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Speed Estimators Based Control of Permanent Magnet Syncronous Motor

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Abstract—**This paper deals several widely used, closed-loop discrete-time, speed estimators, used for the digital control of permanent magnet synchronous motors (PMSM). Aim of the paper was to develop a rotor position/speed sensorless control system with performance comparable to the sensor-based control systems for PMSMs over their entire operating range, including low-speed operation. Simulation analyses are performed and estimation errors are presented and compared for the proposed methods. After centralization of the obtained results, the authors indicate which method of speed estimation is better to be used at high or low speeds.**

Keywords—discrete-time, speed observer; permanent magnet syncronous motor

I. INTRODUCTION

Permanent-magnet synchronous motors (PMSMs) are widely used in industrial applications due to their distinctive advantages, such as high efficiency, high power density, and wide constant power region. AC and DC servo drives are widely used in applications that require permanent movement control. All servo drives require a position sensor for the implementation of vector control of the machine [1].

To achieve high-performance field oriented control, accurate rotor position information, which is usually measured by rotary encoders or resolvers, is indispensable. However, the use of these sensors increases the cost, size, weight, and wiring complexity and reduces the mechanical robustness and the reliability of the overall PMSM control systems.

Designers prefer to estimate the speed using the signal generated by the position transducer (as an incremental encoder). This approach is generally limited by the computation accuracy and quantification errors of the approximation method used for the speed estimation. This happens as the speed loop dynamic performance requires higher gains as compared to the outer position loop.

Speed estimation methods are usually based on digital position information (number of pulses from the position transducer). An alternative is to measure the pulses duration in order to calculate the speed of an electric machine [2], by overlapping pulses generated by the encoder and a high frequency clock signal. Counting the clock signals over an encoder pulse allows one to estimate the speed, as the count position length is a known, fixed value. At low speeds, some estimation schemes provide poor results, and as a consequence, the speed control can become unstable [3].

In most cases the signals collected from the process are accompanied by measurement noise [4]. This can increase the error between the estimated and the real speed. The software estimator can also generate the noise. To avoid this process, it is needed to calculate and calibrate very well the speed estimator. Different sensorless control methods were developed for different speed regions. In the medium- and high-speed regions, quasi-sliding-mode observer- based position estimators were proposed to obtain rotor position information. Several assistive algorithms, including an online observer parameter adaption scheme, a model reference adaptive system based speed estimator, and an estimated speed-based oscillation mitigation scheme, were proposed to improve the performance of the rotor position estimation and the sensorless PMSM control system. The proposed methods were effective for both salient-pole and nonsalient-pole PMSMs. In the low-speed region, saliency-tracking observers are commonly used for rotor position estimation of salient- pole PMSMs. However, for a nonsalient-pole PMSM, due to the symmetric rotor structure, the dependence between rotor position and spatial saliency is weak. The proposed sensorless control offers an effective means to solve the problems incurred in using position sensors in PMSM control systems. Firstly, it provides an alternative to existing sensor-based controls for PMSMs with reduced cost, size, weight, and hardware complexity. Second, it can be used as a supplementary (backup) function in the sensor-based control systems, when the sensor failure occurs. Moreover, the estimated rotor position and speed and other state variables of the PMSMs can be used for condition monitoring of the position sensors and other components in the PMSM drive system.

The rest of the paper is organized as follow: several discrete-time speed estimation methods are presented in Section 2; performance analysis via MATLAB-SIMULINK are presented in Section 3; in section 4 are presented simulation studies regarding load torque variation influence; some overview remarks are presented in Section 5.

II. SPEED ESTIMATION METHODS

Speed estimation schemes based on encoder-like position sensors signals are generally based on recursive algorithms. They are based on rotor position at current and previous sampling time instants. Such methods can be implemented in either hardware or software modes [5].

Differential Estimation Method (DEM), shown in [6], is the simplest speed estimation. DEM is based on the division of the position variation (difference between the current and previous time position) to the sampling time period

$$\hat{\omega} = \frac{\theta(k) - \theta(k-1)}{T} N \tag{1}$$

where T is the sample time period, $\theta(k)$ the current position, and $\theta(k-1)$ the position at previous sampling moment. Using the above formula, one can estimate the average speed during the last sampling period. During acceleration or deceleration regimes, due to sudden motor or load torque changes, one will gets errors in speed computation, with effects in system stability and control performance. The resolution of the estimator is given by the encoder resolution and by the sampling period:

$$\hat{\omega}_{resolution} = \frac{\theta_{resolution}}{T} \tag{2}$$

Discrete Time Observer (DTO) is a closed loop observer used to get a better speed estimation, shown in Fig.1and [7], and is based on the following expressions:

$$\varepsilon = \theta - \hat{\theta} \tag{3}$$

$$\hat{\theta} = \hat{\omega} \cdot \frac{T}{2} \cdot \frac{1+z^{-1}}{1-z^{-1}} \tag{4}$$

$$\hat{\omega} = \frac{T}{j}\left(K_1 \cdot \varepsilon + T_{em}\right) \cdot \frac{z^{-1}}{1-z^{-1}} + K_2 \cdot \varepsilon \tag{5}$$

The electromagnetic torque acts as a feed forward command, and the measured position *θ* is fed to the observer as a state command input.

Integration State Discrete Time Observer (ISDTO) is an improvement of above observer. ISDTO can be obtained if into above-presented observer (5), is replaced with the following expression:

$$\hat{\omega} = \frac{T}{j}\left(K_1 \cdot \varepsilon + T_{em} + \frac{K_s}{1-z^{-1}}\right) \cdot \frac{z^{-1}}{1-z^{-1}} + K_2 \cdot \varepsilon \tag{6}$$

The new added term in (6) contains a position error integration state term. Gains K_1 and K_2 can be adjusted to get a better estimation during steady state or during transient state, shown in Fig. 2 and [8].

Discrete Time PI Compensator Observer (DTPICO) is based on the following equations (see Fig.3):

$$\varepsilon = \theta - \hat{\theta} \tag{7}$$

$$\hat{\theta} = \hat{\omega} \cdot \frac{z^{-1}}{1-z^{-1}} \tag{8}$$

$$\hat{\omega} = K_p \cdot \varepsilon + K_i \cdot T_s \cdot \sum_{i=0}^{T_s} \varepsilon \tag{9}$$

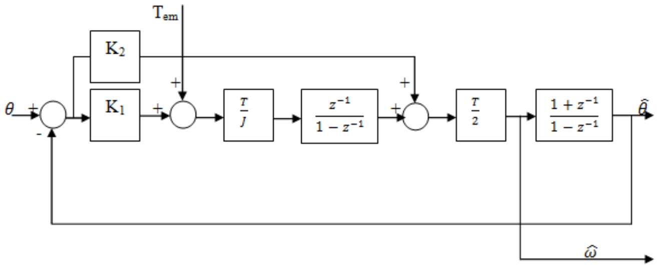

Fig. 1. Bloc diagram of discrete time observer

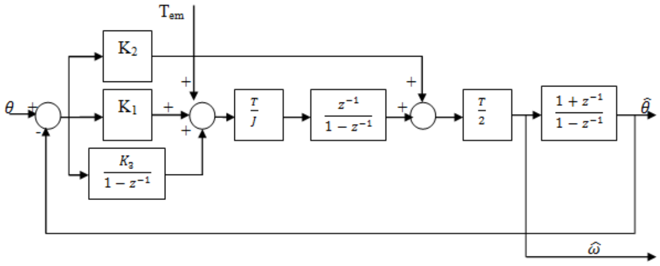

Fig. 2. Bloc diagram of integration state discrete time observer

The error between the measured and the estimated position it is applied as an input to a PI regulator. Its output represents the estimated speed that is integrated to get the estimated position, used to close the estimation loop. Pulse Duration Measuring Observer (PDMO) is an alternative method of speed estimation to the pulse counting is based on the measurement of the time interval between two consecutive pulses, Fig. 4 and Fig. 5. The clock signal *CLK* is the input of a counter having as the output number N_{CLK}, of clock periods over the time. The encoder signal N_p is overlapped with N_{CLK}. At each encoder pulse, the value of signal $N_{CLK(k)}$ is sampled. With equation 10 it is calculated the estimated speed, based on (11) and (12). The time duration of the last pulse is calculated using (12) below. $N_{CLK(k)}$ is saved as $N_{CLK(k-1)}$ for the next pulse computation. At the same time, it is calculated the position difference between the last two pulses using (11). This is a constant value, representing the position length of one pulse.

$$\hat{\omega} = \frac{\Delta_\theta}{n_{CLK}} \tag{10}$$

$$\Delta_\theta = \theta(k) - \theta(k-1) = P(k) - P(k-1) \tag{11}$$

$$n_{CLK} = N_{CLK(k)} - N_{CLK(k-1)} \tag{12}$$

PDMO provides better values as the speed decreases. On the other side, it also provides an average value of the speed, over the last position sensor pulse length. Thus, in spite of accurate estimates at low speeds, one can expect stability problems in the low speed region.

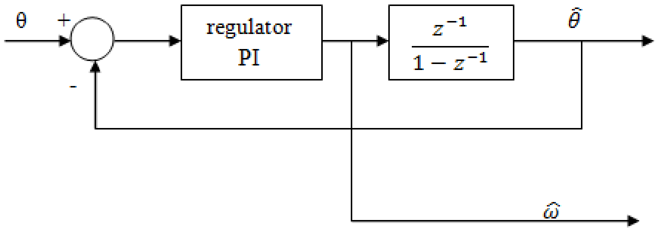

Fig. 3. Bloc diagram of discrete time PI regulator estimator

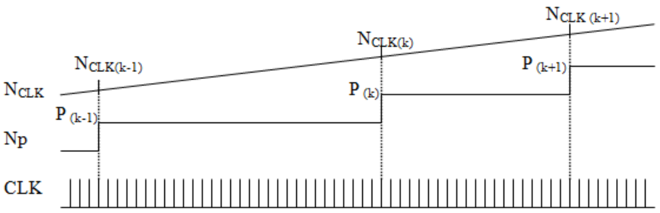

Fig. 4. The principle of speed estimation by measuring the time interval between two consecutive pulses

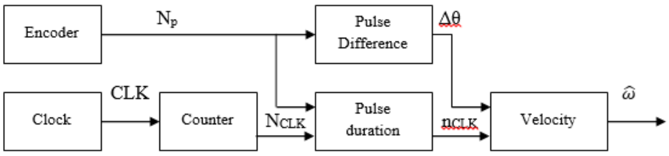

Fig. 5. Bloc diagram of pulse duration measuring estimator

III. PERFORMANCE ANALYSIS VIA SIMULATION

A complete model of a PMSM servo drive was implemented in the Matlab-Simulink environment. Each estimator was build independently as a subsystem to be easy to replace and simulate. All estimators were embedded in the same system and individually simulated for speed references values of 100, 10 and 1 rad/s.

Figure 6 presents the results for a reference of 100 rad/s. When using the differential estimation method, the maximum error between the estimated and the real speed is 2 rad/s. For the discrete time observer, the maximum error is decreased to 1 rad/s. If the observer is improved with an integration state, the maximum error becomes 0.9 rad/s. PI regulator estimator has the maximum error of 1.4 rad/s. The pulse duration measuring method estimates the speed with noise if the CLK signal has a 1MHz frequency, due to method low accuracy at high speeds, and the maximum error is 3.9 rad/s. If the frequency of the CLK signal is increased to 5 MHz, the noise is reduced and the maximum error becomes 0.7 rad/s.

Figure 7 presents the simulation results for each estimator at a reference speed of 10 rad/s. Because the speed regulator has been tuned for the differential estimation method, when the loop was simulated with another kind of estimator, some speed oscillations appear. The differential estimation method gives a maximum error between the estimated and the real speed of 2.2 rad/s. In the case of the observer, the error was

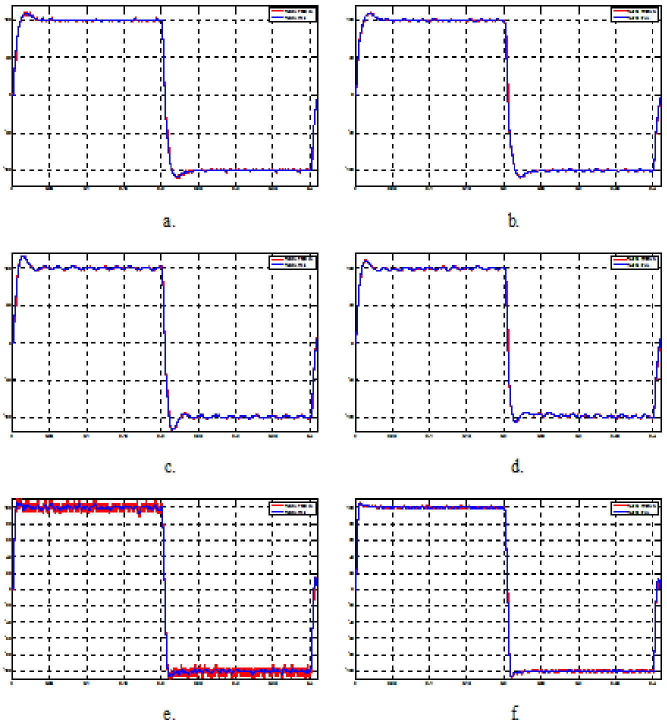

Fig. 6. Estimated and real motor speed at 100 rad/s. a. Differential estimation method; b. Discrete time observer; c. Integration state discrete time observer; d. Discrete time PI regulator estimator; e. Pulse duration measuring estimator, CLK=1MHz; f. Pulse duration measuring estimator, CLK=5MHz.

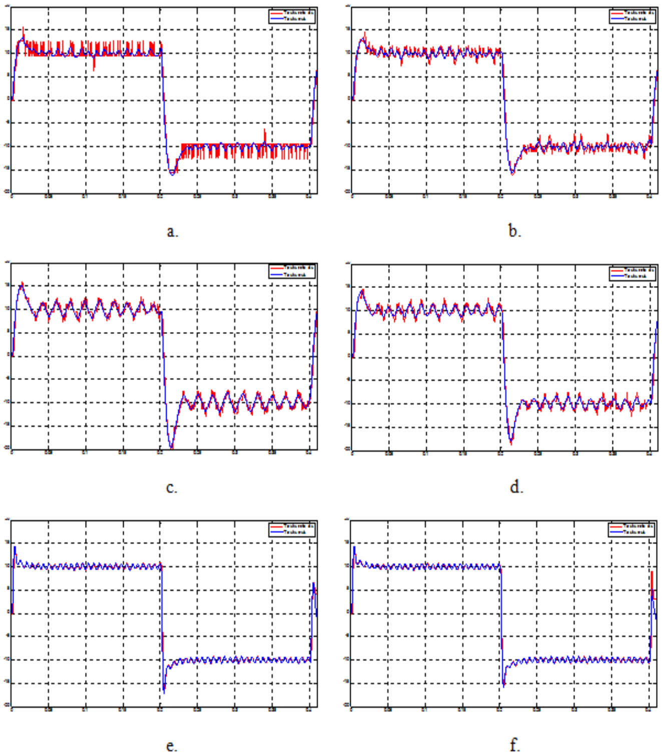

Fig. 7. Estimated and real motor speed at 10 rad/s. a. Differential estimation method; b. Discrete time observer; c. Integration state discrete time observer; d. Discrete time PI regulator estimator; e. Pulse duration measuring estimator, CLK=1MHz; f. Pulse duration measuring estimator, CLK=5MHz.

reduced to 1.2 rad/s. The integration state discrete time observer reduces the error to 1 rad/s. If the PI regulator estimator calculates the speed, the maximum error is 1.1 rad/s. At low speed, the pulse duration measuring estimator with CLK signal of 1 MHz or with 5 MHz, has quite the same performance. The estimate noise is negligible, and the maximum error is 0.16 rad/s. All estimators were simulated also at 1 rad/s (see Fig.8). The differential estimation method gives a maximum speed error of 1.9 rad/s. In the case of the observer, the error decreased to 0.8 rad/s. The integration state discrete time observer has the same error like the simple observer. If the PI regulator calculates the speed, the estimator maximum error is 1.1 rad/s. The pulse duration measuring estimator gives high oscillations of the speed due to the speed regulator bad tuning. Nevertheless, the maximum error between the estimated and real speed is practically 0 rad/s.

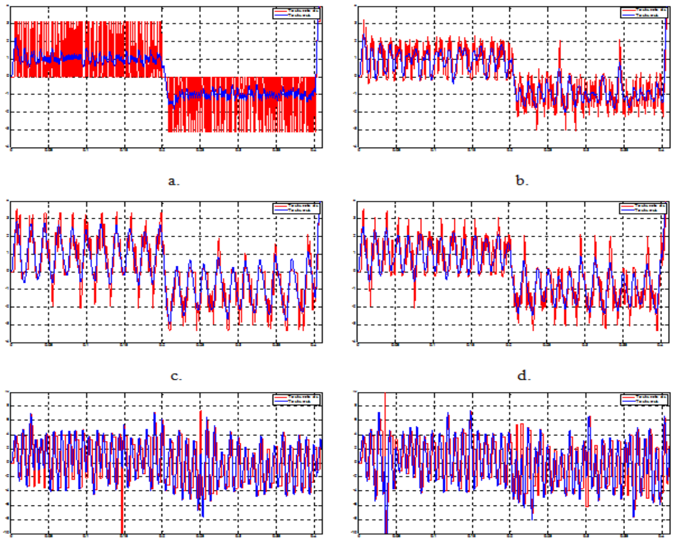
a. b. c. d. e. f.

Fig. 8. Estimated and real motor speed at 1 rad/s. a. Differential estimation method; b. Discrete time observer; c. Integration state discrete time observer; d. Discrete time PI regulator estimator; e. Pulse duration measuring estimator, CLK=MHz; f. Pulse duration measuring estimator, CLK=5MHz.

TABLE I. THE MAXIMUM ERROR BETWEEN ESTIMATED AND REAL SPEED VALUES

No.	Speed estimation method *speed reference->*	Maximum error		
		100 rad/s	***10 rad/s***	***1 rad/s***
A	Differential estimation method	2 rad/s	2.2 rad/s	1.9 rad/s
B	Discrete time observer	1 rad/s	1.2 rad/s	0.8 rad/s
C	Integration state discrete time observer	0.9 rad/s	1 rad/s	0.8 rad/s
D	Discrete time PI regulator estimator	1.4 rad/s	1.1 rad/s	1.1 rad/s
E	Pulse duration measuring estimator, CLK=1 MHz	3.9 rad/s	0.16 rad/s	~0 rad/s
F	Pulse duration measuring estimator, CLK= 5MHz	0.7 rad/s	0.16 rad/s	~0 rad/s

Table 1 presents a synthesis of maximum estimates errors, for the three reference speeds under study.

IV. LOAD TORQUE VARIATION INFLUENCE

The estimation schemes were also tested and compared with the real motor speed, for load torque variation. Fig. 9 presents the estimated and real speed, for a load torque change from no load to a 10% nominal load value, and the system sunning at a speed of 100 rad/s. Estimators based on differential estimation method, discrete time observer, integration state discrete time observer and discrete time PI regulator have similar behavior. While velocity drops to 86-88 rad/s and return to reference after 30 ms (controller tuning aspect), the real and estimated speeds follow the same variation. For pulse duration measuring estimator, if the clock signal is 1MHz, the higher noise of the estimated speed affects the speed controller behavior. Once the clock signal was increased to 5 MHz, both real and estimated speeds become less noisy, and the system speed had a different, more stable behavior.

In Fig. 10 one can see the simulation results for the same load variation, applied at a 10 rad/s reference speed. For the first two estimators, implemented in discrete time, we have approximately the same velocity drop to -2 rad/s and return to reference after 30 ms. The estimator based on integration state discrete time observer and the discrete time PI regulator have a little bit higher speed drop to -3 rad/s but with the same time duration like for the other two methods. Even if the velocity drop is higher, better speed regulator tuning should improve this behavior. More important, as the discrete time and integration state discrete time observers are based on load torque value, their output will have a drift from the real speed, once the load torque change was applied. For the pulse duration measuring estimator, better results were obtained, as the estimator accuracy is good, and not influenced by the load torque variations. The speed dropped to 4.5 rad/s and come back to 10 rad/s after 20 ms.

For a reference speed set to 1 rad/s and the same mechanical load change applied, the simulation results are presented in figure 11. The estimator based on differential estimation method generates a low-resolution speed estimation, which translates into speed ripple of the motor. When the mechanical load variation was applied to the motor shaft, the speed dropped to -10 rad/s for 30 ms. The discrete time observer, integration state discrete time observer and discrete time PI regulator have approximately the same velocity drop for the same time period, but their speed estimate is much more accurate. Once again, for the discrete time and for the integration state discrete time observers, one can see the difference between the estimated and the real motor speed, after the change in the load torque value. Velocity calculated by pulse duration measuring estimator, when CLK frequency is establish to 1 MHz, have same drop to -10 rad/s but for only 10 ms. Increasing clock signal frequency to 5 MHz get a high drop of estimated velocity to -16 rad/s but for same time period like case of 1 MHz clock frequency.

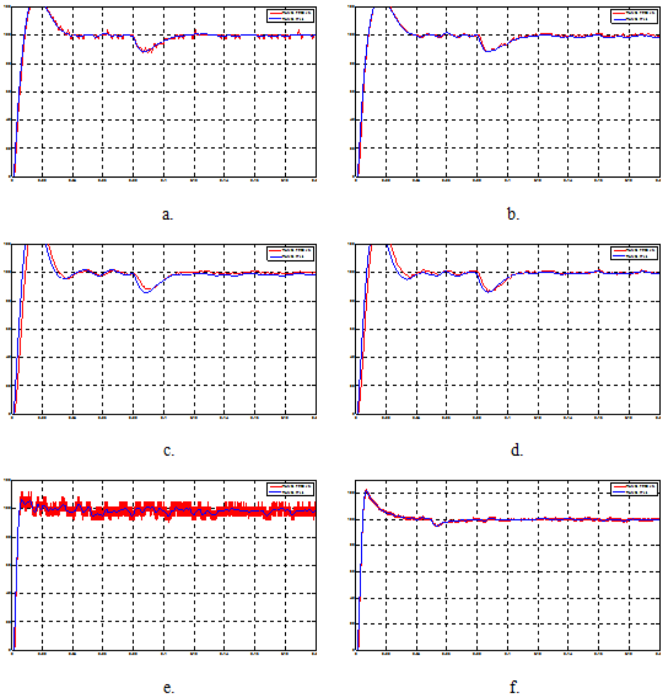

Fig. 9. Estimated and real motor speed at 100 rad/s with load torque step variation: a.Differential estimation method; b.Discrete time observer; c.Integration state discrete time observer; d.Discrete time PI regulator estimator; e.Pulse duration measuring estimator, CLK=1MHz; f.Pulse duration measuring estimator, CLK=5MHz.

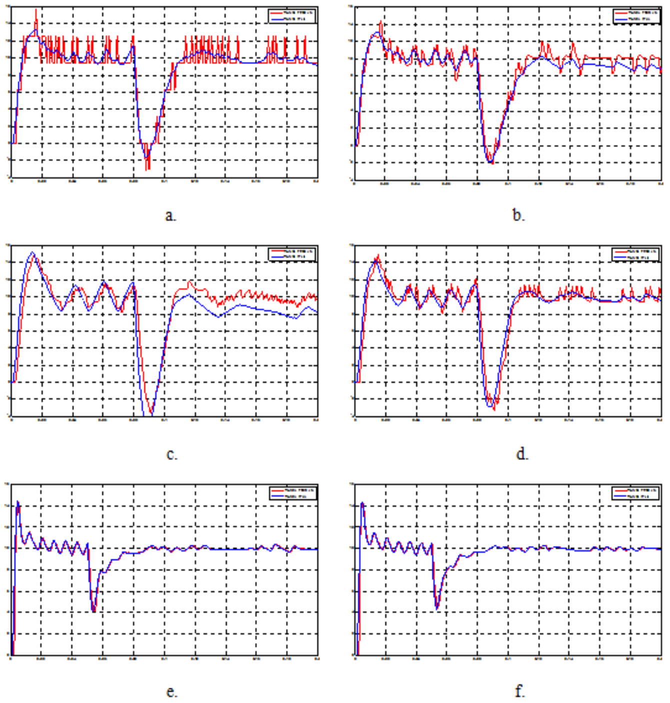

Fig. 10. Estimated and real motor speed at 10 rad/s for load torque variation. a.Differential estimation method; b.Discrete time observer; c.Integration state discrete time observer; d.Discrete time PI regulator estimator; e.Pulse duration measuring estimator, CLK=1MHz; f.Pulse duration measuring estimator, CLK=5MHz.

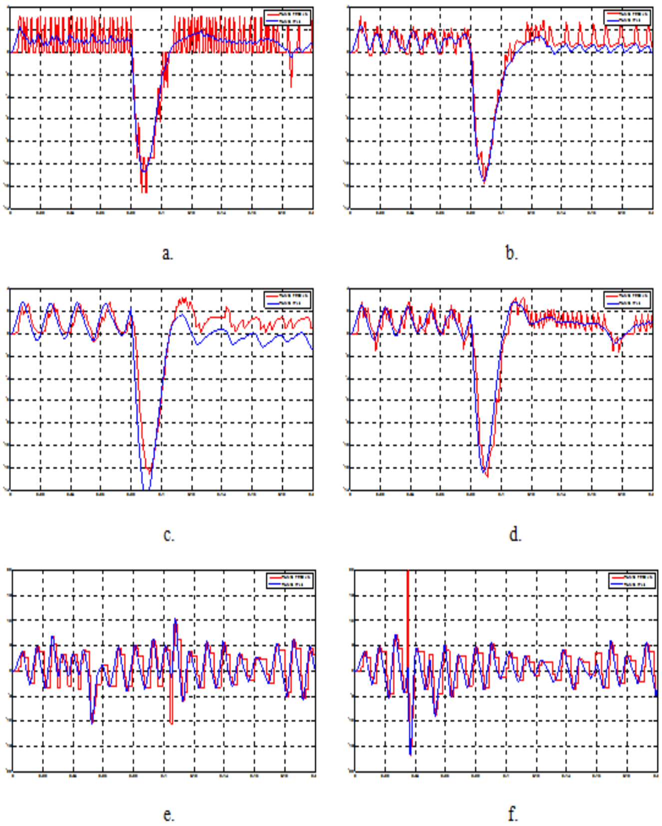

Fig. 11. Estimated and real motor speed at 1 rad/s for load torque variation. a.Differential estimation method; b.Discrete time observer; c.Integration state discrete time observer; d.Discrete time PI regulator estimator; e.Pulse duration measuring estimator, CLK=1MHz; f.Pulse duration measuring estimator, CLK=5MHz.

V. CONCLUSIONS

Digital estimators represent a huge advantage for applications that require accurate speed control. Based only on the position transducer information, the electric motor can be controlled in both position and/or speed loop.

Different estimator schemes can be evaluated, and improved or replaced without changing the structure of the system (hardware).

While the resolution of the differential estimation-based methods is mainly limited by the encoder resolution or by the small values of the sampling periods, the resolution of the other types of estimators (pulse-length type) is also limited by the performances of the hardware system.

Pulse duration measuring estimator is the best performing in the low speed range, if the frequency of the clock generator is high enough.

The worst estimator is the simple pulse difference method, especially at low speeds.

Estimated velocity is much stable when motor have a constant mechanical load compared without load. At high and medium speed, pulse duration measuring estimator, have better performance when mechanical resistive torque is vitiated, with lowest velocity drop. At very low speed all estimators have approximated same behavior when mechanical load of the motor is varying. If usually at high speeds all estimation schemes provide satisfactory results, at low speed the estimation error can be significant and lead to bad performance or even unstable system behavior.

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REFERENCES

[1] D. W. Novotny, R. D. Lorenz, “Introduction to field orientation and high performance ac drives”, 1985;

[2] T. Ohmae, “A microprocessor-controlled high-accuracy wide-range speed regulator for motor drives”, 1982;

[3] K. Kubo, M. Watanable, F. Kozawa,K. Kawasaki, „Disturbance torque compensated speed observer for digital servo drives” , 1990;

[4] Y. Sheng-Ming, K. Shuenn-Jenn, ”Performance Evaluation of a Speed Observer for Accurate Speed Estimation of Servo Motor Drives”, IEEE Transaction on Industry Applications Vol. 36, 2000;

[5] Technosoft S.A., DMCode-MS(BL) MATLAB Library for MCK28335 User Manual

[6] Robert D. Lorenz, Keith W. Van Patten, „High-Resolution Speed Estimation for All-Digital, ac Servo Drives” , 1991;

[7] G. Ellis, ”Control System Design Guide”, Elsevier Academic Press, USA, 2004;

[8] G. Ellis, ”Observers in Control System”, Elsevier Academic Press, USA, 2002;