High Resolution Position Inductive Transducers for Harsh Environmental Conditions

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Abstract **– In this paper the authors present certain theoretical, conceptual and technological aspects on main types of high resolution inductive transducers for harsh environmental conditions. Inductive resolvers, as well as inductive RVDT, have a priority in these applications, even other types of position transducers, as optical, capacitive or magnetic encoders are in competition.**

In the world there are many researchers that continue activity of conceptual and technological development to increase the resolution level of the inductive resolvers and inductive RVDT, as well as to obtain smaller and smaller dimensions, just it is requested in such kind of applications. On the other hand, the inductive transducers are more adapted at harsh mechanical and climatic conditions that are usual for special applications.

The paper is referring, especially, to inductive transformers type resolver.

Key words **– inductive transducers, high resolution, harsh conditions**

I. GENERAL ASPECTS

Position inductive transducers are used as main components in the applications where it is required very high accuracy. For example, a modern measurement and control system including a synchro-resolver transmitter type and a synchro-resolver receiver type represents a most frequent solution to acquire the position information in very accurate manner for large range of applications.

In fact, position inductive transducer is used to translate into electric magnitude an angular or linear dimension and consists of an asynchronous electric machine, especially developed to produce one system of alternative outputs having variable amplitude.

It may be considered that this electric machine is a kind of retort at the general electric transformer that has all elements fix, so has only a certain magnitude of output.

However, the real purpose was not to be a retort, but to solve some important needs that the progress of systems and applications has required at a certain moment. We have to remark that there is an important difference to the situation of a classic asynchronous electric machine: position inductive transformer generates output signals as a transformation component and this one depends insignificantly from rotation speed. Generally, the component depending of rotation speed is taken into consideration inside of global error factory.

Over time, the authors had conceived, developed, built and tested many types of position inductive transducers, paying special attention to analyse back e.m.f. accuracy relative to different types of winding schema, as well as to do a right interpretation regarding the results obtained on vectorial measurements methods. Also, were made many tests in special environment conditions, similar to harsh conditions for special applications. These tests have demonstrated that the level of accuracy and global physical resistance of item are kept in these special harsh conditions.

Writers' opinion is to consider in the position inductive transducers class: **rotary inductive transformers**, to measure the angular position, components that are generally named rotary inductive potentiometers and include resolvers, microsyns and RVDT; **linear inductive transformers**, to measure the linear position, components that are generally named linear inductive potentiometers, including specially the transducer LVDT type.

We have to remark that, especially in the last time, the users have replaced in certain applications the inductive transducers with encoders (based on optical, capacitive or magnetic phenomena) and it was expressed by some producers a concept according with that the inductive transducers shall be replaced totally and forever with the encoders. But, the reality has demonstrated that this concept is completely wrong because it is not based on the whole spectrum of criteria. Some users and producers have considered only the price, but when high accuracy is requested the price of inductive transducers seems to be not decisive.

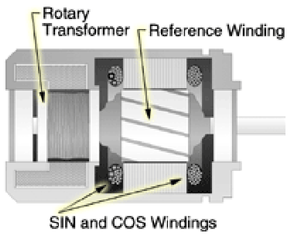
Moreover, some characteristics as: robustness, high resistance at harsh environment conditions, a perfect capacity to operate in an atmosphere with smog, fog, vapour or suspension assure to use the inductive transducers very long time in the future.

Through the evolution of machine development, builders and system integrators alike, agree that the inductive transducer is unsurpassed in its ability to reliably supply rotary position data in the harshest environment conditions. So, any segregation is not useful: the inductive transducers, as well as the encoders, are used and will be used by different users just according with their needs, interests and affinity.

II. INDUCTIVE TRANSDUCERS TYPE RESOLVER

2.1. Construction. Representative equations and diagrams

As we have mentioned above, resolver is the position sensor or transducer which measures the instantaneous angular position of the rotating shaft to which it is attached. Resolvers and their close cousins, synchros, have been in use since before World War II. Resolvers are typically built like small motors with a rotor (attached to the shaft whose position is to be measured), and a stator (stationary part) which produces the output signals.



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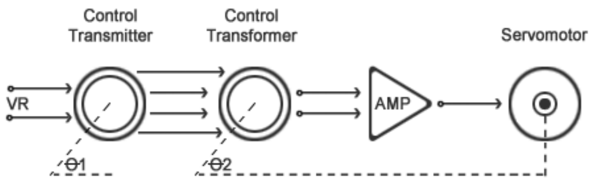


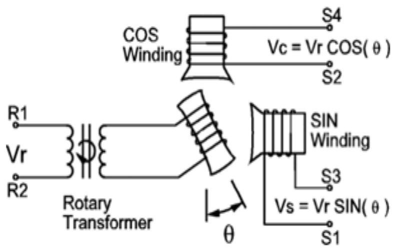
b.

Fig. 1 a. Showing resolver construction with housing, sinus and cosinus windings, bearings and rotary transformer b. Typical control of electromechanical servo-system

The word resolver is a generic term for such devices derived from the fact that at their most basic level they operate by resolving the mechanical angle of their rotor into its orthogonal or Cartesian (X and Y) components. From a geometric perspective, the relationship between the rotor angle (θ) and its X and Y components is that of a right triangle.

Fundamentally, then, all resolvers produce signals proportional to the sine and cosine of their rotor angle, relative to fix position of the stator. Since every angle has a unique combination of sine and cosine values, a resolver provides absolute position information within one electric revolution (360°) of its rotor (**only it has 2 poles**). This absolute (as opposed to incremental) position capability is one of the resolver's main advantages over incremental encoders. However, we have to remark that the absolute character is related only one electric revolution, so to have an absolute reference for whole physical rotation (mechanical 360°) it must to build the resolver only with two poles. Like all transformers, the resolver requires an AC carrier or reference signal (sometimes also called the excitation) to be applied to its primary. The amplitude of this reference signal is then modulated by the sine and cosine of the rotor angle to produce the output signals on the two secondaries. In any transformer, there is a value which relates the output voltage produced by the secondary to that fed into the primary. For resolvers, this quantity is called the transformation ratio or ***TR*** and is specified at the point of maximum coupling between primary and secondary. If we define the reference voltage ***V(R1–R2)*** as ***VR***, then the voltages on the secondaries are given by the following equations:

Primary Input: **V(R1–R2) = VR = E_{1max} sin ωt**
Sine Secondary: **V(S2–S4) = VS = VR TR sin(θ)** ***Cosine Secondary:*** **V(S1–S3) = VC = VR TR cos(θ)** ,
where ***θ*** is the mechanical angle of the rotor as shown in the resolver schematic (**fig. 2 and fig. 3**).



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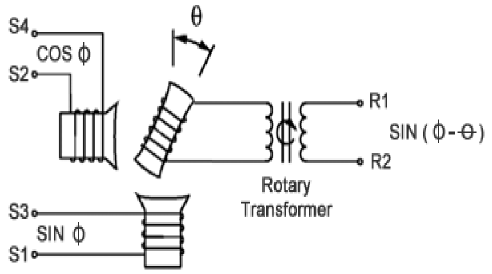

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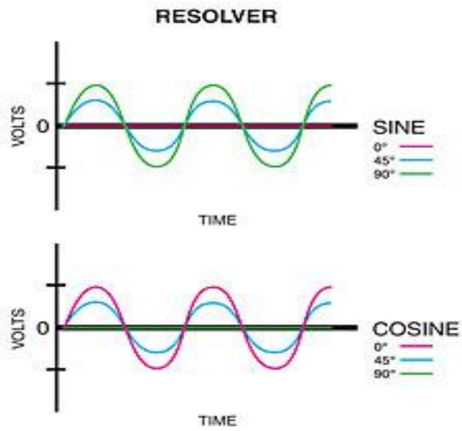
Fig. 2 BL (brushless) transmitter and receiver resolver a. Schematic on construction of BL transmitter resolverb. Schematic on construction of BL receiver resolver



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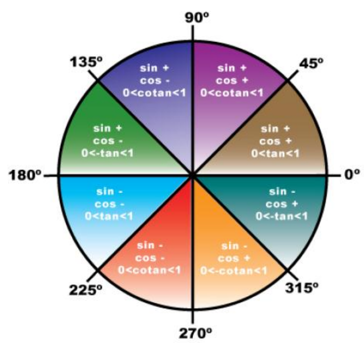


b.

Fig.3 a. Resolver produces a set of analogical outputs sine – cosine b. Absolute character of the resolver

If we excite the resolver primary ***(VR)*** with the recommended sinusoidal reference signal, the secondary voltages are also sinusoidal at the same frequency and nominally in phase with the reference. Their amplitude is proportional to the amplitude of the reference, the transformation ratio of the resolver and the sine or cosine of the mechanical angle of the rotor. Using a typical value of ***TR*** as ***0.5***, we can look at the secondary voltages for different rotor angles as they would appear on an oscilloscope (fig. 4).

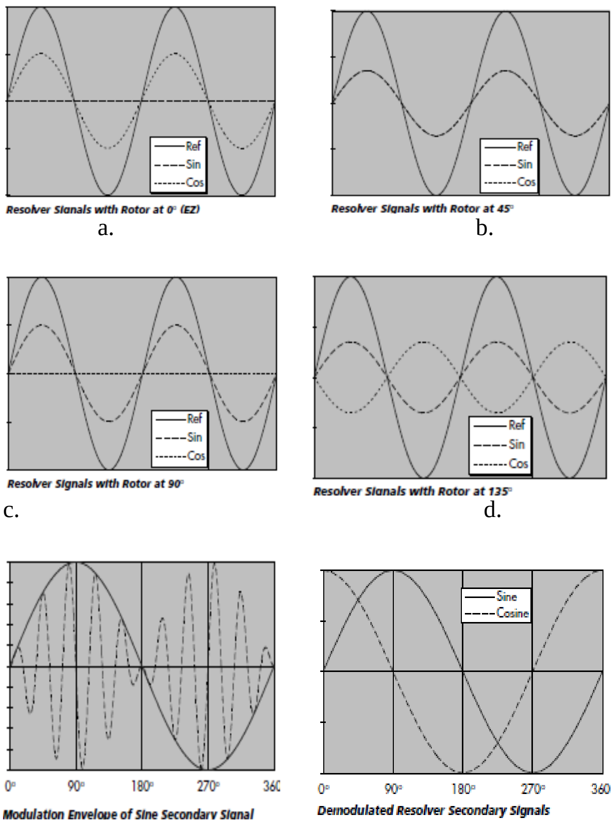


Fig. 4 Explanation on resolver operating principle

While it is helpful to know how the resolver signals appear as functions of time since that is what one sees when one looks at them with an oscilloscope, it is often more convenient to work with the envelope (amplitude at the reference frequency) of the signals with respect to rotor position. Shown in fig. 4e is the envelope of the sine secondary signal with respect to rotor position. The process of removing the carrier signal—leaving just the envelope—is called demodulation and is performed by the Resolver-to-Digital (R/D) converter. The demodulated sine and cosine resolver signals are shown in fig. 4f.

The resolver-to-digital converter 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 most popular method of performing these functions is called ratiometric tracking conversion. Since the resolver secondary signals represent the sine and cosine of the rotor angle, the ratio of the signal amplitudes is the tangent of the rotor angle. Thus the rotor angle, **θ**, is the arc tangent of the sine signal divided by the cosine signal: **θ = arctan(sin(θ) / cos(θ)) = arctan(Vs/Vc)**

The ratiometric tracking converter performs an implicit arc tangent calculation on the ratio of the resolver signals by forcing a counter to track the position of the resolver. This implicit arc tangent calculation is based on the trigonometric identity:

$$\sin(\theta - \delta) = \sin\theta \cos\delta - \cos\theta \sin\delta$$

This equation says that the sine of the difference between two angles can be calculated by cross multiplying the sine and cosine of the two angles and subtracting the results. Further, as long as the difference between the two angles is relatively small (**δ = θ ± 30°**), the approximation **sin(θ - δ) ≈ θ - δ** may also be used, further simplifying the equation. Thus, if the two angles are within 30° of each other, the difference between the angles can be calculated using the cross multiplication shown above.

In the R/D converter, this equation is implemented using multiplying D/A converters to multiply the resolver signals (**proportional to sin θ and cos θ**) by the cosine and sine of the digital angle, **δ** , which is the output of the converter, as shown below. The results are subtracted, demodulated by multiplying by the reference signal, and filtered to give a DC signal proportional to the difference or error between the resolver angle, **θ**, and the digital angle, **δ**. The digital angle, **δ**, stored in the counter, is then incremented or decremented using a voltage controlled oscillator until this error is zero, at which point **δ = θ** (the digital angle output of the converter is equal to the resolver angle). This incrementing and decrementing of the digital angle, **δ**, causes it to track the resolver angle, **θ**, hence the name of this type of converter.

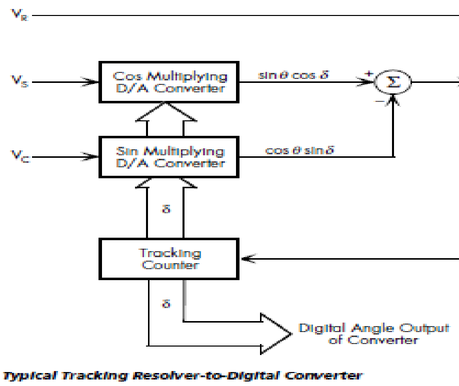


Fig. 5 Schematic on operating principle of analogue – digital converter (resolver to digital converter)

Above were presented some general aspects on bipolar resolver. But, to increase the accuracy, the resolver is built in a version with more poles (2**p**) – 4, 8, 16, or 32 pairs (**p**) of poles. On this way, the resolver is loosing the absolute character and it is necessary to add a supplementary set of windings in a bipolar configuration. In this situation, the operating main and simplified equations are:

Primary Input: **V(R1–R2) = VR =** E_{1max} **sin ωt**
Sine Secondary: **V(S2–S4) = VS = VR TR sin(pθ)** ***Cosine Secondary:*** **V(S1–S3) = VC = VR TR cos(pθ)**

$$p\theta = \arctan(\sin(p\theta) / \cos(p\theta)) = \arctan(Vs/Vc)$$

2.2. Typical windings for resolver

The topology of windings used in resolvers has a sinusoidal character that means a non homogenous distribution of wiring in different slots – the distribution is according with a sinusoidal rule to obtain as final effect an output signal very closed with a sine form. However, using only a sinusoidal type of winding do not solve completely the problem because there are other many factories that influence the accuracy level of resolver, as; quality of magnetic material, using slot solution, mechanical building asymmetries, the influence of the temperature on the material properties and winding characteristics etc. Some from these factories are controllable, but some of them are random. It is very important to take into consideration the controllable factories even from design stage, to reduce at minimum their influence.

In a bipolar resolver (absolute character), a frequent solution used to obtain a good accuracy is a lamination having many slots, to be possible to do better sinusoidal distribution.

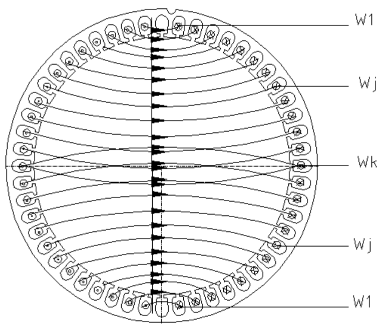
If we discuss about multipolar resolvers, the number of slots per pol, from phisical point of view, is limited, frequently between 1 and two. In this situation, a special winding schema is used, but the final accuracy is a basis accuracy (two poles) divided at number of pole pairs (**p**).

Below it is shown an example of sinusoidal winding, in a concentric configuration, used for bipolar resolver (when it is possible to have more slots per pole). Let us to consider a winding having ***4k*** slots, as it is shown in fig. 5. The concentric windings have different dimensions (paths), from **1÷2** to **1÷k+1**. The windings from the slots **j, (j, 2k-j)** and **(2k-j, 2k+j)**, have the same numbers of turns N_j **/2**, and are equally distanced from the two poles.

If we consider to have **W** turns per pole, so:

$$\sum_{J=1}^{K} Nj = W/2,$$

Also, let us to consider that at a moment of time - t_o – the electric current trough winding is $\mathbf{I\sqrt{2}\sin\omega t_o}$.



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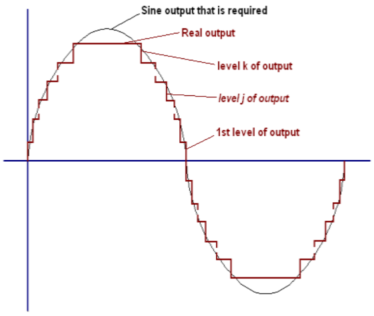

b.

Fig. 6 Relative to sinusoidal winding, in bipolar concentric configuration, for construction with 4k slots

Using the fundamental relations from electromagnetism and superposition method, we can find the solution for winding number in the slot marked with ***j***:

$$\mathbf{N_j=W/2\cdot\sin(j\pi/2K)/[\textstyle\sum_{i=1}^{K}\sin(j\pi/2K)],\quad j=1,2\ldots K}$$

The diagram of this field is shown in fig. 6b.

2.3. Some consideration regarding vectorial measurement methods

Testing resolvers at very small angular increments or at better than 1 arcsecond (.00028 degrees) accuracy requires a high precision instrument. A high precision ratio transformer can provide the accuracy and resolution needed for testing resolvers at small angular increments. To check the angular accuracy of a resolver the AC reference, resolver, ratio transformer and a phase angle voltmeter (PAV) are connected as shown in Fig.7.

Since S4 is the cosine output of the resolver, the output of the ratio transformer should equal the sine output:

[tan(θ) = sin(θ) /cos (θ), or sin(θ) = tan(θ) cos (θ)]

S1 is the sine output of the resolver; the output of the ratio transformer should be equal with S1 output of the resolver. If the two outputs are equal, the PAV will indicate a null condition. If the PAV does not indicate a null condition, the setting of the ratio transformer is adjusted until a null condition is indicated. The arctangent of the ratio transformer setting is the angle that the resolver output is indicating. On the other hand, for different positions of resolver rotor relative to resolver stator, the measurement system measures and computes:

$\mathbf{[\tan(\varphi)]_{sin} = (U_{sin})_f / (U_{sin})_q}$ **si** $\mathbf{(U)_{sin} = sqrt((U_{sin})_f^2 + / (U_{sin})_q^2))}$, respectively

$\mathbf{[\tan(\varphi)]_{cos} = (U_{cos})_f / (U_{cos})_q}$ **si** $\mathbf{(U)_{cos} = sqrt((U_{cos})_f^2 + / (U_{cos}))_q^2}$,

where:

$\mathbf{U_{sin})_f}$ = the part of sine output having the same phase with input

$\mathbf{U_{sin})_q}$ = the part of sine output having 90^0 phase shift with input

$\mathbf{U_{cos})_f}$ = the part of cosine output having the same phase with input

$\mathbf{U_{cos})_q}$ = the part of cosine output having 90^0 phase shift with input

For example, if a resolver shaft were set to angle of 20°, the ratio transformer would be set to the tangent of 20° which is 0.3639702. The null meter does not indicate a null and the ratio transformer are adjusted until it does. The final setting of the ratio transformer is 0.3639200; the arctangent of that value is 19.9975°.

The resolver error is therefore 0.0025°, that means - 9arcseconds.

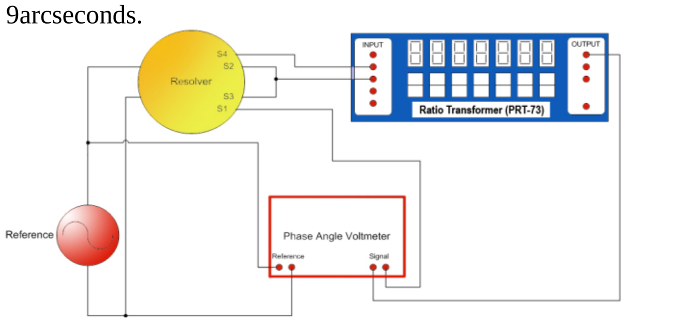

Fig. 7 Schematic on the stand to do vectorial measurement of resolvers

2.4. Aspects on resolver accuracy

The accuracy of the resolver has to be analysed in connectied with the configuration of resolver and application.

If a single phase resolver is used, we can consider only the error relative to the fidelity of the signal according with ideal sinus form. Let us consider that the induced voltage, when the load of resolver is null, can be expressed: E_{bo} = VR TR sin(θ). On the other hand, the induced voltage in load conditions can be expressed: E_b = VR TR sin(θ) – j X I $\cos^2(\theta)$. The last relation can be expressed and as: $E_b = E_{bomax} \sin(\theta) / (1+b \cos^2(\theta))$. On this way, we can define a relative error as:

$$\Delta E_b = (E_{bo} - E_{br}) / E_{bomax} = (b \cos^2(\theta) \sin(\theta) / ((1+b \cos^2(\theta)).$$

In the most part of applications, are used both windings, so we have to consider the differences between the amplitude of the two signals, as well as the error of quadrature.

The main factories that are influencing the accuracy are: the status of general machining (technologies, mechanical accuracy, heat treatment etc.), than the quality of the materials; the total impedance of the measurement system; excursion of amplitude of input voltage, as well as the value of the input frequency; excursion of the temperature during operation; rotation speed of the resolver etc.

III. RESULTS AND CONCLUSIONS

Most part from authors are working from long time as researchers, designers and producers of special electric machines. In these conditions, the resolver was one of main components to develop, to design and to produce. Different configurations, different sizes and different parameters are subjected with the author's activity. Bipolar resolvers 05, 08, 11, 15 or bigger sizes were developed for different applications, in many fields.

20 seconds of arc or 1 minute of arc accuracy were obtained on resolvers 19 or 29 sizes, having 32 poles. The methods of design used the most modern concepts, including numerical analysis of electromagnetic field. The methods of testing are based on vectorial measurement systems.

As conclusion, we can remark that the resolver component is superior to many other kind of absolute or relative position transducers because of its ruggedness and ability to provide a very high degree of angular accuracy under severe conditions.

There are not optical parts to keep clear of smoke or oil that often disrupt the operation of optical encoders. Because the resolver has two outputs that are subjected to tangent function, the input signal anomalies have a low influence. The resolver saves size and weight, being substantially smaller than other transducers approaches and easily integrated into any system.

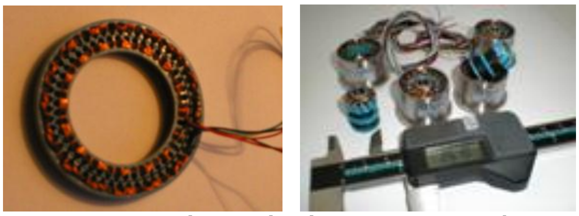

Fig.8 Resolvers produced at S.C. Sistem Euroteh

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