CHAPTER 1

INTRODUCTION

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1.1 INTRODUCTION

The most important requirement in the modern control system, instrumentation and computer technologies is the measurement of rotor shaft angle. The mechanism of any machine or process or monitoring system mainly depends on its rotating shaft. To allow the phase inversions and to enable the control of any modern control system, the measurement of the rotor shaft angle plays a major role.

The sensing of shaft angle is used in the techniques of the mechanism to convert shaft rotation to linear motion. In many control systems, this shaft angle is used to sense and / or control different sets of measurement parameters like position, velocity and acceleration. Thus, shaft angle transducers are key elements in modern control engineering.

From the past few decades, different forms of rotor shaft angle position transducers are developed. On the basis of their physical design, these position transducers are classified into two main groups.

i. Optical angular transducers: A phototransistor or other light sensitive electronic device counts lines on a transparent disk mounted to the rotating shaft. The most common of these devices are incremental and absolute encoders.

ii. Inductive angular transducers: Inductive angular transducers are built like small electrical motors, where inductive coupling between a rotating part (the rotor) and a stationary part (the stator) generates signals indicating shaft position. Resolvers and synchros are the most common devices.

Optical transducers, especially incremental encoders have found wide applications because their digital outputs can be easily processed by both discrete logic and microprocessors. Nevertheless, optical transducers have a number of characteristics that make them less than optimal for many applications. The built in semiconductors in optical transducers are used to amplify and format the digital output signals. These semiconductors are sensitive to temperature and the LED light sources commonly employed are susceptible to aging.

Furthermore, applications that require an absolute output signal require absolute encoders, which are complicated and expensive. Since encoders are typically connected to a shaft having its own bearings, the user must pay for the second set of high quality bearings in the transducer as well as a flexible coupling to connect the two shafts. In many applications, especially brushless servo motor commutation or flux vector control of AC induction motors, the additional length of the optical encoder’s shaft, bearings and coupling is too long, so the optical encoder cannot be used.

On the other hand, inductive transducers such as synchros 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. The manufacturing process of resolvers does not employ any sensitive electronics or optics and are supplied in pancake configuration. These are directly mounted to the shaft of the position measured devices. The mounting of the resolver with the position measured device does not require any shaft to shaft coupling or extra bearings. So, the user can save the cost and length.

The accuracy of the angular position influences the system efficiency, but also the torque control for optimum driving sensation. Such angle sensors need to be able to work in harsh environments, be accurate, safe and reliable. The probability of failure and probability catastrophic failure are intolerable in most modern control applications. Synchro and resolver sensors are undisputed in the above two failures. These sensors does not depend on moving electrical contacts for signal integrity, do not drift with time, and even extreme temperature changes have negligible effect on their performance.

Even before World War II, resolvers and synchros have been used in military applications to measure and control the angle of gun turrets on tanks and warships. These sensors are also used by machine tool and robotics manufacturers to provide the accurate shaft angle and rotational information. Due to small size, long term reliability, absolute position measurement, high accuracy, and low noise operation; these devices are mainly used in aviation applications.

1.2 SYNCHORS

A modern schematic diagram of a synchro is shown in Figure 1.1. The synchros employ single winding rotor that revolves inside a fixed stator. The stator in a simple synchro has three windings positioned 120^0 apart and are electrically connected in a Y-connection [1–3].

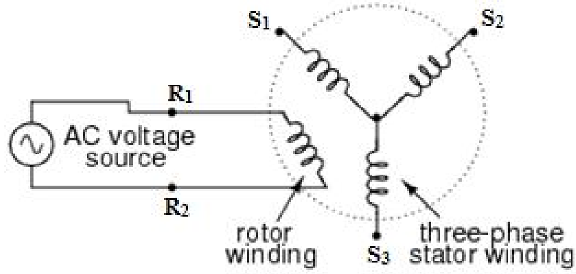

Figure 1.1 Modern schematic diagram of a synchro

The operation of synchros is same as the operation of rotating transformers. An AC reference voltage, at frequencies up to a few kHz, is used to excite the rotor winding of the synchro. The magnitude of the induced voltage in any stator winding is proportional to the SIN of the angle θ, where θ is the angle between the rotor coil axis and the stator coil axis. The induced voltage across any pair of stator terminals of a synchro is the vector sum of the voltages across the two connected coils.

If an AC reference voltage, $V\,Sin(\omega t)$, is used to excite the rotor of a synchro across its terminals R_1 and R_2, then the stator's terminal voltages are :

$$S_1 \text{ to } S_3 = V\,Sin\omega t\,Sin\theta \qquad (1.1)$$

$$S_3 \text{ to } S_2 = V\,Sin\omega t\,Sin(\theta + 120^0) \qquad (1.2)$$

$$S_2 \text{ to } S_1 = V\,Sin\omega t\,Sin(\theta + 240^0) \qquad (1.3)$$

where θ is the shaft angle.

The three stator coils of any synchro are oriented by 120^0 and are too difficult to manufacture and are costly. Due to this manufacturing limitation, synchros find decreasing use except in certain military and avionic retrofit applications.

1.3 RESOLVERS

A resolver is defined as an angular position sensor or transducer used to measure the instantaneous angle of the rotor shaft to which it is attached. These sensors are absolute over a single turn and are originally developed for military and avionic applications. The resolver has benefited from more than fifty years of continuous use and development. The benefits of this rotary position sensor were not recognized by numerous industrial segments. In general applications, the resolver gives rotary angular position information to a decoder, which is stationed in a Programmable

Logic Controller (PLC). PLC interprets this angular position information and runs the commands based on the position of machines [4].

The basic working principle of the resolver is based on converting their mechanical rotor shaft angle into its orthogonal or Cartesian components [5]. From a geometric perspective, the relationship between the rotor angle (θ) and the Cartesian components is that of a right angled triangle, as shown in Figure 1.2.

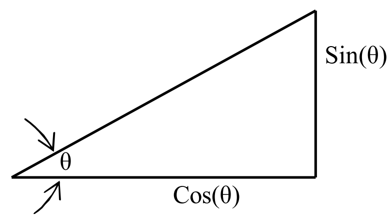

Figure 1.2 Resolving an angle into its components

The frequency response of a resolver is identical to the frequency response of a transformer with high leakage reactance and as shown in Figure 1.3. For any resolver, the corner and peak frequencies depend on the impedance of individual sensor. The generalized specifications of most of the resolvers are given in Table 1.1.

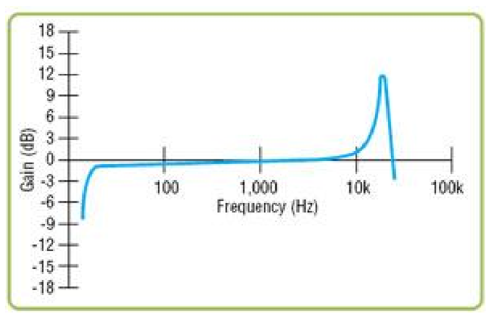

Figure 1.3 Frequency response of a resolver

Table 1.1 Specifications of Most of the Resolvers

Input voltage	: From $2V_{RMS}$ to $40V_{RMS}$
Input frequency	: From 400Hz to 10kHz
Angular accuracy	: From 5 arc-minutes to 0.5 arc-minutes

1.3.1 Resolver Control Transmitter

A resolver is one in which the magnitude of the energy varies sinusoidally through the resolver windings as the shaft rotates. The resolver is basically a rotary transformer and it has one primary winding and two secondary windings. The primary winding is called as the reference winding and the two secondary windings are called as SIN and COS Windings. The primary or the reference winding is placed in the rotor of the resolver whereas the two secondary windings i.e. the SIN and COS windings are located in the stator. The two secondary windings, SIN and COS are mechanically separated by 90^0 from each other.

The cross section of brushless resolver and schematic diagram of its control transmitter are shown in Figure 1.4(a) and Figure 1.4(b) respectively. The energy in brushless resolver is supplied to the rotor (reference winding) through a rotary transformer.

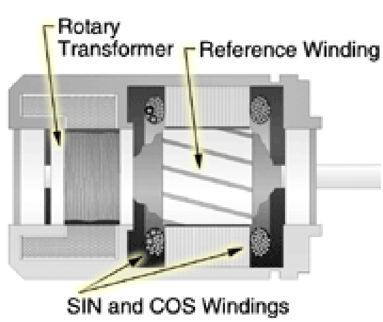

Figure 1.4(a) Cross section of brushless resolver

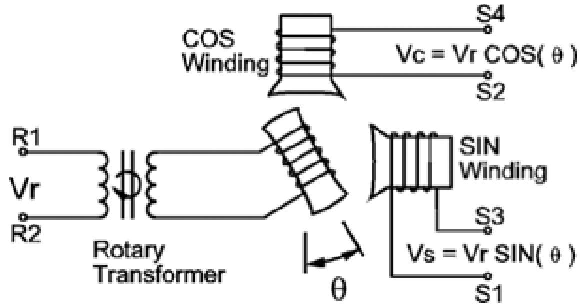

Figure 1.4(b) Schematic diagram of brushless resolver control transmitter

In a control transmitter, the rotor winding is excited by an AC voltage called the reference voltage (V_r). As the rotor winding is excited, two voltages are induced in the two stator windings; SIN and COS. The induced voltages in the stator windings are equal to the value of product of the reference voltage and the SIN or COS of the angle of the input shaft from a fixed zero point. Thus, the resolver provides two voltages whose ratio represents the absolute position of the input rotor shaft.

$$\frac{\mathrm{SIN}(\theta)}{\mathrm{COS}(\theta)} = \mathrm{TAN}(\theta) \qquad (1.4)$$

where θ is the rotor shaft angle. Any changes in the resolver's characteristics caused by aging or temperature can be neglected because of the ratio of SIN and COS voltages. An additional advantage of SIN and COS ratio is that the shaft angle is absolute. Even if the power removed to a rotor shaft when it is rotating, the resolver will report its new angular position value when power is restored.

1.3.2 Resolver Control Transformer

The schematic diagram of brushless resolver control transformer is shown in Figure 1.5. A resolver control transformer has two input stator windings, the SIN and COS windings and one rotor output winding. The rotor output is proportional to the SIN of the angular difference between the electrical input angle of the inputs and the mechanical angular position of its shaft i.e. the voltage induced into the rotor is proportional to $Sin(\Phi - \theta)$, where θ is measured from some reference shaft position called zero. The 3-wire synchro output can be easily converted into the resolver equivalent format using a Scott-T transformer.

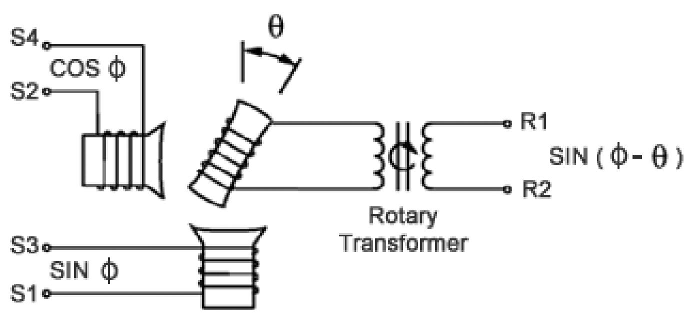

Figure 1.5 Schematic of brushless resolver control transformer

The electromechanical servomechanism of a resolver is shown in Figure 1.6. The shaft position of the control transmitter establishes the command angle. The control transformer's output goes to zero and the servomotor stops when it reaches the commanded position, $\theta_1 = \theta_2$.

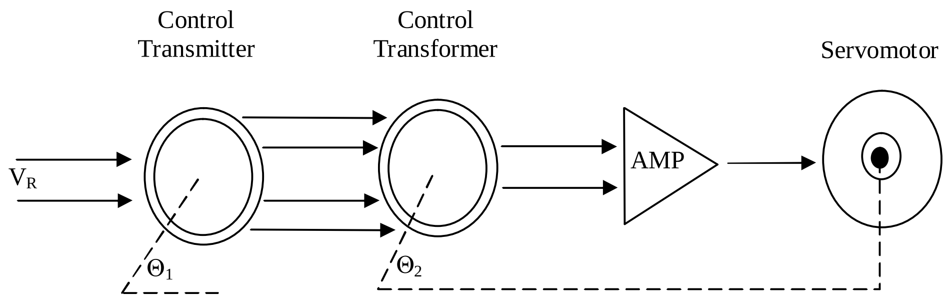

Figure 1.6 Electromechanical Servo mechanism

The electrical input applied to the windings of control transmitter and control transformer will be differed, even though they are unidirectional devices. As per the manufacture's specifications, the electrical input is applied to rotor winding in control transmitter and is applied to two stator windings in control transformer.

1.3.3 Principle of a Resolver

a) Stationary Transformer

Stationary transformer theory is the basis of resolver design. The schematic of stationary transformer is shown in Figure 1.7. An AC voltage is applied to the primary winding (E_{IN}) of a stationary transformer and a proportional output is developed on the secondary winding (E_{OUT}).

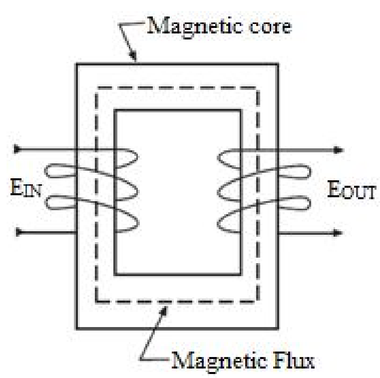

Figure 1.7 Schematic of a Stationary transformer

The proportionality is based on the ratio of turns on the secondary to the primary, known as the transformation ratio.

$$\text{Transformer } E_{OUT} = E_{IN}\left(\frac{N_2}{N_1}\right)$$

b) Rotary Transformers or Resolvers

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 schematic diagram of resolver is shown in Figure 1.8. The output voltage is affected by change in the position of the secondary winding relative to the primary winding.

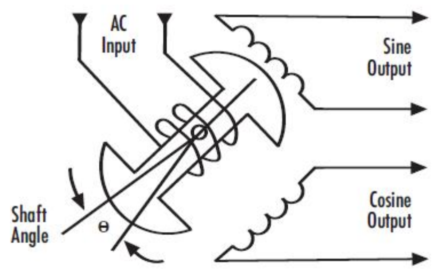

Figure 1.8 Schematic of a Resolver

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 SIN and COS relationship.

i) Position Sensing:

The resolver consists of one reference winding and two feedback or output windings. The transformation ratio from the reference winding to the two feedback windings varies with the position of the resolver rotor. The reference winding is fixed on the stator and is magnetically coupled to both stator output windings through the windings located on the rotating shaft. The placement of the reference and output windings with respect to the shaft of a resolver is shown in Figure 1.9.

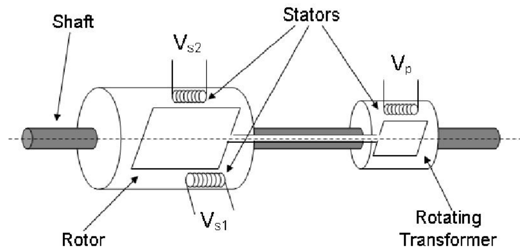

Figure 1.9 Internal view of a resolver

The two output windings are placed in quadrature on the stator to generate two AC signals 90^0 out of phase [6]. An equivalent cross sectional view of the resolver with its rotor angular position, θ, with respect to the windings and the associated signals are shown in Figure 1.10(a) and Figure 1.10(b) respectively.

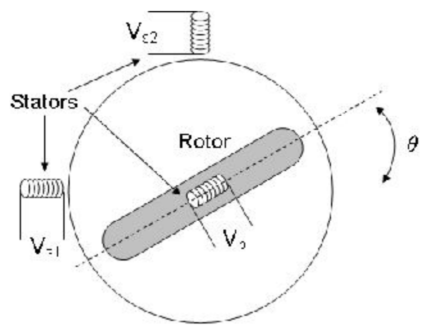

Figure 1.10(a) Equivalent cross sectional view

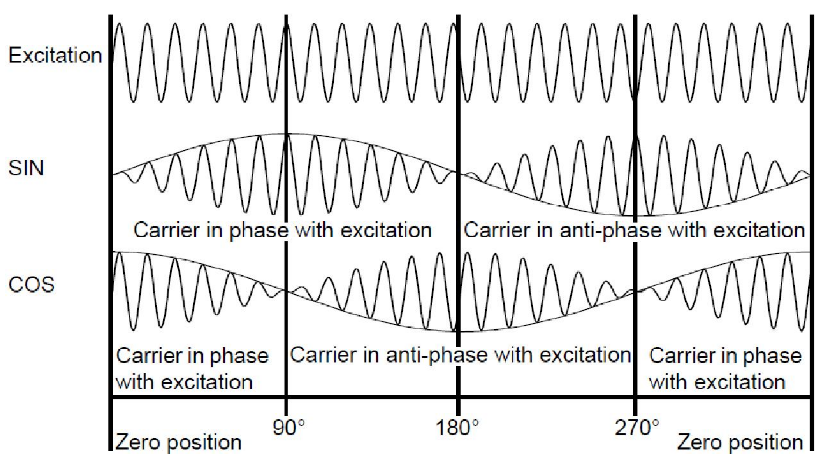

Figure 1.10(b) Resolver excitation and output signals

In consequence of the excitation applied on the reference winding V_p and along with the angular movement of the motor shaft θ, the respective voltages are generated by resolver output windings V_{s1} and V_{s2}. The frequency of the output voltages is identical to the reference voltage and these amplitudes vary according to the SIN and COS of the rotor shaft angle θ. The winding of the rotor is supplied with a high frequency sinusoidal carrier signal:

$$V_p = A \cdot Sin(w_e t) \qquad (1.5)$$

where A is the peak amplitude and $w_e = 2\pi f_e$, where f_e is the frequency of the excitation signal. 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_e. The two stator windings of the resolver modulated signals are given by

$$\left.\begin{array}{l} V_{s1} = \alpha \ A\,Sin(w_e t)\,Sin(\theta) \\ V_{s2} = \alpha \ A\,Sin(wet\,)\,Cos(\theta) \end{array}\right\} \qquad (1.6)$$

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. As the excitation or the carrier signal V_p is applied, the output voltages from the two stator windings are amplitude modulated and are shown in Figure 1.10(b). The spectrum of the amplitude modulated signals, V_{s1} and V_{s2} are identical and symmetrical to the excitation frequency. The spectrum of V_{s1} and/or V_{s2} is shown in Figure 1.11.

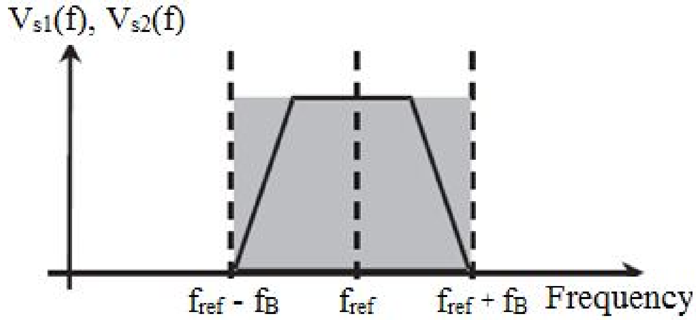

Figure 1.11 Amplitude spectrum of resolver signals V_{s1}, V_{s2}

The bandwidth f_B depends on the maximum angular speed according to:

$$f_B = \frac{1}{2\pi} \frac{d\theta}{dt}\bigg|_{MAX} \qquad (1.7)$$

By simple demodulation of the stator signals in eq. (1.6), the excitation signal may be removed, resulting in SIN and COS signals. The demodulation and amplification of eq. (1.6) results in normalized signals:

$$\left.\begin{aligned} V_S &= Sin(\theta) \\ V_C &= Cos(\theta) \end{aligned}\right\} \qquad (1.8)$$

The rotor angle, θ can be extracted from eq. (1.8) using a suitable Resolver to Digital Converter (RDC).

1.4 RESOLVER TO DIGITAL CONVERTER (RDC)

Resolvers are extensively used in applications that demand instantaneous, accurate and high resolution angular position and/or speed information. A resolver's analog outputs have been modulated by rotor excitation signal and an RDC is always adopted to recover the angular position in digital form.

RDCs are extensively used in automotive and industrial applications to provide motor shaft angle and/or velocity feedback. RDC performs two basic functions: demodulation of the resolver format signals to remove the carrier, and angle determination to provide a digital representation of the rotor angle. The block diagram of resolver and RDC system is shown in Figure 1.12.

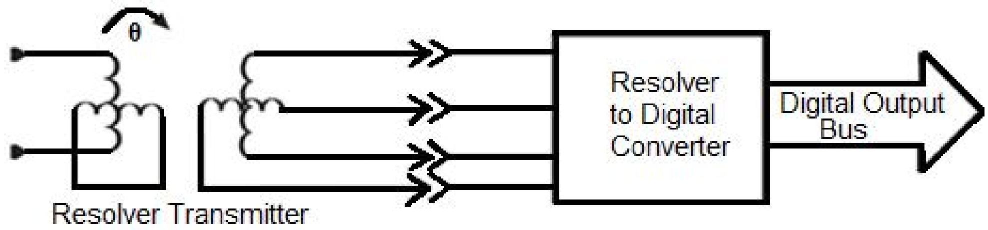

Figure 1.12 Digital data transmission of a resolver system

In all of the applications of RDCs, a sine wave is used as the reference signal to excite the primary winding of the resolver. This sine wave reference signal is transformed into two output signals on the two secondary windings and these signals are referred as sinusoidal output (SIN) signal and differential output signal (COS). The amplitude of the SIN and COS signals are proportional to the position of resolver rotor shaft, transformation ratio of that resolver and the amplitude of the reference sine wave. The resolver secondary signals i.e. SIN and COS are given as input to the RDC. The RDC samples both input signals at the same instant of time and provides the digital data to a digital application. This entire process is known as Type II tracking loop that is responsible for the measurement of position and speed.

The RDC transforms the resolver output signals into digital representation of the angular position. When combined with such converters, resolvers can provide digital outputs with up to 22 bit resolution and system accuracy to 18 bit are achievable.

1.4.1 RDC Methods

The two resolver outputs V_{s1} and V_{s2}, as in eq. (1.6) are amplitude modulated signals at the reference frequency. These signals are demodulated or converted by one of the following methods to obtain precise shaft angle position [7].

- Direct angle (or) Arctangent (or) Inverse Tangent technique
- Phase analog technique
- Sampling technique
- Tracking loop or Angle Tracking Observer (ATO) Technique
- Dual Converter Technique

The aims of each technique are similar, to provide a digital output proportional to the rotor position. The information contained in the two resolver signals is sufficient to define uniquely the position of the rotor relative to the stator over the full 360^0 of rotation. All conversion techniques use the two analog signals to produce a digital output. The differences among 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 [8].

1.4.2 Direct Angle Technique

Direct angle method is also called as an Arctangent or Inverse tangent method. In this method, the resolver rotor winding is excited by an alternating signal called reference signal and the two stator windings generate the amplitude modulated output signals. The two secondary winding output signals have the same time phase angle as the reference signal. However, their amplitudes are modulated by SIN and COS as the shaft rotates.

The block schematic of angle extraction using arctangent method is shown in Figure 1.13. The resolver secondary signals represent the SIN and COS of the rotor angle, as in eq. (1.6), the ratio of the signal amplitudes is the tangent of the rotor angle. Thus the rotor angle, θ, is the arctangent of the SIN signal divided by the COS signal.

$$\theta = \arctan\left(\frac{Sin(\theta)}{Cos(\theta)}\right) \tag{1.9}$$

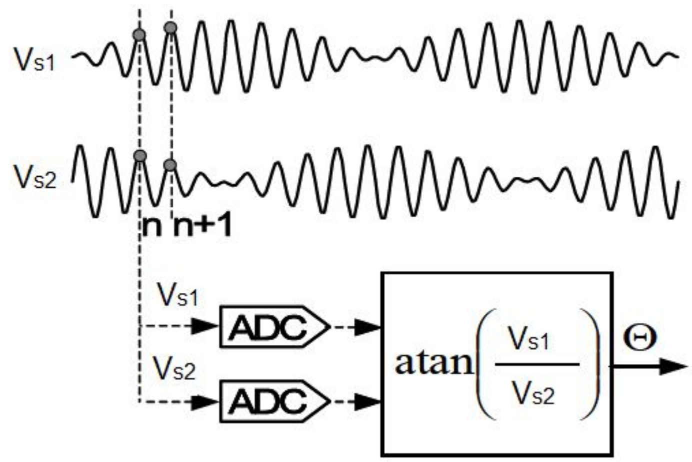

Figure 1.13 Angle extraction using Arctangent Method

The implementation of arctangent is a bit more complicated. Executing a division and an arctangent is not trivial in an embedded system and especially in the moment where the signals due to the carrier are identical zero of eq. (1.9) is not applicable [8]. Sources of error for this method are the resolver accuracies and, if used, the converter accuracy and resolution.

The direct angle technique estimates the unfiltered rotor angle without any speed information. Therefore, for a final application, a speed calculation with smoothing capability should be added. Further, the four quadrant arctangent results in angles between -180^0 and 180^0. Thus the number of turns is not tracked [10]. Moreover, it is open loop technique.

1.4.3 Phase Analog Technique

The two stator windings are excited by signals that are in phase quadrature to each other. This induces a voltage in the rotor winding with an amplitude and frequency that are fixed and a time phase that varies with shaft angle. This method is referred to as the phase analog technique. It has been the most widely used technique since it can be converted to produce a digital signal by measuring the change in phase shift with respect to the reference signal. The accuracy of this type of angle transmission is determined by the accuracy to which the zero crossing intervals can be measured. Sources of error for this method are noise generated by the environment of the resolver. This causes the zero crossing point to be indeterminate and produces variations in the excitation. Any variation of the amplitudes or time phases of the two excitation signals directly influences the time phase of the output signal. This method is used only for slow rotational speeds (20 RPM is a typical maximum speed for a resolution of about 1^0 of arc).

1.4.4 Sampling Technique

When using this method a sample is taken of the SIN and COS output signals of a rotor excited resolver at the peak of the reference input amplitude. These are converted to digital signals by an analog to digital converter. The resulting digital words are used as a memory address to lookup the shaft angles in a processor. The difficulty with this approach is its inability to deal with noise. If a noise disturbance occurs on the signal lines at the time of sampling, a wrong shaft angle position results. If the noise causes only a single wrong reading, the pass band frequency of the drive systems acts as a filter with little resulting error.

1.4.5 Tracking loop or Angle Tracking Observer (ATO) Technique

The tracking conversion technique overcomes all the difficulties described in the previous three methods. This method yields smooth and accurate estimations of both the rotor angle and rotor speed.

Tracking converters are cost competitive with other methods and provide superior accuracy and noise immunity. These converters use the ratio of the two stator winding output signals; SIN and COS that are excited by a rotor. Any distortion or amplitude variations of excitation waveform appears in the correct ratio on both SIN and COS thus it has little effect on accuracy. A tracking converter contains a phase demodulator. Therefore, frequency variation and incoherent noise do not affect accuracy. Tracking converters can operate with any reference excitation, sine or square wave, with only minor accuracy variations. Common mode rejection is achieved by the isolation of the resolver.

A block diagram of typical RDC with tracking control loop is shown in Figure 1.14. The resolver SIN output signal is applied as one of the input to COS multiplier and resolver second output signal; COS signal is applied as one of the input to SIN multiplier. These two multipliers are functions as multiplying digital to analog converters and also incorporate SIN and COS lookup tables.

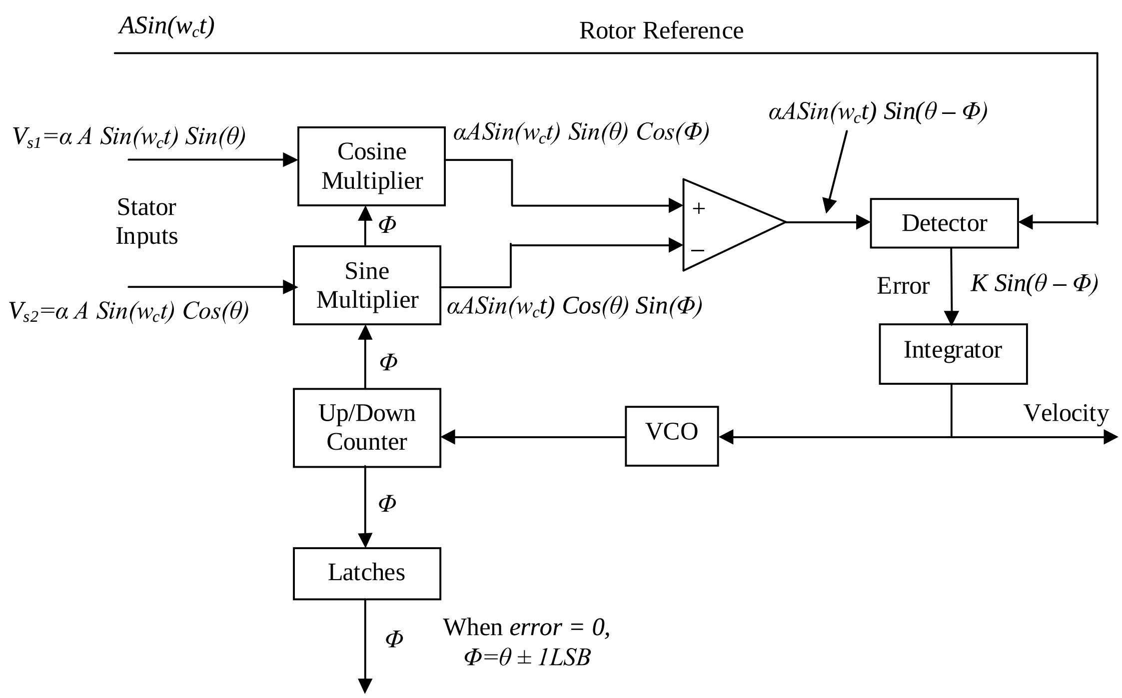

Figure 1.14 Resolver to digital converter based on ATO Technique

Initially it is assumed that the present state of the up/down counter is a digital number corresponding to a trial angle, ϕ. The RDC looks for the correct analog angle, θ to set the digital angle, ϕ, continuously to become equal to and to track θ. The estimated digital trail angle ϕ is applied as one of the input signal to COS multiplier. The cosine value of the trail angle ϕ is multiplied with V_{s1}, as in eq. (1.6), to produce the term

$$\alpha\, A Sin(w_c t)\, Sin(\theta)\, Cos(\phi) \qquad (1.10)$$

The estimated digital trail angle ϕ is also applied as one of the input signal to SIN multiplier. The sine value of the digital trail angle ϕ is multiplied with V_{s2}, as in eq. (1.6), to produce the term

$$\alpha\, A Sin(w_c t)\, Cos(\theta) Sin(\phi) \qquad (1.11)$$

The difference or error amplifier subtracts the two signals as in eq. (1.10) and eq. (1.11) to yield an AC error signal of the form

$$\alpha\, A Sin(w_c t)\left[Sin(\theta)\, Cos(\phi) - Cos(\theta) Sin(\phi)\right] \qquad (1.12)$$

Using trigonometric identity, eq. (1.12) reduces to

$$\alpha\, A Sin(w_c t)\left[Sin(\theta - \phi)\right] \qquad (1.13)$$

The signal in eq. (1.13) is the product of reference signal and the rotor shaft angle. The reference signal needs to be suppressed to resolve the rotor angle. The reference signal $\alpha\, A Sin(w_c t)$ can be removed using synchronous demodulator or synchronous detector. The demodulated signal is a dc error signal and is proportional to $Sin(\theta - \phi)$. This error signal gives as input to an integrator. The integrator output drives Voltage Controlled Oscillator (VCO) that in turn drives the Up/Down counter. Based on the count of Up/Down counter, the estimated angle ϕ can be equated to actual rotor shaft angle θ thus the dc error angle moves towards zero i.e.

$$Sin(\theta - \phi) \to 0 \qquad (1.14)$$

as per the Taylor approximation around zero, the equation (1.14) becomes

$$Sin(\theta - \phi) \approx (\theta - \phi) \quad for\,|\theta - \phi| << 1 \qquad (1.15)$$

when eq. (1.15) is achieved, then

$$(\theta - \phi) \to 0 \qquad (1.16)$$

and therefore

$$\theta = \phi \qquad (1.17)$$

Hence, the digital output of the counter, ϕ represents the rotor shaft angle θ. Finally, this data can be transferred externally by enabling the latches and without interrupting the entire loop's tracking.

This typical RDC circuit with tracking control loop has two integrators and is equivalent to a Type-II servo loop. One of the integrator is working as the counter that accumulates pulses and the second one is working as normal integrator at the output of the detector. The output digital word in a Type-II servo loop continuously tracks or follows the input without any external converter commands. This tracking is achieved with no steady state phase lag between the digital output word and actual shaft angle. The error signal appear only during the periods of acceleration or deceleration. The tracking RDC provides an analog DC output voltage directly proportional to the rotor shaft rotational velocity. This is one of the useful feature of tracking RDCs to measure the velocity without additional tachometers.

Since the error signal is doubly integrated in the tracking converters, the converters offer a high degree of noise immunity. The area under any given noise spike gives an error. However, typical inductively coupled noise spikes have equal positive and negative going waveforms. When integrated, this results in a zero net error signal. When combined with the insensitivity of the converter to voltage, there is a dropping of the resulting noise immunity. Further, this noise rejection can also be increased through detector's rejection of any signal not at the reference frequency, such as wideband noise.

The main advantages of tracking type RDCs are

- The conversion system needs only a sine and cosine function instead of the division and the arctangent functionality.
- A second order noise suppressing filter is built in.

1.4.6 Dual Converter

Dual converters are used to encode the resolver of multispeed units. One channel, the coarse portion of the converter, is connected to the single or coarse speed section of the resolver. The other channel, the fine portion, is connected to the fine speed section. The coarse channel supplies an approximate non-ambiguous rotor position to the demodulator. When the output error of the coarse channel drops below a preset threshold, the crossover detector switches the fine channel error signal into the demodulator. The error angle is multiplied by the speed ratio of the resolver. This increases the voltage sensitivity and enables the servo system to seek a more accurate null. The converter will continue to use the fine error signal for continuous tracking. The basic accuracy and resolution of the converter is therefore divided by the speed of the resolver.

1.5 RESOLVER PARAMETERS

The important parameters of resolver are:

- Accuracy
- Transformation Ratio (TR)
- Phase shift
- Null voltage

1.5.1 Accuracy

Accuracy is the most important parameter associated with resolvers. It can be measured in different ways. Among them the following are generally used.

a. Accuracy is measured by looking each winding separately. It is defined as difference between the actual voltage and theoretical voltage.

b. Accuracy is specified as inter axis error at the angular deviation of null positions at 0^0, 90^0, 180^0 and 270°. It is expressed in arc-minutes or arc-seconds. The lower the inter axis error, the more accurate the resolver. There are 60 arc-minutes in one degree, and 60 arc-seconds in one arc-minute. Hence, 0.0167^0 is equivalent to one arc-minute.

c. Linearity error is defined as the measure of the nonconformity of the secondary voltage over the entire range of rotation. It is expressed as a percentage of the secondary voltage at the maximum excursion. In general, the more linear, the more accurate.

d. Voltage sensitivity or voltage gradient is the output voltage expressed as a function of the shaft angle in mV/degree. This parameter is specified at a shaft angle of 1°. It can be calculated by multiplying the output voltage at maximum coupling by the SIN of 1°.

The accuracy of the rotor angle and speed estimations greatly depends on features of the RDC. Particularly, RDC accuracy, resolution and set of possible operation modes are crucial for achieving the higher accuracy estimations [11].

1.5.2 Transformation Ratio (TR)

Transformation Ratio (TR) is the ratio of output voltage to input voltage when the output is at maximum coupling. In general, practical TRs are between 0.1 and 1.0. TRs greater than 1.0 are possible, depending on the design of the unit. Common values for TR are 0.454, 0.5 and 1.0.

1.5.3 Phase shift

Phase shift is defined as the time phase difference between the primary and secondary voltages at maximum coupling. It is expressed in electrical degrees. Normally single speed resolvers have leading phase shifts between 0 and 20°.

1.5.4 Null voltage

Null voltage is the residual voltage remaining when the in-phase component of the output voltage is zero. When the primary and secondary windings are placed by 90^0 then the voltage induced in the secondary winding is zero. However, mechanical imperfections, winding errors and distortions in the magnetic circuit cause some voltage to appear in the secondary winding at the minimum coupling position.

The null voltage comprises three components: in-phase, quadrature and harmonics. The in-phase fundamental component is an angular inaccuracy that can be cancelled by re-nulling the rotor, thereby introducing an error. Quadrature fundamental component is 90^0 out of phase with the in-phase component and cannot be nulled by rotor rotation. The harmonic voltages consist predominantly of the third harmonic that is three times the excitation frequency.

Null voltages are specified as total null voltage, which is the total of the quadrature fundamental and harmonics. Depending on size, input voltage, and input frequency, the total null voltage is approximately 1 to 3 mV/V of input voltage. The fundamental null voltage is usually slightly less than or equal to the total null voltage.

1.6 APPLICATIONS

Resolvers are used in typical applications like spacecraft and aircraft to transform coordinates from one system to another. Spacecrafts and aircrafts usually require pitch, yaw, and roll to be transformed back to earth references. One resolver readily handles a two axis transformation whereas three resolvers are needed for handling three axes.

Resolver chains are also employed to solve trigonometric problems and for phase shifting. Using a balanced *RC* network and a stable frequency source, resolver based phase shifters can achieve 0.25^0 accuracy or better.

Through the evolution of machine development, builders and system integrators alike, agree that the resolver transducer is unsurpassed in its ability to reliably supply rotary position data in the harsh industrial environments.

1.7 EMBEDDED SYSTEMS

An embedded system is an electronic computing device that is designed using hardware and software to perform one or a limited set of functions. Both the hardware and software in an embedded system are optimized for the specific job. Having hardware and software makes the embedded system as a computer, but this computer performs only a limited set of functions. The word embedded reflects the fact that the systems are usually an integral part of a larger system, known as the embedded system. The embedded system is also defined as an “Application specific system”.

The embedded systems for industrial use are designed to carry out specific tasks such as monitoring the temperature, pressure, humidity, voltage, current, motion control etc., and take appropriate action. Embedded systems are equipped with different types of peripherals to solve these problems. In early 1980s, embedded devices are used in the applications of Minuteman I missile and the Apollo guidance computers. Whereas the guidance system of Minuteman II missile was developed with large number of Integrated Circuits (ICs) that reduces the prices of ICs from 1000$ each to 3$ each. This reduction of the cost leads to wide adoption of embedded systems in consumer electronics. After 1980s, embedded systems are found in all devices. These broad range of applications with totally different requirements leads to various implementation approaches.

The robotics is now becoming very powerful; and carries interesting and complicated tasks such as hardware assembly. To facilitate the control of increasingly complex physical systems such as drive-by-wire automobiles and fly-by-wire aeroplanes; embedded and networked computer systems with numerous hardware and software components are increasingly required [12]. Embedded systems in which some specific task has to be done in a specific time period are called real-time embedded systems. The development of embedded software was earlier done mostly in assembly languages. However, due to the availability of cross compiler, most of the development is now in high-level languages such as ‘C’. Embedded systems are omnipresent and play significant roles in modern-day life.

Today's embedded devices need to run multimedia applications demanding high computational power with low energy consumption constraints [13]. Traditional computer architecture or computer engineering curricula emphasize the hardware and software fundamentals suitable to general purpose computing. However, there is a growing realization that special purpose embedded systems computing requires a different educational emphasis than general purpose computing.

The microcomputer is an embedded chip, which is typically used for control applications, one emphasis must be on communication protocols with other devices such as RS-232, SPI, I2C, or CAN. Similarly, for interactions with the non-digital world, another emphasis must be on analog to digital and digital to analog conversion. Because so many control applications are time-critical, another emphasis must be on timing and interrupts represent only a small fraction of the total number of microprocessor applications. By some estimates, more than 99% of all microcontroller based systems are special purpose embedded systems rather than general purpose computers. The microcontrollers in embedded systems are typically optimized to perform a single task, often a control application.

Embedded systems are characterized by the following special features [14].

a) Embedded systems do a very specific task; they cannot be programmed to do different things.

b) Embedded systems have very limited resources, particularly the memory; generally they do not have secondary storage devices such as the CDROM or floppy disk.

c) Embedded systems have to work against some deadlines to complete a specific job within a specific time. The specified deadlines are so stringent in real time embedded systems. The missing of a deadline may cause a catastrophe loss or life or damage to property.

d) Embedded systems are constrained to power. As many systems operate through a battery, the power consumption has to be very low.

e) Embedded systems have to operate in extreme environmental conditions such as very high temperatures and humidity.

f) Embedded systems need to be highly reliable.

Embedded system is a complex object containing a significant percentage of electronic devices (generally at least one microcomputer) that interacts with the real world (physical environment, human users, etc.) through sensing and actuating devices. The system is heterogeneous, as it is characterized by the co-existence of a large number of components such as microcontroller and digital signal processing, as well as analog components such as Analog to Digital Converters (ADCs) and Digital to Analog Converters (DACs), sensors, transmitters and receivers. In the past, the system design effort has focused on these hardware parts, leaving the software design to be done afterwards as an implementation step. New software technologies are important for the future of control (and vice versa) in an age of increasing complexity [15].

1.7.1 Performance Comparison of Embedded Systems:

The performance of different designs and approaches of embedded systems are compared based on the technical specifications or economical criteria.

1.7.1.1 Technical Specifications:

Technical specifications of an embedded system are used to compare the technical designs and specifications. The technical specifications are:

a. Performance
b. Energy efficiency
c. Size
d. Flexibility.

a. Performance: The performance of an embedded system describes about the execution time or the throughput of that system.
b. Energy efficiency: The energy efficiency of an embedded system specifies the amount of power consumed by the system.
c. Size: It is a technical specification used to represent the constraints on the physical size of an embedded system.
d. Flexibility: It is used for ease of reconfiguration and reusability.

1.7.1.2 Economical Specifications:

The economical Specifications of an embedded system are used to determine which Commercial Off-The-Shelf (COTS) should be use or if the systems will be brought to the market. These specifications are

a. Unit cost
b. Non-Recurring Engineering (NRE)
c. Flexibility.
d. Time to Market

a. Unit cost: The unit cost of an embedded system is the monetary cost excluding the non-recurring engineering cost, if manufacturing each copy of the system.
b. Non-Recurring Engineering (NRE): It gives one time monitory cost for designing the system.
c. Flexibility: Flexibility describes the ability to change the functionality of the system without incurring heavy NRE cost.
d. Time to Market: It indicates the amount of time to design and develop a system to the point that it can be released and sold to customers.

1.7.2 Hardware platforms of an Embedded System

An embedded system is an integration of both hardware and software components. The design decisions among the various hardware platforms for any given embedded system applications must have the capability of including a systematic approach. But there is quite different hardware platforms are available, so the design decisions are nontrivial. The hardware platforms are Central Processing Unit (CPU) based systems such as Micro Controller Units (MCUs) and Digital Signal Processors (DSPs), as well as Programmable Logic Devices (PLDs), Complex Programmable Logic Devices

(CPLDs) and Field Programmable Gate Arrays (FPGAs). For some applications, combinations of different discrete devices or an integration of a microprocessor core in an FPGA is preferable [16]. Moreover, the available hardware devices are constantly changing over time.

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