$$

$$\boldsymbol{B} = \begin{pmatrix} b_1 & 0 & 0 & 0 \\ 0 & b_1 & 0 & 0 \\ 0 & 0 & \frac{1}{L_{ls}} & 0 \\ 0 & 0 & 0 & \frac{1}{L_{ls}} \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \quad \boldsymbol{C} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{pmatrix} \quad (2)$$

$$a_1 = -\frac{R_s L_r^2 + R_r L_m^2}{L_r(L_r L_s - L_m^2)}$$
$$a_2 = \frac{R_r L_m}{L_r(L_r L_s - L_m^2)}$$
$$a_3 = \frac{L_m}{L_r L_s - L_m^2}$$
$$b_1 = \frac{L_r}{L_r L_s - L_m^2}$$
$$L_s = L_{ls} + L_m$$
$$L_r = L_{lr} + L_m. \quad (3)$$