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A novel motor speed calculation method using square wave speed sensor signals via fast Fourier transform

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Abstract

This paper presents a novel motor speed measurement method and experimental results using the fast Fourier transform (FFT). Motor speed is obtained using the square wave output signal of a speed sensor. In the proposed method, the speed can be measured in a wide range, and transient speed changes can also be clearly observed. The experiments were conducted during start-up and in steady state. The sampled speed data were transformed to frequency spectrums using the FFT. The frequency, which corresponds to the maximum amplitude in the spectrum, was used to calculate the motor speed. The test results show that the proposed method is very useful.

Key Words: *Motor speed measurement, transient analysis, fast Fourier transform, signal processing*

1. Introduction

Electrical motors constitute an important component of industrial processes, as they are used to drive moving mechanical loads. Rotor speed is required for high performance to provide feedback information and superior regulation of the load. Different kinds of transducers are available to provide speed information in a digital or analog signal [1]. The output signal of an analog-type tachometer and the voltage-to-noise ratio are very low for low speed measurement. Therefore, a synchronous-based speed measurement technique was proposed in [2]. However, the proposed technique needs extra equipment and focuses on low speed values (0-200 rpm). A rotary encoder measures motor speed using incoming pulses from an encoder mounted to a shaft. They have been used for the speed control of electrical motors. The accuracy of the measurement of speed is an essential requirement to reach a good dynamic response, which can cause stability problems [3]. Speed measurements are typically based on several methods [4,5]:

1. Measurement of a time interval between successive pulses (Method 1),
2. Counting of pulses during the prescribed time (Method 2),

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3. Measurement of time duration for the variable number of pulses (Method 3).

It is summarized that the commonly used speed measurement systems are based on 2 methods: encoder pulse frequency and period measurement. In Method 1, the motor speed, given in rpm, is calculated according to Eq. (1).

$$n_r = \frac{60}{T_{mes} \cdot N_{noc}} \tag{1}$$

Here, N_{noc} is the number of encoder notches and T_{mes} is the measured time between the 2 sequential signals of the encoder. The main disadvantages of Method 1 are that the value of T_{mes} is small at high speeds and the measurement time is long at low speeds. Thus, a quantization error occurs in the calculated speed value in that area. The motor speed for Method 2, given in rpm, is calculated from Eq. (2).

$$n_r = \frac{60}{T_{pr} \cdot N_{noc}} \cdot N_{con} \tag{2}$$

Here, N_{con} is the number of counted pulses from the encoder and T_{pr} is the significant fixed measurement time. In this method, $T_{pr} \cdot N_{noc}$ determines the quantization error of the calculated speed values, which is why the definition of T_{pr} is very important. In Method 3, the motor speed, given in rpm, is calculated according to Eq. (3).

$$n_r = \frac{60}{T_{mes} \cdot N_{noc}} \cdot N_T \tag{3}$$

Here, N_T is the number of fixed pulses of the encoder. The weakness of Method 1 is addressed by this method at high speeds. However, the measurement time is still long for low speeds. Therefore, this method is more suitable for high speeds.

The speed measurement shown in [6] measures multiple periods of the encoder during every period of control to obtain very good precision at high and low speeds. This speed measurement system is named the M/T method. For very low speed values in the M/T method, the detection time for the speed measurement is longer, which results in poor performance of the speed control. To overcome this problem, using higher PPR encoders or developing some speed observers or estimators is suggested. In addition to that, the encoder signal is affected by the sinusoidal line signal and this causes systematic errors [7]. The systematic errors of the resolvers and rotating encoders with the sinusoidal line signal were suppressed using the gain-phase-offset-correction method in [7]. This method requires no additional hardware and low computing power. Thus, the dynamic of the speed values is followed for the speed controller.

In the presented study, the proposed method does not need any equipment other than the rotary encoders and is not affected by the effects of the sinusoidal line signal. It measures the speed in a wide range at a high accuracy for both transient and steady-state conditions. The speed sensor used has a square wave output signal. The signal is sampled via a data acquisition card and is saved on a PC. The speed data are then transformed to the frequency spectrums using the fast Fourier transform (FFT). The frequency corresponding to the maximum amplitude in the spectrum is used to reach the motor speed. Experiments are done for both during start-up and steady state. The motor specifications are a 3-phase, 50-Hz, 380-V, 2-pole, and 50-HP squirrel cage submersible induction motor.

2. Materials and methods

The motor speed is measured via a square wave speed sensor. The speed sensor is connected axially between the motor shaft and the generator. The sampled speed signal is shown in Figure 1. The sampled data are filtered using a low-pass filter, and a sampled part of the speed data is then selected in the desired length and transformed to the frequency domain using the FFT. The algorithm block schema used is given in Figure 2.

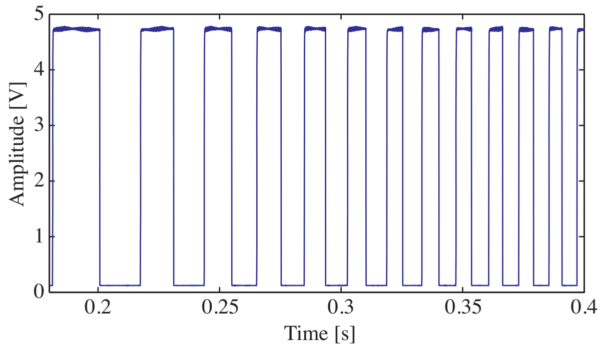

Figure 1. The speed sensor signal.

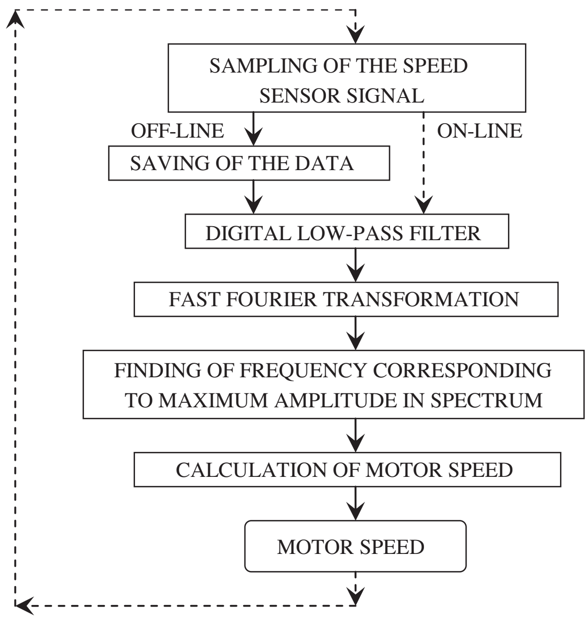

Figure 2. The block schema of the proposed algorithm.

In this study, the speed sensor signal is sampled as an analog signal. The speed data are then windowed and the speed values are calculated using the FFT for each window. Resolution of the speed-time curve is raised via hopping. Figure 3 shows the speed sensor signal, the windows used, window size (M), hop size (s), and the frequency spectrums of some windowed regions, which show that the maximum frequency value corresponds to the maximum amplitude in the spectrum.

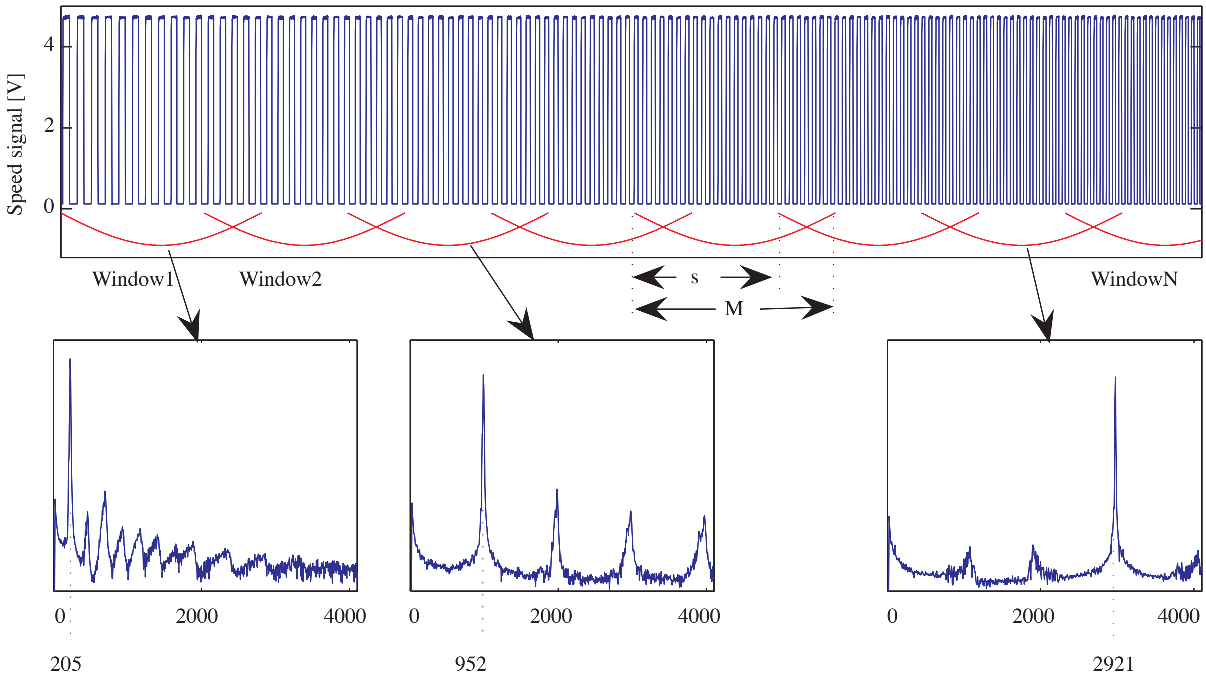

Figure 3. Speed sensor signal and evaluation of the maximum frequency values by the FFT.

Motor speed values are calculated according to the maximum frequency values using Eq. (4).

$$n_r = \frac{f_{s\,\max}}{S_{nn}} \cdot 60 \tag{4}$$

Here, f_{smax} is the maximum frequency value, S_{nn} is the number of sensor notches, and n_r is the unit of speed in rpm.

In the experiment, a 50-HP induction motor is used. The motor is started with a star-delta transformation and passes to the delta connection at the fourth second. For a healthy motor, the obtained speed-time curve during start-up under no-load conditions is given in Figure 4.

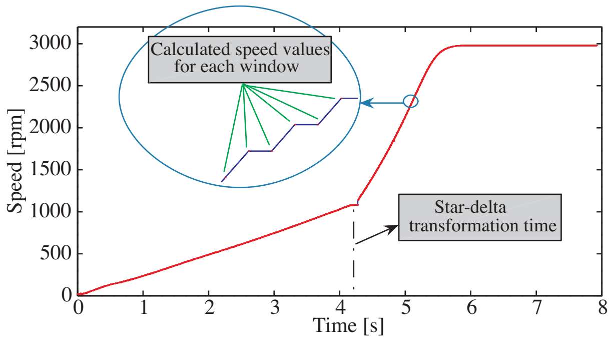

Figure 4. Experimental rotor speed-time curve during start-up using the FFT.

3. Simulation and results

To evaluate the comparison of the mentioned methods according to their simulation speed signals, the MATLAB program is used. Initially, a speed sensor signal with 60 notches is generated at a 22,500-Hz sampling rate. The speed is calculated according to 4 different kinds of methods, as mentioned above. The methods used are:

1. Measurement of a time interval between successive pulses (Method 1),
2. Counting of pulses during the prescribed time (Method 2),
3. Measurement of the time duration for the variable number of pulses (Method 3),
4. Proposed method (Method 4).

The signal starts at 100 rpm, increases by 200 rpm every 0.5 s, and finishes at 2900 rpm. The obtained speed curves for Methods 1, 2, 3, and 4 are shown in Figures 5, 6, 7, and 8, respectively.

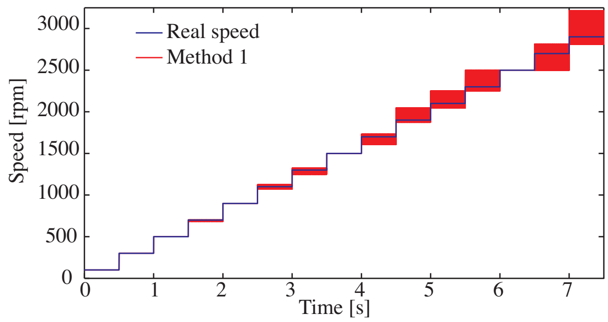

Figure 5. The obtained speed curve according to Method 1.

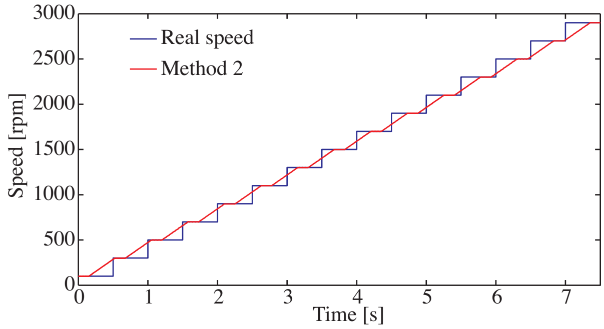

Figure 6. The obtained speed curve according to Method 2.

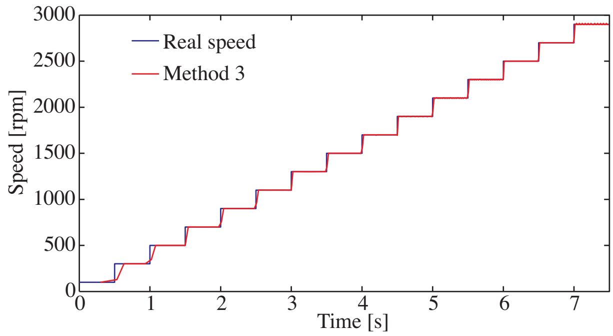

Figure 7. The obtained speed curve according to Method 3.

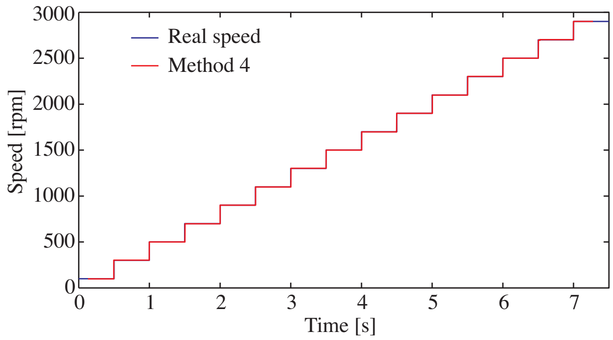

Figure 8. The obtained speed curve according to Method 4.

Analysis of the transient change regions in the speed curves for all of the methods:

Method 1 gives good results for the low speed region values. However, the results are far from real speed values in the high speed region, although the method gives good results for some of the high speed values. This means that the sampling rate is very important in this method.

Method 2 gives bad results across the entire speed range for transient changes.

Method 3 gives good results for the high speed values. However, the transient values are far from real values in the low speed region.

Method 4 gives good results across the entire speed range for transient conditions. Furthermore, stability is achieved for the entire speed region. The results show that the most suitable method for transient speed calculations is Method 4.

Analysis of the steady-state regions in the speed curves:

The calculations for the constant speed regions of the simulation signal are used to compare the methods. The fluctuations and deviations from the mean values are shown from the calculation results. Thus, 2 different criteria (fluctuation and calculation error) are used in the analysis. The fluctuation criterion is computed as in Eq. (5) and the calculation error is computed as in Eq. (6).

$$Fluctuation = \frac{Maximum\,Value - Minimum\,Value}{Real\,Value} \cdot 100 \tag{5}$$

$$Calculation\,Error = \frac{Mean\,Value - Real\,Value}{Real\,Value} \cdot 100 \tag{6}$$

The computed fluctuation and calculation error ratios are given in the Table.

Table. Fluctuations and calculation errors in the calculated speed values.

	Fluctuations				Calculation errors			
Speed [rpm]	Method 1 [%]	Method 2 [%]	Method 3 [%]	Method 4 [%]	Method 1 [%]	Method 2 [%]	Method 3 [%]	Method 4 [%]
100	0.00	2.70	0.00	0.00	0.00	–0.15	0.00	–1.10
300	0.00	1.00	0.00	0.00	0.00	–0.17	0.00	0.70
500	0.00	0.50	0.00	0.00	0.00	–0.15	0.00	–0.02
700	3.04	0.41	0.11	0.00	–1.08	–0.15	–0.01	–0.33
900	0.00	0.00	0.00	0.00	0.00	–0.31	0.00	0.09
1100	4.86	0.00	0.16	0.00	–0.16	–0.03	0.03	–0.12
1300	5.62	0.22	0.19	0.00	–1.04	0.06	–0.06	0.15
1500	0.00	0.00	0.00	0.00	0.00	–0.06	0.00	–0.03
1700	7.29	0.16	–0.25	0.00	–1.82	0.01	–0.11	–0.15
1900	8.89	0.14	0.28	0.00	3.18	–0.01	–0.07	0.03
2100	9.76	0.14	0.33	0.00	2.26	–0.02	–0.02	–0.08
2300	10.87	0.11	0.35	0.00	3.26	–0.03	0.00	0.07
2500	0.00	0.11	0.35	0.00	3.26	–0.03	0.00	–0.02
2700	11.56	0.00	0.00	0.00	–1.63	0.00	0.00	0.10
2900	13.86	0.00	0.41	0.00	3.90	–0.01	0.10	0.01

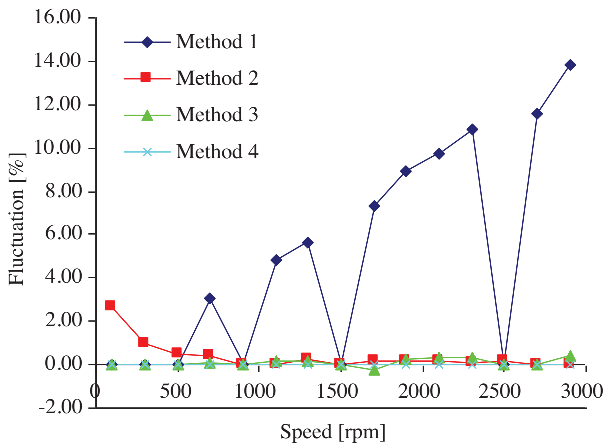

Figure 9. Fluctuations in the calculated speed values.

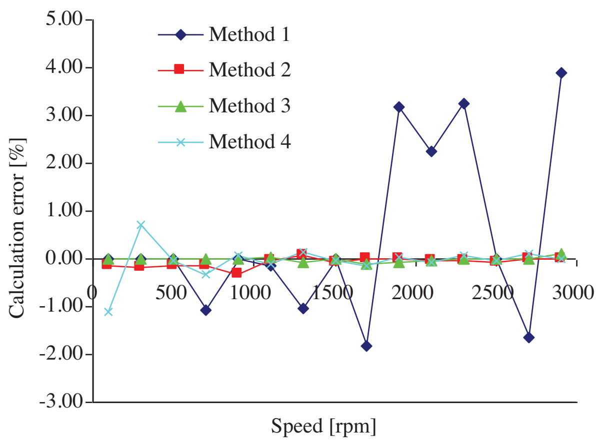

Figure 10. Calculation errors in the calculated speed values.

The fluctuations and calculation errors are respectively given in Figures 9 and 10, to illustrate the results clearly.

Both the fluctuation and calculation errors obtained by Method 1 are 0 in the low speed range values (100-500 rpm). However, they rise as long as the speed increases. The fluctuation value reaches up to about 14% and the calculation error reaches 3%. The values are not acceptable for the calculation of the speed.

In Method 2, the fluctuations are high, reaching up to about 3%. However, the fluctuation decreases to about 0 in the high speed ranges. Otherwise, the calculation error is about 0.2% in the low speed ranges and decreases to about 0.05% in the high speed ranges. Thus, Method 2 is suitable for high speed ranges.

In Method 3, the fluctuations are 0 in the low speed ranges (100-500 rpm). However, they increase as long as the speed increases, up to 0.4%. Furthermore, the calculation error is 0 in the low speed ranges and increases up to about 0.1% in the high speed ranges. Thus, Method 3 is suitable for low speed ranges.

In Method 4, the fluctuation is 0 in the entire speed range. The calculation error is a maximum of 1.2% in the low speed ranges (100-500 rpm). This error value reduces to 0.01% as long as the speed increases.

4. Experimental study and results

The motor used in the tests was a 3-phase, 380-V, 2-pole, 50-Hz, and 50-HP submersible squirrel cage induction motor. A rotary encoder with 60 holes was used. Sampling was done at 22.5 kHz. A photograph of the used test system is given in Figure 11.

Figure 11. Experimental unit, motor, and speed sensor photographs.

The motor was started via a star-delta transformation. The delta transformation lasted for 4 s. The speed sensor signals were sampled during the start-up of the motor under unloaded conditions.

Speed-time curves were obtained for each method. The curves are shown in Figure 12.

Because the speed sensor signal period is long, the measurement time is also long at low speeds (0-200 rpm). Thus, Method 1 gives bad results. Furthermore, the period length of the speed signal becomes smaller when the speed is increased. Therefore, the difference between the 2 sequential speed values (the quantization error) grows, as shown Figure 12.

Method 3 reduces the quantization error by using a large number of periods in the speed calculations. Therefore, the calculated speed values at high speeds get better, but the calculated speed values at low speeds get worse due to prolonged measuring time, as shown Figure 12.

Methods 2 and 4 give good results for all of the speed ranges. However, as shown in Figure 12, at the transient region, Method 2 does not represent the change of speed exactly. This situation can be reorganized using hopping, as in Method 4. Thus, the new speed-time curve in Figure 13 is obtained. Method 4 still gives better results than Method 2.

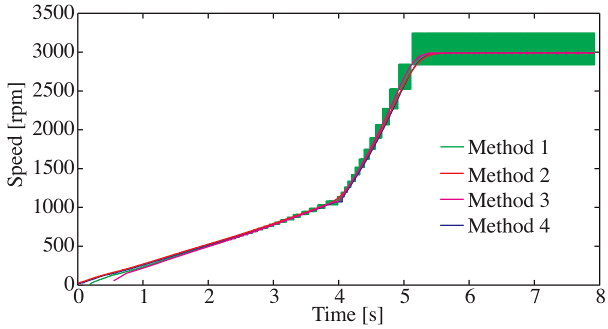

Figure 12. Experimental rotor speed-time curves for each of the used methods.

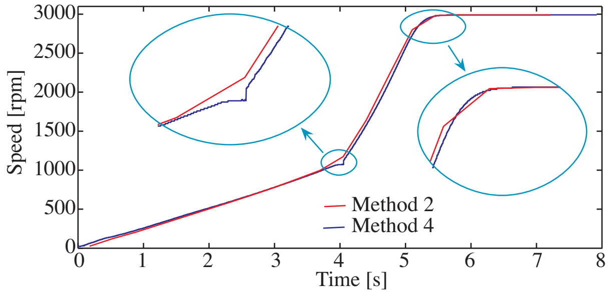

Figure 13. Comparison of the speed-time curves using Methods 2 and 4.

As the supply voltage of the motor is cut off during the star-delta transformation, the motor speed remains constant. This situation is clearly shown in the speed-time curve obtained by Method 4, as shown in Figure 14. Furthermore, the start and stop points of the prescribed time affect the calculated sequential speed values. If the start point of the hopping coincides with the initial part of the speed signal period at a high motor speed, the difference may occur at subsequent speed values. This difference depends on the number of sensor notches and the window length. In this study, 1 pulse corresponds to 2.8 rpm. Thus, fluctuation may occur in the speed curve at high speeds in Method 2. Such a situation does not occur in Method 4, as shown Figure 14.

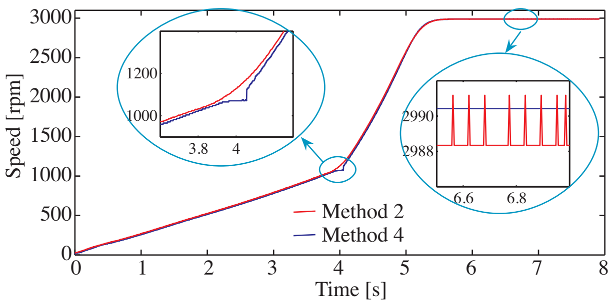

Figure 14. Comparison of the speed-time curves using Method 2 (with hopping) and Method 4.

5. Discussion

Steady-state investigation results show that both fluctuation and calculation errors are very high in Method 1. Thus, Method 1 is useless for the calculation of speed from square wave signals. In high speed ranges, the calculated speed values in Method 2 have minor fluctuations and calculation errors. On the contrary, at low speeds, minor fluctuations and calculation errors are shown for the speed values in Method 3. Therefore, Method 2 is suitable for high speed ranges and Method 3 is useful for low speed ranges. Nevertheless, because the calculation error in Method 3 is low at almost all of the speed ranges (maximum: 0.11%), this method can be used for steady-state conditions. However, a large number of samples and their average value should be used in the calculation of speed, as fluctuations are available in some speed ranges. Method 4 gives a low calculation error (maximum: 0.15%) for the middle and high speed ranges (500-2900 rpm) and a high calculation error (maximum: 1.7%) in the very low speed ranges (100-300 rpm). Furthermore, the fluctuation is 0 over the entire speed trange. Therefore, Method 4 can be used for all of the speed ranges for steady-state conditions.

Transient analysis results show that Method 1 gives good results in the low speed ranges. In the high speed ranges, the results are far from real values. However, this method gives good results for some of the high speed values. This shows that the sampling rate is very important in this method. Method 2 gives bad results in all of the speed ranges for transient changes. Method 3 gives good results in the high speed range. However, transient changes are far from real changes in the lower speed ranges. Method 4 gives good results in all of the speed ranges for transient changes. Furthermore, the stability is steady for the entire speed region. The results show that the most suitable method for transient speed calculations is Method 4.

The number of transactions is very low in the speed calculations for Methods 1, 2, and 3. Therefore, the calculation time is also low. Because the procedure in Method 4 has the FFT algorithm, the calculation time of the proposed method is prolonged. However, the average calculation time is about 2 ms when a 1.6-GHz, 32-bit computer is used. The calculation time is computed as 0.4 ms by another computer with a 2.27-GHz and 64-bit processor. Therefore, the 2-ms calculation time shows that motor speeds can be measured up to 30,000 rpm using the proposed method in online measurements. There is no speed limit in offline studies, due to there not being a time limitation.

The fluctuation and calculation errors are affected by many components that are used in the steps of the procedure in all of the mentioned methods. These components are sampling frequency, sampling length, window size, hop size, and the number of speed sensor notches. The values of the components change the calculation error, fluctuation, and computing time. Thus, the components should be selected to be optimal.

This study shows that the FFT can be used in the calculation of motor speed from square wave speed signals. In future studies, the error rates and computation times can be improved by adding new algorithms.

6. Conclusion

In this study, a new speed calculation method was presented from square wave speed signals using the FFT. The experimental study and simulations were done to investigate both transient speed changes and steady-state conditions. The proposed method showed that the motor speed is calculated with high accuracy in a wide range. The transient changes were clearly shown in the speed-time curve using the proposed method, as shown Figures 13 and 14. As a result, this study showed that the proposed method can be used both in steady-state and transient conditions to evaluate the motor speed for both offline and online studies. It gives much better results for transient conditions compared to the other methods.

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