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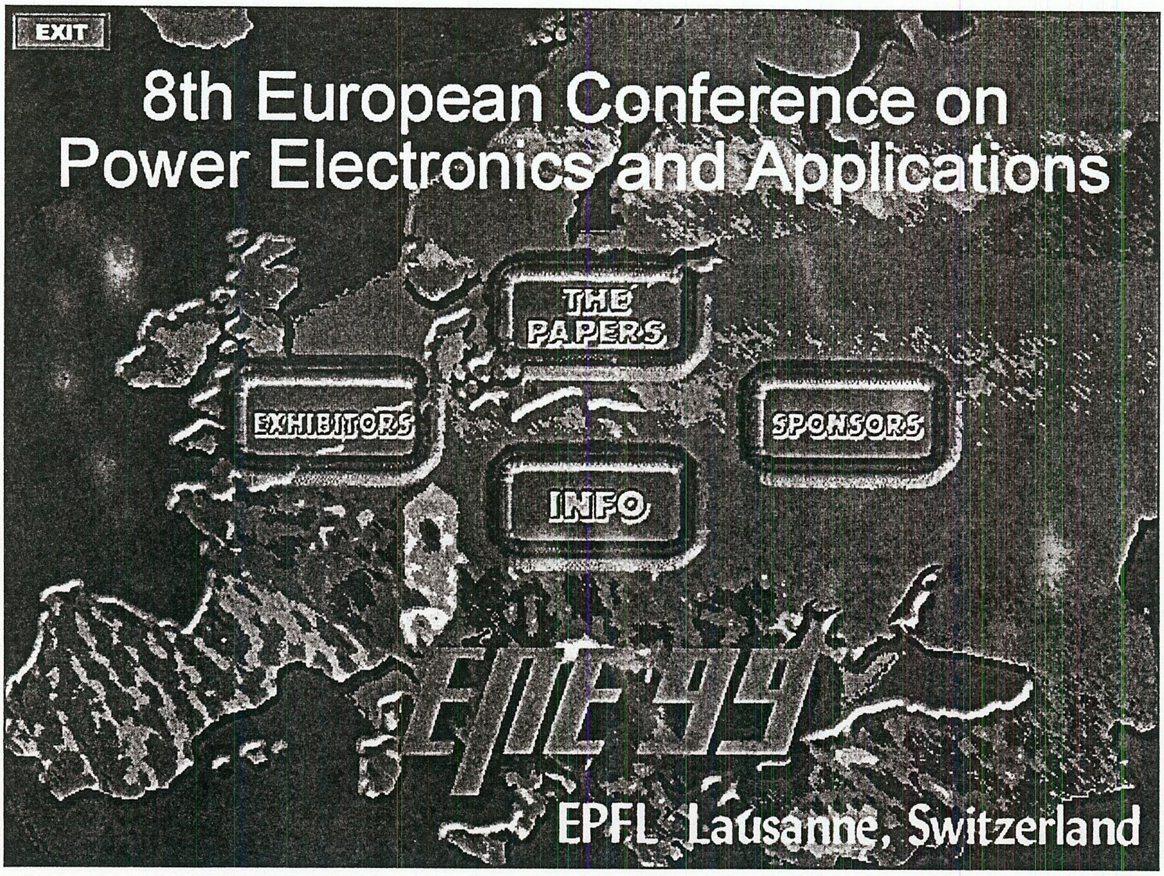
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FPGA Implementation of a Digital Tachometer for Angular Position and Speed Measurement

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Keywords

Measurements, Transducers.

Abstract

A common method for angular position and speed estimation, in adjustable speed drives, uses an incremental shaft encoder and an electronic circuit. This paper presents a high precision electronic conditioning of a biphase incremental encoder generated signal. A digital tachometer, for angular position and speed measurement, is implemented using two simple FPGAs. One FPGA, based on the multirange CET method, is applied to measure the angular speed with a relative error lower than 500ppm. A second FPGA implements a high precision pseudo-absolute angular position sensor. To prove and evaluate the abilities of the proposed measurement system, a PC-AT board has been designed and a 2000 pulses per revolution commercial biphase incremental encoder has been used. Experimental results exhibit an excellent behaviour of the proposed measurement system.

Introduction

Electrical drives play an important role as electromechanical energy converters in transportation and most production processes. In monitoring and control systems of rotary machines it is essential that rotor position and velocity measurements are available. Also, knowledge of these parameters is indispensable in parameter estimation algorithms, sensorless control systems, electric or thermal modelling and in vector control techniques. Anyway, a high precision measurement system is required.

Methods for velocity measurement can be spreadly found in literature. DC tachometers have been used for a long time due to their excellent dynamic performance. However, the following four reasons have encouraged the use of digital against DC tachometers:

- Better accuracy.
- A/D conversion is not required when digital controllers are applied.
- There is no maintenance required (digital tachometers are brushless machines).
- Noise immunity that avoids analogue filtering.

Digital tachometers determine speed measurement by calculating the frequency of a pulse train coming from the shaft encoder. Speed measurement methods are thoroughly reviewed in references [5] and [9]. Two methods are commonly applied:

1. The speed is achieved from the elapsed time between successive encoder pulses, [1].
2. The number of pulses in a fixed period of time is counted, [3].

Different techniques, based on previous methods, have been proposed to obtain better accuracy and response time in the measure:

1. Constant Elapsed Time method (CET), proposed in [2]. This technique measures the elapsed time between a variable number of pulses, K. An optimal value of K is selected for different speed intervals.
2. Combined methods, which use pulse counting and elapsed time for speed calculation, proposed in [7], [10] and [12].
3. Double-buffered method, [5] and [11]. It uses an approach similar to that proposed in [7]. Basically, this method avoids the synchronisation of the incoming pulses and performs a multiplication of the incoming frequency to allow a fast response time.
4. Other advanced methods, i.e. those based on software or hardware observers, have long been discussed in [9] and will not be considered here.

On the other hand, angular position can be obtained from an absolute encoder. However, higher cost systems are required when precision is increased. Lower cost solutions can be obtained using incremental encoders. In this case, signal conditioning can be solved using up and down counters, which store the angle in pulses units. The essential drawback presented by this method is that, in highest frequency range, some pulses can be lost. A zero cross signal pulse can be used for synchronisation.

In this paper a multirange CET method is presented to cover a wide speed range with relative errors below 0.05 percent and 12 bits resolution. Also, a zero-cross synchronised digital conditioning system is proposed to obtain absolute angular position measurement with a resolution equal to $360^o/(4m)$. The digital tachometer has been implemented using two FPGAs to discharge the processor's task. The measurement system has been tested, in monitoring the angular speed and position of an induction machine, by using a PC/AT board.

The paper is organised as following. First, the velocity and position measurement systems are described. Then, experimental results are shown. Finally, conclusions are withdrawn.

Speed measurement

Speed measurement system has been obtained using a multirange CET method. The multirange strategy leads the system to adapt to the defined measurement requirements. These specifications are two: Accuracy in the measure (maximum relative error limited) and sample time (measurement system maximum response time limited).

Two designed restrictions have been imposed: resolution equal to 12 bits and percentage error less or equal to 0.05. The block diagram of the digital speed tachometer design is shown in figure 1.

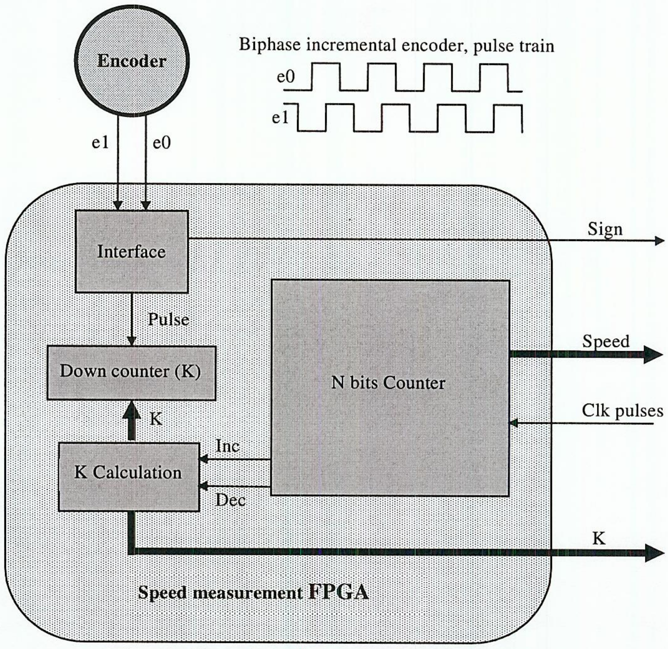
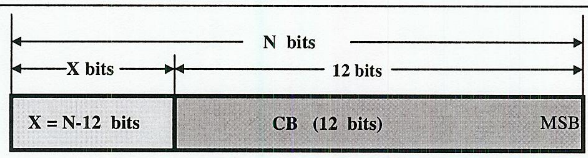


Fig. 1: Speed tachometer block diagram.

The speed tachometer is composed of the following parts:

1. Interface. It can be designed using discrete logic. Efficient implementations, with simple hardware, are described in [4] and [8]. A state machine, analogous to that described in [12], is used for input filtering and direct/reverse discrimination.

2. N-bits counter. It is a clock pulses counter whose 12 most significant bits are used for speed measurement. The less significant bits, X=N-12, are used for 2^X frequency divisor and define the measurement method (4 methods are possible, $K \in \mathrm{N}$, $K \subset [1,4]$. The structure of this counter is shown in figure 2.



- **Cb =** Accumulated value in the last measure period $= CB \cdot 2^x$
- **Cbmax** = Counter maximum value = $2^N - 1$
- **X** = Prescaler bits
- **CB** = Measurement (12 MSBs of Cb counter)

Fig. 2: *Cb* counter.

3. K calculation. It generates, automatically, the value of the parameter K to achieve accuracy in the measure, limiting relative error as it is shown in figure 3.

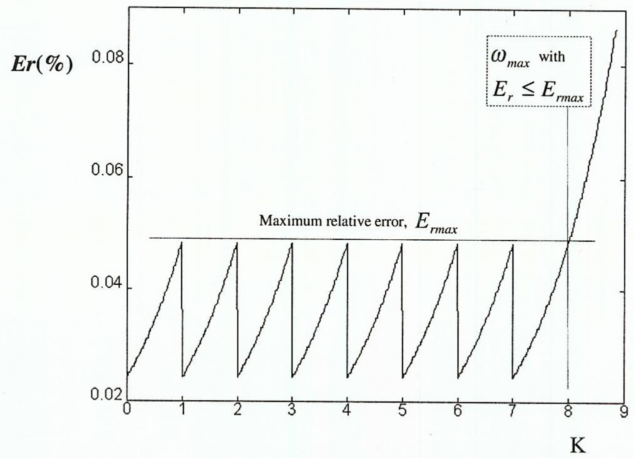


Fig. 3: Parameter K evolution versus relative error.

Down counter. It is a decremental counter, initially set to K. When it reaches zero, N-bits counter is disabled.

Theoretical Analysis

Using definitions of figure 2, the speed value, ω, can be obtained as follows:

$$\omega = \frac{K \cdot fc}{m \cdot Cb} = \frac{K \cdot fc}{m \cdot CB \cdot 2^x} \tag{1}$$

Where, *fc* is clock frequency and *m* is the encoder pulse number.

- *Absolute and relative error. Absolute error,* $\Delta\omega$, can be defined as:

$$\Delta\omega = \omega_{Cb} - \omega_{Cb+\Delta Cb} \tag{2}$$

$$\Delta\omega = \frac{K \cdot fc}{m} \cdot \left(\frac{1}{Cb} - \frac{1}{(Cb + \Delta Cb)} \right) = \frac{K \cdot fc}{m} \cdot \frac{\Delta Cb}{Cb \cdot (Cb + \Delta Cb)} \tag{3}$$

Where $\Delta Cb = 2^x$ and $Cb = CB \cdot 2^x$. Accordingly, *absolute error* is obtained from equations:

$$\Delta\omega = \frac{K \cdot fc}{m \cdot (CB + 1) \cdot CB \cdot 2^x} \tag{4}$$

Relative error, *Er*, is defined as:

$$Er = \frac{\Delta\omega}{\omega} = \frac{1}{(CB + 1)} \tag{5}$$

- *Maximum speed measured,* ω_{max}, with limited relative error, $Er < Er_{max}$. It can be obtained from (5), substituting in (1):

$$\omega_{max} = \frac{K_{max} \cdot fc}{m \cdot \left(\frac{1}{Er_{max}} - 1 \right) \cdot 2^x} \tag{6}$$

- Minimum speed measured.

$$\omega_{min} = \frac{K_{min} \cdot fc}{m \cdot Cb_{max}} = \frac{fc}{m \cdot (2^N - 1)} \tag{7}$$

- Maximum conversion time.

$$T_{max} = \frac{K_{max}}{m\omega_{min}} \tag{8}$$

Table I summarises the values obtained of minimum and maximum speed as well as maximum conversion time, in all measurements methods, using a 2000 pulse per revolution encoder ($m = 2000$).

Method (x)	ω_{MIN} (rad/s)	ω_{MAX} (rad/s)	T_{MAX} (ms)
1	1.53	392.7	2.048
2	0.76	196.35	4.096
3	0.38	98.17	8.192
4	0.19	49.08	16.38

Table I: Minimum and maximum velocity and conversion time in all measurement ranges.

The tachometer is designed to obtain a limited Er value, $Er < Er_{max}$. Whenever velocity overpasses its maximum value, ω_{max}, then speed error increase as it is shown in figure 3. Table II summarises maximum relative error using all measurement methods in all possible speed ranges. A 2000 pulse per revolution encoder is applied. Figure 4 shows absolute error versus speed, using methods 1 and 4.

Method (x)	ω_{MIN} – 49.1 (rad/s)	49.1 – 98.2 (rad/s)	98.2 – 196.4 (rad/s)	196.4 – 392.7 (rad/s)
1	0.0488	0.0488	0.0488	0.0488
2	0.0488	0.0488	0.0488	0.0976
3	0.0488	0.0488	0.0976	0.1952
4	0.0488	0.0976	0.1952	0.3862

Table II: Relative error (%) in all four-measurement methods in another speed range in all cases, absolute error increases when speed increases.

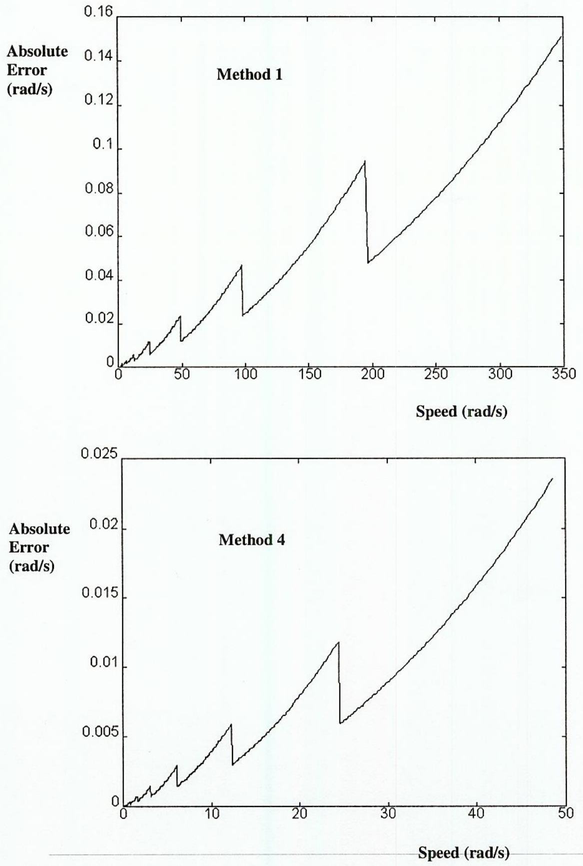


Fig. 4: Absolute error using 1 and 4 methods.

Position measurement

Maximum precision can be obtained using biphase pulse train coming from the encoder ($e0$ and $e1$ signals in figure 1). A precision equal to $360^o/(4m)$ is obtained using m pulse per revolution encoders.

A zero-cross correction method, which requires a zero-cross reference signal coming from the encoder, has been used. Two working zones have been defined:

Zone I: Pulses from the encoder increment the angular counter until the first zero-cross appears.

Zone II: After the first zero cross edge has been taken, pulses, arriving from the encoder, increment, as in previous zone, the angular counter. A revolution counter is incremented or decremented, depending on direct or reverse rotation, and angular counter is reset when zero crosses appear.

Absolute position is obtained by adding the stored value in zone I and the values obtained from the revolution and angular counters, modified in zone II.

Experimental results

To prove the abilities of the proposed measurement system, there has been designed a PC/AT board, which includes speed and position calculus FPGAs. Both FPGAs as well as auxiliary electronic circuitry are depicted in figure 5. Actel A1020B and Texas instruments TPC1020BFN, 2000 gate array equivalent gates capacity FPGAs, and a 2000 pulse per revolution incremental encoder have been used.

In figures 6 and 7, there is shown speed measure response using methods 1 ($X=1$) and 4 ($X=4$). The value of K changes for different velocity intervals. Position measure response is shown in figures 8(a) and 8(b). A precision equal to 0.04^o is obtained.

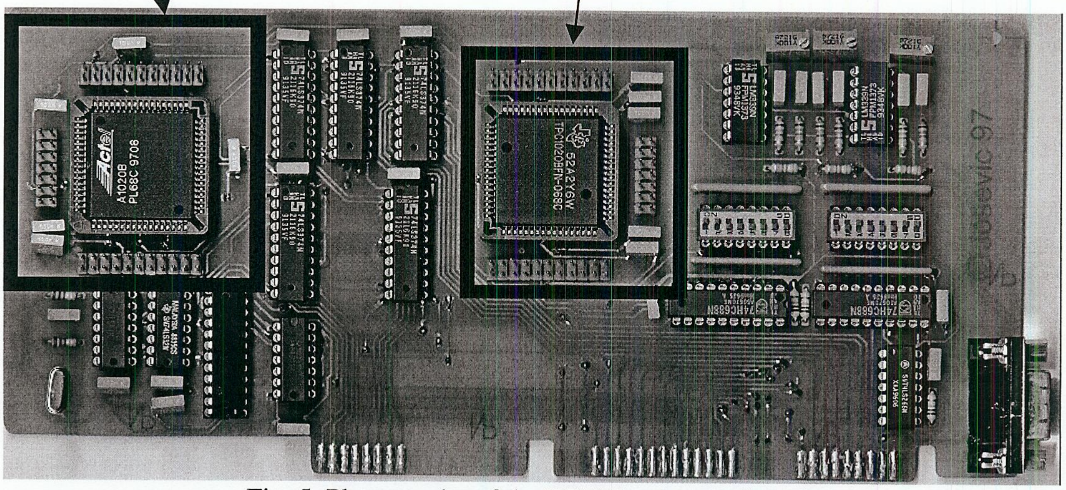


Fig. 5: Photography of the PC/AT prototype board.

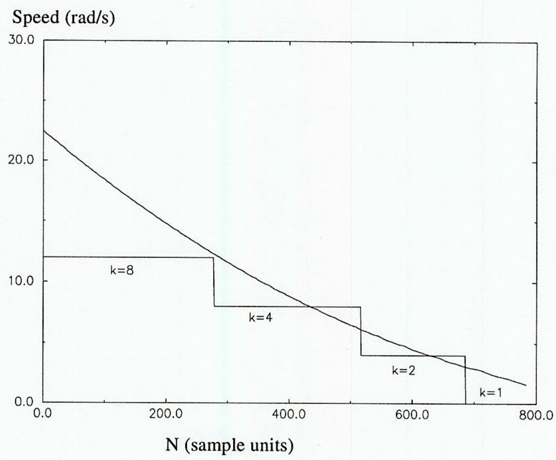


Fig. 6: Measured speed response in normal movement. K evolution using method 1.

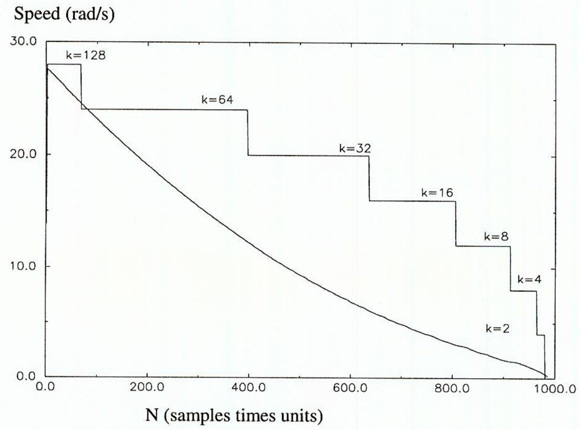
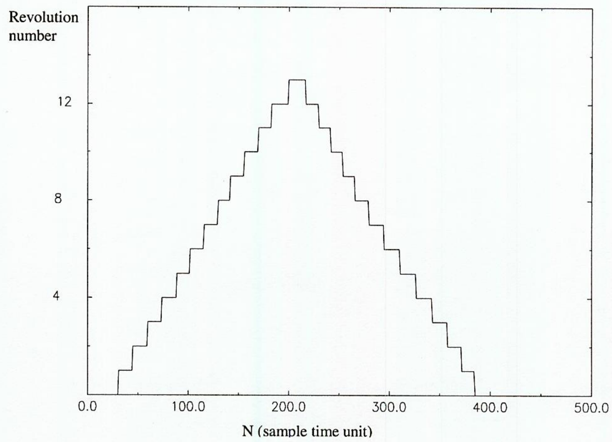
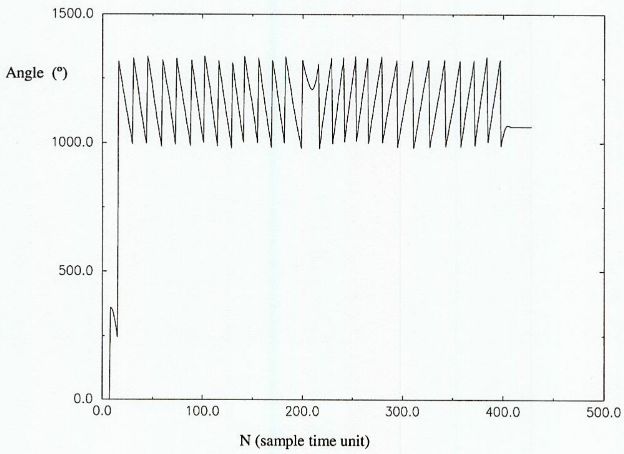


Fig. 7: Measured speed response in normal movement. K evolution using method 4.



(a)



(b)

Fig. 8: Measured position response in direct and reverse movement. (a) Revolution counter. (b) Absolute angular position counter.

Conclusions

In this paper a digital tachometer, for angular position and speed measurement, has been proposed. The speed measurement system is based on a multirange-CET method and generates relative errors below 0.05 percent with 12 bits resolution. The angular position is obtained from a zero-cross synchronised digital conditioning system that defines an absolute position information. The tachometer has been implemented using two simples FPGAs, defining an external hardware that discharges the processor's task. To prove the abilities of the proposed measurement system, there has been designed a PC/AT board to monitor the angular speed and position of an induction machine. The studies show an excellent behaviour of the measurement system.

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