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Passivity-Based Control of Saturated Induction Motors

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the mean of the produced torque to be equal to the command torque. Fig. 3(c) shows the average switching frequency of both schemes; the conventional DTC scheme shows considerable variation in frequency which has been effectively controlled in the duty-cycle control scheme. Fig. 3(d) shows the duty cycle calculated by the torque-ripple reduction scheme.

VI. Conclusion

A simple scheme has been presented for duty-cycle control in a DTC-based induction motor drive. The scheme has been shown to reduce the torque ripple produced by this kind of drive, particularly at low speeds. The scheme has also been shown to effectively control the mean of the output torque and to limit the switching frequency variation.

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Passivity-Based Control of Saturated Induction Motors

Levent U. Gökdere, Marwan A. Simaan, and Charles W. Brice

***Abstract*—A passivity-based controller, which takes into account saturation of the magnetic material in the main flux path of the induction motor, is developed to provide close tracking of time-varying speed and flux trajectories in the high magnetic saturation regions. The proposed passivity-based controller is experimentally verified. Also, a comparison between the controllers based on the saturated and nonsaturated magnetics is presented to demonstrate the benefit of the controller based on the saturated magnetics.**

***Index Terms*—Induction motor, magnetic saturation, passivity-based control.**

I. Introduction

In [1], following the work in [2]–[4], a passivity-based controller for an induction motor was developed, and also experimentally verified, to provide close tracking of time-varying speed, position, and flux trajectories under the assumption of linear (nonsaturated) magnetics. In this letter, the results in [1] are extended to incorporate the magnetic saturation effects.

Heinemann *et al.* [5] have developed a field-oriented controller based on the saturated magnetic model of the induction motor. An input–output linearization controller, which takes the saturation effects into account, was implemented in [6].

In [5] and [6], the saturation is assumed to be entirely in the main flux path of the induction motor. That is, the change in the mutual inductance due to the saturation in the magnetic material is considered and the changes in the stator and rotor leakage factors are neglected. In this letter, the same approach is used to incorporate the magnetic saturation effects into the passivity-based control of induction motor.

II. Incorporation of Magnetic Saturation Effects into Passivity-Based Controller

In the current-command passivity-based control of induction motors and under the assumption of linear magnetics, the asymptotic stability of speed/position tracking errors are achieved by making the flux error dynamics given by (1) exponentially stable at the origin (see [1])

$$\frac{d\tilde{\lambda}_{\mathbf{dq}}}{dt} + \omega_s \mathbf{J}\tilde{\lambda}_{\mathbf{dq}} + \frac{R_r}{L_r}\tilde{\lambda}_{\mathbf{dq}} = \frac{R_r M}{L_r}\mathbf{i}^*_{\mathbf{dq}} - \frac{d\lambda^*_{\mathbf{dq}}}{dt} - \omega_s \mathbf{J}\lambda^*_{\mathbf{dq}} - \frac{R_r}{L_r}\lambda^*_{\mathbf{dq}}. \quad (1)$$

In [1], it is shown that this can be achieved by making the right-hand side of (1) equal to zero, that is, by defining the reference stator current vector and the slip frequency as [1]

$$\mathbf{i}^*_{\mathbf{dq}} \triangleq \begin{bmatrix} \dfrac{\lambda^*_d}{M} + \dfrac{L_r}{R_r M}\dfrac{d\lambda^*_d}{dt} \\ \dfrac{n_{ph}L_r}{2n_p M}\dfrac{\tau^*}{\lambda^*_d} \end{bmatrix} \quad (2)$$

and

$$\omega_s = \frac{n_{ph}R_r}{2n_p}\frac{\tau^*}{\lambda^{*2}_d}. \quad (3)$$

The inductances M and L_r in (1) will not be at their nominal values when saturation occurs. As a result, the controller (2), which is based on the nominal inductance values, does not guarantee the exponential tracking of the flux error. Taking this into account, and also using the approach in [5] and [6], we can then rearrange (2) as

$$\mathbf{i}^*_{\mathbf{dq}} \triangleq \begin{bmatrix} f_m^{-1}(\lambda^*_d) + \dfrac{L_r}{R_r M}\dfrac{d\lambda^*_d}{dt} \\ \dfrac{n_{ph}L_r}{2n_p M}\dfrac{\tau^*}{\lambda^*_d} \end{bmatrix} \quad (4)$$

where $f_m^{-1}(\cdot)$ is the inverse of the magnetization curve function of the induction motor. In (4), the nominal values of L_r and M are used. This is reasonable since $L_r/M = (1+\sigma_r)$, where σ_r is the rotor leakage factor, and the change in σ_r due to saturation is neglected. For the values of λ^*_d which remain in the linear magnetic region, $f_m^{-1}(\lambda^*_d) = \lambda^*_d/M$ with M constant so that (4) reduces to (2).

Note here that this is an *ad hoc* modification to the passivity-based controller based on the linear magnetics [1]–[4], [7], [8] and the following section shows that it improves the performance significantly when the motor is operated in the high magnetic saturation regions.

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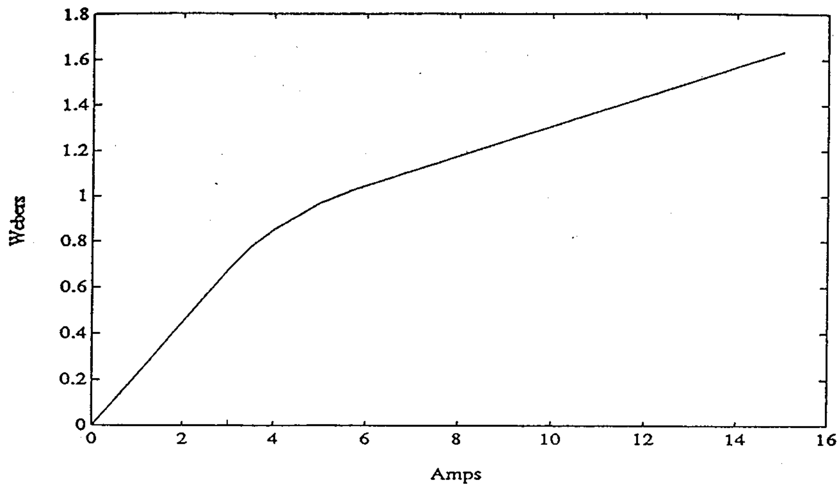
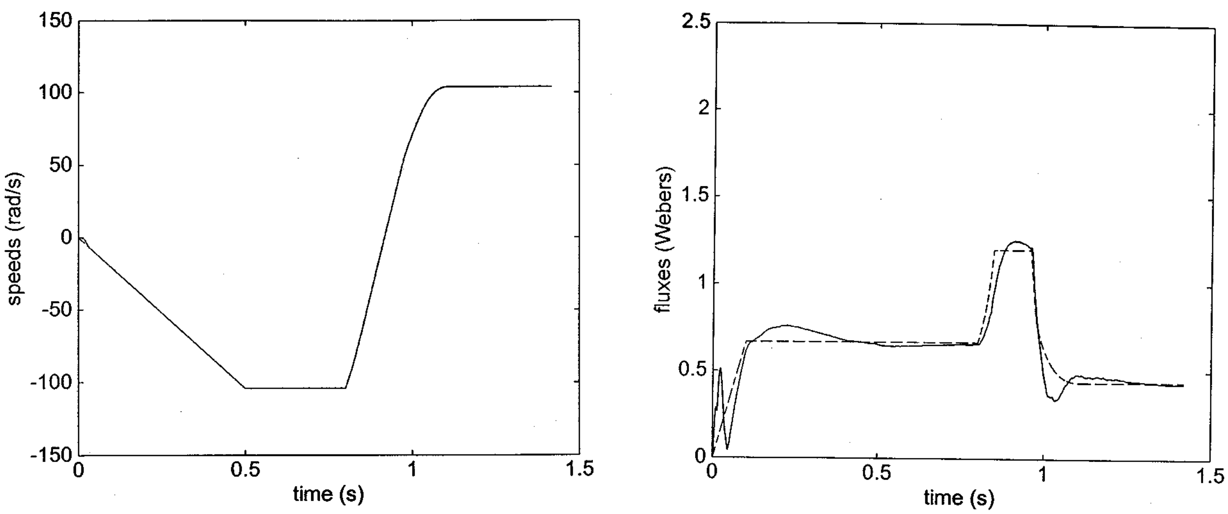


Fig. 1. Magnetization curve of the induction motor.



(a) (b)

Fig. 2. Speed reversal move with the controller based on nonlinear (saturated) magnetics. (a) Estimated (solid line) and reference (dashed line) speeds in radians per second versus time in seconds. (b) $|\hat{\lambda}_{\mathbf{dq}}|$ (solid line) and $|\lambda_{\mathbf{dq}}^*|$ (dashed line) in Webers versus time in seconds.

III. Experimental Results

The passivity-based controller (4) was tested on the same experimental setup as in [6]. The experimental setup consisted of: 1) a three-phase six-pole 1-hp squirrel-cage induction motor; 2) a Motorola DSP96002 (floating-point processor) application development system (ADS) system; 3) a data acquisition board; and 4) three 20-kHz pulsewidth modulation (PWM) amplifiers ($\pm$150 V and $\pm$10 A). The position measurements were obtained through a 2880 pulses/revolution (resolution of $2\pi/2880$ radians) line encoder. The induction motor parameters are: $M = 0.225$ H, $L_r = 0.244$ H, $L_s = 0.244$ H, $R_r = 2.1\ \Omega$, $R_s = 1.85\ \Omega$, $f = 0.0$ N·m/rad/s, and $J = 0.0185$ N·m·s^2 [6]. Fig. 1 shows the magnetization curve of the induction motor, which was experimentally determined in [6].

A. Speed Reversal Move

To demonstrate the benefit of the controller based on the saturated magnetics over the controller based on the nonsaturated magnetics, a demanding speed reversal experiment, which requires the operation of the motor in the high magnetic saturation regions, was conducted. In this move, the motor was required to accelerate from a speed of -104 rad/s to a speed of 104 rad/s in 0.186 s. The magnitude of the flux reference was chosen as the solution of the differential equation

$$\frac{d\lambda_d^*}{dt} = \frac{R_r M}{L_r}\left(-f_m^{-1}(\lambda_d^*) + \frac{1}{\mu\delta_{\mathrm{sopt}}(\omega^*)\lambda_d^*}\,\frac{d\omega^*}{dt}\right) \qquad (5)$$

where $\delta_{\mathrm{sopt}}(\omega^*)$ is the solution to the saturated magnetics optimal torque problem [6].

Fig. 2(a) and (b) shows the speed and flux tracking performance of the controller based on the saturated magnetics. From Fig. 2(a), it is seen that an excellent speed tracking was accomplished. Fig. 2(b) shows the magnitudes of estimated rotor flux vector $\hat{\lambda}_{\mathbf{dq}}$ and reference rotor flux vector $\lambda_{\mathbf{dq}}^*$. The rotor flux vector was estimated offline by solving

$$\frac{d}{dt}\begin{bmatrix}\hat{\lambda}_d\\ \hat{\lambda}_q\end{bmatrix} + \omega_s\mathbf{J}\begin{bmatrix}\hat{\lambda}_d\\ \hat{\lambda}_q\end{bmatrix} + \frac{R_r M}{L_r}\,\frac{f_m^{-1}\left(\sqrt{\hat{\lambda}_d^2+\hat{\lambda}_q^2}\right)}{\sqrt{\hat{\lambda}_d^2+\hat{\lambda}_q^2}}\begin{bmatrix}\hat{\lambda}_d\\ \hat{\lambda}_q\end{bmatrix} = \frac{R_r M}{L_r}\begin{bmatrix}i_d\\ i_q\end{bmatrix} \qquad (6)$$

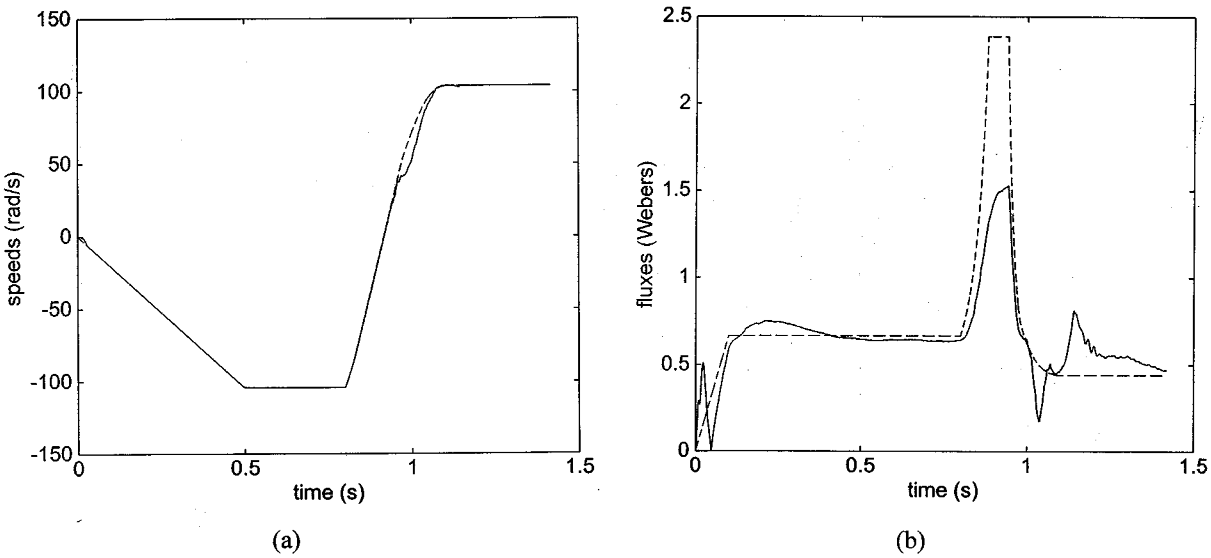


Fig. 3. Speed reversal move with the controller based on linear (nonsaturated) magnetics. (a) Estimated (solid line) and reference (dashed line) speeds in radians per second versus time in seconds. (b) $|\hat{\lambda}_{\mathbf{dq}}|$ (solid line) and $|\lambda^*_{\mathbf{dq}}|$ (dashed line) in Webers versus time in seconds.

where

$$\omega_s = \frac{n_{ph} R_r}{2n_p} \frac{\tau^*}{\lambda_d^{*2}} = \frac{R_r M}{L_r} \frac{i_q^*}{\lambda_d^*}.$$

The values of i_d, i_q, and i_q^* were collected from the experiment.

For comparison purposes, passivity-based controller (2), which is based on the linear magnetic model, was also implemented to control the same motor along the same mechanical trajectory. The magnitude of the flux reference was chosen as the solution of differential equation

$$\frac{d\lambda_d^*}{dt} = -\frac{R_r}{L_r}\lambda_d^* + \frac{R_r M}{\mu L_r \delta_{\text{lopt}}(\omega^*)\lambda_d^*}\frac{d\omega^*}{dt} \tag{7}$$

where $\delta_{\text{lopt}}(\omega^*)$is the solution to the linear magnetics optimal torque problem [9].

Fig. 3(a) and (b) shows the results. From this figure, it is seen that large speed and flux tracking errors occur. In brief, the controller based on the linear magnetics was not able to provide close tracking of the same mechanical trajectory.

In the passivity-based control of induction motors, the speed tracking can only be guaranteed if the flux tracking is achieved. Otherwise, large flux tracking errors act as disturbance input on the system, causing large speed tracking errors.

Another consideration is that the magnetic saturation effects are incorporated assuming that the magnetic saturation curve is a single-valued function. Furthermore, the modified controller is based on the nominal value of the rotor resistance. It is clear that the rotor resistance might vary from its nominal value significantly with a considerable impact on the system performance. Taking this into account, Chang *et al.* [10] proposed, and also experimentally validated, tuning rules for the proportional plus integral (PI) feedback gains to achieve good tracking performance under a wide range of variations of the motor parameters.

IV. Conclusions

A passivity-based controller, which takes into account saturation of the magnetic material in the main flux path of the induction motor, has been developed to provide close tracking of time-varying speed and flux trajectories in the high magnetic saturation regions. The experimental results with a demanding speed reversal move show that the proposed passivity-based controller exhibits an excellent speed tracking performance, while the performance of controller based on the linear magnetics deteriorates considerably in the high magnetic saturation regions.

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