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IMPLEMENTATION OF SPEED MEASUREMENT FOR ELECTRICAL DRIVES EQUIPPED WITH QUADRATURE ENCODER IN LabVIEW FPGA

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ABSTRACT: The paper introduces the basics of speed measurement with quadrature encoders. It explains the theory of the basic sensor types, and the signals of the quadrature encoder. It introduces the theory of the two main methods for speed measurement with quadrature encoders: the time based, and the frequency based method. It describes the quantization and relative errors of these two methods, and the considerations of their implementation. Finally it gives a short example of the practical implementation in LabVIEW FPGA, for the frequency based speed measurement method.

KEYWORDS: quadrature encoder, speed measurement, LabVIEW FPGA

INTRODUCTION

Controlling the speed of a motor is a basic functionality of modern electric drives. In order to precisely control the speed of an electric motor, it is necessary to measure the actual speed of the motor. This measurement can be done with various tools and methods. In most cases it is usually done with a sensor built in the motor or mounted to its shaft externally. These sensors vary in their principle, output signal, and resolution. Some of them are suitable for position measurement either. Selecting the right sensor is crucial, since this decision greatly influences the quality and the total cost of the drive [3].

In the past, tachogenerators were widely used for speed measurement purposes. This sensor is basically a small DC generator, which produce a voltage proportional to its speed [7]. Measuring its output voltage the speed can be calculated easily. With precise design and construction, good accuracy can be achieved in wide speed ranges. Determining the position of the shaft is not possible by measuring the output voltage of the tachogenerator.

THE QUADRATURE ENCODER

Nowadays mostly optical encoders are used for position and speed measurement of electric motors [3]. The theory of their operation is the following: in the sensor, there are phototransistor and LED couples facing each other [2]. Between them there is a disc which is mounted on the shaft of the encoder. On this disc, there are alternating transparent and non-transparent zones. When the motor is rotating, the light of a LED can reach the corresponding phototransistor depending on the type of zone which is between them at the moment [6].

There are two main types of optical encoders: absolute and incremental. With simply reading the signals of an absolute encoder it is possible to determine the position of the shaft [7]. This kind of sensor is more complex, thus more expensive than the incremental encoder.

In the incremental encoder there are three couples of phototransistors and LEDs. The disc between them has three different bands of alternating transparent and non-transparent zones. The disc and the position of the phototransistor and LED couples are designed to produce the following signals when the motor is rotating with constant speed:

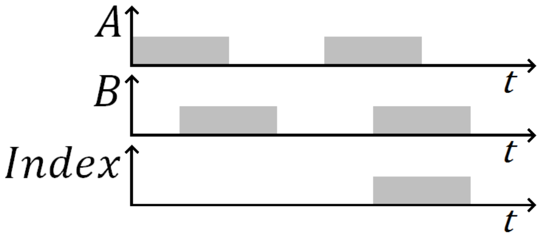

Figure 1. The typical signals of the incremental encoder

The signals of channel A and B are square waves, and there is a 90 degrees phase shift between them [1][2]. Based on this feature, incremental encoders are usually referred to as quadrature encoders. The index channel has only one impulse per revolution. Most of the applications use only the first two channels for speed measurement purposes. The Index channel can be used to get absolute position after the first revolution [1].

USING THE INCREMENTAL ENCODER

One of the most important properties of an incremental encoder is its resolution, what is equal with the total number periods of the signals of channel A or B, under one revolution. The information about the motion of the motor is carried by the changes in the state of channel A and B. Hence this, there are four main points of every period of the signals:

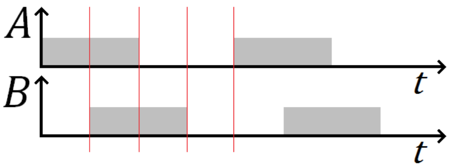

Figure 2. The main points of the two channel

By measuring the frequency of these points or the elapsed time between them, the speed of the motor can be calculated [3]. Based on how many of these points are used for the measurement, there are three different types of evaluation methods. The single evaluation method uses only one channels rising or falling edges, the double evaluation method using only one channel, but both its rising and falling edges, and the quadruple evaluation method uses every edges of the two channels. The selected evaluation method must be considered when the speed is calculated from the measured value.

A. Determining the direction of the rotation

This function can be easily realized with basic logic operations. When detecting a rising or falling edge on one of the channels, the current state of the other channel gives the direction [6]. For example: when there is a rising edge on channel A, the level of channel B is always high in one direction, and always low in the other one [1]. This information then can be stored in a Boolean variable, or in the sign of the measured value of the motors speed.

B. Time based speed measurement

One solution for measuring speed with incremental encoder is to measure the elapsed time between two of the main points shown in Figure 2 [3] [6]. Time measurement can be done by counting clock cycles:

$$T_1 = \frac{X \cdot E}{f_{clk}} \tag{3.1}$$

Where T_1 is the elapsed time between the two points, E is the evaluation multiplier (E = 1, 2, 4), f_{clk} is the frequency of the used clock in Hz, and X is the count of clock cycles. From this, the time needed for one revolution can be calculated the following way:

$$T_{rev} = R \cdot T_1 \tag{3.2}$$

Where T_{rev} is the time needed for one revolution and R is the resolution of the sensor. The speed of the motor is the reciprocal of this value:

$$w[rpm] = \frac{60}{T_{rev}} = \frac{60 \cdot f_{clk}}{R \cdot X \cdot E} \tag{3.3}$$

Since this method basically calculates from the time needed for one revolution, the quantization error of the measurement is the following:

$$\Delta T_{rev} = \frac{E \cdot R}{f_{clk}} \tag{3.4}$$

C. Frequency based speed measurement

Another solution for speed measurement is counting the main points (shown in Figure 2) for a certain amount of time, called the measurement time [3] [6]. From the result of the counting the time needed for one revolution can be calculated based on the following equation:

$$\frac{E \cdot R}{T_{rev}} = \frac{X}{T_m} \tag{3.5}$$

Where E is the evaluation multiplier (E = 1, 2, 4), R is the resolution of the sensor, T_{rev} is the time needed for one revolution in seconds, X is the counted number of edges, and T_m is the measurement time in seconds. The speed can be calculated the following way:

$$w[rpm] = \frac{60}{T_{rev}} = \frac{60 \cdot X}{T_m \cdot E \cdot R} \tag{3.6}$$

The quantization error of the measurement is the following [3] [6]:

$$\Delta w[rpm] = \frac{60}{T_m \cdot E \cdot R} \tag{3.7}$$

CONSIDERATIONS OF THE SPEED MEASUREMENT METHODS

One most important property of the speed measurement is the quantization error. When using the frequency based method, it is recommended to use the quadruple evaluation if it is possible. Choosing the correct measurement time is essential. Basically, the longer the measurement time, the better the results are. In exchange for the longer measurement, the speed controller will be slower and this will decrease the quality of the drive [3]. This method is ideal for drives with high resolution encoders, because the higher resolution decreases the quantization error. Another advantage of this method that the measurement always as long, as we want it to be. The relative error of the measurement can be calculated, by dividing the quantization error with the actual speed of the motor [3]:

$$e_{rel\_freq} = \frac{\Delta w_{freq}}{w} \tag{4.1}$$

Because the actual speed is in the denominator, the precision of this method increases with the speed.

With the time based method, the quantization error is smaller when low resolution encoders are used. The length of the measurement depends on the speed being measured: the lower the speed, the longer the measurement. Usually there is a maximum measurement time, and above that, the result is set to zero. The relative error is calculated by dividing the quantization error with the actual time what is needed for one revolution:

$$e_{rel\_time} = \frac{\Delta T_{rev}}{T_{rev}} \tag{4.2}$$

Because the measured speed value is calculated from T_{rev} by division, the relative error of the speed measurement is the same. Since the time of one whole rotation decreases as the speed is higher, this method is more precise at lower speeds.

Because of the link between the speed and the relative errors, the two methods are often used together [3] [6]. Based on the speed of the motor, the software can switch between the two methods. The speed where the two methods have the same relative error can be calculated (in Fig 3. this point is *at 21 rpm) [3]. The switching point, or points should be somewhere around this speed.*

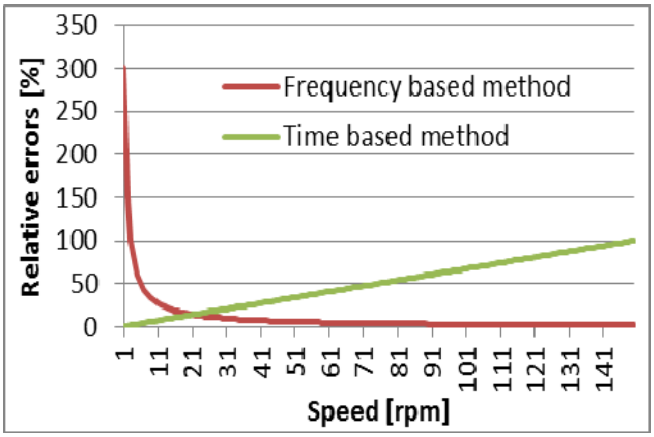

Figure 3. The relative errors of the two methods in the the function of the speed

If the drive is operating in position controlled mode, then the minimum speed the drive can measure gets very important at the end of the positioning. This value can be reduced by using higher-resolution encoders, better evaluation method, or increasing the length of the measurement. Both of the frequency and time based methods takes the same time when the drive is at the minimum speed. It is possible to reduce the effect of the quantization error if the start of measurement is synchronized with the signals of the quadrature encoder. For example: after the frequency based method finished the counting the edges of the signals and calculating the actual speed of the motor, the next measurement starts with the next edge. This function can also be important when the time based method is being used.

IMPLEMENTATION OF SPEED MEASUREMENT WITH THE FREQUENCY BASED METHOD IN LABVIEW FPGA

Practical implementation of speed measurement methods in LabVIEW FPGA is really simple. The following example will describe the algorithm and programming of the speed measurement with the frequency based method. The used quadrature encoder has a resolution of 5000 pulses per revolution. The example uses quadruple evaluation and a three milliseconds long measuring time. Based on the equation (3.7), the quantization error is one revolution per minute.

The whole code is in a "Single-Cycle Timed Loop". The clock associated with the loop has an 80 MHz frequency. This means that the loop is executed in every 12.5 nanosecond [4]. The channel A and B of the quadrature encoder is read by the purple colored "FPGA I/O Node" block shown in Fig. 4. Then the two signals are compared to their value from the last cycle saved by shift registers [5]. The comparison is made by the exclusive or gates. The signals of the exclusive-or gates then connected to an or gate which produces a signal that contains every impulse shown in Fig. 2. The case structure (the box with the black border) is in "Standby" state by default. When an edge is detected on one of the two channels of the encoder, the "Counting" state will be activated by the select element.

The "Counting" state is shown in Fig. 5. In this state the edges of the encoder are counted in a variable (the lower blue shift register). Another variable is incremented in every cycle. This variable is then compared to a constant outside the case structure. When the variable is greater/equal to the constant, it means that 240000 cycles have been elapsed (it equals with 3 milliseconds).

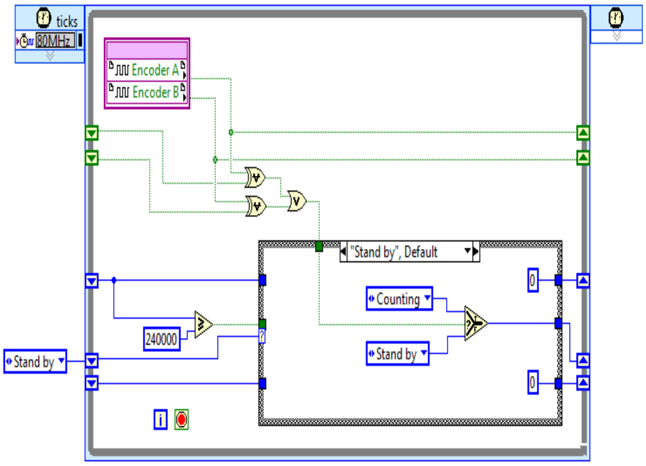

Figure 4. The timed loop of the frequency based speed measurement software with the "Standby" case

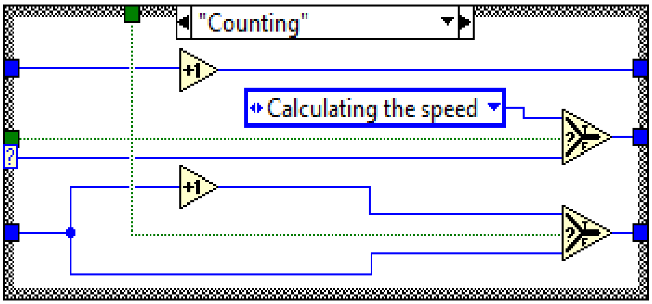

Figure 5. The "Counting" case of the speed measurement software

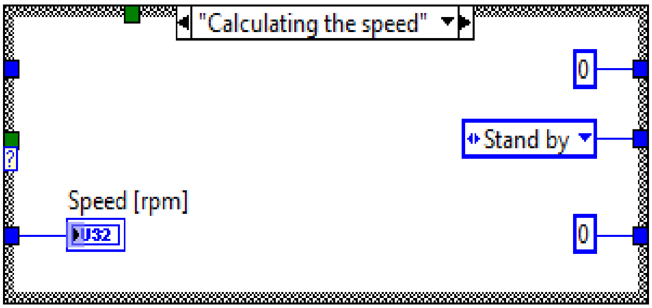

Figure 6. The "Calculating the speed" case of the speed measurement software

After this, the case structure will switch to the "Calculating the speed" case, shown in Fig. 6. In this case the speed is calculated from the variable that contains the count of the edges. In this example the speed in revolutions per minute equals with the count.

CONCLUSIONS

Speed measurement with quadrature encoder is a basic function of modern electric drives. As it can be seen in this paper, the basic theory of this function is simple, and it can be easily implemented. In simple cases, where only speed control is required (and the drive is not operating in the lower speed ranges), it is sufficient to use only the frequency based method

[6]. This makes the practical implementation easy and reliable. When positioning is required, it is recommended to use the two methods together, with an appropriate switching method to reduce the effect of the quantization and relative errors [3] [6]. This is also advised when the motor is equipped with a low-resolution sensor.

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