Modeling and Simulation of an Incremental Encoder Used in Electrical Drives

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Abstract: Electrical drives use frequently incremental encoders as position sensor. The paper deals with modeling and simulation of an incremental encoder and Matlab-Simulink® simulation structure is realized and tested. In order to process the information provided by the encoder it was built a structure to determine the direction of the rotation in an angular interval equal to a quarter of the angular step of encoder graduation. The encoder signal based position computation was also simulated. Experimental measurement were performed.

Keywords: position sensor, angle transducer, incremental encoder, simulation, electrical drive

1 Introduction

One of the most frequently used position transducers is the incremental encoder. It is a device which provides electrical pulses if its shaft is rotating [3], [6].

The number of generated pulses is proportional to the angular position of the shaft. The market offers a variety of incremental encoders realized in different technologies, like electromechanical, magnetic etc, however the optical encoders are very popular.

Together with the shaft of optical encoder there is rotating a transparent (usually glass) rotor disc with a circular graduation-track realized as a periodic sequence of transparent and non-transparent radial zones which modulates the light beam emitted by a light source placed on the fix part (stator) of the encoder on one side of the disc. On the opposite side the modulated light beam is sensed by a group of optical sensors and processed by electronic circuits. The output of encoder will generate one pulse when the shaft rotates an angle equal to the angular step of graduation, i.e. the angle according to one successive transparent and non-transparent zone. The number of the generated pulses is proportional to the rotation-angle of the shaft, i.e. to its angular position [5]. The counting of the pulses is realized by external electronic counters [3].

Due to the fact that the sequence of generated pulses does not offer any information about the direction of rotation, the encoder is provided with a second group of optical sensors, shifted with a quarter angular step of graduation in comparison to the first group of sensors. A second channel of the electronic circuits processes the signals generated by the second group of sensors. During rotation of the shaft the second channel will generate on its output pulses identical to those generated by first output but these are shifted with a quarter angular step of graduation. By the reversal of the rotation the phase-shift between the two outputs will be also reversed. In this manner the mutual phase-shift of the outputs contains information regarding the direction of rotation. This information may be extracted by relatively simple logic circuits.

In order to have a reference position the encoder is provided on its disc with a second track having a single graduation, and on the stator the corresponding light source, group of optical sensors and electronic processing circuits. This arrangement produces on the output of this third channel in the course of a complete (360°) rotation a single pulse of width equal to a quarter angular step of graduation. The shaft position corresponding to this pulse may be considered as reference position.

Usually the two shifted outputs are named A respectively B, the reference "marker" output is named Z. Mostly, in order to facilitate the differential signal transmission and further processing of the position information in the user's equipment, the encoder provides also the opposite logic value of above signals.

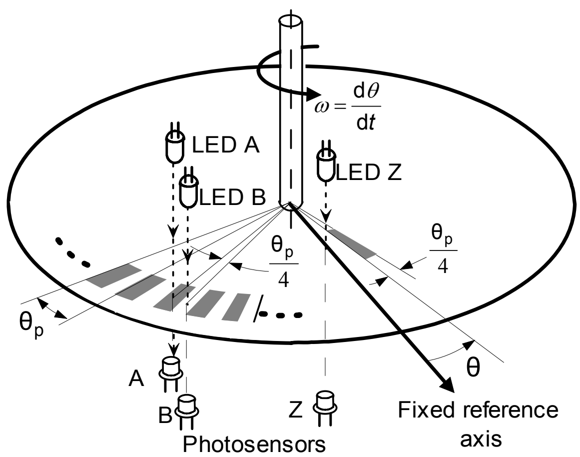


Figure 1

Construction principle of the incremental encoder: the gray surfaces are optically transparent

The principle of incremental encoder with the used notations is presented on Figure 1. Usually the whole construction is closed in an enclosure (not shown on figure), provided with mounting possibilities. The shaft rotates on bearings located in enclosure.

Figure 2 presents the diagram of the generated output signals.

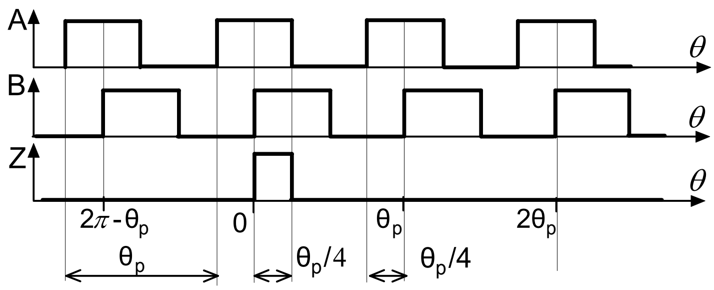


Figure 2
Diagram of the output signals generated by the incremental encoder

The control of the modern adjustable-speed electrical drives needs the knowledge of position and/or speed of the rotor [1], [4]. This information in some applications is computed or estimated without the use of mechanical transducers (in case of sensorless drives) or – more frequently – the position/speed information is provided by position or speed transducers (is the case of sensored drives). Incremental encoders are frequently used as position transducers.

The modern drive systems are controlled digitally. Usually in these systems the processing is accomplished at a fixed sampling rate. However, the position information furnished by incremental encoder is inherently digital, with a rotation-speed-dependent sampling rate. This statement is true also for speed information, computed using the encoder signals. Accordingly, the whole drive system may be considered as a complex system composed of some parts working with fixed sampling rate, other parts with variable one. Frequently, the sampled character of the position or speed information is neglected, they are treated as continuous quantities.

In order to take into account the real character of the information provided by the encoder already in extensive simulation works during research and early development stages of the drive systems, it is necessary to create the mathematical model and the corresponding simulation structure of the encoder.

2 Modeling of the Incremental Encoder

The input signal of the incremental encoder is the angular position θ of its shaft with respect to a fixed reference axis. The output signals are the two pulses shifted by a quarter angular step $A(\theta)$ and $B(\theta)$, respectively the marker signal $Z(\theta)$. If θ_p is the angular step of the encoder, the outputs may be described by the following equations:

$$A(\theta)=\begin{cases}1 & \text{if} \quad 0<\text{modulo}_{\theta p}(\theta)<\theta_p/2\\ 0 & \text{if} \quad \theta_p/2<\text{modulo}_{\theta p}(\theta)<\theta_p\end{cases} \tag{1}$$

$$B(\theta)=\begin{cases}1 & \text{if} \quad 0<\text{modulo}_{\theta p}(\theta-\theta_p/4)<\theta_p/2\\ 0 & \text{if} \quad \theta_p/2<\text{modulo}_{\theta p}(\theta-\theta_p/4)<\theta_p\end{cases} \tag{2}$$

$$Z(\theta)=\begin{cases}1 & \text{if} \quad \text{modulo}_{2\pi}(\theta)=0\\ 0 & \text{if} \quad \text{modulo}_{2\pi}(\theta)\neq 0\end{cases} \tag{3}$$

It is important to note, that during a rotation angle of the shaft equal to the angular step of graduation θ_p there are four switching events in the output pulses, and therefore the minimal rotation-angle-increment detectable by the encoder is $\theta_p/4$. It is obvious that the number of pulses generated by the encoder in the course of a rotation will be

$$N_r=\frac{2\pi}{\theta_p} \tag{4}$$

which is equal with the number of angular steps of the-graduation on the circular track on the rotor. The number of pulses per rotation together with the angular speed of the shaft will determine the frequency of encoder's output signals.

$$f_A=f_B=\frac{\omega}{2\pi}N_r \tag{5}$$

From point of view of simulation the above equation is important because offers a starting point in choosing of the simulation step. For usual values of N_r and ω one concludes that the encoder signal is far the highest frequency quantity in a usual drive system. A numerical example underlines this fact: the N_r=1000 pulses/rotation value is very common for low-cost incremental encoders, angular speed ω=314 rad/s is typical for the wide-spread 1 pole-pair/50 Hz motors; this combination yields an encoder signal frequency of 50 kHz (accordingly, the period is $2*10^{-5}$ s) it is about an order of magnitude higher than the highest frequency in the drive system, supposing a 5 kHz PWM frequency.

The environment used for simulation is the Matlab/Simulink®, because it is the most used software in simulation of electrical drives. The simulation structure is shown in Figure 3. It is created mainly based on equations (1)–(3) with some modification in order to easy the building of the structure. The output Sense of the "Sens Detect" block indicates if the input angle θ is increasing or decreasing. The output of the "modulo θp/2" function is compared to upper-limit U and lower limit L. Based on the four possible outputs of the block "Relational Operators" and the Sense signal, the "AB Logic" block generates the A_t or B_t switching moment signals. The output signals of the encoder are obtained using two T-type flip-flops, one "T-FF A" for outputs A, A_N, triggered by A_t and the other "T-FF B" for B, B_N triggered by B_t. The flip-flops hold their actual state until a new switching moment occurs due to the rotation of the shaft.

The "hollow-shaft encoders" are special constructions which avoid the coupling parts between encoder and controlled machine shaft. Their shaft is very short, has a tubular form and is pulled up on the controlled machine shaft.

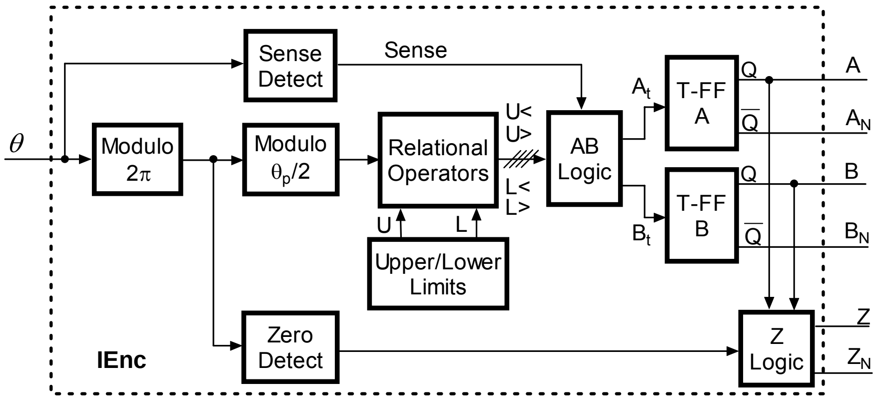


Figure 3
Simulation structure of the incremental encoder

By every complete, (i.e. 2π rad.) shaft rotations identified by $modulo_{2\pi}$ function the "*Zero Detect*" block produces an output signal which in block "*Z Logic*" is synchronized with A and/or B signals producing the marker output Z.

3 Identification of Direction of Rotation

The direction of rotation will be identified comparing the relative position of the outputs A to B. This may be accomplished on different ways.

A trivial solution of de problem may be a sampling with a D type flip-flop at every rising front of the B output pulses the A output logic value. For counterclockwise (CCW) direction of rotation the output of flip-flop will be at 1 logic value, for the clockwise (CW) direction at 0 value. The drawback of the method is that the direction changing is detected only after a time interval according to a rotation of 3 $\theta_p/4$ – 5 $\theta_p/4$; it is depending on the moment of direction changing relative to signals A and B.

A more precise approach takes into account the all four possible combinations of A and B signals for the both situations: when the actual direction is CCW and is changing to CW, and the CW is changing to CCW. Table 1 summarizes all combination of signals which detect the reversal of rotation sense. This strategy permits detection of direction changing in all cases during a rotation of $\theta_p/4$, namely in minimal detectable rotation-angle-increment.

Table 1

From CCW to CW Q=1 to Q=0			From CW to CCW Q=1 to Q=0		
Occurs if		Triggered by	Occurs if		Triggered by
A	B	R	A	B	S
0	0	A_N & B↑	0	0	B_N & A↑
0	1	B & A↑	0	1	A_N & B↓
1	0	B_N & A↓	1	0	A & B↑
1	1	A & B↓	1	1	B & A↓

Note: The subscript symbol $_N$ denotes negated logical variable; The ↑ and ↓ denote the raising- respectively the falling-edge of associated logic variable.

The realized direction-detector-block is based on above idea. The block scheme of the simulation structure is presented in Figure 4.

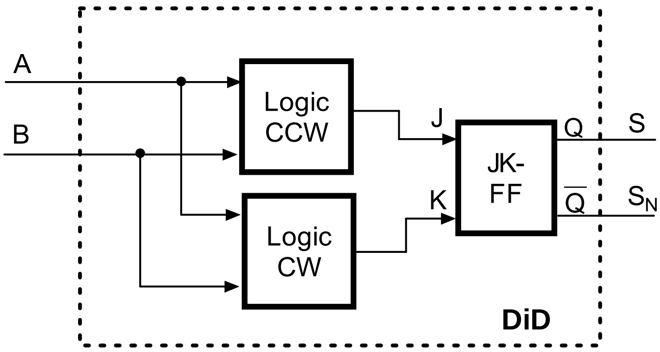


Figure 4
The scheme of the simulation structure of the direction-detector block

Corresponding to the two possible direction changes the logic blocks detects all combinations of input signals shown in Table 1, the actual combination triggers a flip-flop of which Q output retain the direction of rotation until another changing occurs. The logic circuits of the direction-detector may be easy implemented in FPGA or other programmable logic.

4 Encoder-based Position Computation

In incremental encoder based system the angular position θ referenced to a fixed reference axis (corresponding to θ=0 rad.) is obtained by counting the number of generated encoder pulses and multiplying it with the angular step θ_p of the encoder. The counting of the pulses is made by electronic counters, which usual is not contained in the structure of the encoder.

The simulation structure is presented on Figure 5. The encoder-output signal A is the common input signal for the two counter blocks: Counter CCW and Counter CW. The counters are resettable by the marker pulse, if the shaft is positioned in the reference position. Both counters receive on their En input distinct "enable to count" signals generated from the "DiD" direction detector block according to the detected direction of the rotation. By counterclockwise rotation of the shaft the Counter CCW will be enabled by signal S and will count the encoder pulses A. If the shaft rotates clockwise, the Counter CW will be enabled by signal S_N and will count the pulses A. The content of the Counter CW is subtracted from that of the Counter CCW. The difference N will indicate the number of pulses according to position of the shaft. In order to obtain the angular position θ the difference N has to be multiplied by the angular step θ_p.

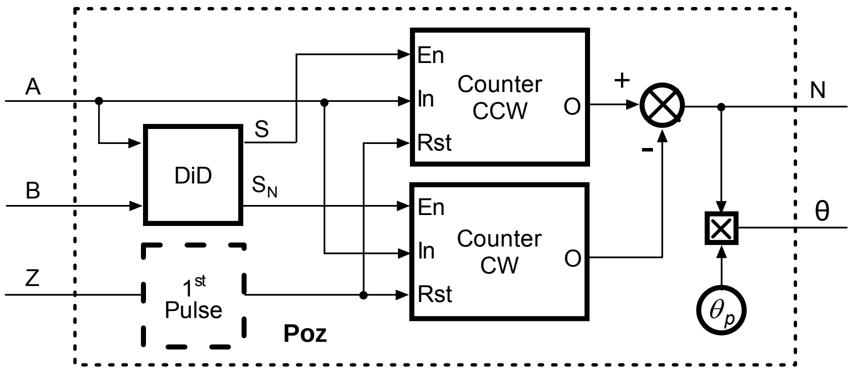


Figure 5
The simulation structure of the position computing block

It is to note, that this structure provides the position information in interval 0–2π rad., because the counters will be reset by every complete rotation by the marker signal Z. To extend the position measurement to more rotation the structure has to be provided with 1st Pulse block (broken line on Figure 5), which transmits to the counters only the first reset pulse after the switch on. Obviously, if the counters for certain reasons are switched off and again on, the position information is lost, the shaft has to be rotated to its reference position and resumes the rotation in the desired position.

5 Simulation Results

Using the above presented functional units the simulation structure presented on Figure 6 was build. The Function Generator block realized using the Repeating Sequence Simulink® block, produces the input signal θ_{ref} for encoder (it is equivalent to angular position of the shaft). Its amplitude and the time-profile of the variation is editable by the user. The IEnc encoder block presented in Chapter 2, generates the A, B and Z output signals. Based on A and B signals the DiD block (described in Chapter 3) determines the direction of the rotation. The Poz block has the structure presented in Chapter 4. Based on A, B and Z output signals counts the number N of impulses and computes the angular position θ of the shaft. All signals are saved in Matlab's Workspace for further analysis.

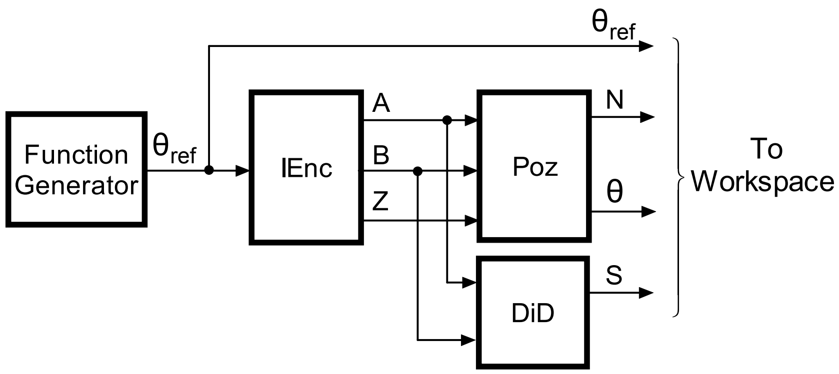


Figure 6
The simulation structure of the interconnected functional units.
IEnc – incremental encoder; Poz - position computing block; DiD - direction-detector block

The reversal process was analyzed. The reference angle generated by function generator has a saw-tooth-like variation versus time. Its parameters were selected in such manner, that all possible combinations of reversal were captured and presented in Figures 7 a)-d). In all cases the sensing of the reversal is done in a quarter of angular step. This fact is underlined in the diagrams for case CCW to CW reversal (left column): the S signal starts with 0 default value (corresponding to CW rotation), but after a quarter angular step the DiD block observes the CCW rotation and rises its S output to 1, corresponding to CCW rotation.

Figure 8 presents the computed position in comparison with the reference position. The generated reference angle start in CW direction with a ramp of 80 rad./s, at 0.05 s occurs the reversal in CCW direction, with the same ramp. At 0.015 s occurs another reversal and this direction will be preserved until to the end of the simulation. The computed angular position follows the reference as is shown in Figure 8a.

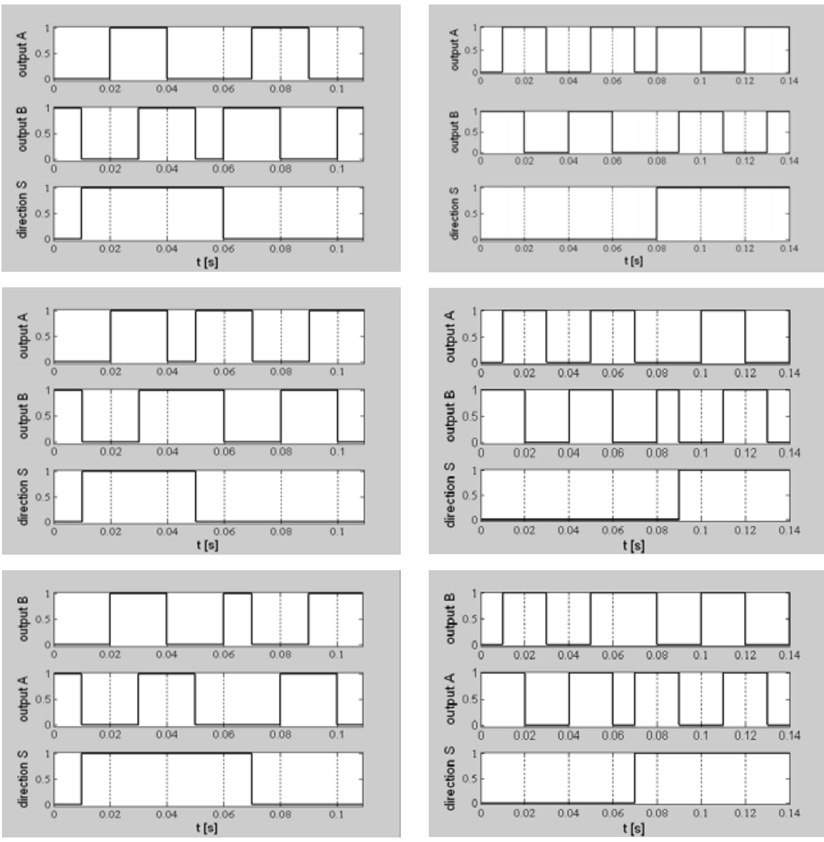
The incremental character of the computed position is reflected by the enlarged detail of both position angles represented in Figure 8 b).

From CCW to CW   From CW to CCW

a)

b)

c)



d)

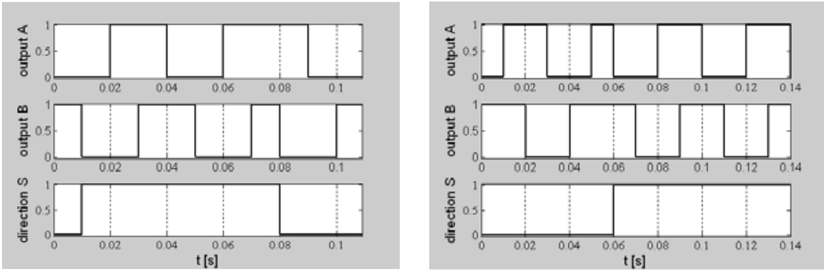
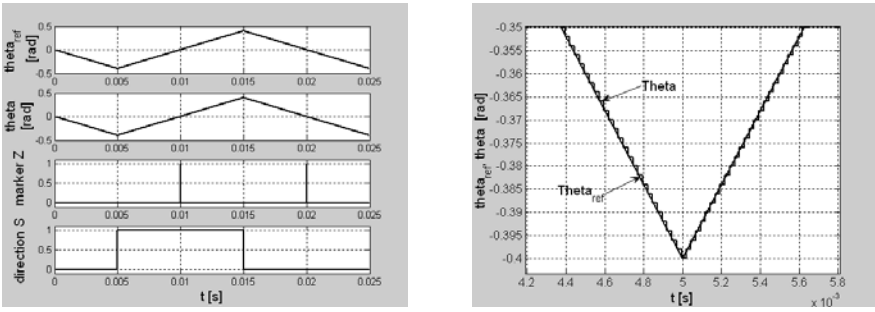


Figure 7
The simulation results representing all possible combinations of the reversal process.
Left column: From CCW to CW, Right column: from CW to CCW,
Top trace: signal A, Middle Trace: signal B, Down trace: direction signal S.
Reversal occurs at: a) A=0, B=0; b) A=0, B=1; c) A=1, B=0; d) A=1, B=1.

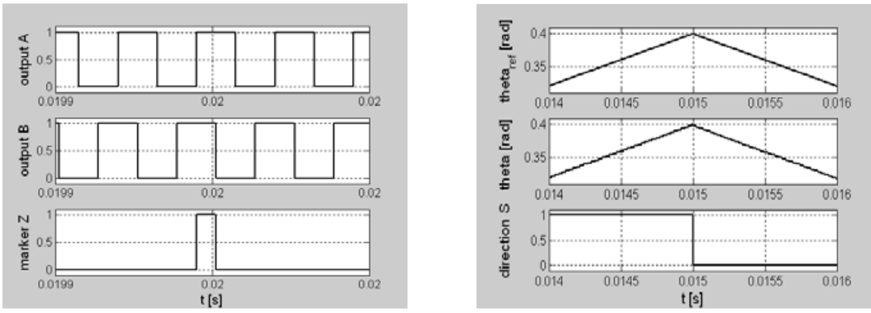
Figure 8 a) shows also, that the marker pulses Z occurs every time when the angle passes through zero value.



a) b)

Figure 8
The simulation results representing the reference angle and computed angle during reversal.
Left, from top to down: reference angle θ_{ref}, computed angle θ, marker output Z, direction signal S.
Right: Detail of the reference angle θ_{ref} and computed angle θ versus time.

Figure 9 a) presents at enlarged detail the marker pulse referred to the A and B output signals, its width obviously is a quarter angular step. The direction signal S is changing according to the sense of rotation as is seen in Figure 8 a) and in enlarged details Figure 9 b). The simulation results correspond with those expected.



a) b)

Figure 9
The simulation results representing and computed angle during reversal.
Left: The marker signal referred to outputs A and B.
Right: The direction signal S referred to angular position (detail).

The structure presented in Figure 6 may be integrated in simulation structures of electrical drives. In this case the angular position – the input signal of the encoder – will be provided by the drive structure; usually it is obtained from the machine model. The control scheme of the drive system will use as position information the position determined on base of encoder signals by the Poz block.

6 Experimental Measurements

Experimental measurements were performed using a 1XP8001-1 (*Siemens*) incremental encoder. The encoder has 1024 divisions per 360°, and provides the output signals A, B, Z and their negated values AN, BN, ZN compatible with HTL logic. The encoder was mounted on a 1LA7073 series (P_N=0.55 kW, n_N=2800 rpm) induction motor. The rotational speed of the motor was controlled in large limits: (0-200 Hz in steps of 0.01 Hz) by a *Micromaster 440* static frequency converter configured in vector-control mode. The converter uses the encoder signals as speed-feedback. The scheme of the experimental set-up is presented on Figure 9. Figure 10 presents the three encoder signals i.e. A, B and Z captured by a storage scope at a CW running. Figure 11 shows the A and B signals at CCW to CW rotation sense reversal. The captured figures correspond with those simulated.

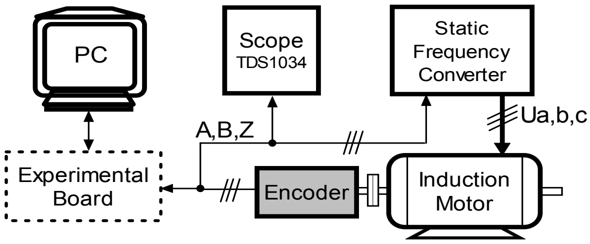


Figure 10
The block scheme of the experimental set-up

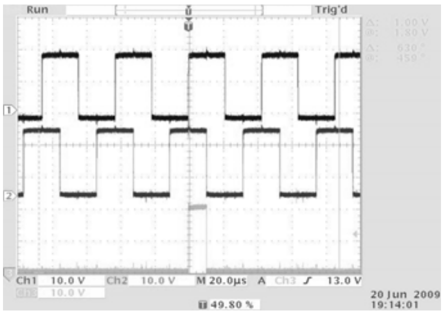


Figure 11
Experimentally captured encoder signals by CW operation.
Top: output A, Middle: output B,
Down: Marker signal.

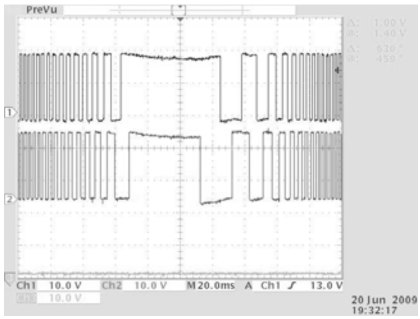


Figure 12
Experimentally captured encoder signals by CCW to CW reversal.
Top: output A, Down: output B.
Reversal occurs at A=1, B=1.

The experimental board (under development) is built around of the *TMS320F2812 TI* DSP based *eZdsp kit* from *Spectrum Digital*. The used software environment is the Matlab/Simulink® and Code Composer®. The verified simulation structure is completed with the *Real Time Interface* blocks to link to the hardware. Based on this structure automated DSP code generation is performed. The Code Composer® permits the download of the code to target-DSP memory, its real-time execution and data acquisition.

Conclusions

The information provided by the incremental encoders is inherently digital. The provided pulses are counted by an electronic counter; their number is proportional to the angular position of the encoder shaft. The direction of the rotation may be determined by a digital decoding scheme using the two quadrature signals provided by the encoder. The direction changes are detected in an angular interval equal to or less then a quarter of angular step of the encoder disc.

The presented simulation structure of the incremental encoder may be integrated in any Simulink® structure. Due to the fact that the encoder signals are the highest frequency quantities in an electrical drive system, consequently the choose of the simulation step has to be done accordingly. The simulation results correspond to those expected and are very close to the experimental one.

Acknowledgement

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