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An Easy Speed Measurement for Incremental Rotary Encoder Using Multi Stage Moving Average Method

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***Abstract*—Classical theoretical algorithms to calculate rotation speed from incremental encoder information, frequency counting and period counting algorithm, delivers notable measurement error which is a function of rotation speed. This error will cause failure in overall motor control algorithm, resulting in both motor and drive failure. Furthermore, the needs of FPGA as high frequency clock calculation device in period counting algorithm made the implementation cost higher. Two stages moving average method was implemented to reduce error. In addition, DSP sampling time will be used to replace high frequency clock generated by FPGA. With these proposed methods, more accurate speed measurement result can be achieved and no FPGA needed to implement the algorithm. In addition, less data samples are needed compared to classical method. Implementation result in PMSM motor control shows that these methods are able to reduce quantization error that generated when measuring speed using rotary incremental encoder, showing no observable electrical or mechanical problem.**

Keywords—speed measurement; rotary encoder; two stages moving average; PMSM

I. Introduction

From [1] and [2], rotor speed information is required to control Permanent Magnet Synchronous Motor (PMSM), especially Field Oriented Control Method (FOC). Rotary encoder widely used as an easy solution of displacement angle transducer. Angle displacement information's provided by two pulse encoder signal which transmitted to control system. From this information, one can measure the displacement angle and calculate the rotation speed.

Classical theoretical algorithm which commonly used to calculate rotational speed has different disadvantages for low speed and high speed. For low rotation speed,frequency counting algorithm produces a huge measurement error. On the other hand, the period counting algorithm gives comparable huge measurement error in high speed rotation. For this reason, combination of both algorithms is used to achieve more accurate result in wide speed range measurement.

However, to implement period counting algorithm needs FPGA as high frequency clock source. This requirement will make the implementation cost of the controller become very expensive.

Another problem which usually escalated in implementation of the classical algorithm is the quantization error. Naturally, the discrete measurement product from the encoder will brought a noticeable, fluctuatingerror in speed calculation using this algorithm.

Since inaccurate speed measurement will cause failure in FOC, a filter is needed to minimize the inaccuracy. Moving average method has already used in many application to reduce the noise. However, to achieve higher measurement accuracy, it needs more samples in calculation. In this paper, an improved method to filter output noise using moving average window is proposed. As shown in experimental results, output error reduced after implementation of two stages averaging process.

Utilization of DSP sampling time will be introduced in this paper to substitute high frequency clock from FPGA. Thus, implementation cost can be lower.

II. CLASSICAL THEORETICAL ALGORITHM

A. Frequency Counting Algorithm

The simplest approach to get a rotary speed is to count the number of pulses from encoder within sampling time period [3], [4], [5]. Since φ is the angle displacement represented by one encoder pulse, which depends on encoder teeth resolution as seen in equation (2), the total rotated angle in one sampling calculated as equation (1).

$$\theta = n \cdot \varphi \tag{1}$$

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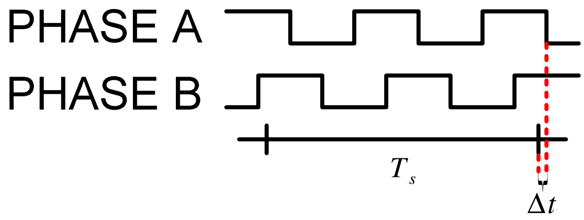

Fig 1. Frequency counting illustration

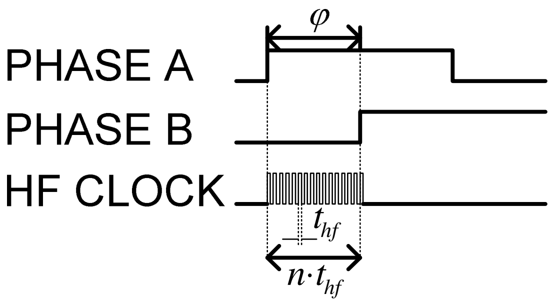

Fig 2. Period counting illustration

$$\varphi = \frac{2 \cdot \pi}{4 \cdot N_{enc}} \tag{2}$$

Furthermore, the rotor speed will be easily calculated using equation (3).

$$\omega = \frac{\theta}{T_s} \tag{3}$$

Provided that θ is the product of an integer (n) which is the number of encoder pulse in one sampling time and φ, ω calculations sometimes give quantization errors. The event when the error occurs is illustrated in Figure 1.

The figure shows that there is a slight time difference after the sampling period until the next encoder increment. As a result, there is an inaccurate angle displacement measurements which vary from zero to φ at maximum. This inaccuracy will lead to a noisy speed calculation although it will be lower in higher rotation speed.

According to [3], speed measurement errorsgiven by (4).

$$e_\omega\% = \frac{2\pi}{\omega \cdot N_{enc} \cdot T_s} \cdot 100 \tag{4}$$

Equation (4) gives the evidence that measurement error which shown in Figure 3 will increase as the speed lower. By this reason, frequency counting method is not suitable for low speed measurement.

B. *Period Counting Algorithm*

Another way to measure rotation speed using incremental encoder is by period counting algorithm [3], [4], [5]. Using a high frequency clock device, this method calculates the time

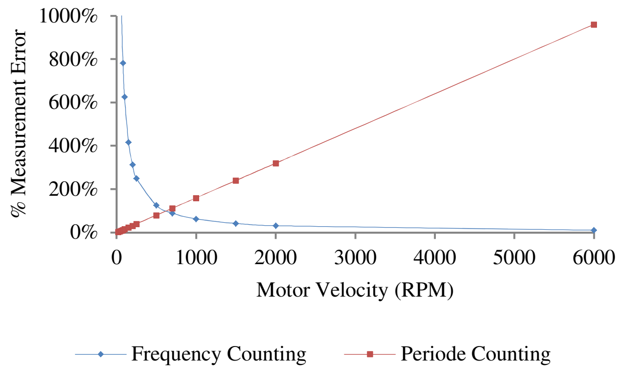

Fig 3. Frequency counting and period counting error trends

difference between two encoder pulses. Figure 2 illustrates the period counting algorithm.

Rotor speed can be easily calculated using equation (5).

$$\omega = \frac{\varphi}{n \cdot t_{hf}} \tag{5}$$

According to [3], speed measurement errorsgiven by (6).

$$e_\omega\% = \frac{\omega \cdot N_{enc} \cdot T_{hf}}{2\pi} \tag{6}$$

Equation (6) gives evidence that the error measurement which shown in Figure 3 will increase as the speed increase. By this reason, period counting method is not suitable for high speed measurement.

Figure 3 shows that there is a critical speed which is the intersection point between frequency and period counting error trends. The critical point calculated using equation (7).

$$\omega_{crit} = \frac{-\pi \cdot T_{hf} + \pi\sqrt{T_{hf}^2 + 4 \cdot T_{hf} \cdot T_{sc}}}{T_{hf} \cdot T_{sc} \cdot N_p} \tag{7}$$

III. PROPOSED METHOD

In vehicle application, speed transducer must be able to operate in wide speed range. The challenge is to minimize error occurred in low and high speed region. To resolve this objective, both frequency and period counting algorithm will be used.

Furthermore, the use of FPGA as high frequency clock source in period counting algorithm will increase the implementation cost. To reduce the cost, sampling time of DSP will be used in this paper to implement the period counting algorithm. Thus, t_{hf} in equation (4) will be substituted by T_s.

Because of the difference between method which applied in low speed and high speed area, a scheduling mechanism will be needed to achieve a smooth transition between two algorithms. Unhandled transition can deliver a significant error since error in period counting method algorithm which applied in low speed region goes higher as the rotation speed increase.

Since both algorithms have quite similar equation to obtain speed, it can be simplified as equation (8).

$$\omega = \frac{delta \cdot \varphi}{null \cdot T_s} \tag{8}$$

Using this mechanism, a controller does not need to decide whether frequency or period counting algorithm used to calculate speed. While there is no encoder pulse (delta) detected in one sampling period (T_s) controller will wait until it detect pulse from encoder. Right after encoder pulse detected, controller will obtain rotation speed using the proposed equation. Otherwise, if there is one or more pulses detected in one sampling period, controller will directly calculate the rotation speed.An easy scheduling mechanism which proposed in this paper is illustrated in Figure 4.

The previous method has quantization error for whole speed range. To reduce the produced error from calculation, moving average filter is proposed in this paper. The idea of moving average filter is to calculate the mean value of instantaneous speed until (i-1) previous speed samples, as written in equation (9).

$$\bar{\omega} = \frac{\omega_j + \omega_{j-1} + \cdots + \omega_{j-(i-1)}}{i} \tag{9}$$

Instead of the commonly used moving average filter, this paper will discuss the application of two stages moving average filter. Speed average from previous process will be used in the second stage of moving average, as seen in equation (9). This method delivers better result by using less data samples than the single stage moving average.

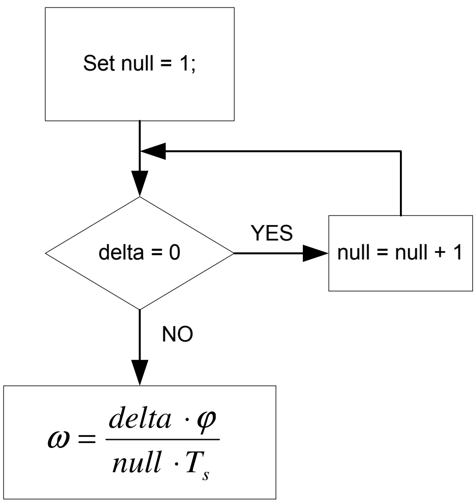

Fig 4. Scheduling mechanism of speed measurement

$$\bar{\bar{\omega}} = \frac{\bar{\omega}_k + \bar{\omega}_{k-1} + \cdots + \bar{\omega}_{k-(m-1)}}{m} \tag{10}$$

IV. SIMULATION RESULTS

All proposed methods were implemented in PSIM simulation platform according to parameter shown in TABLE I. The simulation results are categorized in three sections, each shows the difference between moving averages strategies, from low speed to high speed region.

The simulation results are categorized in three sections, each shows the difference between moving averages strategies, from low speed to high speed region. The proposed method that simulated used i = 12 and j = 8. While the conventional one stage moving average used 24 data samples. The critical speed obtained using equation (7), RPM_{crit} = 698.77 rpm.

TABLE 1. Simulation Parameter

Encoder Teeth (N_{enc})	120
DSP Sampling Time (T_s)	0.2 ms

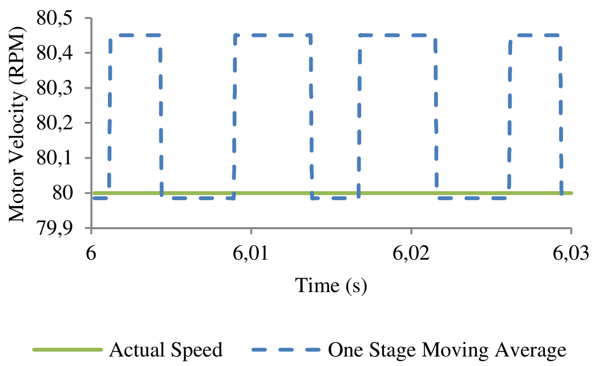

Fig. 5. Simulation result for one stage moving average measurement compared to actual speed in low speed region

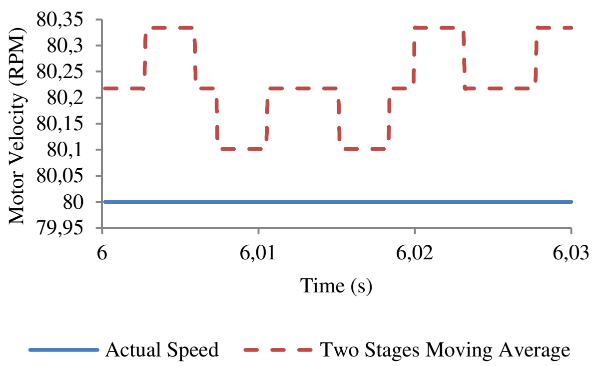

Fig. 6. Simulation result for two stages moving average measurement compared to actual speed in low speed region

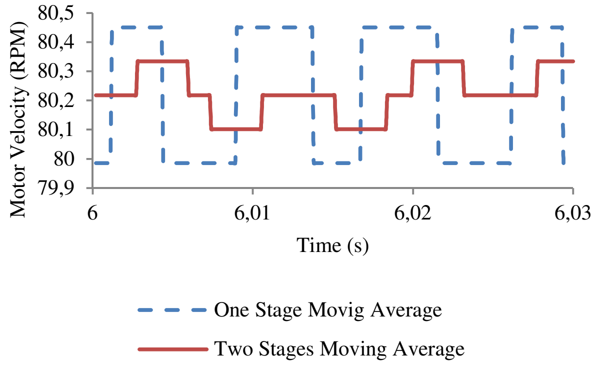

Fig. 7. Comparison between one stage and two stages moving average in low speed region

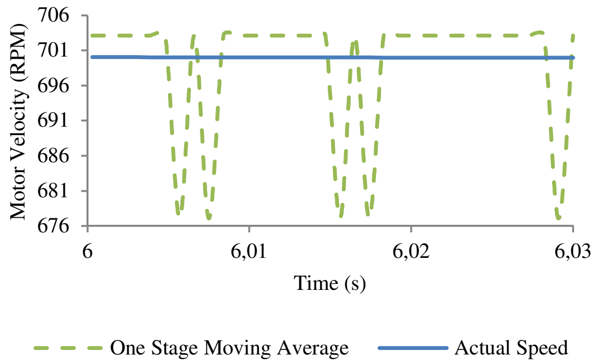

Fig. 8. Simulation result for one stage moving average measurement compared to actual speed in critical speed region

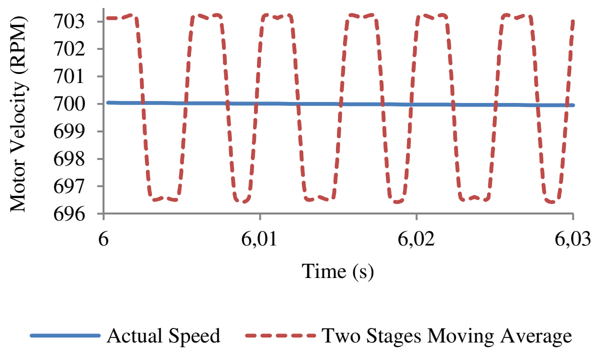

Fig. 9. Simulation result for two stages moving average measurement compared to actual speed in critical speed region

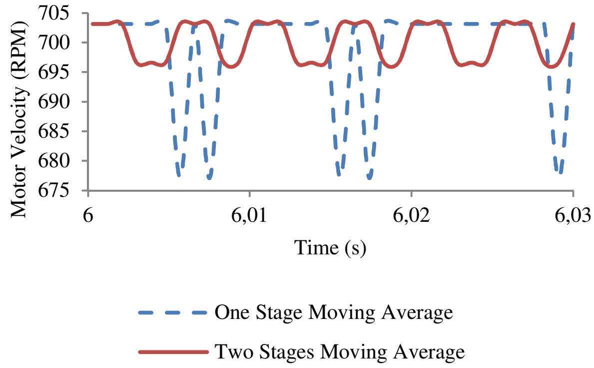

Fig. 10. Comparison between one stage and two stages moving average in critical speed region

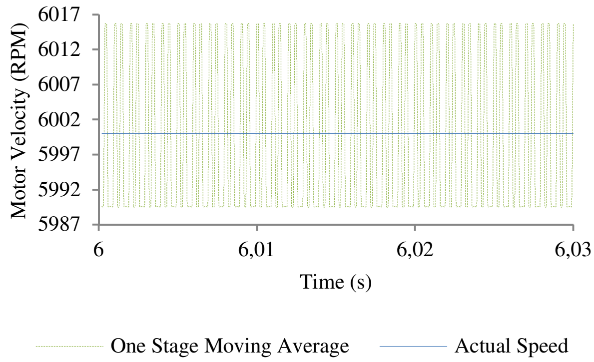

Fig. 11. Simulation result for one stage moving average measurement compared to actual speed in high speed region

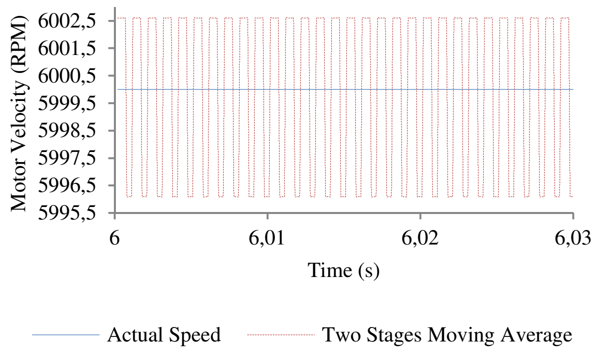

Fig. 12. Simulation result for two stages moving average measurement compared to actual speed in high speed region

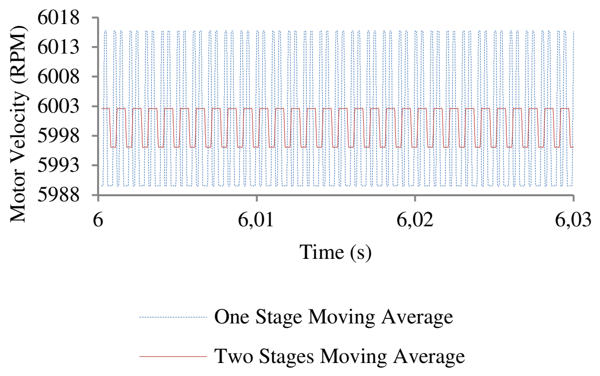

Fig. 13. Comparison between one stage and two stages moving average in high speed region

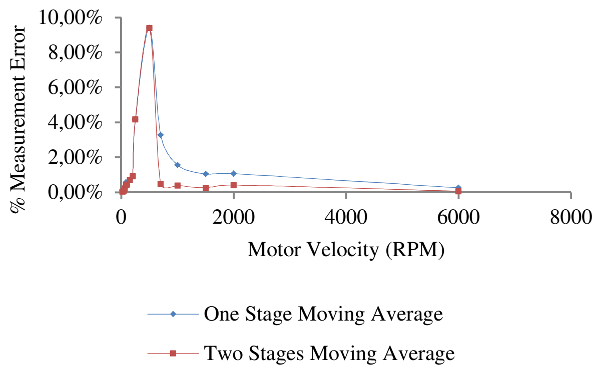

Fig. 14. Error comparison between one stage and two stages moving average

Figure 5, 6 and 7 shows the simulation result of low speed measurement, 80 rpm, using one stage moving average and two stages moving average. As seen in figure 5 and 6, measurement error of two stages moving average method is lower than the one stage moving average. In addition, the variation of measurement result is more stable, as seen in Figure 7. However, the measurement speed is always higher than the actual speed.

The simulation result for critical speed region illustrated in Figure 8, 9 and 10. As we seen in Figure 8 and 9, two stages moving average method yield measurement results, which it's averages closer to actual speed, compared to one stage method. Again, Figure 10 shows that two stages method has more stable measurement than one stage method.

As the speed higher, the measurement error for both method is lowered. However, two stages method give better measurement result, showing less fluctuating values, than one stage method, as seen in Figure 11, 12, and 13.

V. IMPLEMENTATION RESULT

The simulation result shows that the proposed method gives better measurement error, although used less data sample than conventional method. From the curve above,

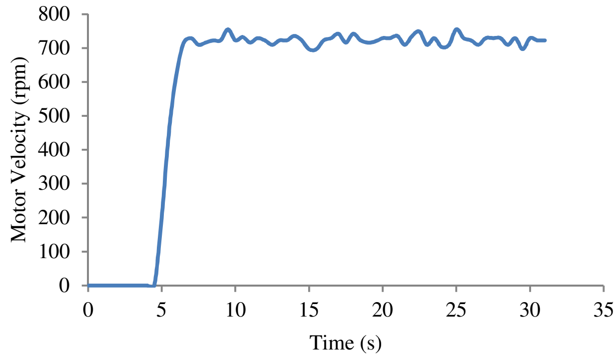

Fig. 15. Implementation result with TMS320F28335 DSP to control 75 kW PMSM motor

highest measurement error percentage is obtained at 500 RPM, which both moving average methods yield the same results. In high velocity region, the proposed method successfully outperforms the conventional method in term of measurement error percentage.

The proposed method successfully implemented in TMS320F28335 DSP platform to control 75 kW PMSM motor using FOC. The result shows that the measurement method has delivered acceptable low speed measurement error. The motor rotation is still in good control, showing no problematic mechanical rotor vibration, although there is a little fluctuating error reading in steady state speed as shown in Figure 15.

VI. CONCLUSION

In this paper an easy speed measurement for rotary incremental encoder has been presented. From the simulation and implementation results, there are four points can be concluded:

1. As seen in Figure 14, one stage and two stages averaging method has quite same error percentage when the rotating speed is lower than the critical speed. However, in the higher speed region, two stages averaging method has a lot better result compared to one stage method.
2. Moving average method successfully reduced quantization error that generated when measuring speed using rotary incremental encoder and also gives better result than conventional method.
3. Moving average method can be further expanded to multi layer moving average method, to minimize even more noise, while also reduced data sample needed in first layer.
4. As seen in implementation result, this method delivered acceptable measurement error to drive PMSM using FOC algorithm.

Since the usage of encoder increases production cost and decreases control reliability for market use, a sensor less speed estimation methods need to be implemented in the future work.

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