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Digital Sensors and Sensor Systems: Practical Design

Sergey Y. Yurish



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High Accuracy Resolver to Digital Converter Based on Modified Angle Tracking Observer Method

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Abstract: A resolver is a rotary transformer where the magnitude of the energy through the resolver windings varies sinusoidally as the shaft rotates. These are unsurpassed in its ability to reliably supply rotary angular position data in the harsh industrial environments. This paper presents the design of software based resolver to digital converter based on modified angle tracking observer method to estimated the rotor shaft angle. The proposed resolver to digital converter has been successfully implemented in MATLAB® Simulink and the results are verified by simulation for different rotor speeds. This method brings down the hardware cost and increases the accuracy and reliability. *Copyright © 2012 IFSA.*

Keywords: Resolver, resolver to digital converter, angle tracking observer, synchronous demodulator

1. Introduction

The measurement of rotor shaft angle is one of the important requirements in the modern control system, instrumentation and computing technologies. Every machine, process and monitoring system has a rotating shaft in its mechanism. The techniques of the mechanisms for converting shaft rotation to linear motion extend the usefulness of shaft angle sensing. Over the years, many different forms of shaft angle transducers have been developed.

On the basis of their physical design, these angular transducers can be classified into two main groups: optical and inductive. The built in semiconductors in optical transducers are used to amplify and to

format the digital output signals. Whereas these semiconductors are sensitive to temperature and the LED light sources commonly employed are susceptible to aging. Inductive transducers such as synchro and resolvers are intrinsically absolute and require no semiconductors on the transducer itself and the raw output signal can be transmitted over distances of more than 100 meters. In addition, since they consist primarily of copper and steel, resolvers are virtually insensitive to temperature over a wide range. Because of no sensitive electronics or optics are employed, resolvers are often supplied in an unhoused or pancake configuration and can be mounted directly to the shaft whose position is to be measured. Cost and length savings are realized by the user since no shaft−to−shaft coupling or extra bearings are required. Synchros have three stator coils in a 120^0 orientation. They are more difficult than resolvers to manufacture and are more costly. Today, synchros find decreasing use, except in certain military and avionic retrofit applications.

The resolver output analog signals have to be converted to estimate the rotor angular position. The resolver to digital converter (RDC) is used to convert the resolver output signals into angular position data. RDC performs two basic functions: demodulation of the resolver signals to remove the carrier, and angle determination to provide a digital representation of the rotor angle. All RDC techniques use the two analog signals to produce a digital output. The differences between the various converter methods is in the resolution available, the speed at which the shaft can be rotated and still maintain the designed resolution and the sensitivity of the system to the unwanted distortion of the resolver signals [1]. The main drawback of RDC is its cost, which is about the same price as that of the resolver [2] and [3].

Recently, researchers have paid attention on RDCs with soft computing techniques to improve the linearity, resolution and accuracy of the rotor shaft angle of the resolvers. Several simple and cost effective methods are proposed in the literature to convert the resolver signals into digital data and to avoid the use of RDCs.

An angle tracking based RDC with bang-bang type phase comparator is proposed for fast tracking [4] to solve the problem in PLL based technique. This method suffers from tracking errors at high speeds and out of lock conditions of the PLL, amplitude demodulators and carrier oscillators. A simple hybrid structure board for RDC that contains a clock unit, two analog to digital converters (ADCs), two signal conditioning circuits and an electrically programmable read only memory (EPROM) proposed in [3] and [5]. However, the proposed method is a low cost but requires hardware and is an open loop method. In [6], the calculated angular position of a resolver is obtained by a closed loop operation. This method may not be practical when the low cost fixed point digital controller is used. A resolver-to-360^0 linearized converter method that doesn't need a processor is proposed in [7]. This method does not provide the advantage on hardware like oscillators, amplitude demodulators and consequently weight, size and cost.

A high precision, hybrid electronic structure for RDC is developed in [8]. The instantaneous rotor shaft angle is determined by using a linearization technique. In addition, a separated waveform generator is required. In [9] and [10], an open loop angle estimation method was introduced and is based on the comparison between the excitation signal and output signals of the resolver. However, a separate signal generator is required to generate signals for resolver excitation and demodulation. Based on the principle of synchronous demodulation of the resolver output signals, a software-based RDC algorithm is presented in [11]. In this method, a lookup table is used with arctangent function to estimate the angular rotor shaft position. This method increases the software load on the control processor. However, the usage of a waveform generator is avoided and economized the related cost. The drawbacks of this method are that it is limited to low-speed applications and the sampled angular position envelopes are very sensitive to noise. A linearized tangent/cotangent converter using analog circuitry is implemented in [12]. The tangent/cotangent method is an open loop method that may not provide high angle accuracy. To make the sampled angular position envelopes insensitive to noise, an

improved of version of [11] is proposed in [13]. The demodulation method of output signals and design aspects of RDC have not been discussed.

Software based RDC allows saving on costly oscillator required for excitation of rotor and hardware efficient demodulation of the resolver output, even in the presence of wide variations in the resolver carrier. This software based approach does not cause any time delay and the dynamics of the system using this method is not affected. Based on the above literature, it is concluded that it is essential to implement a high accuracy software based RDC to measure the rotor angle and speed of a resolver.

In this paper, an RDC algorithm based on modified angle tracking observer method (ATO) is presented. This algorithm is simple and can be incorporated in an advanced motor control drive system. The cost of the RDC is reduced by exciting the resolver with a square wave signal that can be generated by any microprocessor. The proposed algorithm attempts to minimize the error between actual rotor angle and estimated rotor angle using a feedback loop.

The paper is organized into five sections. Section 2 describes the basic principle of a resolver. This is followed by the design procedure of the proposed RDC in section 3. Simulation, results and discussions are presented in section 4 and 5 respectively. Finally conclusions are drawn in section 6.

2. Basic Principle of a Resolver

A resolver is a position sensor or transducer which measures the instantaneous angular position of the rotating shaft to which it is attached. The resolvers are derived from the fact that they operate by resolving the mechanical angle of their rotor into its orthogonal or Cartesian components [14]. The frequency response of resolver is shown in Fig. 1 and is similar to that of a transformer with a high leakage reactance. Corner and peak frequencies depend on the impedance of the individual sensor. Most resolvers are specified to work over 2 V to 40 V rms and at frequencies from 400 Hz to 10 kHz. Angular accuracies range from 5 arc-minutes to 0.5 arc-minutes.

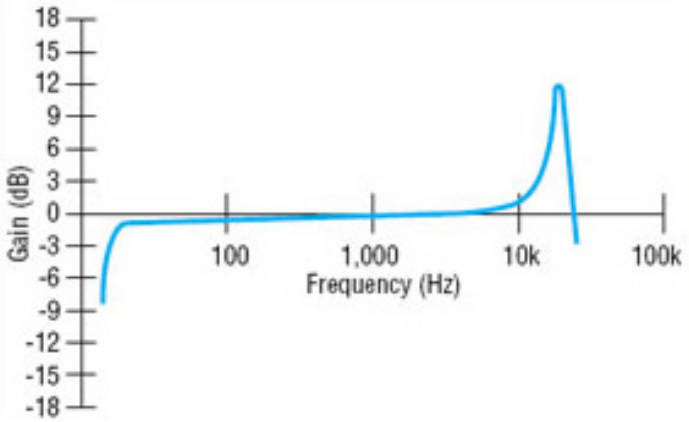


Fig. 1. Frequency response of a resolver.

Fundamental transformer theory is the basis of resolver design. The placement of the reference and output windings with respect to the shaft of a resolver is shown in Fig. 2. In a resolver, the iron core for the primary and secondary are two multi toothed lamination stacks, one being stationary (stator) and one which rotates (rotor). The output voltage is affected by change in the position of the secondary winding relative to the primary winding.

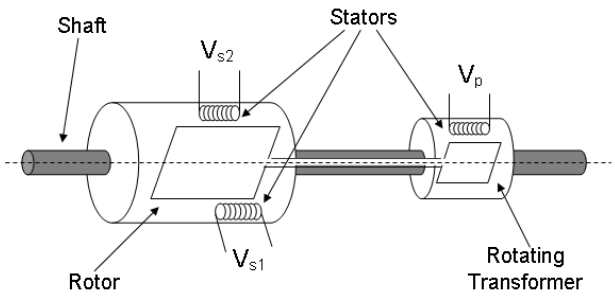


Fig. 2. Internal view of a resolver.

As the rotor turns, the amplitude of the secondary voltage changes by modulating the input carrier. Secondary windings are always placed with their axes at right angles. This establishes two separate outputs having a sine and cosine relationship. An equivalent cross sectional view of the resolver with angular position of the rotor, θ, with respect to the windings and the associated signals are shown in Fig. 3 and Fig. 4 respectively.

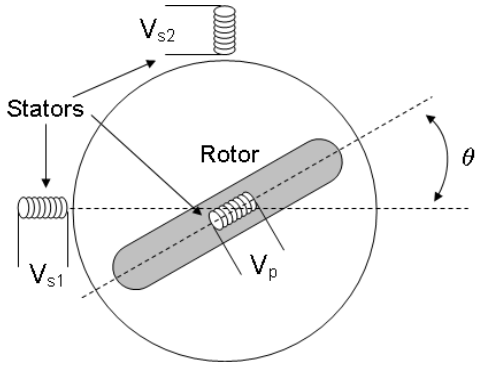


Fig. 3. Equivalent cross sectional view.

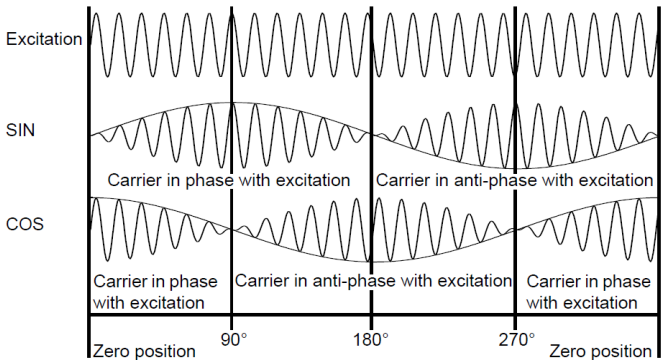


Fig. 4. Resolver excitation and output signals.

The winding of the rotor is supplied with a high-frequency sinusoidal carrier signal:

$$V_p = A \cdot Sin(w_c t), \tag{1}$$

where A is the peak amplitude and $w_c = 2\pi f_c$, where f_c is the frequency. The resolver operates as a rotary transformer with two outputs. The angular velocity $\frac{d\theta}{dt}$ of the rotor is much lower than w_c, the two stator windings of the resolver modulated signals are given by

$$\left.\begin{aligned} V_{s1} &= \alpha\, A\, Sin(w_c t)\, Sin(\theta) \\ V_{s2} &= \alpha\, A\, Sin(w_c t)\, Cos(\theta) \end{aligned}\right\}, \tag{2}$$

where θ is the angular position of the shaft of the resolver and α is the transformation ratio constant between rotor and stator windings. These two output signals V_{s1} and V_{s2} are called as quadrature signals. By simple demodulation of the stator signals in (2), the excitation signal may be removed, resulting in sine and cosine signals. The demodulation and amplification of (2) results in normalized signals:

$$\left.\begin{aligned} V_S &= Sin(\theta) \\ V_C &= Cos(\theta) \end{aligned}\right\} \tag{3}$$

The rotor angle, θ can be extracted from (3) using a suitable RDC. The RDC uses the excitation signal and both output signals of resolver to determine the rotor shaft position. The RDC is based on ATO method in which an estimated angle tracks the real angle of the rotor. This RDC also gives the speed information of the rotor.

3. Proposed Method

3.1. Generalized Angle Tracking Observer (ATO) Method

The block diagram of generalized ATO based RDC is shown in Fig. 5. The two outputs of the resolver are applied to cosine and sine multipliers. These multipliers incorporate sine and cosine lookup tables and function as multiplying digital to analog converters. Assume that the current state of the up/down counter is a digital number representing a trial angle, ϕ. The converter seeks to adjust the digital angle, ϕ, continuously to become equal to and to track θ, the analog angle being measured.

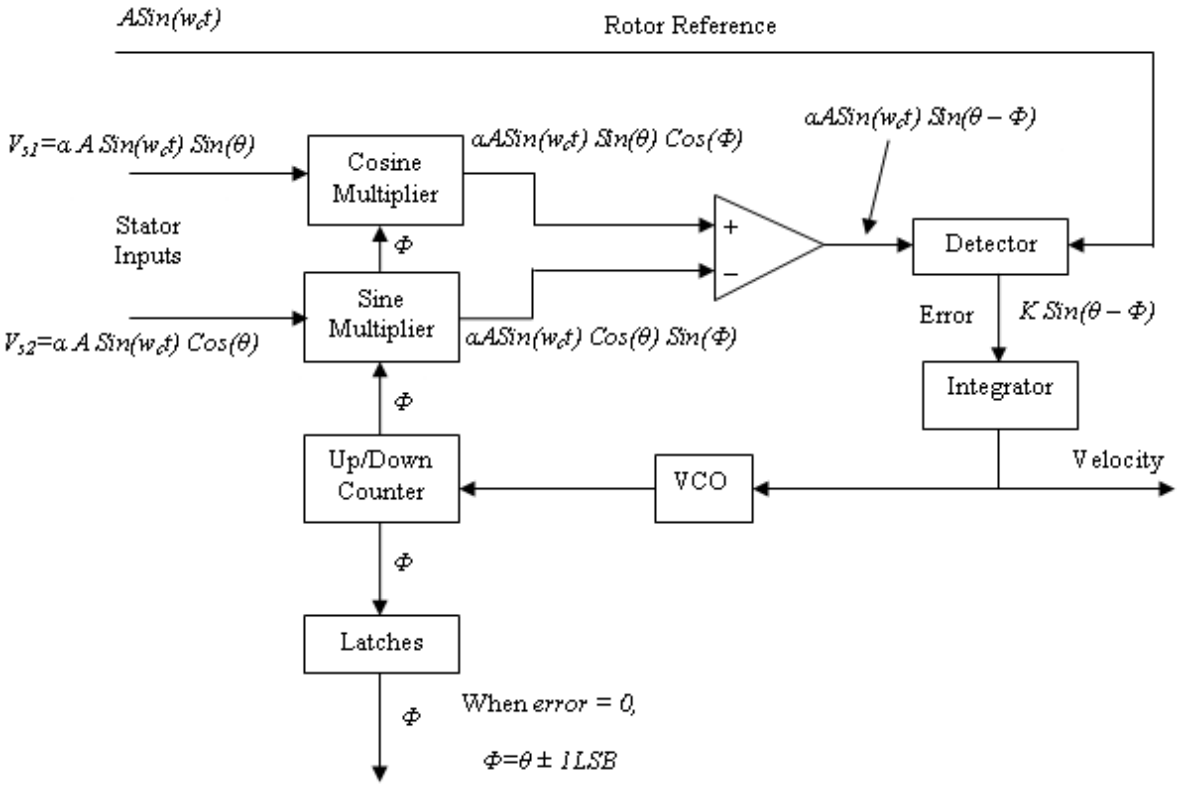


Fig. 5. Generalized angle tracking observer based resolver to digital converter.

$$\alpha A Sin(w_c t) Sin(\theta) Cos(\phi) \tag{4}$$

The digital angle ϕ is also applied to the sine multiplier and multiplied by V_{s2} to produce the term:

$$\alpha A Sin(w_c t) Cos(\theta) Sin(\phi) \tag{5}$$

These two signals in (4) and (5) are subtracted from each other by the error amplifier to yield an AC error signal of the form:

$$\alpha A Sin(w_c t)\left[Sin(\theta)Cos(\phi) - Cos(\theta)Sin(\phi)\right] \tag{6}$$

Using a simple trigonometric identity, this reduces to:

$$\alpha A Sin(w_c t)\left[Sin(\theta - \phi)\right] \tag{7}$$

The detector synchronously demodulates this AC error signal, using the resolver's rotor voltage as a reference. This results in a DC error signal proportional to $Sin(\theta - \phi)$. The dc error signal feeds an integrator, the output of which drives a Voltage Controlled Oscillator (VCO). The VCO, in turn, causes the up/down counter to count in the proper direction to cause:

$$Sin(\theta - \phi) \to 0 \tag{8}$$

And using the Taylor approximation around zero

$$Sin(\theta - \phi) \approx (\theta - \phi) \quad for \left|\theta - \phi\right| << 1 \tag{9}$$

When this is achieved,

$$(\theta - \phi) \to 0 \tag{10}$$

and therefore

$$\theta = \phi \tag{11}$$

to within one count. Hence, the counter's digital output, ϕ, represents the angle θ. The latches enable this data to be transferred externally without interrupting the loop's tracking.

In this ATO method, the estimated angle was accepted as a real angle and this can be accepted at low speeds only. Whereas at high speeds, the value of $(\theta - \phi)$ is dependent on the rotor speed. In order to remove this error at high speeds, a new modification is proposed in the generalized ATO method.

3.2. Implementation of Modified ATO based RDC

The basic idea of the proposed RDC is to trigger the two samples and hold circuits to demodulate the resolver output signals. The excitation of rotor is a square wave signal with a frequency of 5kHz, which is high enough for high speed applications. The triggering must be in synchronous with the excitation signal. The sampling and conversion is performed when the raising edge of the excitation signal. This is a synchronous demodulation method requires the sampling frequency to be perfectly synchronized with the input signal. For perfect synchronization, it is proposed to use the same square wave signal source for resolver excitation and to trigger the two samples and hold circuits. By using this technique the cost of the oscillator circuit is saved.

The proposed modified RDC block diagram is shown in Fig. 6. After sampling the resolver output signals, the available demodulated signals are

$$\left.\begin{aligned} V_{sn} &= \frac{\alpha A}{2} Sin(\theta_n) \\ V_{cn} &= \frac{\alpha A}{2} Cos(\theta_n) \end{aligned}\right\} \tag{12}$$

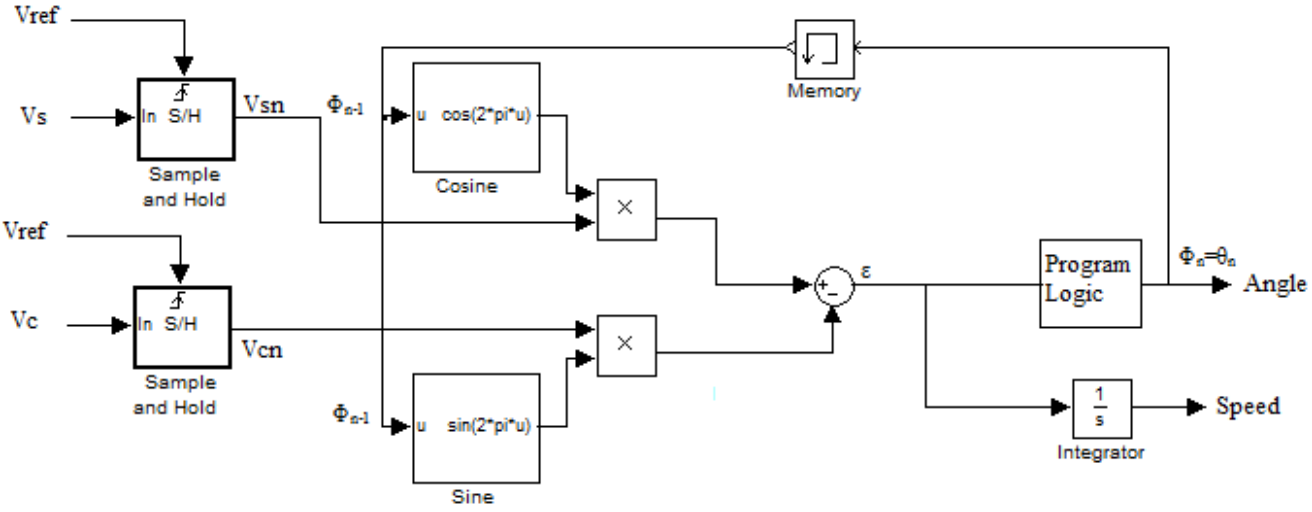


Fig. 6. Block diagram of the Proposed modified RDC.

For an observer, it is very critical to have an appropriate initial estimated value, Φ. As the values of $Sin(\theta_n)$ and $Cos(\theta_n)$ are available after the first sampling, the rotor angle can be estimated based on the quadrant of the rotor angle at the initial stage. For the first cycle $(0, 2\pi)$, the values of $Sin(\theta_n)$ are less than $Cos(\theta_n)$ in the interval $\left(0, \frac{\pi}{4}\right)$ and $\left(\frac{5\pi}{4}, 2\pi\right)$ thus the initial estimation of the rotor angle for these intervals is taken as the mean of two angles and it is equal to $\frac{\pi}{8}$ and $\frac{13\pi}{8}$ respectively. Similarly the values of $Sin(\theta_n)$ are greater than $Cos(\theta_n)$ in the interval $\left(\frac{\pi}{4}, \frac{5\pi}{4}\right)$ and the initial estimation of the rotor angle for this interval is taken as the $\frac{3\pi}{4}$. This initial estimated angle at time, t=0 second is taken out from a conditional statement and is implemented in MATLAB® Simulink. For other than t=0 second, the estimated angle is equal to the output of the proposed system. By using this algorithm the maximum possible angle error at the initial time t=0second is equal to or less than $\frac{\pi}{8} = 22.5^0$.

The initial estimated value of the rotor position, ϕ_{n-1} is given as input to the sine and cosine multipliers. Any error, ε between the estimated values and next sampled values of $Sin(\theta_n)$ and $Cos(\theta_n)$ results in nonzero value in the following equation:

$$\frac{\alpha A}{2}\left[Sin(\theta_n)Cos(\phi_{n-1}) - Cos(\theta_n)Sin(\phi_{n-1})\right] = \frac{\alpha A}{2} Sin\left(\theta_n - \phi_{n-1}\right) = \varepsilon_{n-1} \tag{13}$$

The equation (13) provides good approximation for small values of $(\theta_n - \phi_{n-1}) = \varepsilon_{n-1}$. The estimated value of the angle Φ_{n-1} has been modified to decrease the error ε_{n-1}. The modified Φ_n value is given as:

$$\phi_n = \phi_{n-1} + K\varepsilon_{n-1}, \tag{14}$$

where K is the gain factor. The value of K is important for stability of ATO to force the error to converge to zero and it is calculated as

$$K = \left(\frac{\pi}{8}\right) \Big/ Sin\left(\frac{\pi}{8}\right) = 1.02617 \tag{15}$$

To have a good convergence of the estimated value of the rotor angle, the value of K is assigned in the range (1, 1.026). In the proposed RDC, the value of K is taken as 1.01.

This angle tracking observer functions as an integrator and provides a robust noise insensitive system because of its inherent filtering behavior.

4. Simulation

The proposed system is crated in MATLAB® Simulink blocks. The main blocks in the model of modified ATO based RDC are synchronous demodulator, sample and hold circuit and angle tracking program logic. MATLAB® Simulink model of modified ATO based RDC is shown in Fig. 7. The excitation signal generator feeds the high frequency square wave signal to the resolver. When the rotor of the resolver is rotated, the resolver induces two amplitude modulated output signals, as in (2). These amplitude modulated signals need to be demodulated using synchronous demodulator to obtain the rotor shaft angle position. The block diagram of synchronous demodulator system is shown in Fig. 8.

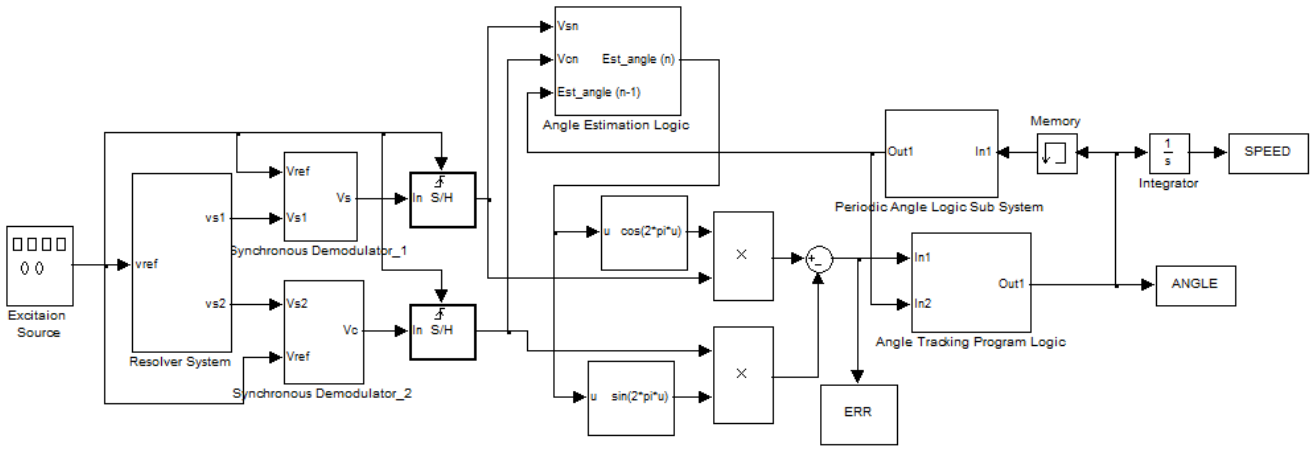


Fig. 7. MATLAB® Simulink model of modified ATO based RDC.

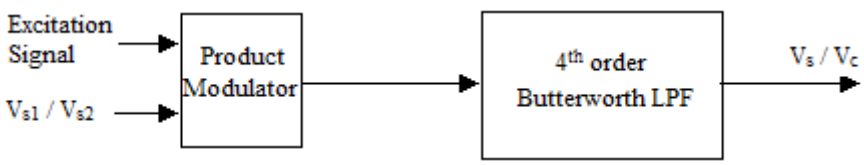


Fig. 8. Block diagram of synchronous demodulator.

5. Results and Discussions

The proposed RDC and its angle tracking algorithm are validated through several tests with different speeds. The frequency of excitation square signal is taken as 5kHz and is applied to the resolver. In Fig. 9, the square wave signal and resolve two output signals for a rotor speed of 1200 rpm are presented. The output signals of the resolver are amplitude modulated with the square wave. In Fig. 10 and 11, the demodulated signals of the output of the resolver using synchronous demodulator are presented. The same square wave signal is used to synchronize the resolver and demodulator. The square wave signal of frequency 5 kHz is eliminated perfectly from the output signals of the resolver.

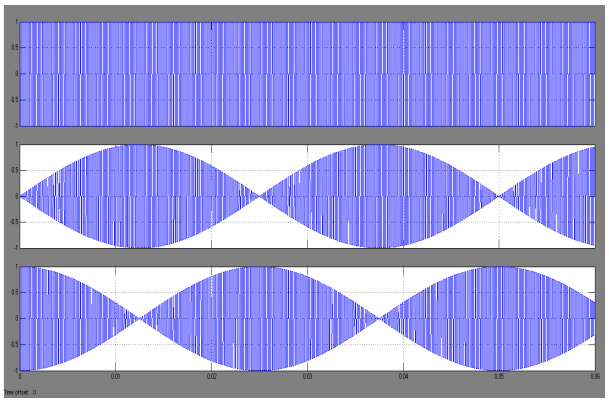


Fig. 9. Excitation and resolver output signals.

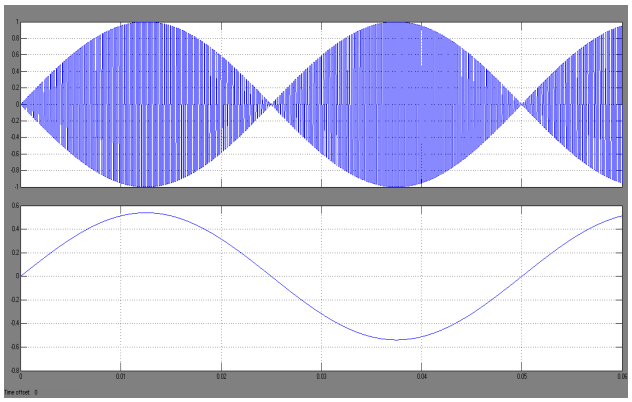


Fig. 10. Resolver sine output and its demodulated signal.

The rotor angle is extracted from the demodulated signals based on the software algorithm. Fig. 12 shows the V_s, V_c and the estimated angle for a rotor speed of 1200 rpm. As per the results shown in Fig. 12, the maximum estimated angle error of the proposed RDC is 0.0136 for a rotor speed of 1200 RPM. The Plots of excitation signal, resolver output signals; V_s, V_c, estimated angle; estimated angle estimated angle and angle error, and actual angle and measured angle are obtained with the help of MATLAB® Simulink and are shown in Fig. 13, 14, 15 and 16 respectively for the rotor speed of 3000 rpm.

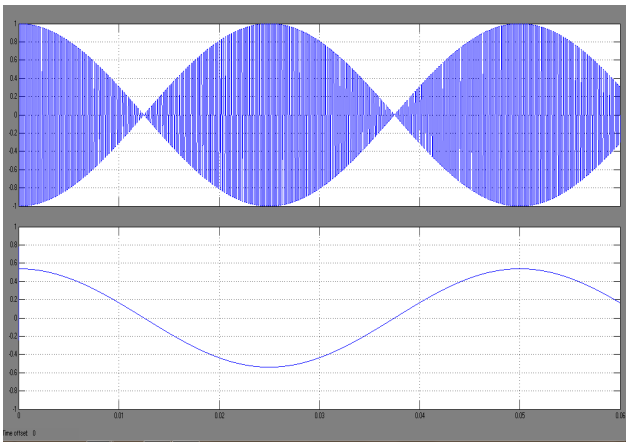


Fig. 11. Resolver output and its demodulated signal.

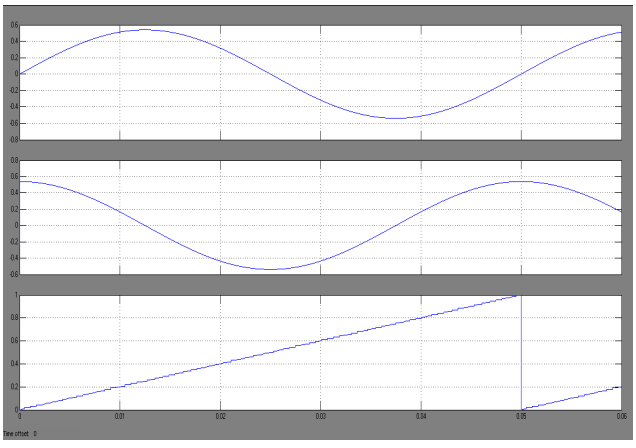


Fig. 12. V_s, V_c and estimated angle.

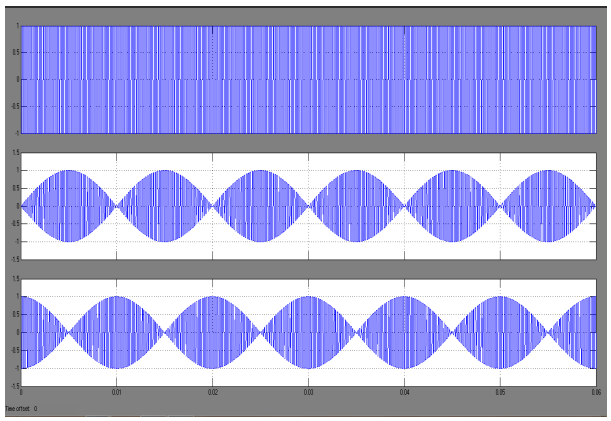


Fig. 13. Excitation and resolver output signals.

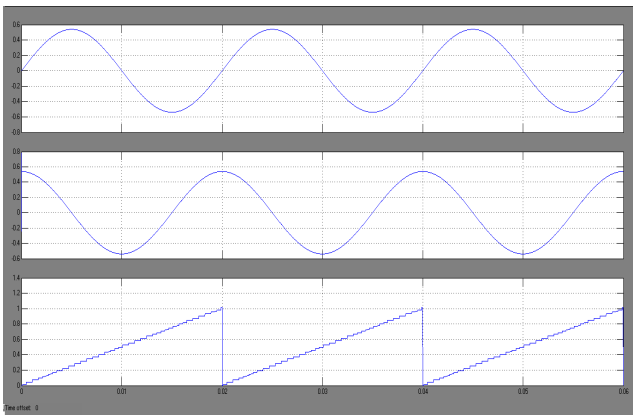


Fig. 14. V_s, V_c and estimated angle.

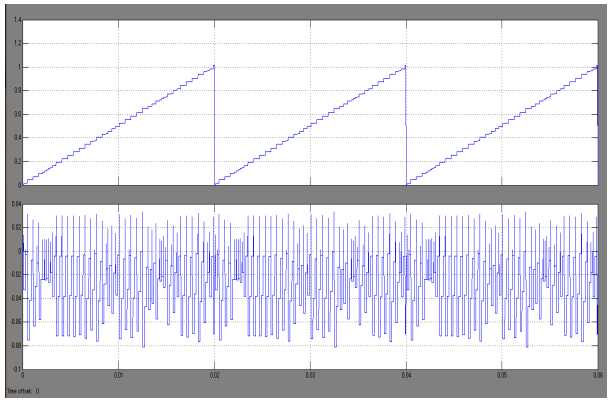


Fig. 15. Estimated angle and error.

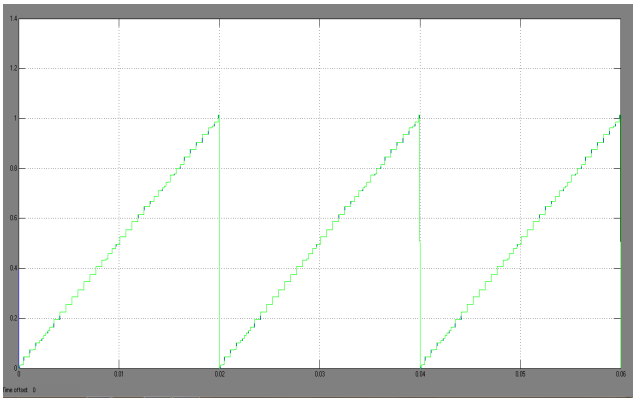


Fig. 16. True and estimated angles.
(blue color is true angle and green is estimated angle)

The estimation error has been obtained for different speeds and the results are presented in Table 1. For speeds less than 600 rpm the proposed method gives a negligible error and as the speed of the rotor is increased the error will increase by a factor of 0.003^0. The graph between the rotor speed and estimated error is shown in Fig. 17.

Table 1. Estimated error for different speeds.

Rotor Speed (rpm)	Estimated error (degrees)
120	0.0017
240	0.0030
300	0.0038
600	0.0071
900	0.0104
1200	0.0136
1500	0.0172
2400	0.0272
3000	0.0335

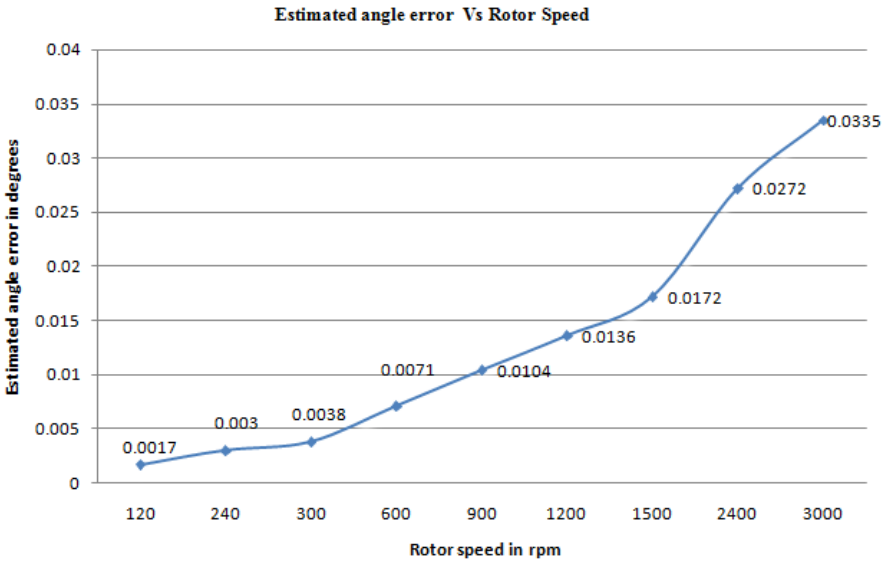


Fig. 17. Graph between estimated angle error and rotor speed.

6. Conclusions

Through mathematical performances analysis, it is showed that all the proposed blocks computed the estimated angle with negligible error through simulation implementation. The proposed modified ATO based RDC has been successfully implemented in MATLAB® Simulink. This method brings down the hardware cost and increases the accuracy and reliability. According to simulation results, the angle tracking program algorithm tracks the angle and force the error to zero. Thus the estimated angle eventually matches with the true rotor angle.

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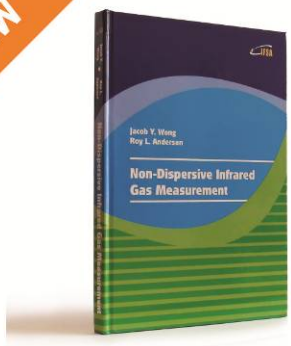
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Non-Dispersive Infrared Gas Measurement

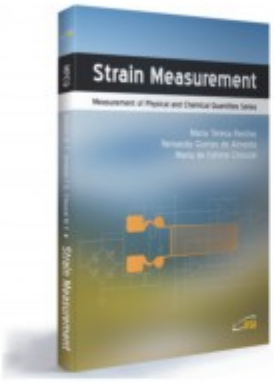
Written by experts in the field, the *Non-Dispersive Infrared Gas Measurement* begins with a brief survey of various gas measurement techniques and continues with fundamental aspects and cutting-edge progress in NDIR gas sensors in their historical development.

- It addresses various fields, including:
- Interactive and non-interactive gas sensors
- Non-dispersive infrared gas sensors' components
- Single- and Double beam designs
- Historical background and today's of NDIR gas measurements

Providing sufficient background information and details, the book Non-Dispersive Infrared Gas Measurement is an excellent resource for advanced level undergraduate and graduate students as well as researchers, instrumentation engineers, applied physicists, chemists, material scientists in gas, chemical, biological, and medical sensors to have a comprehensive understanding of the development of non-dispersive infrared gas sensors and the trends for the future investigation.

http://sensorsportal.com/HTML/BOOKSTORE/NDIR_Gas_Measurement.htm

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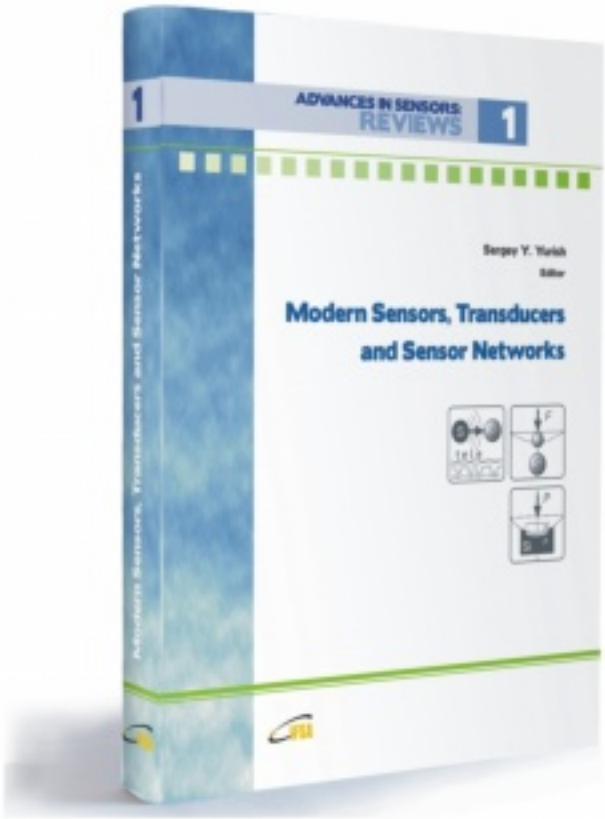
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