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Trade-offs analysis in predictive current control of multi-phase induction machines

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ABSTRACT

In this paper, an assessment tool for stator-current predictive control of multi-phase induction machines is presented. The tool stems from a parameter analysis of the class of predictive controllers. This analysis exposes the underlying trade-offs among variables of interest. A reduced set of performance criteria is proposed for the parameter analysis. It is shown how the locus of the performance measures can be used to compare different types of predictive controllers. As application examples, some of the most common predictive strategies are reviewed. It is shown that the proposed assessment tool allows ranking the types of controllers under comparison. Additionally, the proposed tool can be used in control design and parameter tuning. The simulation results are backed by real experimentation using a six-phase motor.

1. Introduction

Multi-phase systems have been proposed in the literature based on their inherent traits of low torque ripple, low harmonics, high reliability and good power distribution per phase (Levi, Bojoi, Profumo, Toliyat, & Williamson, 2007). Predictive Current Control (PCC) is a strategy where a predictive inner control loop is used for stator current control and an outer loop for flux and speed control (Arahal, Barrero, Toral, Durán, & Gregor, 2009). The inner current controller avoids the use of Pulse Width Modulation (PWM); instead, the state of the Voltage Source Inverter (VSI) is computed at each sampling period. A predictive model is used to derive the best VSI state according to some objective function penalizing the deviation of stator currents from their references.

Multi-phase VSIs are characterized by a higher number of switching states compared with the traditional three-phase one (Lim, Levi, Jones, Rahim, & Hew, 2012). Space vector representation maps them into primary (α–β) and secondary (x–y) subspaces. This decomposition is useful in the context of PCC as it allows assigning different priorities to various objectives (primary and secondary tracking) using just one objective function (Zanchetta, 2011).

In this paper a trade-off analysis of PCC is performed. From the analysis a graphical tool emerges. It will be shown that this tool can be used for controller assessment and design. Controller assessment and trade-off analysis are topics not commonly found in the discrete-time predictive control literature. In fact, most reports of performance analysis are devoted to compare different systems such as IM vs. permanent magnet or switched reluctance machines. In those cases, the study is normally conducted using static characteristics (such as torque–speed response) derived from the system's equations. This kind of analysis can be extended to assess controllers provided that a continuous-time representation of the closed loop system is available (Karttunen, Kallio, Honkanen, Peltoniemi, & Silventoinen, 2017).

In the case of PCC there are no equations linking the controller parameters to performance indices; hence, the above strategy cannot be used. For this reason, comparative analyses are based on experimentation. However, in most cases they use just a handful of operating points. Moreover, a parameter analysis of the control strategy is usually not considered. Some exceptions are reviewed in the following. In Arahal et al. (2009) an analysis of the ratio of α–β vs. x–y penalties within the objective function is presented. In Barrero, Arahal, Gregor, Toral, and Durán (2009a) the contour maps of some performance indices across the whole operating range of a six-phase IM are shown. In Lim, Levi, Jones, Rahim, and Hew (2014) and Martín et al. (2017), a suite of simulations and experiments is performed in order to globally assess predictive controllers for a five-phase IM.

The proposed method uses a low dimensional tool that embeds the performance criteria. It considers the whole operating space. Additionally, it can be used to compare, not just particular controllers, but whole controller classes (e.g. controllers with different cost functions, with different prediction methods, etc.). In this work, a reduced set of performance criteria is proposed. The variables in this set are independent figures of merit that summarize the system's behavior in the sense that most other figures of merit are related to this set. The paper then shows

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Nomenclature

IM variables

i	Current
v	Voltage
ω	Angular speed
f_e	Electrical frequency

IM parameters

L	Inductance
R	Resistance

Subscripts

α–β	Energy conversion related subspace
x–y	Non-energy conversion related subspace

Superscripts

$*$	Reference value
$\hat{}$	Prediction

Control parameters

λ	Weighting factor
T_s	Sampling period
J	Cost function
Γ	Performance index

that PCC results lie, in performance-space, in a certain locus of low dimensionality. From this observation the inherent trade-offs of PCC are exposed. The analysis of such trade-offs explains results found in different previous reports (Arahal et al., 2009; Barrero et al., 2009a; Lim et al., 2014; Martín et al., 2017). The usefulness of the proposed analysis is however not limited to explaining previous results. Several of its uses are showcased in the paper, including the comparison different controller families, analysis of controller parameters and controller design (i.e. parameter tuning).

The paper includes simulations illustrating all the above possibilities of the trade-off analysis. A VSI-driven six-phase (asymmetrical dual three-phase) motor is used as case study. The simulation results are backed by real experiments that support the conclusions. The next section provides background material on PCC for multi-phase AC drives and presents the asymmetrical dual three-phase IM used for the study. Section 3 introduces the trade-off analysis. The different uses of the trade-off analysis are showcased using simulations in Section 4 that are later backed by experimental results. The derived conclusions are presented at the end of the paper.

2. Predictive current control of multi-phase IM

Multi-phase IM are typically used for high-performance drives and, consequently, require a precise speed control. The regulation of speed can be done using a control loop with proportional–integral (PI) controllers as done with three-phase drives. However, the inner current loop requires some further attention in order to properly track not only α–β components, but also the additional x–y currents.

In distributed-winding IMs it is assumed that spatial harmonics can be neglected, and then the electromechanical conversion process is fully restricted to the α–β plane. For this reason the regulation of α–β currents is identical to that of a three-phase IM. On the other hand, the x–y components are useless for flux/torque production. Hence, and for the sake of efficiency, they are regulated to follow null reference values (Levi et al., 2007). It is possible to use conventional PI control for

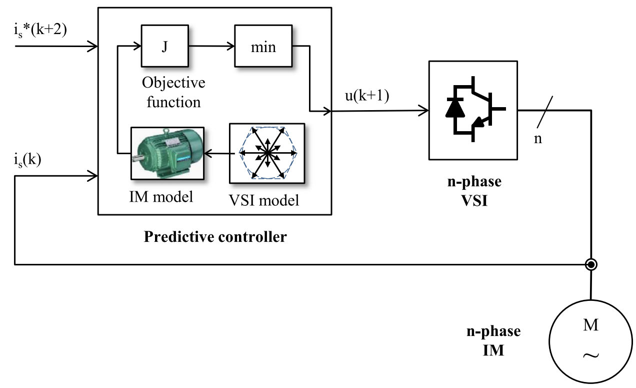

Fig. 1. Diagram of predictive current control of a n-phase IM.

both α–β and x–y currents. This is done by using a proper Park rotation and an external modulation stage (either carrier-based or space vector). However, the inner current control can be replaced by a predictive approach with no need for a modulation stage (Arahal et al., 2009). In this case, the current regulation is termed predictive current control.

Fig. 1 presents the general diagram of PCC for a n-phase drive. At discrete time k, the controller computes the optimal state of the VSI for the next sampling period $\mathbf{u}(k+1)$. The VSI in turn supplies a voltage $\mathbf{v}(k+1)$ whose objective is the generation of stator currents $\mathbf{i}_s$ that follow a reference trajectory $\mathbf{i}_s^*$. The procedure is repeated at each sampling period following the receding horizon rule.

The PCC uses a model of the IM and VSI to derive the 2-step ahead predictions for each possible VSI state. The IM model is based on the standard IM equations in phase variables. Using the vector space decomposition approach, and following standard procedures, a predictive model can be obtained with the general form given by

$$\hat{\mathbf{i}}_s(k+2|k) = \mathbf{A}(\omega)\mathbf{i}_s(k) + \mathbf{B}_1\mathbf{u}(k) + \mathbf{B}_2\mathbf{u}(k+1) + \mathbf{g}(k) \tag{1}$$

where matrices $\mathbf{A}(\omega)$, $\mathbf{B}_1$ and $\mathbf{B}_2$ are obtained discretizing the systems' dynamic equations considering the actual angular speed ω (see Arahal et al. (2009) for details). The state space vector $\mathbf{i}_s(k) = \left(i_{s\alpha}, i_{s\beta}, i_{sx}, i_{sy}\right)^\top(k)$ is obtained from the measurement of stator currents. Vector $\mathbf{g}$ accounts for the dynamics due to rotor currents that are usually not measured. Thus, $\mathbf{g}$ must be estimated at each discrete-time point (k) using either a backtracking procedure (Arahal et al., 2009), a discrete-time observer (Martín, Arahal, Barrero, & Durán, 2016), or a Kalman estimator (Rodas, Barrero, Arahal, Martín, & Gregor, 2016). In this paper the backtracking procedure is used for simulations and experiments using the following expression

$$\mathbf{g}(k) = \left(\mathbf{i}_s(k) - \mathbf{i}_s(k-1)\right) T_s^{-1} - \mathbf{A}(\omega)\mathbf{i}_s(k-1) - \mathbf{B}_1\mathbf{u}(k-1) \tag{2}$$

where T_s is the sampling period.

In previous equations, the control signal $\mathbf{u}$ is a vector of gating signals of the VSI legs: $\mathbf{u} = \left(K_1, K_2, \dots, K_n\right)^\top$ where $K_h \in \{0, 1\}$ for $h = 1, \dots, n$. Each phase of the motor can be either connected to the positive ($K_h = 1$) or negative ($K_h = 0$) rail of the DC-link. As a result, 2^n values for u are possible. This set produces just $\epsilon < 2^n$ different voltages due to redundancy for some pairs of gating signals (Arahal et al., 2009). Each non-redundant gating vector is denoted as S_j with $j = 1, \dots, \epsilon$. The selection of $\mathbf{u}(k+1)$ at discrete time k is made considering S_{opt} that minimizes the objective function J. The simplest objective function is

$$J = \|\hat{\mathbf{e}}_{\alpha\beta}\|^2 + \lambda_{xy}\|\hat{\mathbf{e}}_{xy}\|^2 \tag{3}$$

where $\|.\|$ denotes vector modulus, and $\hat{\mathbf{e}} = \left(\mathbf{i}_s^* - \hat{\mathbf{i}}_s\right)$ is the predicted current error in either α–β or x–y subspace. The PCC algorithm is presented in Fig. 2.