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# Multiphase rotor current observers for current predictive control: A five-phase case study

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ABSTRACT

The use of multiphase drives has gained importance in recent times due to some advantages that they provide over conventional three-phase ones. High performance stator current control can be achieved by means of direct command of voltage source inverter. In this context finite-state model predictive control is a very flexible strategy that has been recently proposed and analyzed. Nevertheless, its implementation must solve the problem of estimating rotor quantities, being the conventional solution a simple backtracking procedure. In this respect, observers appear as an attractive alternative. However, while they have been used with FOC, sensorless drives and for fault detection, they have not been used yet for predictive control of drives as a way to provide rotor values estimates. In this paper the authors propose to incorporate a full-order rotor current observer in a finite-state model predictive controller of a five-phase induction machine. Pole placement design based on Butterworth filters is used. The new estimation scheme and the standard procedure are compared. By means of experimental tests, the differences between both approaches and the benefits of including a rotor observer are illustrated and verified.

## 1. Introduction

In the last decade, research on multiphase electrical machines area has increased due to some specific advantages that they present over the conventional three-phase machines: less current harmonic content, higher overall system reliability, better power distribution per phase and better fault tolerance (Levi, 2008; Levi, Bojoi, Profumo, Toliyat, & Williamson, 2007). Among these machines, asymmetrical six-phase and five-phase induction machines (IM) with sinusoidally distributed stator windings are the most analyzed and proposed in recent works.

Current control strategies in multiphase drives are usually based on a multidimensional extension of common three-phase current controllers, dealing with the difficulties of large harmonic current, unbalanced currents and machine asymmetries (Che, Levi, Jones, Hew, & Rahim, 2014; Jones, Vukosavic, Dujic, & Levi, 2009; Yepes, Malvar, Vidal, Lopez, & Doval-Gandoy, 2015). However, these difficulties can be easily overcome eliminating the PWM and commanding the voltage source inverter (VSI) directly by means of model-based predictive control (MPC). Although MPC is a well-established control technique for electrical systems (Chai, Wang, & Rogers, 2013; Holtz & Stadtfeld, 1983; Lopez, Rodriguez, Silva, & Rivera, 2015; Wang, Zhang, Davari, Rodríguez, & Kennel, 2014), its application to multiphase IM has increased well after the publication of Levi (2008). Particularly, a new MPC configuration was proposed in Holmes and Martin (1996) in order to eliminate the classical PWM method, giving birth to a control structure that was later named as finite-state MPC (FSMPC) used in multi-phase IM for the first time in Arahal, Barrero, Toral, Duran, and Gregor (2009). Since the number of available converter switching states is a finite set, this control structure is also known as finite control set MPC (Choi & Lee, 2015; Rodriguez et al., 2013; Xie et al., 2015). Whatever the denomination, the fast control derived from direct command of the VSI combined with robustness and fault tolerant features that characterize multiphase drives have been analyzed in a number of recent papers (Arashloo, Salehifar, Romeral, & Sala, 2015; Guzman et al., 2016; Lim, Levi, Jones, Rahim, & Hew, 2014; Martinez, Arashloo, Salehifar, & Moreno, 2015; Riveros et al., 2013).

A problem encountered in the implementation of FSMPC is the estimation of non-measurable state components; for instance rotor quantities for which sensors are not available. A good knowledge of such quantities is often required in order to provide high performance control. Concerning this, observer theory (Luenberger, 1971) is a well known discipline that provides a framework for understanding and designing estimation schemes and it has been

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used in electrical systems such as IM drives. Basically, observers used in IM machines can take two forms, a full-order one that permits estimation of stator and rotor components from measurements of stator voltages, stator currents and speed (Jansen & Lorenz, 1994), and a reduced-order form which provides just the rotor components estimation using only measurements of stator currents and speed.

Most proposals of observers for IM have been made with field oriented control (FOC) method and related ones (El Fadili, Giri, El Magri, Lajouad, & Chaoui, 2014), even though FOC has been found in practice to be satisfactorily robust and effective without complex flux estimation structures. By contrast, FSMPC is highly sensitive to prediction errors (Arahal, Castilla, Alvarez, & Sánchez, 2013) that are caused by parameter mismatch among other reasons (Bogado, Barrero, Arahal, Toral, & Levi, 2013). In Alireza Davari, Khaburi, Wang, and Kennel (2012) sliding mode full-order and reduced-order observers are applied for flux and speed estimation for predictive torque control of IM. A robust model predictive current controller with a disturbance observer is also presented in Xia, Wang, Song, and Liu (2012), where a Luenberger observer is constructed for parameter mismatch and model uncertainty which affects the performance of the MPC. The gains of the disturbance observer are also determined using a root-locus analysis, and the stability of the disturbance observer is analyzed when there are errors in the inductor filter parameter. In Merabet, Ouhrouche, and Bui (2006), a nonlinear predictive control law with a disturbance observer is applied to track speed and flux profiles in an IM, considering the robustness to parameters variations and the disturbance rejection. This is in contrast to most applications of FSMPC to electrical systems, where observers are not used as such. Instead non-measurable quantities, disturbances and parametric and non-parametric uncertainties are lumped into one single term of the predictive model. This term is then updated using a simple procedure and the update is held until the next sampling period (Arahal et al., 2009).

In this paper a rotor current observer is included in the conventional FSMPC structure. The advantages of this new estimation scheme over the original one are analyzed and experimentally illustrated. For this purpose, a five-phase IM drive is used as a case study. However, the control method can be extended to any $n$-phase IM drive. Two observers, full-order and reduced-order, are studied. The observer design is tackled using pole placement methodology based on Butterworth filters. The rest of the paper is organized as follows. The general principles of the FSMPC technique and its application to the considered case study system are presented in the next section, where the standard rotor quantities estimation is reviewed and analyzed. The rotor current observers, full-order and reduced-order, are presented in Section 3 together with the design procedure. Experimental results comparing the different estimation methods are shown and discussed in Section 4. The paper ends with the conclusion section.

## 2. Finite-state model predictive control in five-phase IM drives

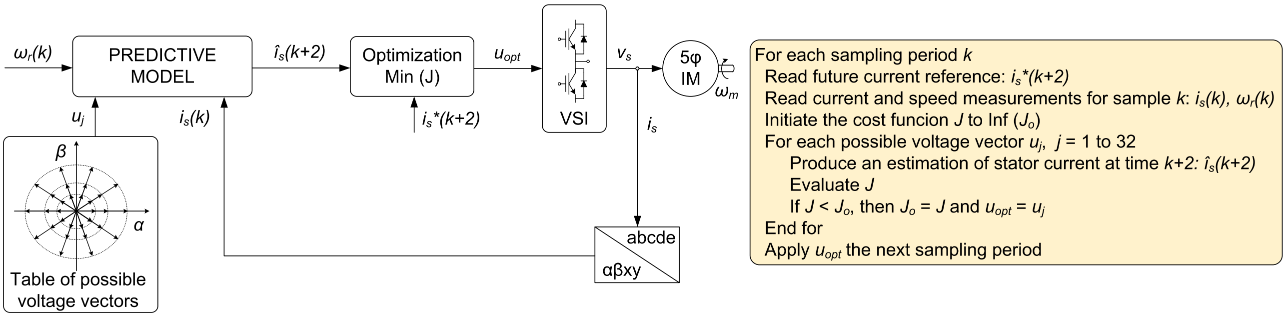
The FSMPC application to stator current control in a five-phase drive is schematically illustrated in Fig. 1. The objective of the controller is to track the reference stator currents represented by $i_s^*$. For this purpose, a discrete model of the physical system is used to predict the future behavior of the output variables $\hat{i}_s$. The prediction is computed making use of measured values of the rotor speed $\omega_r$ and the stator phase currents $i_s$ and tentative value of the control vector $u_j$ (the VSI gating signal). The most adequate control action $u_{opt}$ is selected by minimizing a cost function $J$ by means of exhaustive search over all possible control signal values. The optimum gating signal is applied to the VSI during the next sampling period. Finally, this process is repeated every sampling period. More details can be found in Arahal et al. (2009).

### 2.1. IM drive model

A symmetrical five-phase induction machine with distributed windings equally displaced $\vartheta = 2\pi/5$ and fed by a five-phase two-level VSI is used for testing the proposed method. An approximate scheme of the five-phase IM is shown in Fig. 2, where the gating signals of the VSI are represented by $(K_a, \ldots, K_e)$ and their complementary values $(\bar{K}_a, \ldots, \bar{K}_e)$.

The drive modeling process is made using some standard assumptions: uniform air gap, symmetrical distributed windings, sinusoidal MMF distribution, and negligible core losses and magnetic saturation. The sinusoidal MMF distribution is a well-known assumption in conventional and multiphase induction machines' modeling, provided that a distributed-winding induction machine is used, as it is discussed in Barrero and Duran (2016), Duran and Barrero (2016), and Levi et al. (2007). Then, from the five-phase machine equations in phase variables and following the vector space decomposition (VSD) approach the machine modeling can be represented in two orthogonal subspaces (Levi et al., 2007). One of them, the $\alpha$–$\beta$ subspace, is involved in the fundamental flux and the torque production, representing the fundamental supply component plus supply harmonics of the order $10n \pm 1$ with $n = 0, 1, 2, 3, \ldots$. The other, the $x$–$y$ subspace, is related to the losses and represents supply harmonics of the order $10n \pm 3$. Additionally, a zero sequence harmonic component of the order $5n$ with $n = 1, 2, 3, \ldots$ is projected in the $z$-axis, but it is not considered because the neutral point is isolated and consequently zero sequence currents cannot flow. Selecting the $\alpha$–$\beta$ and $x$–$y$ stator currents and the $\alpha$–$\beta$ rotor currents as state variables $x = (i_{s\alpha}, i_{s\beta}, i_{sx}, i_{sy}, i_{r\alpha}, i_{r\beta})^T$, the drive equations can be cast in the form

$$\begin{aligned} \dot{x}(t) &= A(\omega_r(t))x(t) + Bv(t) \\ y(t) &= Cx(t) \end{aligned} \tag{1}$$



```
For each sampling period $k$
  Read future current reference: $i_s^*(k+2)$
  Read current and speed measurements for sample $k$: $i_s(k)$, $\omega_r(k)$
  Initiate the cost funcion $J$ to Inf ($J_o$)
  For each possible voltage vector $u_j$,  $j$ = 1 to 32
      Produce an estimation of stator current at time $k+2$: $\hat{i}_s(k+2)$
      Evaluate $J$
      If $J < J_o$, then $J_o = J$ and $u_{opt} = u_j$
  End for
  Apply $u_{opt}$ the next sampling period
```

**Fig. 1.** General scheme of the FSMPC method applied to a symmetrical five-phase IM drive (left), and control algorithm (right).