A DSP-Based Performance Monitor for Induction Motors

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Abstract **- A performance monitor for both controlled and uncontrolled induction motors, based on the TMS320F240 DSP controller from Texas Instruments, is presented. Estimation of the stator flux and developed torque is discussed and a speed observer utilizing the voltage-current model of the motor is described. Operating algorithms, details of digital implementation, and example test results are shown.**

I. INTRODUCTION

Induction motors are the primary workhorse of industry, but their domestic applications are on the rise as well. The motors are robust, simple, and inexpensive, with only minimum maintenance required. Adjustable-speed induction motor drives enjoy a rapid growth, although most motors still run uncontrolled. Sensors of the speed or position in an adjustable-speed drive tend to spoil the ruggedness of the drive, so efforts are made to replace them with estimators and observers utilizing the voltage and current signals [1]. The magnetic flux, developed torque, and rotor speed are of particular interest. Estimates of these variables in uncontrolled motors are also valuable, as a source of information about operating conditions of the motor. The estimation algorithms require substantial amount of signal processing, best performed by DSPs.

This paper describes a performance monitor for induction motors, based on the Texas Instruments' TMS320F240 DSP controller [2]. The operating algorithms, implementation issues, and test results are presented.

II. MATHEMATICAL MODEL OF THE INDUCTION MOTOR

The monitoring functions are based on the induction motor vector model and estimation theory [1], [3], [4]. The dynamic model of the induction motor for an arbitrary reference frame is described by the following equations:

$$\underline{u}_s = R_s \underline{i}_s + s\underline{\psi}_s + j\omega_e \underline{\psi}_s \tag{1}$$

$$\underline{0} = R_r \underline{i}_r + s\underline{\psi}_r + j(\omega_e - \omega_r)\underline{\psi}_r \tag{2}$$

$$\underline{\psi}_s = L_s \underline{i}_s + L_m \underline{i}_r \tag{3}$$

$$\underline{\psi}_r = L_r \underline{i}_r + L_m \underline{i}_s \tag{4}$$

where

$\underline{u}_s$	stator voltage vector
$\underline{i}_s$, $\underline{i}_r$	stator and rotor current vectors

$\underline{\psi}_s$, $\underline{\psi}_r$	stator and rotor flux vectors
R_s, R_r, L_s, L_r, and L_m	motor resistance and inductance parameters
ω_e	reference frame speed (arbitrary)
ω_r	rotor speed
s	derivative operator, d/dt.

III. The State Estimator

The stator flux calculator is based on (1), in the stator reference frame ($\omega_e = 0$):

$$\underline{\psi}_s = \frac{1}{s}(\underline{U}_s - R_s \underline{i}_s) \tag{6}$$

Direct implementation of this equation is not realistic. Due to the offset present in the measured signals, large drift can be experienced in the estimated flux. The simplest solution to avoid this problem is to use a low pass filter:

$$\underline{\psi}_s = \frac{1}{1+sT}(\underline{U}_s - R_s \underline{i}_s) \tag{7}$$

with a possibly large T. The rotor flux $\underline{\psi}_r$ is calculated from (6) as

$$\underline{\psi}_r = \frac{L_r}{L_m}\underline{\psi}_s - \frac{L_s L_r - L_m^2}{L_m}\underline{i}_s \tag{8}$$

Estimation of both fluxes is illustrated in Fig. 1.

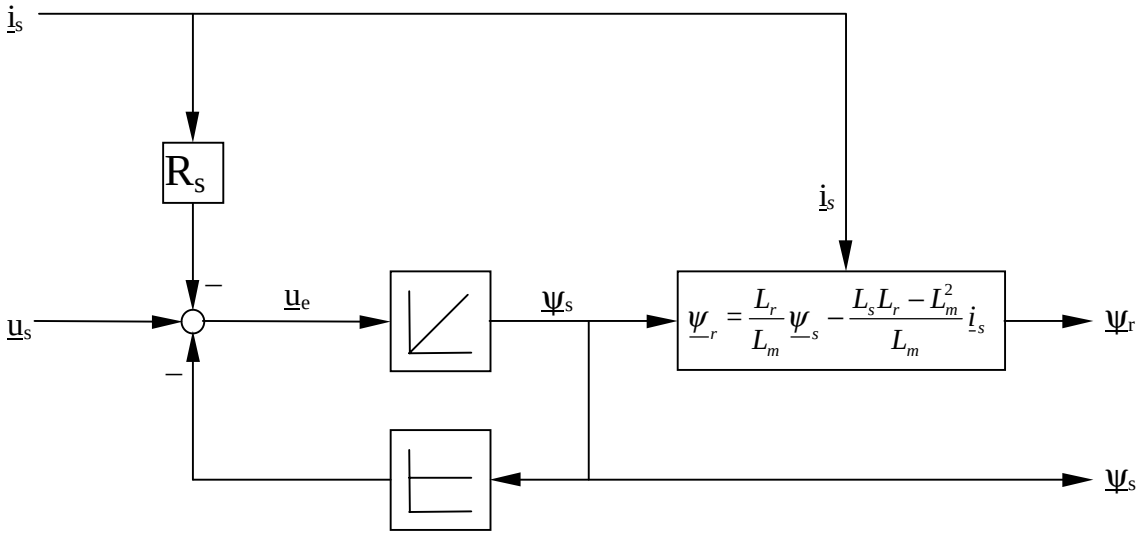

Fig. 1. Stator and rotor flux estimation.

The electromagnetic torque is given by

$$M_e = \frac{3}{4} p(\psi_{sd} i_{sq} - \psi_{sq} i_{sd}) \tag{7}$$

where p is the number of motor's poles and subscripts "d" and "q" denote the two orthogonal components of the stator flux and current vectors. The speed of rotor flux can be determined as

$$\omega_{\psi r} = \frac{d}{dt} \arctan \frac{\psi_{r\beta}}{\psi_{r\alpha}} \tag{9}$$

and the rotor speed is calculated from (7 - 9) as

$$\omega_r = \omega_{\psi r} - \frac{4R_r}{3p} \cdot \frac{M_e}{\psi_r^2} \tag{10}$$

where ψ_r is the amplitude of the rotor flux, given by

$$\psi_r = \sqrt{\psi_{rd}^2 + \psi_{rq}^2} \tag{11}$$

Similarly, the amplitude of the stator flux is

$$\psi_s = \sqrt{\psi_{sd}^2 + \psi_{sq}^2} \tag{12}$$

The torque and speed estimation is illustrated in Fig. 2.

IV. Signal Measurement and Processing

To perform the required calculations, two line to line voltages and two line currents are measured. The phase quantities (subscripts a, b, c) are determined depending on the motor connection (Y or Δ). The voltage and current vectors (subscripts d and q) are then calculated, using the abc to dq transformation equations

$$\underline{U} = u_{sd} + j u_{sq} \tag{16}$$

where

$$u_{sd} = \frac{2}{3} u_a - \frac{1}{3}(u_b + u_c) \tag{17}$$

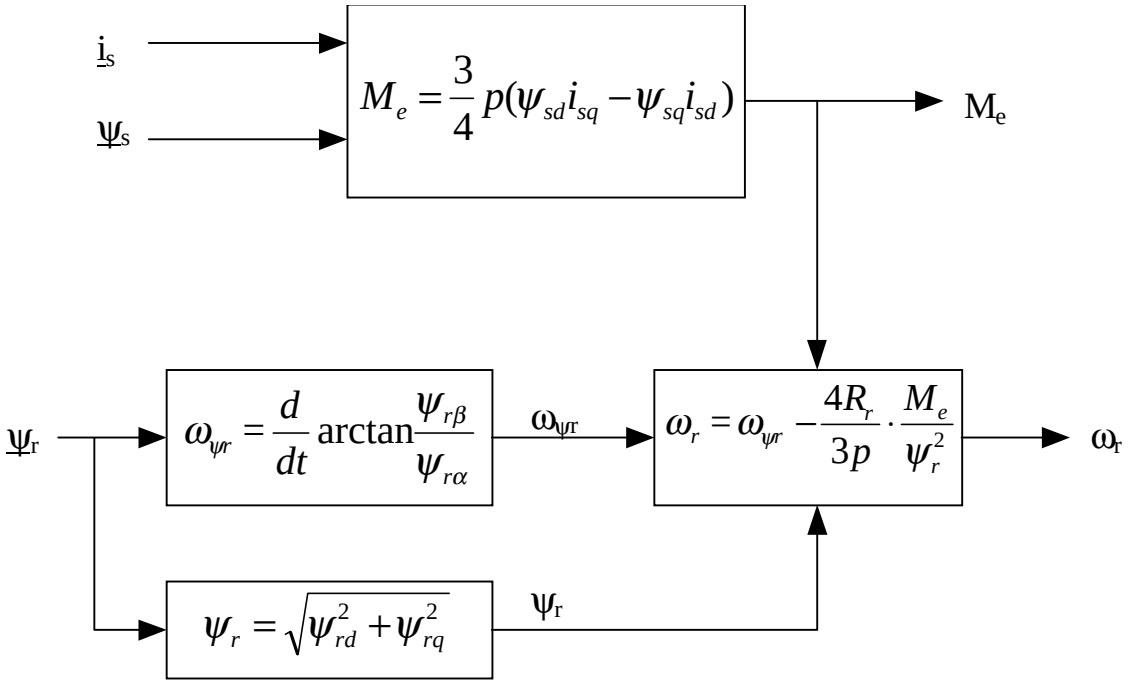

Fig. 2. Torque and speed estimation.

$$u_{sq} = \frac{1}{\sqrt{3}}(u_b - u_c) \tag{18}$$

and

$$\underline{I} = i_{sd} + j i_{sq} \tag{19}$$

where

$$i_{sd} = \frac{2}{3} i_a - \frac{1}{3}(i_b + i_c) \tag{20}$$

$$i_{sq} = \frac{1}{\sqrt{3}}(i_b - i_c) \tag{21}$$

Equations (6) – (21) were digitally implemented in the Texas TMS320F240 DSP controller, as illustrated in Fig. 3. The system is able to operate with voltages up to 480 V. and inverter frequencies from 1 to 100Hz. The current range depends on the motor power and the current transducers' current range. For the experiments, 50A current transducers were used.

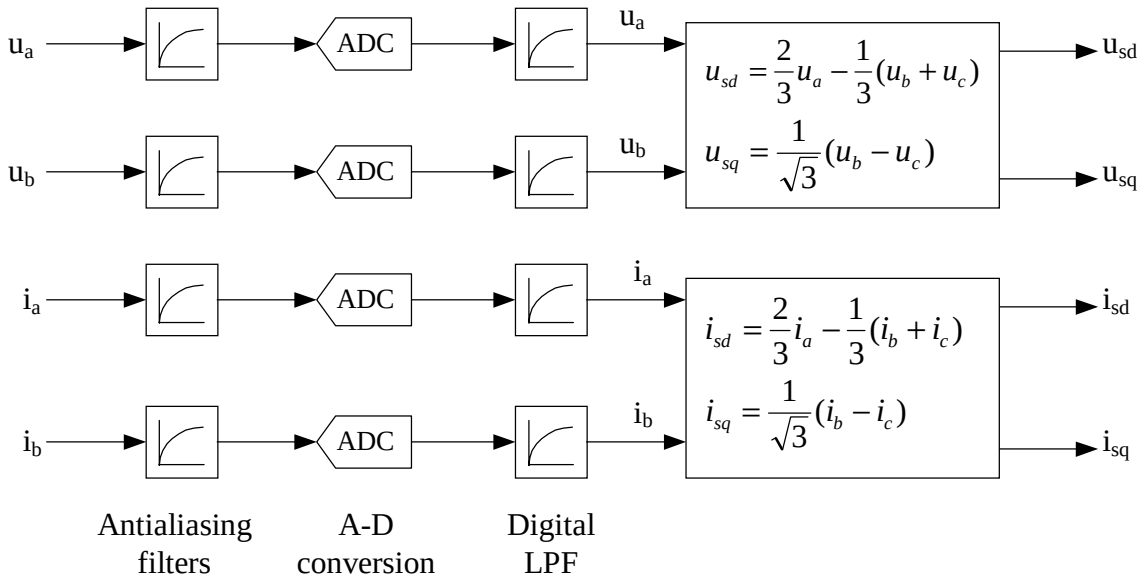

Fig. 3. Signal measurement and preprocessing.

V. Implementation

The TMS320F240 DSP controller was designed to meet a wide range of motor control applications. Through integration of the high performance DSP core and the on-chip microcontroller peripherals into a single chip solution, it offers, at a speed of 20 MIPS, an in expensive alternative over traditional 16-bit microcontrollers and microprocessors [2]. In designing the motor monitor described, every advantage was taken of the existing set of peripheral units and functions.

The analog signals are measured by the dual 10bit, 6μs ADC. The sampling and estimation period is 500μs. During this period, the stator flux, the rotor flux, the torque and the speed are estimated. The sampling time is controlled by the DSP's Event Manager timer T1 which activates the ADC by a compare signal. In each sampling period, the ADC makes two sets of conversions: two line currents followed by two line-to-line voltages. Once the measurements are done, the estimation process begins. All the formulas presented are digitally implemented using the powerful instruction set provided by the DSP. The calculations employ the DSP's native fixed-point mathematics, and the Q.15 format is used to represent the data.

The user interface (switches and LCD) is controlled by timer T3 with a low frequency (2 Hz) interrupt. The PC-DSP link uses the RS232 serial communication at rates up to 115,200 baud. The measured and estimated waveforms are displayed on the PS's display.

VI. Experimental Setup

The experimental setup consisted of the TMS320C240 Evaluation module (EVM), an Input/Output Module, and an Analog Interface, as shown in Fig. 4. The Input/Output Module contained a small keyboard (input switches) and a LCD. The names of monitored

quantities were displayed on both the LCD and the computer display. The measured and estimated waveforms could also be shown on the computer display. The Analog Interface included the current and voltage transducers and the antialiasing filters.

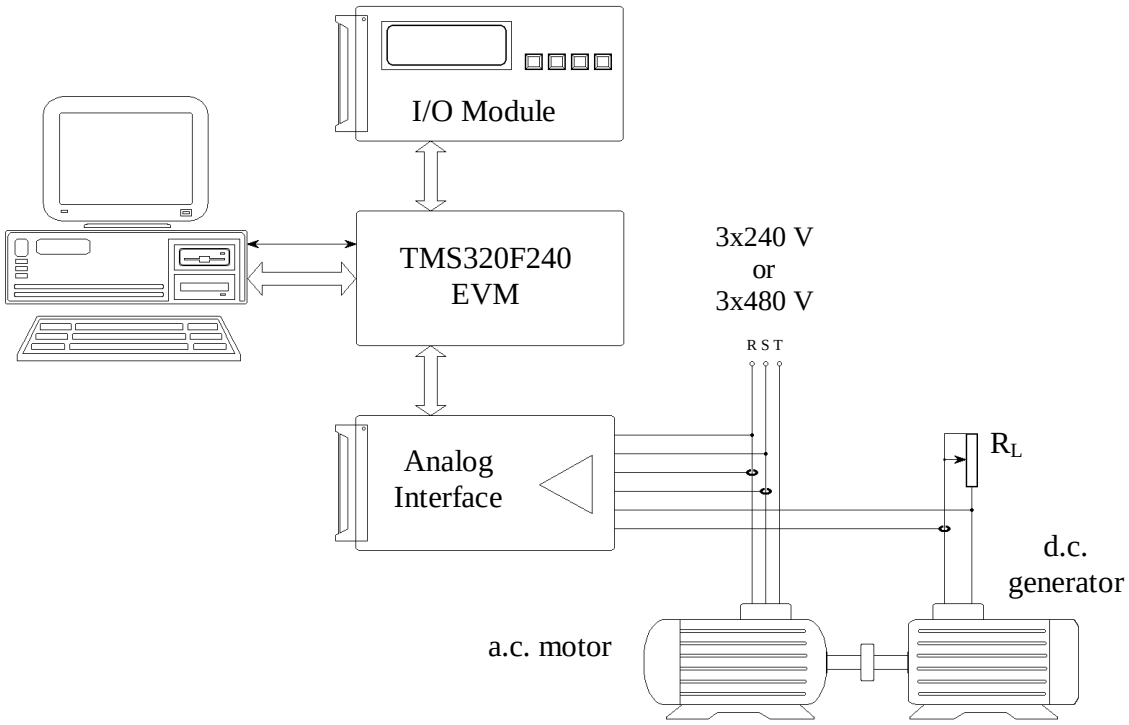

Fig. 4. Experimental setup.

For the system development, a 5-hp, 230-V, 6-pole induction motor, driving a dc generator, was used. The generator provided an adjustable mechanical load for the motor. The output voltage and current of the generator were measured in order to determine the torque and speed of the motor. This allowed a simple but accurate validation of the estimated motor variables.

VII. Example Experimental Results

Some experimental results with the motor performance monitor are presented below. The motor run with no load and with the speed close to the synchronous value of 1200 r/min. Oscillograms of the estimated stator and rotor fluxes are shown in Figs. 5 and 6. Waveforms of the estimated electromagnetic torque and rotor speed are shown in Figs. 7 and 8, respectively. For uniformity, the monitor yields the torque and speed values of an equivalent 2-pole machine, which explains the high level of the estimated rotor speed.

VIII. Conclusion

The availability of today's fast DSPs allows efficient on-line estimation of induction motor variables, needed for performance monitoring, automated diagnostics, and control

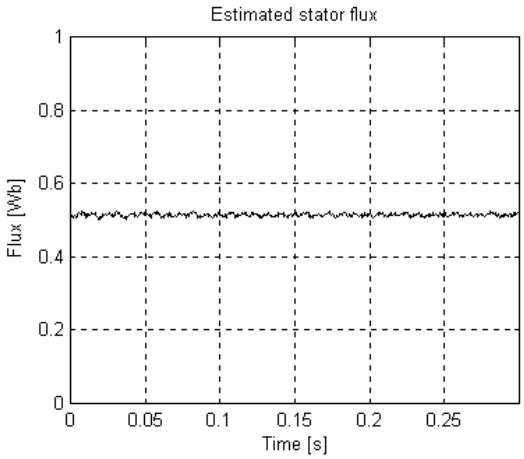

Fig. 5. Estimated stator flux.

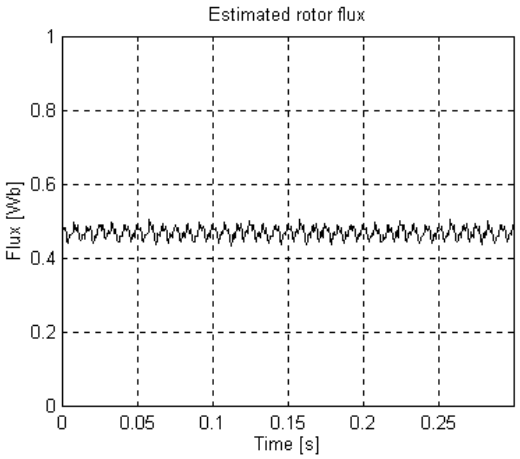

Fig. 6. Estimated rotor flux.

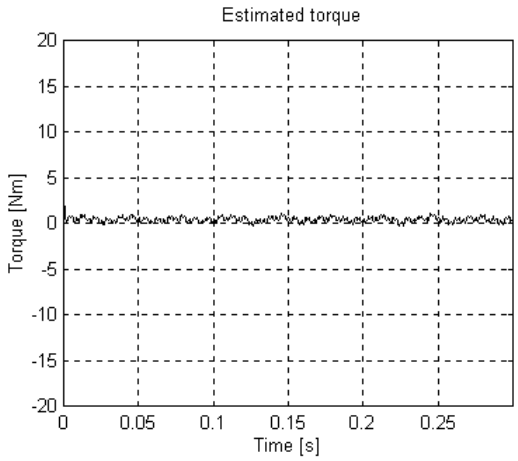

Fig. 7. Estimated torque.

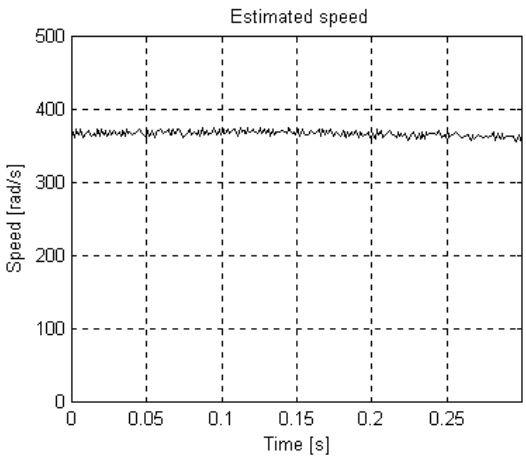

Fig. 8. Estimated rotor speed.

of these popular machines. The inexpensive TMS320F240 DSP controller from Texas Instruments has been shown as sufficient for that purpose, at least in the most common uncontrolled and scalar control drives.

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