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Commutation of Permanent-Magnet Synchronous AC Motors for Military and Traction Applications

P. Stewart and V. Kadirkamanathan

***Abstract*—A commutation method for the permanent-magnet ac motor is presented, which combines a Hall-effect encoder with a quadratic extrapolation scheme, and reduced-order state estimation in order to satisfy the design constraints prescribed by certain military and traction applications.**

***Index Terms*—Hall-effect devices, permanent-magnet machines, state observer, torque controller.**

I. Introduction

THE permanent-magnet ac (PMAC) motor requires accurate position information to be supplied to the controller so that the applied currents can be modulated in synchronism with the rotor. In the flux-weakening region of operation, accurate rotor position information is critical to control the relative phase of the applied stator voltages. The design of controllers, which can operate without direct position feedback, have been the subject of intense development. The most commonly cited justifications for the elimination of the absolute position encoder are those of cost, and the reduction of the overall dimensions of the motor. However, certain military specifications apply stringent constraints to the use of both sensors and estimation techniques. Absolute encoders are frequently prohibited for applications such as tank turret drives due to their relatively fragile nature. Fully sensorless operation has been the focus of development for all classes of electric motors, but again is precluded not only in certain military applications, but also in traction applications for a number of manufacturers.

The permanent-magnet dc motor is generally commutated with position information from a Hall-effect or optical encoder which gives a resolution of 60 electrical degrees. The PMAC motor can also be commutated with position feedback from this type of encoder, however, the six-step excitation leads to increased amplitude of torque ripple [1], and also prohibits or makes difficult the use of certain advanced operating regimes [2]. The applications under consideration in this paper require the reduced torque ripple which the PMAC motor offers, but due to a variety of constraints do not allow the use of high-resolution encoders. This leaves the Hall-effect encoder as a potential solution, if the problem of torque ripple can be addressed. Many sensorless techniques suffer from performance limitations at startup and also at low speed. Six-step operation supplemented by flux position estimation has been shown to reduce the amplitude of torque ripple produced by the motor, however, position tracking at low speeds and during velocity transients is shown to be poor [3]. A method for obtaining high-resolution position information is developed, being based upon the output of a Hall-effect position encoder. The six-step position information is supplemented by a quadratic interpolation scheme, which gives accurate position output during constant acceleration operation. A reduced-order state estimator is finally introduced to supplement the scheme during disturbances.

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II. Extrapolation and Estimation

The rotor position can be predicted between the encoder input points by applying polynomial extrapolation via a Newton Predictor [4], [5]. However, as the applications are dynamic, the events from the encoder are unevenly spaced, thus, a multirate prediction must be applied [6]. Applying Newton's divided difference interpolation formula, pairs (x_i, y_i) represent the time x_i when the value y_i arrives from the encoder. Values of a polynomial of arbitrary degree n can be calculated by

$$\begin{aligned} y(x) =& y_0 + (x - x_0)d[x_0, x_1] \\ &+ (x - x_0)(x - x_1)d[x_0, x_1, x_2] + \cdots \\ &+ (x - x_0)\dots(x - x_{n-1})d[x_0, \dots, x_n]. \end{aligned} \tag{1}$$

The differences are defined recursively by

$$\begin{aligned} d[x_0, x_1] =& \frac{y(x_1) - y(x_0)}{x_1 - x_0}, \\ d[x_0, x_1, x_2] =& \frac{d[x_1, x_2] - d[x_0, x_1]}{x_2 - x_0}, \dots \\ d[x_0, \dots, x_k] =& \frac{d[x_1, \dots, x_k] - d[x_0, \dots, x_{k-1}]}{x_k - x_0}. \end{aligned} \tag{2}$$

In this case, a quadratic polynomial was found to be adequate and , also, no recursive noise filtering was found necessary. The quadratic scheme is valid only for operation during approximately constant acceleration, and it is proposed to supplement the operation of the dc encoder with a nonlinear observer to operate during torque disturbances. The motor dynamics can be described in a stationary two-axes frame [7], [8] derived by nonlinear transformation such that

$$i_\alpha = \frac{2}{3}\left(i_a - \frac{i_b}{2} - \frac{i_c}{2}\right) \dots \text{and} \dots i_\beta = \frac{i_b - i_c}{\sqrt{3}} \tag{3}$$

$$v_\alpha = \frac{2}{3}\left(v_a - \frac{v_b}{2} - \frac{v_c}{2}\right) \dots \text{and} \dots v_\beta = \frac{v_b - v_c}{\sqrt{3}} \tag{4}$$

where i_α, i_β, v_α, and v_β are the transformed current and voltage components in the two-axes frame. The reduced-order observer is chosen as the position estimation extension since the electrical states of the system can be directly measured, leading to a compact implementation. The position estimation implemented with the Hall encoder and quadratic scheme fulfills the primary role and is acceptable under both military and vehicle manufacturers' restrictions. The addition of a reduced-order observer is to correct any errors during disturbances and runs as a secondary rather than primary control task, and is also acceptable. Considering a nonlinear system given by

$$\frac{dx}{dt} = f(x) + g(x)u \tag{5}$$

$$y = h(x) \tag{6}$$

a nonlinear observer can be designed so that the observer equation is given by

$$\frac{d\hat{x}}{dt} = f(\hat{x}) + g(\hat{x})u + G(\hat{x}, u, y)[y - h(\hat{x})] \tag{7}$$

where u is input, y is output, and G is the adaptation gain. A reduced-order observer of the form

$$\left|\begin{matrix} \frac{d\hat{\theta}}{dt} \\ \frac{d\hat{\omega}}{dt} \end{matrix}\right| = \left|\begin{matrix} \hat{\omega} \\ \hat{a} \end{matrix}\right| + G\left(\hat{\theta}, \hat{\omega}\right)(y - \hat{y}) \tag{8}$$

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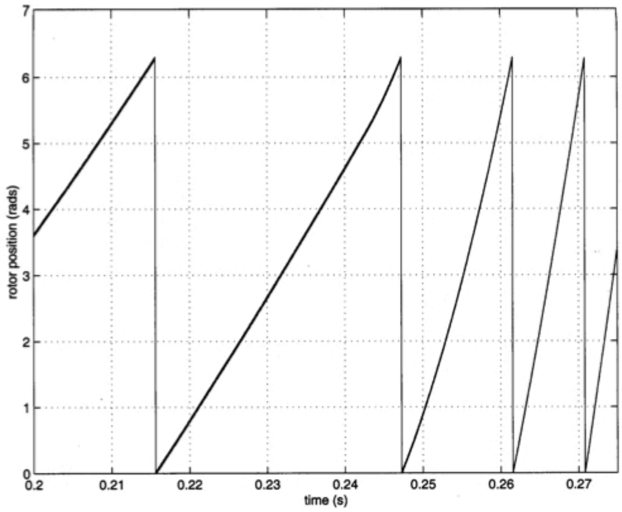

Fig. 1. Absolute and estimated position during disturbance.

where

$$\hat{a} = \frac{-3}{2}\frac{\phi}{J} i_\alpha \sin\left(\hat{\theta}\right) + \frac{3}{2}\frac{\phi}{J} i_\beta \cos\left(\hat{\theta}\right) \tag{9}$$

and

$$y = \begin{vmatrix} \frac{di_\alpha}{dt} \\ \frac{di_\beta}{dt} \end{vmatrix} = \begin{vmatrix} \frac{-R}{L} i_\alpha + \frac{\phi}{L}\omega \sin(\theta) + \frac{v_\alpha}{L} \\ \frac{-R}{L} i_\beta - \frac{\phi}{L}\omega \cos(\theta) + \frac{v_\beta}{L} \end{vmatrix} \tag{10}$$

$$\hat{y} = \begin{vmatrix} \frac{d\hat{i}_\alpha}{dt} \\ \frac{d\hat{i}_\beta}{dt} \end{vmatrix} = \begin{vmatrix} \frac{-R}{L} i_\alpha + \frac{\phi}{L}\hat{\omega} \sin(\hat{\theta}) + \frac{v_\alpha}{L} \\ \frac{-R}{L} i_\beta - \frac{\phi}{L}\hat{\omega} \cos(\hat{\theta}) + \frac{v_\beta}{L} \end{vmatrix} \tag{11}$$

can be derived from the system equations [7]. In this representation, ϕ is the permanent-magnet flux linkage [8], J is the rotor inertia, R is the phase resistance, and L is the phase inductance. Estimated quantities are denoted by a superscript hat. The adaptation gain G was ascertained in simulation and confirmed experimentally to give a fast convergence to an accurate solution.

III. Experimental Results

The position estimation schemes were implemented experimentally with a Hall-effect encoder fitted to the PMAC machine in tandem with a 12-bit absolute encoder, which provides a reference with which to assess the performance of the estimation schemes. In the experimental verification, the test motor and load motor are connected by a gearbox and clutch. At 50 rad/s, the electromechanical clutch was disengaged, and the motor accelerates with just its own inertia. In the position estimation results shown in Fig. 1, the estimated rotor position is superimposed onto the output of the absolute position encoder, which represents the waveform of accurate position. The position feedback scheme accurately tracks the rotor position even during a severe disturbance.

IV. Conclusion

A method of commutating the PMAC motor has been presented which satisfies several strict caveats. The commutation can be performed without recourse to the relatively fragile external absolute position encoder. The physical dimensions of the motor can remain untouched by building a Hall-effect encoder into the motor casing. This has the dual advantage of physical robustness and small size. Primary position feedback is provided by a quadratic estimator which is acceptable for the applications under consideration. The estimator is extended in the background by a reduced-order state estimator which provides position estimation during external disturbance. The technique has shown itself to be robust during experimentation, and satisfies the design constraints.

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