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High-Precision Angle Measurement for Position Control in Industrial Drives Systems with Shaft Resolver

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Abstract: Resolver is a shaft angle sensor, which is mechanically connected to the motor shaft and operates according to the induction principle. A high frequency sinusoidal signal is applied to its input and produces two signals in the form of sine and cosine at its output. The output signals include the angle information of the motor shaft. Using these signals, the shaft angle of the motor is determined. In the study, a sinusoidal signal at the 5 kHz frequency was applied to an input resolver as the conventional method. After, the fact that applied to two PWM signals which has a duty ratio d=0.5 at 20 kHz and 100 kHz frequency is proposed as different from the conventional method. These PWM signals are the input signals of the resolver. Thus, complex equipment will not be needed to produce the high frequency sinusoidal signal. With only a simple amplifier circuit, a high frequency input signal will be produced. More sensitive angle information will be obtained with high frequency stimulation. A simulation study of conventional and proposed methods has been performed in MATLAB/Simscape environment. As a result of the simulation study, the information on the motor angle obtained from both methods was compared by using figures and details. By increasing the applied PWM signal from 20 kHz to 100 kHz, measurement errors related to shaft angle change were minimized and more precise position information was obtained.

Key words: Shaft resolver, position control, ındustrial drives, robotic.

Mil Resolver'li Endüstriyel Sürücü Sistemlerde Pozisyon Kontrolü İçin Yüksek Hassasiyetli Açı Ölçümü

Öz: Resolver motor miline mekanik olarak bağlanan ve indükleme prensibine göre çalışan mil açısı algılayıcısıdır. Girişine yüksek frekanslı sinusoidal sinyal uygulanır ve çıkışında sinus ve cosinus formunda iki adet sinyal üretir. Bu çıkış sinyalleri, motor milinin pozisyon bilgisini içerir. Bu sinyaller kullanılarak motorun mil açısının tespiti yapılır. Bu çalışmada resolver'in girişine önce geleneksel yöntem olarak 5 kHz frekansında bir sinusoidal sinyal uygulanmıştır. Daha sonra bu geleneksel yöntemden farklı olarak resolver'in davranışını analiz etmek amacı ile girişine 20 kHz ve 100 kHz frekansında d=0,5 görev periyoduna sahip iki ayrı PWM sinyalinin uygulanması önerilmiştir. Bu PWM sinyalleri resolveri'n giriş sinyallerini oluşturmaktadır. Böylece yüksek frekanslı sinusoidal sinyali üretmek için karmaşık donanıma ihtiyaç duyulmayacaktır. Sadece basit bir yükselteç devresi ile yüksek frekanslı giriş sinyali üretilmiş olacaktır. Yüksek frekanslı uyartım ile daha hassas açı bilgisi elde edilecektir. Geleneksel yöntem ile önerilen yönteme ilişkin benzetim çalışmaları MATLAB/Simscape ortamında gerçekleştirilmiştir. Benzetim çalışmaları sonucunda her iki yöntemden elde edilen motor açı bilgisi verilen grafikler yardımı ile detaylı olarak karşılaştırılmıştır. Uygulanan PWM sinyalinin 20 kHz 'den 100 kHz 'e yükseltilmesi ile birlikte mil açı değişimine ait ölçüm hataları minimize edilerek daha hassas konum bilgisi elde edilmiştir.

Anahtar kelimeler: Mil resolver, konum kontrolü, endüstriyel sürücüler, robotik.

1. Introduction

A stable measurement of speed and position is required in many industrial applications. Electric motors are used for position control in many industrial applications such as robotic systems, machine tools, telescopes, and radars [1]. Resolvers, on the other hand, are preferred for detecting the angular displacement of the motor shaft due to their high stability, mechanical durability, stable behavior in transient states, and lack of common mode noise [2, 3]. Resolvers are electrical machines with three windings that work based on Faraday's principle of electromagnetic induction and are mechanically connected to the motor shaft. The second and third windings are mechanically placed in the body at an angle of 90°. By applying a high-frequency sinusoidal signal to the first winding, signals varying depending on the shaft angle of the motor are obtained from the second and third windings. The signals obtained from the second and third windings are converted into sine and cosine signals by using modulation techniques. Using these obtained signals and with the help of mathematical operations, the determination of the shaft angle of the motor is easily made [4, 5]. To achieve this, many different Resolver-to-Digital (R/D) converter circuit applications have been performed in the literature. The main purpose of these R/D

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converters is to reduce the cost and error amount [6, 7]. Here, the input signal applied to the first winding of the resolver is generated by Digital Signal Processors (DSPs). The output signals of the Resolver are measured using the analog inputs of DSP. Thus, DSP, which is used for motor control applications, is also used for determining the shaft angle. As a result, the reduction of the total cost has been ensured. On the other hand, tables have been used for the purpose of realizing simpler software [8-10]. In recent years, quite a lot of studies have been conducted on the realization of R/D converters through software instead of being realized by circuit design [11-13]. In many other studies, nonlinear state observers, dq transformations, and modified angle tracking observers have been used to reduce the measured angle error [14-15]. With the help of FPGA, which has been widely used in motor control applications in recent years, resolver signals have been measured, and shaft angle has been obtained. Thus, it has been shown that high-level processors can be used to measure resolver signals [16-17]. Artificial Neural Networks (ANNs) used for speed estimation in motor control applications have been used to reduce noise in resolver signals and errors in signal measurement [18-19].

The fact that the excitation signal of the first winding, which is the input winding of the resolver, is in sinusoidal form and has high frequency makes it difficult to apply from the point of view of microprocessors. In addition, making an analog circuit makes it difficult to implement. To eliminate this problem, a square wave excitation signal was applied to the first winding of the resolver. Thus, the process was simplified considerably, and operation with low error amounts at high speeds was achieved by applying high frequency [20]. In a very recent study, a PCB-based axial intelligent resolver was developed. Square wave excitation is used in the resolver decoder. Thus, excitation at a frequency of 10 kHz is provided and motor control is also realized at the same time [21]. A trapezoidal excitation system derived from square wave excitation was developed to reduce measurement errors. Thus, output signals with lower harmonic content could be produced [22]. Considering the studies related to measuring the resolver signal with the help of DSP and determining the shaft angle, it is seen that additional circuits or filters are needed for the excitation of the first winding of the resolver. In this study, a Pulse-Width Modulation (PWM) signal with a duty period of d=0.5 was used as the resolver input signal. Thus, it is envisaged that the resolver operating with the logic of a transformer will act as a pulse transformer, and the shaft angle can be determined by regular sampling. With this method, it was aimed to generate the resolver input signal directly using hardware PWM blocks of DSP without using any additional signal circuit. The proposed method offers significant improvements in terms of software and hardware. The simulation study of the proposed method was carried out with MATLAB/Simscape blocks.

2. Material and Method

2.1. Resolver

Resolver is a motor shaft position-measuring sensor that is mechanically connected to the motor shaft and operates based on the principle of induction. The resolver is comprised of one first winding and two second windings placed with a 90° angle difference, as shown in Figure 1. A high-frequency sinusoidal voltage between 1 kHz and 10 kHz is applied to the first winding. Depending on the displacement of the motor shaft, sine and cosine signals are obtained from the second windings. These obtained signals include both the signal of the first winding and vary depending on the change of the shaft angle. From these signals, sine and cosine signals, from which the shaft angle will be calculated using different modulation techniques, are obtained. The expression of the first winding voltage and the second winding voltages of the resolver are given in Equations (1), (2), and (3).

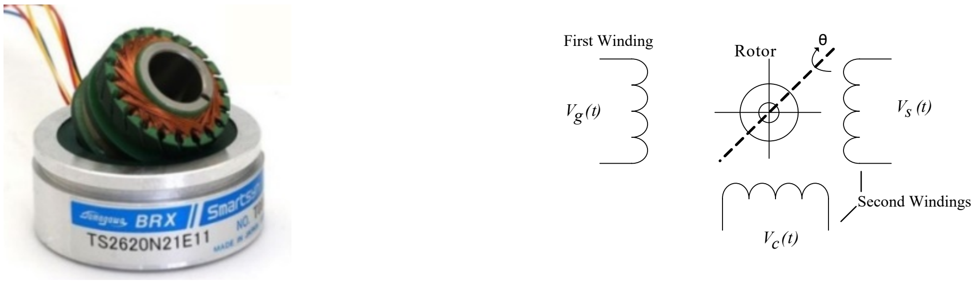

Figure 1. Mechanical and electrical structure of Resolver.

$$V_g(t) = V_m \times sin\,(\omega_e t) \quad (1)$$

$$V_s(t) = K_i \times V_m \times sin\,(\omega_e t) \times \sin(\theta) \quad (2)$$

$$V_c(t) = K_i \times V_m \times sin\,(\omega_e t) \times \cos{(\theta)} \tag{3}$$

where ω_e is the angular velocity of the input voltage and has a high frequency. K_i is the resolver constant, V_m is the maximum value of the first winding voltage, and θ is the shaft angle. The maximum values of the second winding voltages change depending on the input voltage in each period, and by sampling them in each period, sine and cosine signals, from which the motor angle will be calculated, are obtained. The waveforms of the resolver's first winding voltage and second winding voltages are seen in Figure 2.

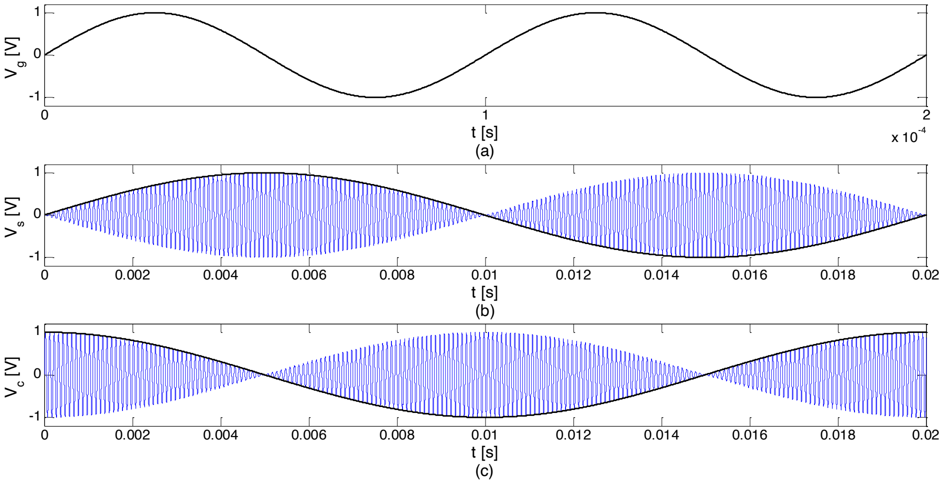

Figure 2. a) First winding voltage, b) Sinus voltage of first winding, c) Cosine voltage of second winding.

The motor shaft angle is calculated using these sine and cosine signals with the help of the equation given in Equation 4.

$$\theta = atan\,(\frac{V_s}{V_c}) \tag{4}$$

2.2. Applied Signals to the Resolver Input

In conventional methods, a sinusoidal voltage is applied to the resolver input as shown in Figure 3(a). An analog circuit design is being made to obtain this sinusoidal signal. This analog circuit design adds cost and difficulty to the system. In the newly developed methods, as shown in Figure 3(b), a bidirectional square wave signal with positive and negative amplitude is applied to the resolver input to increase the frequency of the resolver input signal and thus to perform angle measurement more effectively and with a lower error rate in high-speed applications. However, in this method, it is necessary to make an additional circuit design to produce the input signal. On the other hand, in the method proposed in this article, a unidirectional square wave signal with only positive amplitude obtained from the output of the PWM block of the DSP, as shown in Figure 3(c), was applied to the resolver input.

In this study, the positive part of the hysteresis curve is used because the input voltage is used in the range between + Vmax and 0 V. Since -Vmax is not used, the resolver has been thought of as a pulse transformer that triggers in a positive direction. In the secondary windings in pulse transformers, there will be short-term voltage changes on the rising edge and falling edge of the pulse on the primary side. The reason for these tensions is a short-term magnetic flux change. If it is in the steady state, the induced voltage will be zero. In this study, the maximum values of short-term voltage changes were sampled.

Microprocessors have been extensively used in recent years for processing resolver signals and obtaining angle information. However, high frequency sine input cannot be produced directly with a microprocessor. Additional circuits are needed here. With the proposed study, a +5V logic signal to be generated by the microprocessor can be applied to resolver with a simple amplifier. On the other hand, producing the sinusoidal input signal requires a complex and well-designed structure. As mentioned in the literature, if it is desired to generate a sinusoidal input signal with a microprocessor, this can be accomplished using high-grade filters and additional circuits.

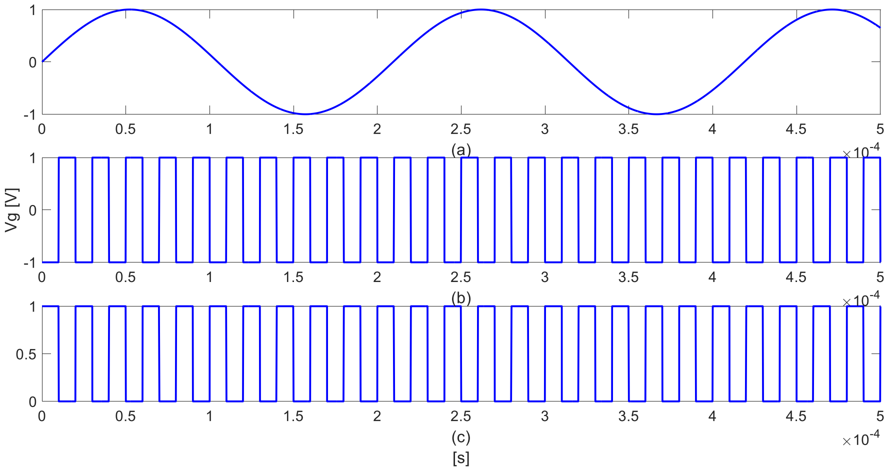

Figure 3. Different input signals to resolver a) Conventional method, b) Square wave, c) Proposed method.

In addition, delays caused by filters must also be compensated with software. High-frequency excitations are challenging situations for magnetic circuits. In the literature, there are experimental studies carried out at a frequency of 40 kHz. However, the developing material technology has brought about significant improvements in the technical properties of magnetic cores. With these developments, these levels of stimulation are now possible.

The expression of the input signal belonging to the conventional method is given in Equation 1. The frequency of the signal used in the proposed method and its transmission time are given in Equations (5) and (6).

$$f_s = \frac{1}{T_p} \tag{5}$$

$$T_{on} = dxT_p \tag{6}$$

f_s is the switching frequency, T_p is the period of the input signal, T_{on} is the duration of the transmission, and d is the duty cycle. Duty cycle (d) is calculated as in Equation 7 and varies between 0 and 1.

$$d = \frac{T_{on}}{T_{on} + T_{off}} \tag{7}$$

where T_{off} is the time passing during the off period. The duty cycle was taken as constant d=0.5 in this study. The use of a fixed duty cycle significantly reduces the operational load density required for the production of the PWM mark. Thus, higher frequency PWM signals can be obtained from the PWM outputs of the DSP. If the value of the duty cycle d is too small, voltage induction in the opposite direction occurs without the desired level of induction event occurring. To induce positive and negative voltages and to equal the slope going toward zero, d=0.5 was chosen.

Sampling of the voltage waveform obtained from the second side windings is performed on the rising and falling edges of the input signal. Depending on the amplitude and rate of change of the ∅ flux generated by the input voltage at these points, a voltage is induced in the secondary windings on the second side in accordance with Equation 8. This induced voltage is a short-term impulse voltage formed at the rising and falling edges of the primary winding voltage.

$$e = -N\frac{d\emptyset}{dt} \tag{8}$$

where N is the winding number, ∅ and is the magnetic flux. Since the sampling process is performed in a very short time, this voltage can be considered as a DC voltage. Instead of the input signals seen in Equations 2 and 3, the output voltages given in Equations 9 and 10, which can be sampled in a short time, can be written. Here, V_{m2} also includes the voltage component.

$$V_s(t) = K_i \times V_{m2} \times \sin(\theta) \tag{9}$$

$$V_c(t) = K_i \times V_{m2} \times \cos(\theta) \tag{10}$$

3. Results

In this study, the input and output signals of the resolver connected to the shaft of a DC motor were examined. For this purpose, a simulation study was carried out using MATLAB/Simscape blocks. In the simulation study, the sinusoidal input signal of the conventional method given in Figure 3(a) was applied to the resolver input first, and then the unidirectional square wave positive input signal of the proposed method given in Figure 3(c) was applied. The simulation model is given in Figure 4. The shaft angle information obtained for both cases was compared in detail. High sampling rate comparisons were made with fewer errors, especially in the high-speed region.

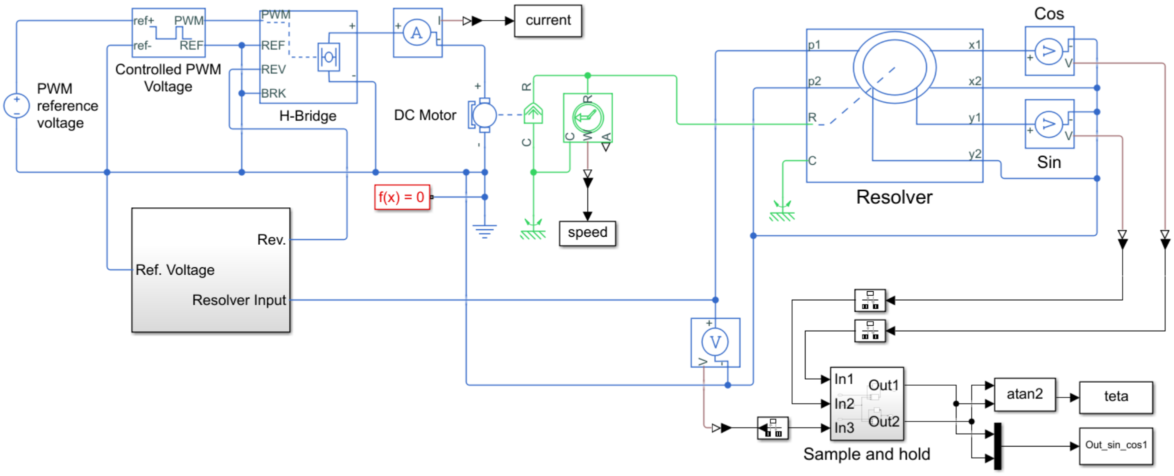

Figure 4. Simulation model consisting of DC motor, resolver, and drivers.

In this simulation study, a *TS2620N21E11* coded resolver belonging to Smartsyn company and a DC motor with the no-load operating speed of 10700 rpm were preferred. An H-bridge driver was used for the bidirectional operation of the motor. The sampling frequency of the simulation study was 1µs. The motor was operated at ±10700 rpm without load. The speed and current graphs of the motor are shown in Figure 5. While a sinusoidal voltage at a frequency of 5 kHz was applied as the resolver input signal in the conventional method, a PWM with a frequency of 20 kHz and a duty cycle of d=0.5 was applied first in the proposed method. While the sampling process is performed at the peak values of the sinusoidal signal in the conventional method, it was performed at each rising edge in the proposed method. Since the reading speeds of the analog inputs of DSPs are very high today, there will not be any problems during the reading process. The most important point in the proposed method is that the analog measurement to be made works synchronously with the rising edge of the input signal. The resolver output signals related to the conventional method in which a sinusoidal input voltage of 5 kHz is applied are shown in Figure 6(a), and the sampled resolver output signals at the maximum points of the input signals in sine form are shown in Figure 6(b).

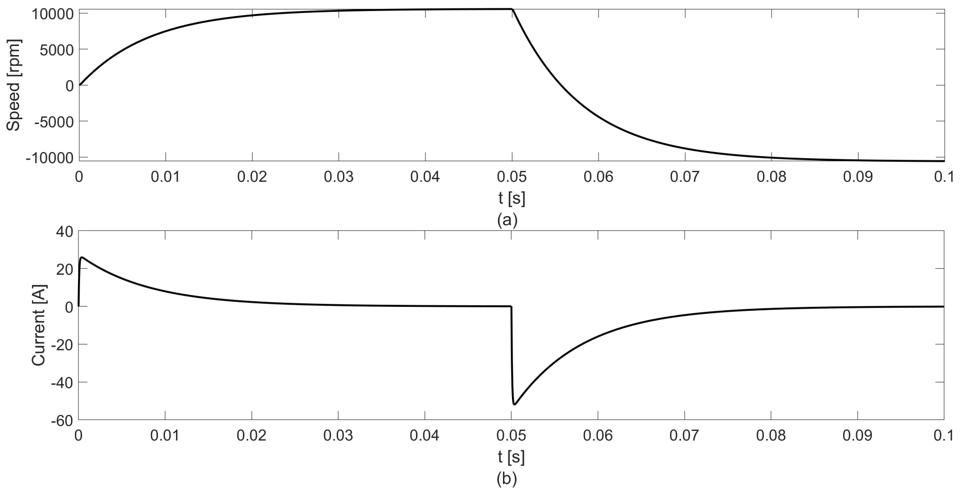

Figure 5. a) DC motor speed curve, b) DC motor current curve.

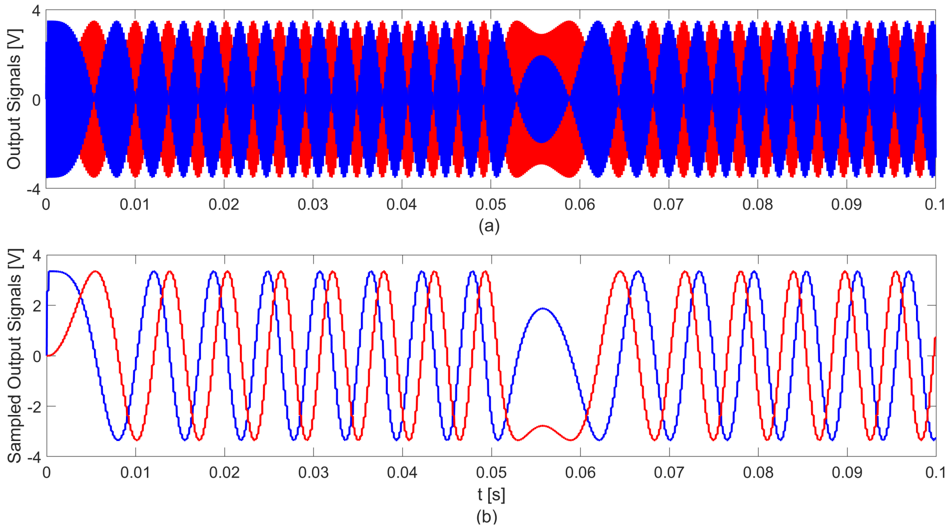

Figure 6. The Conventional Method - for 5 kHz a) Resolver output signals, b) Resolver output signals sampled at maximum points.

In Figure 7(a) and Figure 7(b), the variation of the output signals obtained by the conventional method and the output signals sampled at the maximum points of the input sine signal over a time interval of 0.02s to 0.024s is observed. The resolver output signals obtained by the 20 kHz input PWM signal related to the proposed method are seen in Figure 8(a), while the resolver output signals sampled on the rising edge of the input PWM wave are seen in Figure 8(b). In Figure 9(a) and Figure 9(b), the change in the time interval of 0.02s to 0.024s of the output signals obtained in Figure 8 is observed. In order to see the advantage of the proposed method, sampled sine and cosine signals can be compared using conventional and recommended methods. In addition, it is possible to increase the frequency of the PWM resolver input signal by hardware. Therefore, examining the resolver output signals at an input frequency of 100 kHz will be useful to better understand the advantage of the proposed method.

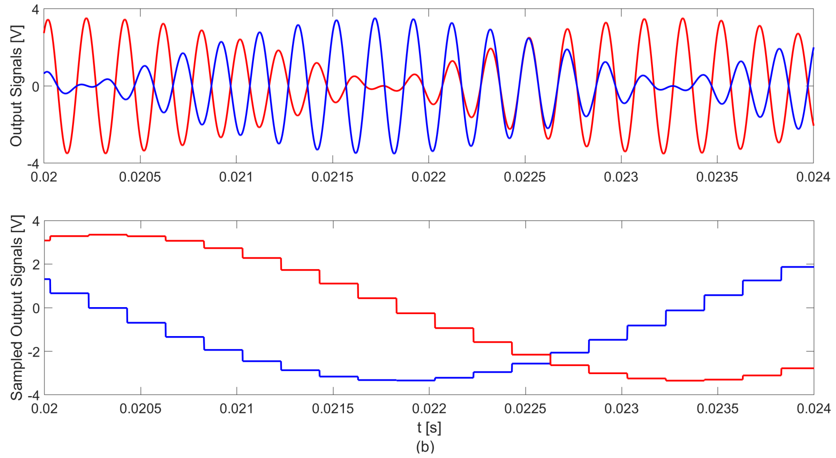

Figure 7. The Conventional Method - for 5 kHz (at an interval of 0.02-0.024 s) a) Resolver output signals, b) Resolver output signals sampled at maximum points.

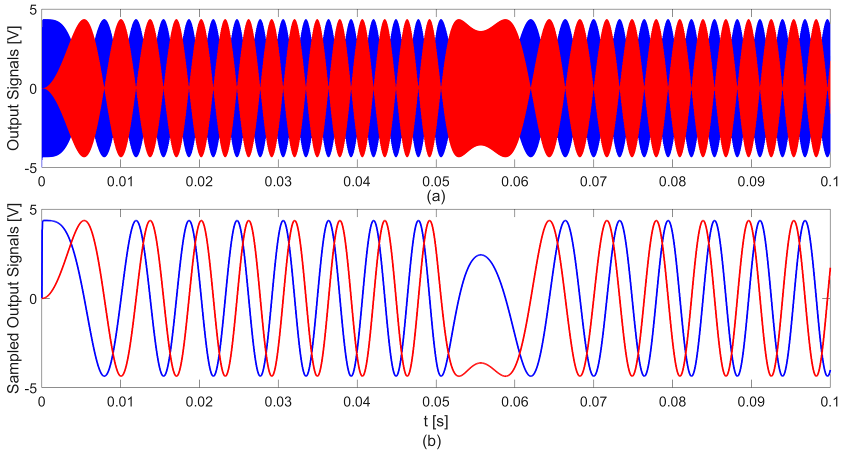

Figure 8. The Proposed Method - for 20 kHz a) Resolver output signals, b) Resolver output signals sampled on the PWM rising edge.

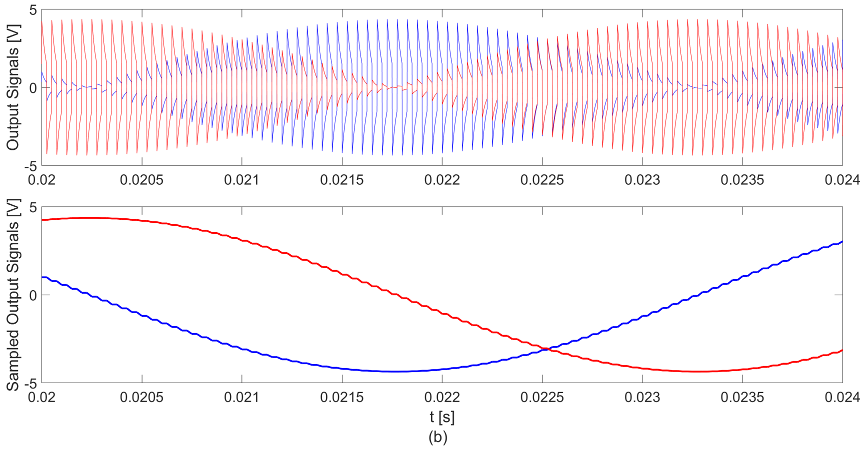

Figure 9. The Proposed Method - for 20 kHz (at an interval of 0.02-0.024 s) a) Resolver output signals, b) Resolver output signals sampled on the PWM rising edge.

Regarding the proposed method, the resolver output signals obtained by the 100 kHz input PWM signal are seen in Figure 10(a), while the resolver output signals sampled on the rising edge of the input PWM wave are seen in Figure 10(b). In Figure 11(a) and Figure 11(b), the change in the time interval of 0.02s to 0.024s of the output signals obtained in Figure 10 is shown.

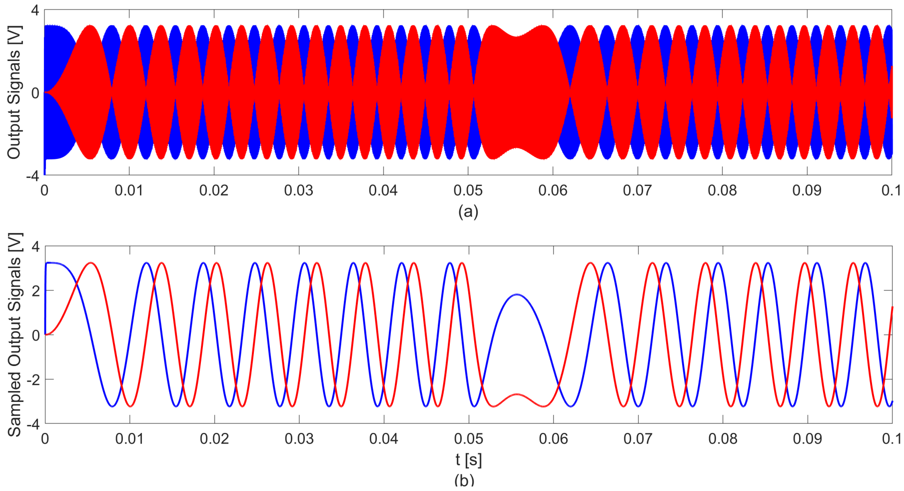

Figure 10. The Proposed Method - for 100 kHz a) Resolver output signals b) Resolver output signals sampled on the PWM rising edge.

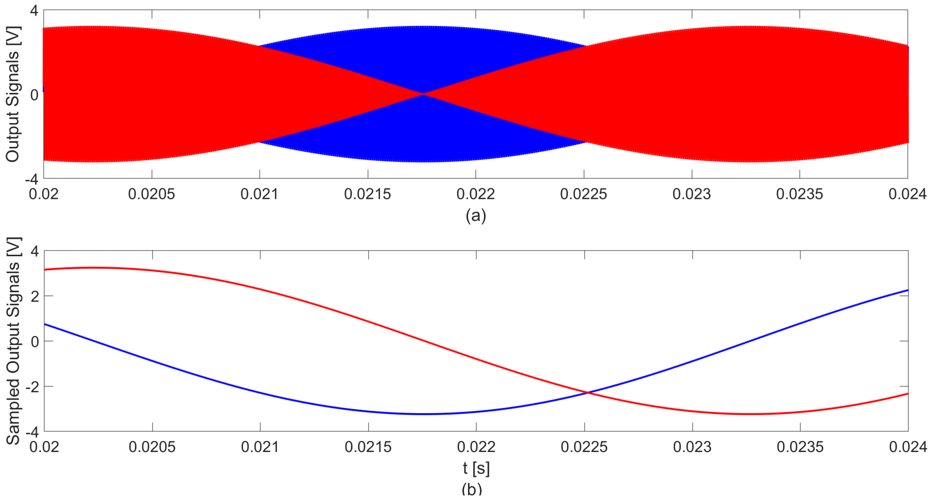

Figure 11. The Proposed Method - for 100 kHz (at an interval of 0.02-0.024 s) a) Resolver output signals, b) Resolver output signals sampled on the PWM rising edge.

The resolver shaft angle changes obtained from simulation studies carried out with 5 kHz, 20 kHz, and 100 kHz input signals are given comparatively in Figure 12. The shaft angle change was obtained by sampling the sine and cosine signals at the resolver output. As seen in Figure 12, the measurement error that may occur due to the shaft angle change obtained by the proposed method with an input signal of 100 kHz is the lowest. On the other hand, the measurement error that may occur due to the shaft angle change obtained by the traditional method with a 5 kHz input signal is higher because the sampling time is low. The proposed method performs the motor control based on software while, at the same time, it generates the resolver input signal and measures the output signal.

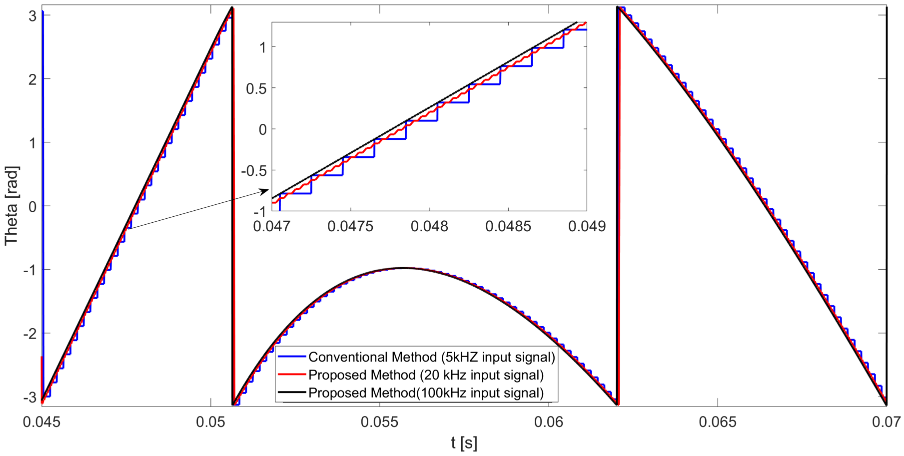

Figure 12. Resolver shaft angle changes obtained from simulation studies carried out with resolver input signals of 5 kHz, 20 kHz, and 100 kHz.

Generating a sinusoidal excitation signal is both a costly process and has difficulties in application. For this reason, square wave excitation based resolver decoders have been developed in recent years. Thus, excitation signals can be generated more easily at higher frequencies. H bridge circuits are used to provide this excitation. In this study, resolver excitation was performed with the microcontroller PWM output using only one power switch. Thus, both the cost was reduced and high frequency excitation was provided. A microcontroller will be able to generate angle information from resolver signals and also perform motor control at the same time. Almost exactly linear angle information was obtained at an excitation frequency of 100 kHz. This precise angle measurement information is very important, especially in high speed applications. Thus, it will be easier to create systems that operate with lower errors, especially in industrial robotic applications.

4. Discussion

High-level processors are used in motor control applications. The measurement and use of Resolver signals for control purposes can also be performed with these processors. Thus, as the software of the resolver application becomes simple, it will also pave the way for its use on the same processor. More precise motor control can be performed using the high-accuracy shaft position information obtained by the proposed method. Both the conventional and the proposed methods require filtering against noise for more precise control. However, since software-based measurement is preferred instead of analog card design in the proposed method, digital filtering techniques can be used instead of analog filtering.

5. Conclusion

Resolver is used to measure the shaft angle of electric motors for making position control in industrial applications. Resolver directly changes the waveform of the input signals and the frequency of the output signals. In this study, a sinusoidal input voltage with a frequency of 5 kHz was used in the conventional method. In the proposed method, on the other hand, a unidirectional PWM input signal with a duty cycle of d=0.5 and a positive amplitude at frequencies of 20 kHz and 100 kHz was used. Generating high-frequency sinusoidal input signals in the conventional method is both difficult and poses some problems in terms of card and system design. In order to eliminate these problems, both a high-frequency input signal was obtained using the proposed method and a high-accuracy measurement process was performed by sampling only without making an analog card design. As a result, with this study, two significant advantages have been obtained reducing the cost of the system and measurement errors. It is estimated that higher performance can be achieved by obtaining a high-accuracy shaft angle in control systems where position and position control are performed using the proposed method. In the continuation of this study, the advantages of the proposed method will be shown experimentally by performing the position control on a real system.

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