



Optimal winding selection for wound-rotor resolvers

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Abstract. Wound-Rotor (WR) resolvers are the most commercially used resolvers in industrial applications. In this regard, the present study evaluates the effect of different winding arrangements on the accuracy of WR resolvers. To this end, three windings were proposed for the stator of the resolver containing on-tooth overlapping winding, distributed lap winding, and distributed concentric winding. Those windings were also applied to the rotor. All the rotor windings were assumed to be single- and two-phased. In addition, the effect of damper winding was also evaluated in this study. The analysis was done using time-stepping finite element method, and the most accurate resolver was built and tested. Close agreement between the results from experimental measurements and finite element confirms the obtained results.

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1. Introduction

Resolvers are one of the most common position sensors in industrial applications. In industries with special conditions such as wide temperature variation, high vibration level, and polluted environments, resolvers are the most promising choice [1–3]. In such applications, the optical encoders, the only competitors of the resolvers in terms of accuracy, lose proper operation. However, compared to encoders, resolvers are costly. In this regard, Variable Reluctance (VR) resolvers have recently caught researchers' attention to be applied in some industries [4,5]. The rotor of VR resolvers is characterized by a solid structure without any winding. Therefore, there is no need for rotary transformer in VR resolvers. In other words, VR resolvers are more efficient than the conventional WR resolvers in terms of cost. However, the application

of VR resolvers is subject to several challenges. To discuss such challenges, the VR resolvers should be categorized first. These resolvers operate based on the sinusoidal variation of air-gap reluctance. In this regard, two types of VR resolvers emerge: Sinusoidal Air-Gap Length (SAGL) ([3–9]) and Sinusoidal Area (SA) resolvers [10–14]. The commercial VR resolvers are SAGL types. They suffer from inappropriate performance in two-pole applications and high accuracy deterioration under eccentricity faults. To overcome the first challenge in [8], a new structure is proposed for SAGL resolvers. Despite the acceptable accuracy of that resolver, it has an excessive axial length in comparison with that of conventional SAGL resolvers. To improve the resiliency of the SAGL resolver under eccentricities, disk type resolvers were proposed [3,9]. Furthermore, SA resolvers were also proposed to overcome the disadvantages of the SAGL resolvers [10]. However, they have their own drawbacks, i.e., huge dimensions and inappropriate performance under run-out fault. In [11,12], a new optimized structure was proposed to solve the problems. However, their proposed structure needs more improvements to be

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comparable with conventional WR resolvers from the accuracy point of view. Some other affordable two-pole resolvers were proposed in [15] that were not applicable in high-accuracy applications.

Finally, according to the authors' best knowledge, the most accurate commercial two-pole resolvers are still WR resolvers. Accordingly, this paper sets forth the accuracy improvement of two-pole WR resolvers. Numerous studies have been conducted on the performance improvement of WR resolvers [16–23]. For instance, in [17], the effect of physical parameters of a disk-type WR resolver on its accuracy was discussed. As shown, for a given number of slots, the estimated position error affects the pole numbers of resolvers. Increasing the number of poles ensures the higher accuracy of the resolver. However, mechanical difficulties hinder the manufactures' ability to increase the pole numbers by increasing the slot numbers. To overcome this constraint, in [18,19], new winding methods including fractional slot concentrated winding were proposed for large-pole-number WR resolvers with a small number of slots. However, it seems that the accuracy of the estimated position can increase further. In this regard, in [2], the genetic algorithm was used to calculate the optimal winding of a high pole number disk type resolver. Moreover, in [20], it was suggested that damper winding be used to improve the performance of a disk-type resolver under eccentricities. The frequency response of a cylindrical resolver was presented in [21]. In [22], the performance of a cylindrical WR resolver under static, dynamic, and mixed eccentricities was evaluated. An analytical model based on the d-q axis theory was proposed in [23]. However, most of the mentioned studies have employed the distributed winding or fractional slot concentrated winding for their studied resolvers. The winding arrangement had significant influence on the performance of WR resolvers. In this respect, different winding methods were used for the stator and rotor of WR resolvers in this study, and the best one was selected for experimental evaluation based on the minimization of position error.

2. The studied resolver

The studied resolver is a two-pole WR cylindrical resolver containing 24 slots in the stator and 20 in the rotor. A Rotary Transformer (RT) is used to feed the excitation winding of the rotor. The primary winding of the RT is fed by a high-frequency sinusoidal voltage, and the induced voltage in the secondary coil of the RT located on the rotor is used to supply the excitation voltage of the rotor. There is single- or two-phase winding on the rotor of the resolver. The first mandatory phase is called excitation winding which is connected to the secondary coil of RT. The next optional winding with a 90-degree phase difference with

respect to the excitation winding is a short-circuited winding, also called damper winding. The effect of the existence of the damper winding on the accuracy of the resolver was taken into account in this paper. The stator of the resolver is equipped with two-phase windings that have 90-degree phase difference with each other, called signal windings (sine and cosine windings). The signal windings are connected to a Resolver-to-Digital Converter (RDC) that has high input impedance [24]. In this respect, the signal windings can electrically be assumed as an open circuit. Figure 1 shows the stator and rotor of the studied resolver, and Table 1 presents its geometrical dimensions. Both of the stator and rotor cores are made of identical laminated ferromagnetic materials.

The present study mainly focuses on the winding arrangement of the stator and rotor. Different arrangements are suggested for the studied resolver in the next section.

To better clarify the position detection strategy, it is assumed that the primary coil of the RT is fed by an input voltage as shown in the following:

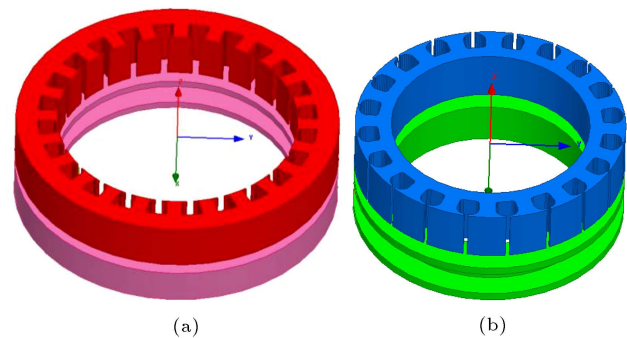


Figure 1. The studied resolver: (a) The stator core and the primary core of RT and (b) the secondary core of RT and the core of rotor.

Table 1. The geometrical dimensions and the excitation information of the studied resolver.

Parameter	Unit	Value
Slot numbers: stator/rotor	-	24/20
Pole pairs	-	1
Air-gap length	mm	1
Stator/ rotor outer diameter	mm	46/32
Stator slot opening width/height	mm	1/0.2
Rotor slot opening width/height	mm	0.5/0.3
Stator/rotor slot height	mm	2/2.4
Stator/rotor slot width	mm	3/2.4
core length: stator/rotor	mm	6.7
Rotational speed	rpm	300
Excitation voltage amplitude	V	5
Excitation frequency	kHz	4

$$V_{RT1} = V_m \cos(\omega t), \quad (1)$$

where V_m is the amplitude of the voltage fed to the primary coil of RT and ω is the angular frequency. The induced voltage in the secondary coil of RT (V_{RT2}) can be written as:

$$V_{RT2} = \frac{N_2}{N_1} V_m \cos(\omega t), \quad (2)$$

where N_1 and N_2 are the numbers of primary and secondary coils turn, respectively. The excitation current (I_{ex}) can be calculated as follows:

$$I_{ex} = I_{\max} \cos(\omega t - \varphi), \quad (3)$$

$$I_{\max} = \frac{N_2 V_m}{N_1 \sqrt{R_{ex}^2 + L_{ex}^2 \omega^2}}, \quad (4)$$

$$\varphi = \text{Arctan} \frac{L_{ex} \omega}{R_{ex}}, \quad (5)$$

where R_{ex} and L_{ex} are the resistance and inductance of the excitation winding, respectively. The induced voltage in the signal windings can be written as follows [25]:

$$V_a = -r_s i_a + M I_{ex} \frac{d\vartheta}{dt} \cos(\vartheta) - M I_{\max} \omega \sin(\vartheta) \sin(\omega t - \varphi), \quad (6)$$

$$V_b = -r_s i_b - M I_{ex} \frac{d\vartheta}{dt} \sin(\vartheta) - M I_{\max} \omega \cos(\vartheta) \sin(\omega t - \varphi), \quad (7)$$

where V_a and V_b are the phase voltages, r_s the resistance of the signal winding, M the mutual inductance between stator circuit and excitation winding, ϑ the rotor position; and i_a and i_b are the phase currents. The two first phrases in Eqs. (6) and (7) are negligible. Since the stator currents are almost zero and the excitation frequency (ω) is much higher than the rotor speed ($d\vartheta/dt$), the rotor position (ϑ) can be calculated as follows:

$$\vartheta = \tan^{-1} \left(\frac{V_a}{V_b} \right). \quad (8)$$

A comparison of this position with the reference position yields the position error.

3. Proposed winding arrangements

Three different arrangements were examined for the stator winding namely Swdg1, Swdg2, and Swdg3. Those arrangements are shown in Figure 2. In this figure, Swdg1 is an overlapping on-tooth variable turn

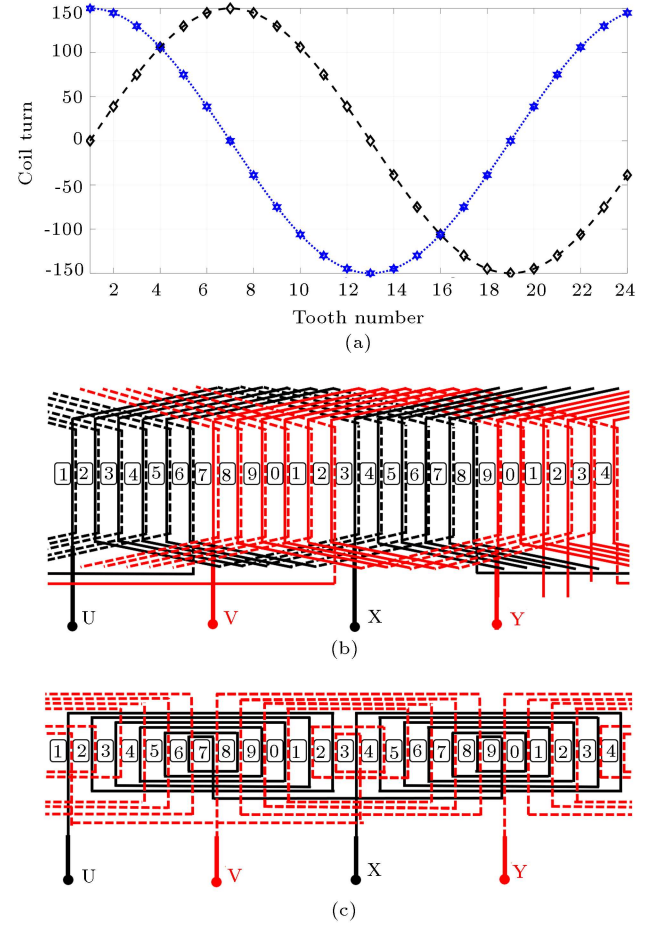


Figure 2. The proposed stator windings: (a) Swdg1, (b) Swdg2, and (c) Swdg3.

winding. The turns of sine and cosine coils on the i th stator tooth are determined as follows [1]:

$$N_{s,i} = N_{\max} \times \sin P_w \left[\frac{2\pi}{Z} (i-1) \right], \quad (9)$$

$$N_{c,i} = N_{\max} \times \cos P_w \left[\frac{2\pi}{Z} (i-1) \right]. \quad (10)$$

Here, $N_{\max} = 150$ represents the maximum number of coil turns, $P_w = 1$ the winding pole pair, and $Z = 24$ the number of stator teeth. Although using different turns in each coil and overlapping configuration make Swdg1 practically too hard to be implemented, short overhang length and significant slot space usage are deemed as the merits of this configuration.

Swdg2 is a lap-distributed winding. Usually, in such a winding type, all the coils have identical coil pitch and turn numbers. Therefore, preparation of the coils for winding is easy. However, to improve the performance of the resolver in this paper, the sinu-soidally distributed turn numbers are used for winding. Generally, it is believed that using distributed winding

in electrical machines results in higher efficiency, higher amplitude of fundamental harmonic, and more desirable performance. These advantages should be evaluated for resolvers. However, Swdg2 has one drawback, i.e., its overhang length is longer than that of Swdg1.

Swdg3 is a concentric winding. The coil pitch and the turn number of coils are subject to variation in this configuration. It is also a common winding type in the commercial WR resolvers.

The above-mentioned three arrangements are considered for rotor as well. The proposed rotor windings, Rwdg1, Rwdg2, and Rwdg3, are listed in Figure 3. As mentioned in [20], using damper winding had no significant effect on the accuracy of the aligned resolver; however, under eccentricities, it could help improve the accuracy of faulty resolver. Consequently, despite the increasing copper usage, it is preferred to add the damper winding on the rotor of WR resolvers.

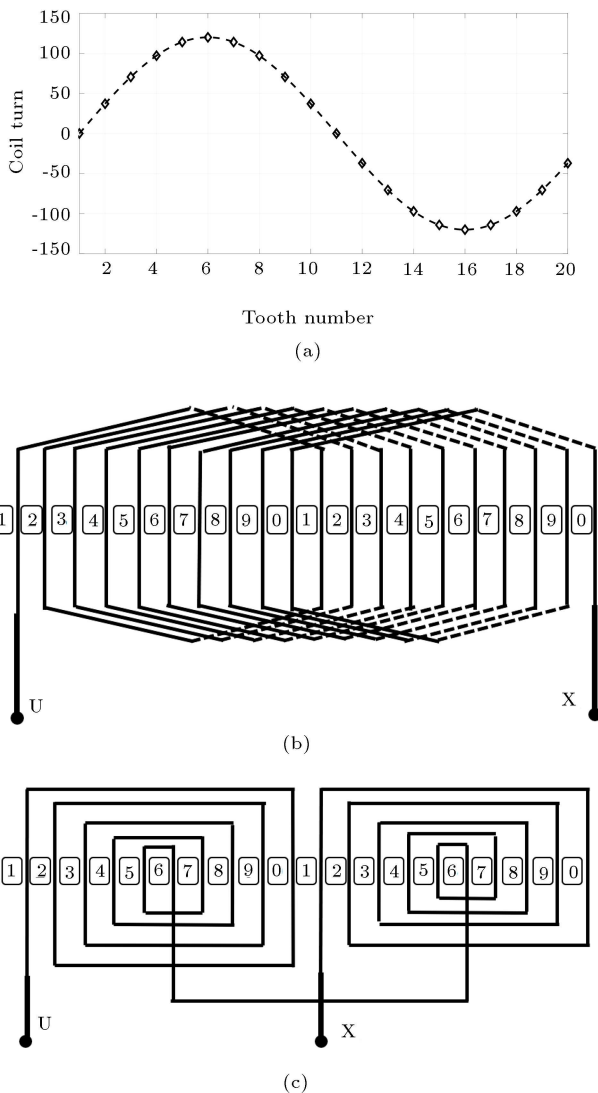


Figure 3. The proposed rotor windings: (a) Rwdg1, (b) Rwdg2, and (c) Rwdg3.

4. Finite element analysis

Time-stepping finite element analysis was employed to evaluate the proposed windings. To ensure that the employed mesh quality was good enough to obtain accurate results within a well-advised computation time duration, the optimal mesh was imported from magnetostatic solution to transient solution environment [26]. Furthermore, the distribution of magnetic flux density on the studied sensors was checked to ensure that the sensor was working in the linear part of the magnetization curve of the ferromagnetic material.

Another important point in resolver simulation is the correct selection of the time step and excitation frequency. The time step must be chosen such that at least 16 points would exist in one cycle of excitation frequency. Although both current source and voltage source are commonly used in the finite element simulation of resolvers, the last one is selected in this paper to take both space and time harmonics into account.

The simulations are categorized into two parts: without damper winding and with damper winding.

4.1. Without using damper winding

In this section, the simulation results for nine resolvers with the described windings listed in Table 2 are presented. Figure 4(a) shows the analogue voltages of Res1. As observed, the envelopes of the voltages are sine and cosine functions which are used for calculating the position. To calculate the envelope of the voltages, Hilbert transform was used in MATLAB software. Frequency analysis of the envelope presented in Figure 4(b) denotes the dominant harmonic in output voltage as the third one. Total Harmonic Distortion (THD) of the envelope is about 0.11%. It should be mentioned that although low THD is a required term for the acceptable performance of a resolver, it is not an adequate condition, because it is devoid of sensitivity to harmonic order and the harmonic phase. So, it is required to calculate the

Table 2. Different combinations of stator and rotor windings.

Resolver	Stator winding	Rotor winding
Res1	Swdg1	Rwdg1
Res2	Swdg1	Rwdg2
Res3	Swdg1	Rwdg3
Res4	Swdg2	Rwdg1
Res5	Swdg2	Rwdg2
Res6	Swdg2	Rwdg3
Res7	Swdg3	Rwdg1
Res8	Swdg3	Rwdg2
Res9	Swdg3	Rwdg3

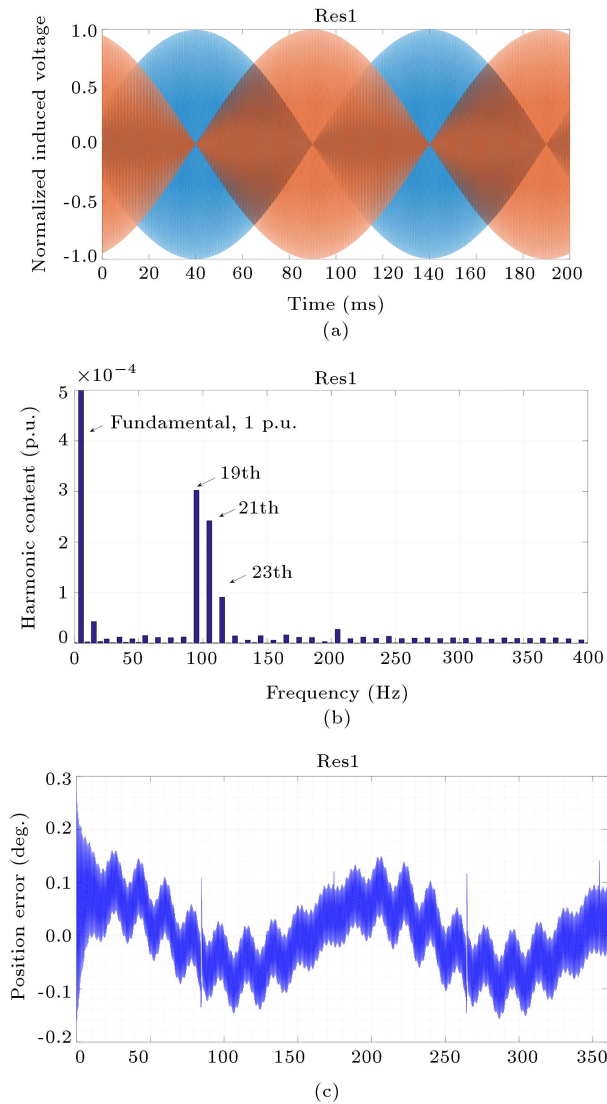


Figure 4. The results of finite element simulation of Res1: (a) The analogue voltages, (b) frequency spectrum of voltages' envelope, and (c) position error.

position error to ensure fair and accurate judgment about resolver's performance.

Figure 4(c) shows the position error of Res 1. It can be seen that the Maximum Position Error (MPE) and the Average of Absolute Position Error (AAPE) are 0.2684° and 0.0545° , respectively.

For the sake of brevity, the results of performance analysis of the other resolvers are reported in the next section along with those of resolvers with damper.

4.2. With damper winding

As mentioned earlier, damper winding is a short-circuit winding that has a 90-degree phase difference with respect to the excitation winding on the rotor. The rotor windings considering the damper winding are shown in Figure 5(a) to (c), called Rwdg4, Rwdg5, and Rwdg6, respectively. So, all the simulations are

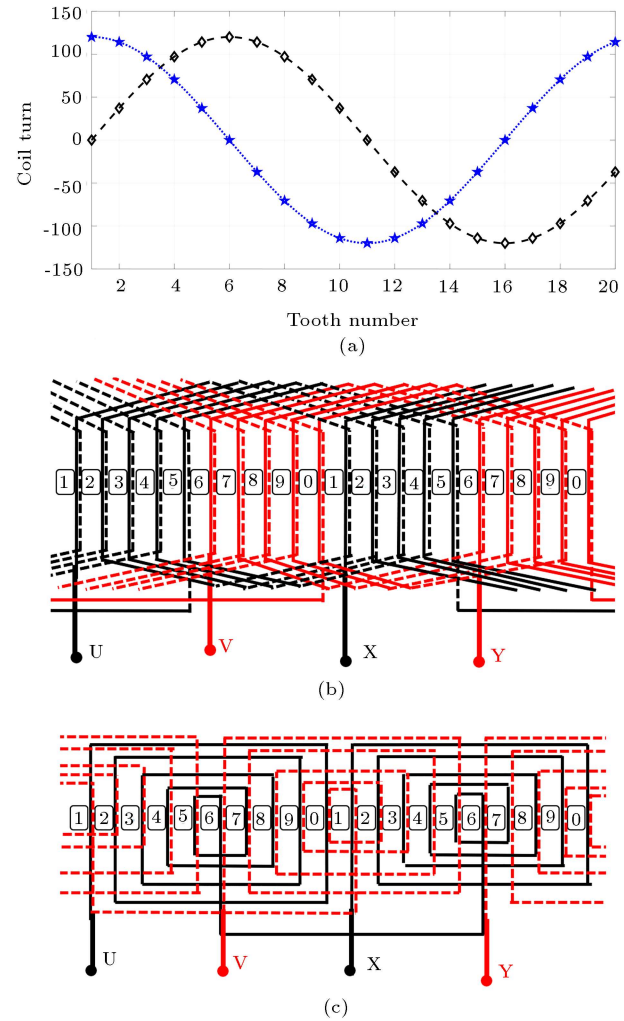


Figure 5. The proposed rotor windings equipped with damper winding: (a) Rwdg4, (b) Rwdg5, and (c) Rwdg6.

repeated with new rotor windings. Figure 6(a) to (c) compare the THD of voltages' envelopes, MPE, and AAPE of the Res1 through Res9 with and without damper winding. It can be seen that from THD point of view, the lowest THDs without damper winding belong to Res 9 (0.076%) and Res 3 (0.082%), respectively. Using damper winding improves the THD in all cases. However, when the stator has distributed lap winding and the rotor has distributed concentrated winding (Res6), the improvement is insignificant. On the other hand, Res9 with concentrated winding on both the stator and the rotor shows the highest improvement on the value of THD. The THD of Res9 decreases from 0.076% to 0.035% after using damper winding. Comparison of the MPE of the resolvers before and after using damper winding in Figure 6(b) shows that the worst case is related to Res6 that is equipped with distributed lap winding on the stator and concentrated winding on the rotor. Furthermore, using concentrated winding on the stator with on-tooth or concentrated

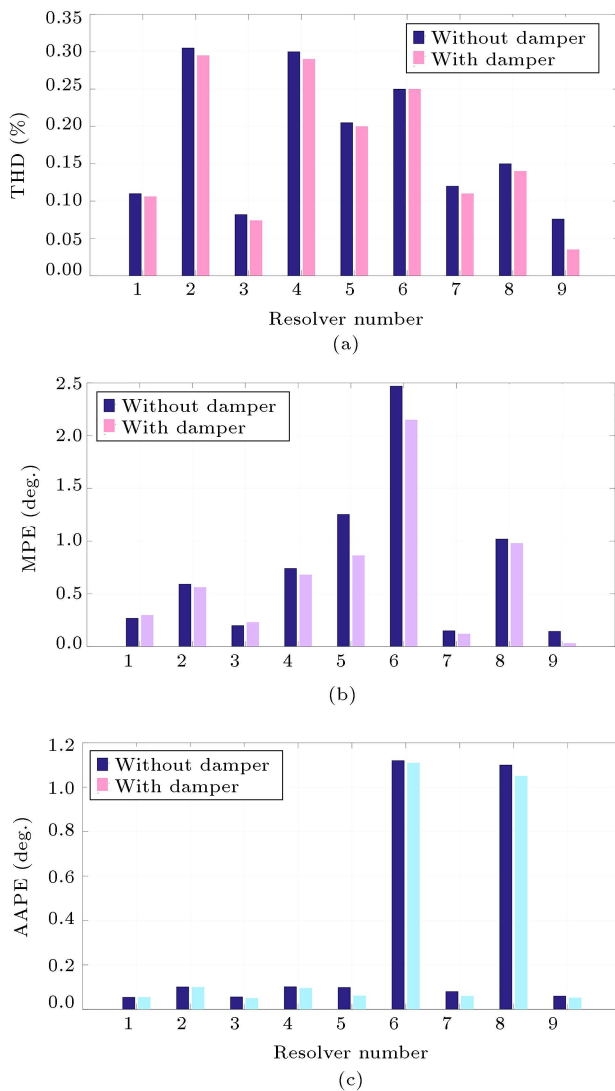


Figure 6. Comparing the performance of different resolvers with and without damper winding: (a) THD of voltages' envelope, (b) MPE, and (c) AAPE.

winding on rotor generates lower MPE than other winding combinations. However, it is worth mentioning that the best indicator for resolver accuracy is AAPE. Therefore, AAPEs of different resolvers are compared in Figure 6(c). It can be seen that the combination of lap and concentrated windings does not yield a promising result. The two most accurate resolvers without using damper winding are Res1 and Res3 with the AAPEs of 0.0545° and 0.0556° , while the most accurate resolver after adding damper winding is Res3 with the AAPE of 0.0497° .

5. Experimental evaluation

The most accurate resolver (Res3, with damper winding) is chosen for experimental evaluation. The prototype of the sensor is built and the optimal winding

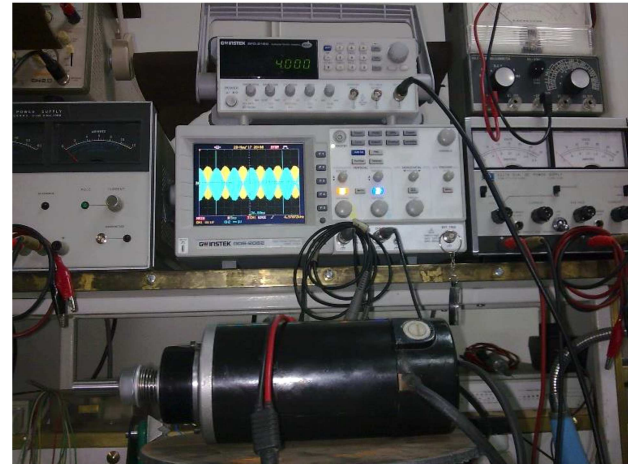


Figure 7. The test circuit of the studied resolver.

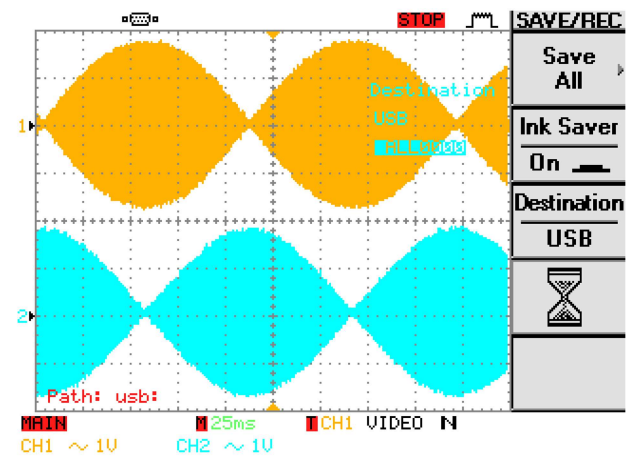


Figure 8. The analogue voltages of the prototype resolver.

is applied for measurements. Figure 7 shows the test circuit of the resolver where a DC motor is employed as a prime mover and a programmable optical encoder as a reference sensor. The output voltages of the resolver are saved and captured using a digital oscilloscope. The excitation voltage of the RT's primary coil is obtained from a digitally synthesized function generator.

The measured analogue voltages are shown in Figure 8. Similar to simulation results, the Hilbert transform is used to calculate the envelopes and the position error in off-line method. Table 3 shows THD of envelopes, MPE, and AAPE in comparison with those of simulation results. It can be seen that the error between the simulation and experimental results is less than 10%, which confirms the accuracy of the simulations.

6. Conclusion

In this study, the effect of stator and rotor windings' arrangement on the accuracy of wound rotor cylindrical

Table 3. Comparison between the simulation and measured results of Res3 with damper winding.

	Measured	Finite element simulation
THD (%)	0.082	0.0740
MPE (deg.)	0.252	0.2302
AAPE (deg.)	0.055	0.0497

resolver was discussed. Three different windings were applied to the stator including on-tooth winding, lap winding, and concentrated winding. For rotor, the mentioned windings were applied with and without damper winding. Therefore, the effect of damper winding on the performance of the resolver was also clarified. Finally, it was shown that the highest improvement for the average of absolute position errors was achieved in the application of damper winding in Res3, which was equipped by both on-tooth winding on the stator and concentrated winding on the rotor.

Simulations were done using time stepping finite element analysis and verified by experimental measurement on the prototype of the most accurate resolver.

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