Discussion on: “A Saturated PI Velocity Controller for Voltage-Fed Induction Motors”

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The paper by Hernandez-Guzman and Santibanez is an interesting contribution to the induction motor field oriented control (FOC) literature. Standard FOC schemes can only prove local asymptotic regulation to the speed and flux references. The authors modify the classical indirect voltage-fed FOC methodology and propose the use of a saturated PI velocity control loop to ensure global asymptotic regulation.

Two variations of the original scheme will be presented in this discussion note. The first one, addresses the following question: can we select a reference torque \( \tau^* \) such that for the simple PI control law (19)

\[
V_{dq} = -\bar{R}I_{dq} - Ki \int_0^t \dot{I}_{dq}(s) ds
\]

global asymptotic regulation is achieved? The answer is positive if we modify the \( z_\omega \) dynamics given by (21) that represents the integral error term in \( \tau^* \) to

\[
\dot{z}_\omega = \tilde{\omega} - \frac{R_L L_r}{n_p M_e \psi_d} \left[ \begin{array}{c} 0 \\ 1 \end{array} \right]
\]

Observe that the term \(-RI_{dq}^*\) which remains uncanceled in the current error dynamics can be decomposed as follows

\[
-R_I I_{dq}^* = -R_I \left[ \begin{array}{c} \psi_d^* \\ \frac{L_r b}{n_p M_e \psi_d} \end{array} \right] + \frac{R_I L_r}{n_p M_e \psi_d} \left[ \begin{array}{c} 0 \\ 1 \end{array} \right] \sigma_1(k_{pq}\tilde{\theta})
\]

If we redefine the integral error variable \( z_1 \) to account for the constant term from the above identity

\[
z_1 := \int_0^t \dot{I}_{dq}(s) ds + K_i^{-1}(-\alpha_1 \psi_{dq}^* + \alpha_2 \omega^* J \psi_{dq})
\]

then, the Lyapunov function candidate (33) yields subsequently (36) with \( Q_{34}, Q_{44} \) modified as follows

\[
Q_{44} := \mu_1 \lambda_{\min}(R_a) - k_{res} L_r L_d^2
\]

\[
Q_{34} := -\frac{(k_{pq} + R_I)L_r}{2n_p M_e \psi_d^*}
\]

The analysis following (36) can then be invoked to prove asymptotic regulation under similar parameter selection.

The second variation that we propose lies within the adaptive control framework [1], [2]. Note that, in the paper, the system parameters such as rotor and stator resistances are assumed known. This restriction can be removed if we consider the adaptive control modification

\[
U_{dq} = -\bar{R}I_{dq} - K_i \int_0^t \dot{I}_{dq}(s) ds + \left[ \tilde{R}_I + (\lambda_1 \omega + \lambda_2 I_d) J \right] I_{dq}
\]

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with (20), (21), update laws
\[
\dot{\hat{R}}_I = -\gamma_1 \tilde{I}_{dq}^T \tilde{I}_{dq} \\
\dot{\hat{\lambda}}_1 = -\gamma_1 \omega \tilde{I}_{dq}^T \tilde{I}_{dq} \\
\dot{\hat{\lambda}}_2 = -\gamma_2 I_q \tilde{I}_{dq}^T \tilde{I}_{dq}
\]
and adaptation gains \(\gamma_{RI}, \gamma_1, \gamma_2 > 0\). Functions \(\hat{R}_I, \hat{\lambda}_1, \hat{\lambda}_2\) estimate the parameters \(R_I, \lambda_1 := n_p L_I, \lambda_2 := \frac{L_I R_e M_e}{L_v \psi_d}\) with estimation errors \(\tilde{R}_I := \hat{R}_I - R_I\) and \(\tilde{\lambda}_i := \hat{\lambda}_i - \lambda_i\) \((i = 1, 2)\), respectively. Defining now the candidate Lyapunov function
\[
V_0 := V(\hat{\omega}, z_o, \vartheta, \tilde{I}_{dq}, \tilde{\psi}_{dq}, z_1) + \frac{1}{2\gamma_I} \tilde{R}_I^2 + \sum_{i=1}^{2} \frac{1}{2\gamma_i} \tilde{\lambda}_i^2
\]
we can prove that
\[
\dot{V}_0 \leq -x^T Q x + \beta \| \tilde{\psi}_{dq} \|^2 - (\mu_2 + \mu_3) \lambda_{\min}(R_\alpha) \| \tilde{I}_{dq} \|^2.
\]
Now, a similar analysis to the one after (36), yields the desired asymptotic regulation result and the boundedness of the estimated signals for a suitable parameter selection.

References

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1. Introduction and review of the control structure

Indirect Field-Oriented Control (IFOC) is a standard high-performance control method, widely adopted in commercial induction motors, that has been proposed well before the application of modern theory of nonlinear feedback control to electric machines, [1], [2]. The main idea of “Field-Orientation” is to use a suitable coordinate transformation (often referred to as Clarke-Park transformation) to obtain a decoupling between the magnetic flux and the mechanical dynamics, by thus obtaining a transformed model similar to the one describing separately-excited DC machines. The description of the system in the new coordinates makes natural to approach the control problem by means of cascade approaches for the speed and torque control, with inner and outer loops governing respectively the current and the speed dynamics. This, in turn, is the structure underlying IFOC solutions, where the adjective “Indirect” means that the correct decoupling transformation is obtained asymptotically, in an open-loop fashion. This is in contrast with another standard solution, referred to as Direct Field-Oriented Control (DFOC), where magnetic flux measurements or, most commonly, estimations are exploited.

Although a rigorous global stability analysis of the “standard” IFOC is still lacking, many variants have been presented in literature with solid global stability proofs, most of them have been appropriately quoted in the paper. In this framework, the main contribution of the paper is to propose a further slight variant of the classical IFOC supported with a rigorous global asymptotic stability analysis of the resulting closed-loop system. The structure of the controller proposed in the paper can be commented as follows:

- A time-varying state-dependent coordinate transformation (rotation) is adopted to “indirectly” (i.e. asymptotically) align the variables representation with the rotor magnetic flux vector. The transformation, specified in (16)-(17), mimics perfectly standard commercial IFOC.