Comparing Different Configurations for Rotary Transformer of Wound-Rotor Resolvers

M. Khazaee, and F. Tootoonchian*, Senior Member, IEEE

Abstract—Wound-Rotor resolvers are the oldest and the most widely used resolvers. They are two-phase synchronous generators with high frequency AC excitation. Rotary Transformers (RTs) are used to supply the rotating excitation winding of the resolver. Although RTs offer the benefits of contactless power transmission, harmonic contents of the secondary voltage, phase shift error between the primary and the secondary voltages, and high leakage flux are the main challenges in their usage along with resolvers. Therefore, in this paper, different configurations are examined for RT’s ferromagnetic core to overcome the mentioned problems. All the simulations are done using 3-D time variant finite element method (TVFEM) and the best configuration is chosen for experimental prototyping and measurements. Close agreement between the simulation and the experimental test results approves the performed analysis.

Keywords—Wound Rotor (WR) Resolver, Rotary Transformer (RT), Time Variant Finite Element Method (TVFEM), Phase Shifting Error, Leakage Flux, Total Harmonic Distortion (THD)

M. Khazaee is with Iran University of Science and Technology (IUST), Tehran, Iran (Email: mehrzadkhazaee13721379@gmail.com )

*F. Tootoonchian (Corresponding author) is with Electrical Engineering Department, Iran University of Science and Technology (IUST), Tehran, Iran, (Email: tootoonchian@iust.ac.ir), +98-9121792802.
1. INTRODUCTION

The widely used commercial position sensors are resolvers, optical encoders and hall-effect sensors. Although the last one is the most cost efficient position sensor [1], it has no acceptable accuracy in high performance motion control systems [2]-[3]. Optical encoders have the advantages of high accuracy and acceptable price simultaneously. However, they suffer from sharp accuracy reduction in harsh environments [4]-[5]. In such applications, resolvers are the best choose [6]. Commercial resolvers are divided into two groups: wound-rotor (WR) resolvers and variable-reluctance (VR) ones. From historical point of view, WR resolvers are the oldest type of resolvers. Their simple description is two-phase, AC excited synchronous generators. They can be built in brushed or brushless configuration. The first is extinct now and for the second configuration a rotary transformer (RT) is required. However, since the employed RT is a non-ideal electrical machine its usage leads to some difficulties due to leakage flux of the RT and the phase shift error between the primary and the secondary voltages. The first challenge leads to the necessity of using shields along with the resolver and the next causes higher position error of the resolver to digital converter (RDC). In fact, the commercial RDCs, tracking RDCs, use the voltage of the RT’s primary coil as the excitation voltage of the resolver and any phase shift between the real excitation voltage of resolver (the secondary voltage of RT) and the primary voltage of RT leads to increase the error in finding the envelope of the amplitude modulated voltages and consequently, higher position error of the resolver. The mentioned challenges are the research area of this paper. It means different geometrical configuration of RTs are examined to achieve the best structure with the aim of minimum phase shift error and the lowest leakage flux. Another solution for the mentioned challenges is omitting RT. Without RT, the rotor of the resolver should have had no winding. VR resolvers have such specification. They work based on sinusoidal variation of air-gap permeance and their excitation winding is transferred to the stator side. Therefore, they need no RT [7]. However, they have two main drawbacks: high sensitivity against mechanical tolerances and low accuracy absolute position measurement [8]-[9]. Therefore, despite the simple structure of VR resolvers, WR ones are the mostly available sensors in industrial applications.
There are many researches on WR resolvers, while those of RTs are limited. In [10] RT’s individual core is omitted and the resolver’s core is used for the RT. Although the proposed structure helps to reduce the sensor’s overall volume, the flux interference between the RT’s coils and resolver’s windings leads to sensor’s accuracy deterioration. In [11] some solutions are proposed to reduce the mentioned flux interference. Then, an analytical model based on magnetic equivalent circuit is proposed to improve the accuracy of the resolver with no RT core in [12]. However, the accuracy of that resolver after all improvements is lower than a similar sensor with RT core.

In [13] a new method based on DC-pulse response of RT’s primary coil is proposed for parameter identification of a rotary transformer. Although the proposed method is verified by experimental measurements, the performance evaluation of the studied RT was out of paper’s area. A flat plane RT is proposed in [14] for feeding the rotor winding of a wound rotor machine. In [15] a cascade RT configuration is proposed for using with brushless doubly fed induction machine (BDFIM). Another configuration so-called L-form configuration is proposed in [16]. RT with wafer-form winding is developed in [17] for hybrid vehicle applications. In [18] a new configuration with segmented primary core is proposed for supplying circuit of an ultrasonic shaker. The proposed design of [18] has a high leakage inductance and low power loss. Another configuration based on toothed primary and secondary cores is proposed in [19]. In that configuration the weight of the employed ferromagnetic material is less than that of conventional RTs in the price of higher leakage inductance. In [20] another configuration with non-magnetic rotor core is presented for RT that make it suitable for high speed applications. However, due to high electromagnetic air-gap length the performance of the design in the term of magnetization current and leakage flux is not appropriate.

Despite different innovate configurations that are proposed in literatures, their performance evaluation in the terms of phase shift error, the amplitude of leakage flux is not studied, yet. Therefore, in this paper the performance of different configurations is compared using finite element analysis. The outer/inner diameter of ferromagnetic core, its horizontal length and the number of copper coil’s turn and wire’s diameter are kept constant for all configurations. The load and the excitation of the studied RTs are assumed to be identical.
and finally, the best configuration is chosen for experimental evaluation. It worth mentioning that leakage inductance of the windings is calculated and compared to decide on the configuration with the lowest leakage flux.

2. The Studied Configurations

Six different configurations as given in Fig. 1-a through 1-f are studied in this paper. RT1, Fig. 1-a, is referred to the conventional RT that usually is used with cylindrical resolvers. Flat-plane, disk type RT [14] that is given in Fig. 1-b, is called RT2. RT3, L-form RT, is given in Fig. 1-c [16]. Fig. 1-d, shows RT4, segmented primary core RT [18]. RT with toothed cores is given in Fig. 1-e [19], so-called RT5. Finally, RT6 is shown in Fig. 1-f that equipped with sandwiched winding [20]. All the studied configurations are designed to have a constant volume in constant outer diameter and constant overall length. Other geometrical dimensions of the RTs are presented in Table I.

Primary coil of all RTs has 100-turn conductors and their secondary coil has also 100-turn. The primary coil is fed using 5V, 4 kHz sinusoidal voltage as given in Fig. 2.

The design steps for a rotary transformer are the same as high frequency transformers. The common design method for such transformers is the area product, i.e., transformer window area times the cross-sectional area. However, the main difference between the design of RT with that of common high frequency transformers (HFTs) is referred to the selecting core. In design of HFT, the dimensions of the core is determined using area product and then, the closest dimensions to the calculated one is selected along available commercial cores. However, the employed cores for RTs have no standard. Therefore, the main dimensions must be calculated according to the calculated area product. The design process for the RTs is shown in Fig. 3. According to Fig. 3, the first step in the design is choosing the ferromagnetic martial (maximum flux density of the core, Bm), frequency (f), primary nominal voltage (V1), current density (Jw), wave form factor (Kf), and the space factor (Ku). Then, the area product can be calculated as:
\[ A_p = A_c.A_w = \frac{V_1I_1 + V_2I_2}{K_f.K_u.f.B_m.J_w} \]  \hspace{1cm} (1)

where \( A_c \) is the appropriate core size and \( A_w \) is the transformer’s window area. The core dimensions should be determined according to the selected geometry, maximum speed, and the allowed volume of the RT. The next step is calculating the turn numbers considering the nominal voltage. The diameter of the copper conductors are determined considering the nominal current and the current density. After, approving the performance of the RT, its electrical and mechanical parameters can be calculated.

Considering the flux linkage of the primary (\( \lambda_1 \)) and secondary (\( \lambda_2 \)) coils as:

\[ \lambda_1 = N_1\varphi_1 = N_1(\varphi_{11} + \varphi_m) \]  \hspace{1cm} (2)

\[ \lambda_2 = N_2\varphi_2 = N_2(\varphi_{22} + \varphi_m) \]  \hspace{1cm} (3)

Where \( N_1/N_2 \) is the turn number of primary/secondary coils, \( \varphi_1/\varphi_2 \) is the total flux of primary/secondary coils, \( \varphi_{11}/\varphi_{22} \) is leakage flux of primary/secondary coils and \( \varphi_m \) is the mutual flux.

Considering the relation between the magnetomotive force (MMF), magnetic flux (\( \varphi \)) and permeance (P) as:

\[ \varphi = P \times \text{MMF} \]  \hspace{1cm} (4)

Substituting the permeance relation, (3), into the flux linkage expressions, (2)-(3):

\[ \lambda_1 = N_1\{P_{i1}(N_1i_1) + P_m(N_1i_1 + N_2i_2)\} = (N_1^2P_{i1} + N_1^2P_m)i_1 + N_1N_2P_m i_2 = (L_{11} + L_{1m})i_1 + L_{12}i_2 \]  \hspace{1cm} (5)

\[ \lambda_2 = N_2\{P_{i2}(N_2i_2) + P_m(N_1i_1 + N_2i_2)\} = (N_2^2P_{i2} + N_2^2P_m)i_2 + N_1N_2P_m i_1 = L_{21}i_1 + (L_{22} + L_{2m})i_2 \]  \hspace{1cm} (6)

Where \( L_{i1} \) and \( L_{i2} \) are the leakage inductances of the coils, \( L_{m1} \) and \( L_{m2} \) are the magnetizing inductances, \( L_{11} \) and \( L_{22} \) are the self-inductance of the windings, and \( L_{12} \) and \( L_{21} \) are the mutual inductances between them.

The leakage inductance of the coils can be calculated as:

\[ L_{i1} = L_{i1} - L_{m1} = L_{11} - \frac{N_1}{N_2}L_{21} \]  \hspace{1cm} (7)
\[ L_{t2} = L_{22} - L_{m2} = L_{22} - \frac{N_2}{N_1} L_{21} \]  \hspace{1cm} (8)

Finally, the total leakage inductance in the 1\(^{\text{st}}\) side can be written as:

\[ L_{t,\text{total}} = L_{t1} + \left(\frac{N_1}{N_2}\right)^2 L_{t2} \]  \hspace{1cm} (9)

The matrix inductance of studied RTs can be calculated using Magnetostatic, finite element simulations. Then, using (7)-(9) are used for calculating the total leakage inductance of the studied RTs. Table II presents the calculated inductances. Following to Table II, the lowest value of the leakage inductance is referred to RT2 and the worst case (highest value of total leakage inductance) is devoted to RT4.

3. **TIME VARIANT FINITE ELEMENT ANALYSIS**

In this section, TVFEA of the studied RTs is presented. At first, the distribution of employed mesh and magnetic flux density on different RT’s volume is presented in Figs. 4-a through –f. It can be seen the maximum flux density is less than 40 mT, therefore there is no concern of saturation in ferromagnetic parts. The performed analysis is done considering eddy current effect and the employed mesh for all the studied configurations is “Length Based” with restrict length (Max. length is set equal to 0.1 mm) and for the moving parts “Cylindrical Gap Based” moving mesh is considered.

It worth mentioning that the presented magnetic flux density is referred to the TSFEA of the RTs considering resolver as the load of RTs that has been modeled using series RL load (R=19 \(\Omega\), L=2.289 mH).

No-load induced voltage in the secondary coil of different configurations and the no-load current are given in Fig. 5. The voltage’s amplitude in steady state, steady state no-load current’s amplitude, and the phase shift error of the induced voltage are compared in Fig. 6 for different RTs. It can be seen; the maximum/minimum amplitude of the no-load voltage devotes to RT2/RT4. While the maximum/minimum excitation current is referred to RT4/RT3. The amplitude of phase shift error for all the studied RTs is the same, except RT6 that has the highest phase shift error. Considering the highest ratio of the induced voltage to the excitation current as the index of RT’s no-load performance, RT2 has the best no-load performance.
among the studied RTs.

For better judgment about the performance of the studied RTs, their performance under load condition is considered. Two different loads, resistive (R=100 kΩ) and resistive-inductive (RL), have been examined. The resistance and the inductance of the RL load has been determined based on the equivalent circuit of a commercial wound-rotor resolver. Since the output windings of the resolver are connected to the resolver to digital converter (RDC) and the input impedance of RDC is extremely high, the output current of the resolver is almost zero. Therefore, the studied resolver can be modeled with a resistance (resistance of rotor winding= 19 Ω) in series with an inductance that is the series of rotor’s leakage inductance (0.2 mH) and the magnetizing inductance (2.089 mH). Considering the excitation voltage of Fig. 2, the induced voltage in secondary coil of different RTs, the current of primary coil, and the secondary current are given in Figs. 7-a through 7-f, for R, and RL loads.

The voltage’s amplitude in steady state, steady state primary and secondary current’s amplitude, and the phase shift error of the induced voltage are compared in Fig. 8 for different RTs.

The highest amplitude of induced voltage considering resolver load (RL load) is devoted to the second RT. While the minimum primary current and the minimum phase shift are referred to RT3 and RT4, respectively. The objective function of the selecting RT is depended on the RT’s application. If RT is used for suppling the excitation winding of a resolver a proper objective function can be defined as:

\[
O.F. = \frac{V_2}{I_1} + \frac{1}{\theta}
\]  

(10)

Where \(V_2\) (V) denotes the amplitude of induced voltage in the secondary coil, \(I_1\) (A) the amplitude of the primary coil’s current and \(\theta\) (Deg.) the phase shift between the primary and secondary voltages. The lowest phase shift is appreciating due to the difficulties associate with detecting the envelope of resolver’s output signals using RDC. The highest value of (10) is achieved using RT2. Therefore, RT2 is chosen as the best configuration considering the application of RT along with resolver. The value of objective function for
different configurations are calculated in Table III. It can be seen from Table II that the commercial RT, RT1, has a medium performance. The worst and the best configurations are RT2, and RT4, respectively.

4. EXPERIMENTAL MEASUREMENTS

Referring to the highest value of the objective function, RT2 is considered as the optimal configuration. Furthermore, the prototype of the commercial RT, RT1, is also built. The primary and the secondary cores have been prototyped as shown in Fig. 9. The geometrical dimensions of the cores are the same as those of simulated RTs, as given in Table I.

The test circuit is given in Fig. 10. The required equipment for the experimental test and their specifications are listed in Table IV. In the test circuit, the primary coil of the prototype RTs is fed with a 4 kHz sinusoidal voltage using a digital synthesized function generator. The frequency resolution of the employed function generator is 0.1 Hz and the amplitude of excitation voltage is adjusted using an automatic gain control (AGC) circuit. The induced voltage in the secondary coil of them in no-load, under R=100 kΩ, and using a resolver as the load (series RL load: R=19 Ω, L=2.289 mH) is sampled and saved using a digital oscilloscope with the sampling rate of 1 GS/sec. A resistive current sensor is used for measuring the primary and secondary currents. It worth mentioning that series RL load is a model of wound rotor resolver. Therefore, in the experimental test, the real wound rotor resolver is used.

Fig. 11 shows the test results in no-load condition. The primary and the secondary voltages for RT1 and RT2 are given in Figs. 11-a, and 11-b, respectively. The current of primary coil (excitation current of the RTs) for RT1 and RT2 are presented in Figs. 11-c, and 11-d, respectively. The measured results of RT1, and RT2 under load conditions are presented in Figs. 12, and 13.

Since the experimental measurements are done in zero speed, the simulations are repeated in zero speed. As it was expected, rotating the secondary core of the prototype RTs has no significant influence on the obtained results. For better comparison of the experimental results are given along with simulation ones in Table V. As can be seen in Table V, in the worst case, the error between the simulation and measured results
is less than 7%. The close agreement between the experimental results and those of TVFEM verified the performed simulations.

5. CONCLUSION

In this paper, different configurations were examined for rotary transformers. Those configurations were compared in the terms of induced voltage’s amplitude, the current of primary coil, and the phase shift error between the primary and secondary voltages. Among six studied configurations, RT2, disk type rotary transformer, had the best performance while RT4, segmented primary core RT, had the worst performance. Conventional rotary transformer, RT1, that is the commercially employed with resolvers had an intermediate function. To verify the obtained results, prototype of the disk type and commercial RTs are built and tested. Experimental measurements closely followed by the simulations ones.

REFERENCES


Mehrzad Khazaee received his Bachelor’s degree from Iran Technical and Vocational University (ITVU) in Power Engineering. He is currently a graduate student of Energy Systems at Iran University of Science and Technology (IUST). Researches in the fields of electrical machines and renewable energy. He is currently teaching at Shahid Shamsipour Technical College.

Farid Tootoonchian received the B.Sc. and M.Sc. degrees in electrical engineering from the Iran University of Sciences and Technology, Tehran, Iran, in 2000 and 2007, respectively, and the Ph.D. degree from the K. N. Toosi University of Technology, Tehran, in 2012. He is currently an Associate Professor with the Department of Electrical Engineering, Iran University of Sciences and Technology. His research interests include design, optimization, finite-element analysis, and prototyping of ultrahigh-speed electrical machines and ultrahigh-precision electromagnetic sensors.

Fig. 1. The studied configurations for RT: (a) RT1: Conventional RT, (b) RT2: Flat-plane, disk type RT [14], (c) RT3: L-form RT [16], (d) RT4: segmented primary core RT [18], (e) RT5: with toothed cores [19], and (f) RT6: equipped with sandwiched winding [20].

Fig. 2. The employed sinusoidal voltage as the excitation of primary coil.

Fig. 3. The flowchart of the RT design.

Fig. 4. The distribution of employed mesh and magnetic flux density on the studied RTs: (a) RT1, (b) RT2, (c) RT3, (d) RT4, (e) RT5, and (f) RT6.

Fig. 5. The induced voltage in the secondary coil of different RTs and the excitation current in no-load condition: (a) RT1, (b) RT2, (c) RT3, (d) RT4, (e) RT5, and (f) RT6.

Fig. 6. Performance evaluation of different RTs in no-load: (a) the amplitude of secondary voltage, (b) amplitude of no-load current, and (c) phase shift error.

Fig. 7. The induced voltage in the secondary coil of different RTs, the primary coil’s current, and the current of secondary coil considering R, and RL loads: (a) RT1, (b) RT2, (c) RT3, (d) RT4, (e) RT5, and (f) RT6.

Fig. 8. Performance verification of studied RTs under load condition (R=100 kΩ, RL: R=19Ω and L=2.289 mH): (a) amplitude of induced voltage, (b) amplitude of primary current, (c) the amplitude of secondary current, and (d) phase shift between the primary and the secondary voltages.

Fig. 9. The prototype of RTs: (a) RT1, and (b) RT2.

Fig. 10. The test circuit: (a) RT1 with the resistive load, and (b) RT2 with resolver load.

Fig. 11. The experimental results in no-load: (a) primary and secondary voltages of RT1, (b) primary and secondary voltages of RT2, (c) excitation current of RT1, and (d) excitation current of RT2.
Fig. 12. The experimental results of RT1 under load: (a) primary and secondary voltages considering $R=100\ \text{k}\Omega$, (b) primary and secondary voltages considering a resolver as the load, (c) primary and secondary currents considering $R=100\ \text{k}\Omega$, and (d) primary and secondary currents considering a resolver as the load.

Fig. 13. The experimental results of RT2 under load: (a) primary and secondary voltages considering $R=100\ \text{k}\Omega$, (b) primary and secondary voltages considering a resolver as the load, (c) primary and secondary currents considering $R=100\ \text{k}\Omega$, and (d) primary and secondary currents considering a resolver as the load.

Table I: Geometrical dimensions of the studied RTs.

Table II. The inductance of different RT configurations.

Table III: The value of objective function considering different load conditions.

Table IV. The specifications of employed equipment in the experimental setup.

Table V. The comparison between the measured results and those of TVFEM, considering $V_1=5\text{V}$, $4\ \text{kHz}$, as the excitation voltage of primary coil.

Fig. 1. The studied configurations for RT: (a) RT1: Conventional RT, (b) RT2: Flat-plane, disk type RT [14], (c) RT3: L-form RT [16], (d) RT4: segmented primary core RT [18], (e) RT5: with toothed cores [19], and (f) RT6: equipped with sandwiched
winding [20].

Fig. 2. The employed sinusoidal voltage as the excitation of primary coil

Fig. 3. The flowchart of the RT design
Fig. 4. The distribution of employed mesh and magnetic flux density on the studied RTs: (a) RT1, (b) RT2, (c) RT3, (d) RT4, (e) RT5, and (f) RT6
Fig. 5. The induced voltage in the secondary coil of different RTs and the excitation current in no-load condition: (a) RT1, (b) RT2, (c) RT3, (d) RT4, (e) RT5, and (f) RT6
Fig. 6. Performance evaluation of different RTs in no-load: (a) the amplitude of secondary voltage, (b) amplitude of no-load current, and (c) phase shift error.
Fig. 7. The induced voltage in the secondary coil of different RTs, the primary coil’s current, and the current of secondary coil considering R, and RL loads: (a) RT1, (b) RT2, (c) RT3, (d) RT4, (e) RT5, and (f) RT6

Fig. 8. Performance verification of studied RTs under load condition (R=100 kΩ, RL: R=19 Ω and L=2.289 mH): (a) amplitude of induced voltage, (b) amplitude of primary current, (c) the amplitude of secondary current, and (d) phase shift between the primary and the secondary voltages
Fig. 9. The prototype of RTs: (a) RT1, and (b) RT2

Fig. 10. The test circuit: (a) RT1 with the resistive load, and (b) RT2 with resolver load
Fig. 11. The experimental results in no-load: (a) primary and secondary voltages of RT1, (b) primary and secondary voltages of RT2, (c) excitation current of RT1, and (d) excitation current of RT2.
Fig. 12. The experimental results of RT1 under load: (a) primary and secondary voltages considering R=100 kΩ, (b) primary and secondary voltages considering a resolver as the load, (c) primary and secondary currents considering R=100 kΩ, and (d) primary and secondary currents considering a resolver as the load.
Fig. 13. The experimental results of RT2 under load: (a) primary and secondary voltages considering R=100 kΩ, (b) primary and secondary voltages considering a resolver as the load, (c) primary and secondary currents considering R=100 kΩ, and (d) primary and secondary currents considering a resolver as the load

<table>
<thead>
<tr>
<th>Description</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer/inner diameter of RTs</td>
<td>mm</td>
<td>42.7/32</td>
</tr>
<tr>
<td>Number of primary/secondary coils</td>
<td>-</td>
<td>100/100</td>
</tr>
<tr>
<td>Air-gap length</td>
<td>mm</td>
<td>0.35</td>
</tr>
<tr>
<td>Horizontal length of the core</td>
<td>mm</td>
<td>8.5</td>
</tr>
<tr>
<td>Vertical core length</td>
<td>mm</td>
<td>5</td>
</tr>
</tbody>
</table>

Table II. The inductance of different RT configurations

<table>
<thead>
<tr>
<th>The studied RT</th>
<th>$L_{total}$ (nH)</th>
<th>$L_{m1}$ (nH)</th>
<th>$L_{total}/L_{m1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>RT1</td>
<td>90.11</td>
<td>389.28</td>
<td>0.23</td>
</tr>
<tr>
<td>RT2</td>
<td>38.36</td>
<td>403.83</td>
<td>0.09</td>
</tr>
<tr>
<td>RT3</td>
<td>85.73</td>
<td>402.26</td>
<td>0.21</td>
</tr>
<tr>
<td>RT4</td>
<td>110.54</td>
<td>96.79</td>
<td>1.14</td>
</tr>
<tr>
<td>RT5</td>
<td>80.08</td>
<td>326.25</td>
<td>0.24</td>
</tr>
<tr>
<td>RT6</td>
<td>69.81</td>
<td>189.71</td>
<td>0.37</td>
</tr>
</tbody>
</table>
Table III: The value of objective function considering different load conditions

<table>
<thead>
<tr>
<th>Configuration</th>
<th>O.F.</th>
<th>Under load: R</th>
<th>Under load: RL</th>
</tr>
</thead>
<tbody>
<tr>
<td>No-load</td>
<td>90.8357</td>
<td>89.8975</td>
<td>36.3107</td>
</tr>
<tr>
<td>RT1</td>
<td>140.7867</td>
<td>144.7198</td>
<td>43.2257</td>
</tr>
<tr>
<td>RT2</td>
<td>139.0568</td>
<td>140.9145</td>
<td>41.5179</td>
</tr>
<tr>
<td>RT3</td>
<td>33.9075</td>
<td>33.2290</td>
<td>18.9503</td>
</tr>
<tr>
<td>RT4</td>
<td>120.0000</td>
<td>122.8018</td>
<td>40.2510</td>
</tr>
<tr>
<td>RT5</td>
<td>55.0311</td>
<td>54.8275</td>
<td>29.4377</td>
</tr>
</tbody>
</table>

Table IV. The specifications of employed equipment in the experimental setup

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prototype RT1 and RT2</td>
<td>geometrical dimensions according to Table I</td>
</tr>
<tr>
<td>Function Generator</td>
<td>digital synthesized with an automatic gain control (AGC) circuit, The frequency resolution: 0.1 Hz</td>
</tr>
<tr>
<td>Digital Oscilloscope</td>
<td>sampling rate: 1 GS/sec</td>
</tr>
<tr>
<td>Current Sensor</td>
<td>Resistive current sensor</td>
</tr>
<tr>
<td>Feeler gauge</td>
<td>Flexible feeler</td>
</tr>
<tr>
<td>Resistive load</td>
<td>100 Ω</td>
</tr>
<tr>
<td>Resolver as a load</td>
<td>An axial flux, disk type wound rotor resolver</td>
</tr>
</tbody>
</table>

Table V. The comparison between the measured results and those of TVFEM, considering $V_{1}=5V$, 4 kHz, as the excitation voltage of primary coil

<table>
<thead>
<tr>
<th></th>
<th>RT1</th>
<th>RT2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$V_2$ (V)</td>
<td>$I_1$ (mA)</td>
</tr>
<tr>
<td>No-load</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TVFEM</td>
<td>2.50</td>
<td>28</td>
</tr>
<tr>
<td>Measured</td>
<td>2.55</td>
<td>28</td>
</tr>
<tr>
<td>Error %</td>
<td>1.96</td>
<td>0</td>
</tr>
<tr>
<td>R=100 kΩ</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TVFEM</td>
<td>2.48</td>
<td>27.82</td>
</tr>
<tr>
<td>Measured</td>
<td>2.6</td>
<td>28</td>
</tr>
<tr>
<td>Error %</td>
<td>4.26</td>
<td>1</td>
</tr>
<tr>
<td>Resolver:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R=19 Ω, L=2.289 mH</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TVFEM</td>
<td>1.25</td>
<td>35.16</td>
</tr>
<tr>
<td>Measured</td>
<td>1.30</td>
<td>36</td>
</tr>
<tr>
<td>Error %</td>
<td>3.85</td>
<td>2.33</td>
</tr>
</tbody>
</table>