The Comparative Analysis of AC-Flux and DC-Flux Resolvers

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Abstract—Resolver, as an electromagnetic sensor, is widely used in many industrial applications. It can detect the position of the rotary part of the electric machines precisely. In commercial resolvers, the excitation winding is connected to the high frequency (HF) AC source. The amplitude-modulated voltages induced in the signal windings need to be demodulated in order to calculate the envelope of the output signals and accordingly detect the position. On the other hand, in PM-resolver, signal windings replaced by Hall-effect sensors to measure the DC magnetic flux which is produced by permanent magnets. In this study, the performance of both AC and DC flux resolvers is investigated under different circumstances. All the simulations are done by the time-stepping finite element method (TSFEM).

Index Terms—Electromagnetic Sensor, Variable Reluctance (VR) Resolver, Time-stepping Finite Element Method (TSFEM), Hall-effect Sensor, External Magnetic Field

I. INTRODUCTION

Position sensors play a crucial role in closed-loop motion control systems, especially in inverter-driven electric machines [1]. There are different types of position sensors one of which is a resolver. Resolver is categorized as an electromagnetic position sensor and widely used in different industrial applications [1]-[3]. The main competitors to resolvers are optical encoders. Since optical encoders contain some delicate fragile parts, they cannot tolerate mechanical stresses and cannot be utilized in high-temperature environments. In addition, the performance of optical encoders is highly sensitive to the contamination while resolvers have acceptable performance in those conditions due to their robust structure. The working principle of resolvers is similar to the two-phase Synchronous Generators (2-ph SGs) and the only difference is that the excitation winding of the resolver is supplied by an AC voltage/current source rather than the DC one [3].
The windings of the traditional brushless resolvers are located in the slots of both the rotary part and the stationary part. The induced voltage in the secondary coil of a rotary transformer (RT) fed the excitation winding which is located in the slotted core of the rotary part. Using RT has advantages such as providing a contactless excitation supply \[4\]-\[5\]. However, it causes phase shift error and also increases the size and the price of the resolver as well. The proposed structures, nevertheless, use a great volume of copper and have a complicated manufacturing process. Eventually, variable reluctance (VR) resolvers are developed with a winding-less solid ferromagnetic rotor \[6\]-\[8\]. All of the aforementioned resolvers supply the excitation winding with AC voltage/current source \[7\] and as a result, the AC-excited coils of excitation winding produce AC magnetic field which flows into the core of the sensor and induced HF voltage in signal windings. In addition to the radial flux resolvers, axial flux resolvers \[9\] and linear resolvers \[10\]-\[12\] have been investigated. In \[13\], a new PM-Resolver with permanent magnets (PMs) in its structure investigated which shows that the resolver also can work properly with DC magnetic flux rather than AC magnetic flux. In the aforementioned resolver, PMs produced DC magnetic flux and due to the position of sinusoidal-form 5-X shape rotor, the sinusoidal magnetic flux flows through the Hall-effect sensors which are located in the teeth instead of signal windings to measure the amplitude of flux density. DC flux resolver has outstanding advantages such as lower cost due to the replacement of signal windings with cheap Hall-effect sensors and easy calculation of the position. Although the performance of a resolver with both AC and DC flux is well-proved, no previous research covers the comparative analysis of those two types of flux in resolvers. As a result, in this study, the performance of the AC magnetic flux and DC magnetic flux resolver with different types of excitation is investigated firstly. For the sake of similar conditions, the excitation winding of DC magnetic flux resolver is connected to the DC supply and its performance is compared with the commercial AC magnetic flux resolver. Second, the impact of different constant speeds and different constant accelerations on the output signals is studied. Eventually, the performance of both AC flux resolver and DC flux resolver in the presence of an external magnetic field is examined. All the simulations are done using the time stepping finite element method.

II. STUDIED RESOLVER

The stator and the coils of the commercial VR resolver, excited with AC supply are shown in Fig. -a. The conventional stator of the resolver has 12-slots, 4 excitation coils, and 8 signal coils. The stator, the excitation coils, and Hall-effect sensors of the VR resolver excited with DC supply are shown in Fig. -b. The stator of the DC excited resolver has also 12-slots, 4 excitation coils, and 8 Hall-effect sensors (UGN3503). The rotor of both resolvers is the 5-X shape and shown in Fig. -c. The geometrical dimensions
of both resolvers and other characteristics of them are listed in TABLE VI. It is worth mentioning that the output voltages of the Hall-effect sensor can be obtained as:

\[ V_s = V_{\text{offset}} + \Delta V \]  

(1)

where \( V_{\text{offset}} \) is depended on the amplitude of the voltage supply of the Hall-effect sensor and \( \Delta V \) depends on the flux vector of the Hall-effect sensor divided by the area section of the sensor (\( \frac{\mathbf{B}}{A} \)). The output voltages of the \( h_{s1}, h_{s2}, h_{s3}, \) and \( h_{s4} \) Hall-effect sensors are combined to form the output voltage of the sine signal and output voltages of \( h_{s1}, h_{s2}, h_{s3}, \) and \( h_{s4} \) Hall-effect sensors are combined to form the output voltage of the cosine signal, as below:

\[ V_s = V_{s1} + V_{s2} - V_{s3} - V_{s4} \]  

(2)

\[ V_s = V_{s1} + V_{s2} - V_{s3} - V_{s4} \]  

(3)

As can be seen in equation (2) and (3), the offset voltages of the Hall-effect sensors will be eliminated and the output voltages are only dependent on the magnitude of flux density of the sensors’ section and not the amplitude of Hall-effect sensor supply. As a result, even if the amplitude of the sensors’ supply varied, the sine signal and cosine signal as outputs will not be distorted, this proves the robustness of the resolver against amplitude changes of the sensors’ supply.

### III. DIFFERENT SUPPLY TYPE

Supplying the excitation winding with voltage or current source is a challenge for simulation of resolvers [10], [14]. In this section, to investigate the performance of the resolvers, both AC flux resolver and DC flux resolver are simulated using TSFEM to study the influence of the excitation type on the output signals. Fig. -a shows the output signals of the conventional resolver with the AC voltage source excitation and Fig. -b shows the output signals of the aforementioned resolver with AC current source. As can be seen in Fig. , the output signals of AC excited resolver are not affected by the type of voltage or current source. Fig. -a shows the output signals of the DC magnetic flux resolver excited with DC voltage source and Fig. -b shows the output signals of the aforementioned resolver excited with DC current source. Despite the conventional resolver, the performance of the DC flux resolver is subjected to the supply type. As it can be seen in Fig. -a, the output signals of voltage excitation suffer from slow dynamic, which means when the mechanical speed of the rotary part of the resolver changes rapidly, it takes output signals a long time to (approximately 0.4ms at 600rpm) to get stable and it is disadvantageous to those applications which need a high-speed dynamic response. In addition, the accuracy of position detection is not sufficient and the total harmonic distortion (THD) of the output signals is not acceptable. On the other hand, as it
can be seen in Fig. -b, the output signals of the DC flux resolver excited by current source have desirable sinusoidal form and also get stable very fast. The average of absolute position error (AAPE) and maximum position error (MPE) of both resolvers excited with voltage and current source are listed in TABLE VII.

IV. IMPACT OF CONSTANT AND VARIABLE SPEED

Resolver as a position sensor should be able to work properly and calculate the angular position and the angular speed of electric machines not only in a wide range of speeds but also in different accelerations. In this section, the performance of AC and DC resolvers are compared under constant/variable speed conditions. For the sake of fair comparison, the outputs of both resolvers with AC flux and DC flux are sampled with the same and constant sampling rate.

a) Constant Speed

For the AC flux resolver, the voltage source with the amplitude of 5V and 3.2 kHz supplied the excitation winding and for the DC flux resolver, the current source with the amplitude of 50mA supplied the excitation winding. Simulations are repeated at 600, 1200, 2400, 4800 rpm. the results are presented in Fig. 4 and Fig. 5 for AC and DC resolvers, respectively. The frequency of the sampling rate is 51.2 kHz applied for both outputs. As can be seen in Fig. , the quality of the low frequency (LF) envelope of the induced voltages in the AC flux resolver reduced dramatically when the mechanical speed of the resolver is increasing. The main reason for this is in each period of HF signal, only two extremum points of the LF envelope are sampled and the position of the rotary part calculated using the LF envelope in the peak-detection method.

\[ f_{HF\, Signal - AC} = n_{HF} \times f_{exc}, \quad n_{HF} \geq 16 \]  
\[ f_{LF\, Signal - AC} = f_{exc} \]  

In the DC flux resolver, nevertheless, all sampling points building the output signals of the resolver are used in calculating the position. As a result, the DC flux resolver kept the quality of its output signals while the mechanical speed of the resolver was increasing.

\[ f_{LF\, Signal - DC} = f_{HF\, Signal - AC} \]  

Consequently, the quality of the output signals in the DC flux resolver is \( n_{HF} \) times better than the quality of the output signals in the AC flux resolver. The calculated AAPE and MPE at different speeds are listed in TABLE VIII.

b) Variable Speed
To investigate the performance of both AC- and DC-flux resolvers in variable speeds, AC flux resolver is simulated in two different angular accelerations. Fig. -a shows the real speed of the resolver as a reference and calculated the speed of the resolver using output signals of the AC flux resolver simultaneously when the speed of the rotary part increases with 628 rad/s² and 1256 rad/s². Fig. -b shows the speed error of the aforementioned resolver. Simulations repeated for DC flux resolver with the same angular accelerations for the sake of fair comparison. Fig. -a shows the real speed and also calculated the speed of the DC flux resolver and Fig. -b shows the speed error. Eventually, the average of absolute speed error (AASE) and the maximum speed error (MSE) of both resolvers with the same angular accelerations are listed in TABLE IX. It can be concluded that both AC flux resolver and DC flux resolver operate well when the rotary part is accelerating. Although the AASE of both resolvers is almost equal, the MSE of the DC flux resolver is bigger than the AC one. In conclusion, the AC flux resolver has a better performance in comparison with the DC flux resolver.

V. EFFECT OF EXTERNAL ELECTROMAGNETIC FIELD ON THE PERFORMANCE OF THE RESOLVER

By distorting the magnetic flux which passes through the Hall-effect sensors, escalation of the resolver’s position is inevitable. In order to study the influence of external electromagnetic interference on the performance of both resolvers, two intense asymmetric electromagnetic fields are simulated in the simulation environment, one of them is DC field with the amplitude of 2kA/m and the other one is 16 kHz AC field with the amplitude of 2kA/m. In these simulations, in order to provide similar conditions, both excitation windings of AC flux and DC flux resolvers are excited with current source excitation with 50 mA amplitude and 3.2 kHz frequency for AC flux resolver. The outputs of the resolver such as AAPE and MPE are listed in TABLE X. As it can be seen, the position error of the AC flux resolver is increased exponentially in the presence of the external electromagnetic field. Fig. shows distorted induced voltages in signal windings especially in zero-crossings. Due to the low amplitude of the signal in the zero crossing section, the rate of the signal to noise decreases and this leads to dramatic position error. On the other hand, Fig. shows the output signals of the DC flux resolver in the presence of the external DC electromagnetic field. As it can be seen, the external field distorted output signals of the DC flux resolver by injecting offset to sine and cosine signal and consequently, cause increasing the position error of the resolver. The injected offset by external field can be calculated as:

\[ \Delta V = V_{LP} - V_{UP} = 0.022^{\text{pu}} \]  (7)

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On the other hand, the DC electromagnetic field has a little effect on the performance of the AC flux resolver, and also the performance of the DC flux resolver in the presence of the AC electromagnetic field is acceptable.

VI. CONCLUSION

In this paper, a comparative analysis between AC flux and DC flux resolvers was done. A variable reluctance resolver with 12-slot stator and 5-X shape rotor was taken as a study case. The position errors of both resolvers in normal conditions examined when the current source and voltage source supplied the excitation winding and among different scenarios, DC flux resolver with current source had the lowest AAPE and MPE. In order to study the accuracy in different conditions, both AC flux and DC flux resolvers were simulated in a wide range of speeds and accelerations. It was shown that the quality of output signals and their envelope in AC flux resolver reduced dramatically when the angular speed of the rotor increased. On the other hand, the DC flux resolver kept its acceptable accuracy even at high speed. Although DC flux resolver has proved its practicality in high-speed applications, the performance of both resolvers was close to each other in different angular accelerations. At last, the output signals of both resolvers examined in the presence of external distortions. Simulation results indicated that AC flux resolvers almost kept their accuracy when an external DC magnetic field exists; however, an external AC magnetic field distorted their output signals. On the other side, DC flux resolver has shown acceptable performance against an external AC magnetic field while its accuracy highly affected by an external DC magnetic field. To sum up, DC flux resolvers have a great number of advantages such as lower cost, easy position calculation, ability to measure the position in a wide range of speed, and robust performance against AC distortions in comparison with commercial AC flux resolvers which have complex winding configuration and as a result, they deserve more attention.

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Fig. 1. The conventional and DC supplied resolver: (a) the stator of the conventional resolver, (b) the stator of the DC supplied resolver, and (c) the rotor of both resolvers

Fig. 2. The commercial resolver with AC magnetic flux: (a) the output signals with voltage source excitation and (b) the output signals with current source excitation

Fig. 3. The DC magnetic flux resolver: (a) the output signals with voltage source excitation and (b) the output signals with current source excitation

Fig. 4. Induced voltages of AC flux resolver in different speeds

Fig. 5. Output Signals of DC flux resolver in different speeds

Fig. 6. Performance of the AC flux resolver with two different angular accelerations: (a) real speed of the resolver and calculated speed by output signals and (b) Speed error

Fig. 7. Performance of the DC flux resolver with two different angular accelerations: (a) real speed of the resolver and calculated speed by output signals and (b) Speed error
Fig. 8. The effect of an AC external electromagnetic field on the induced voltages of the AC flux resolver

Fig. 9. The effect of a DC external electromagnetic field on the DC flux resolver

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TABLE VI. THE GEOMETRICAL DIMENSIONS OF THE RESOLVERS AND SUPPLY CHARACTERISTICS

| Parameters                          | Unit | Value   |
|-------------------------------------|------|---------|
| **Geometrical Dimensions**          |      |         |
| Pole Pairs \( (p_w) \)              | -    | 5       |
| Air-gap Length (min~max)            | mm   | 0.5~2   |
| Shaft Diameter                      | mm   | 8       |
| Number of Teeth \( (N_t) \)         | -    | 12      |
| Stator Outer Diameter \( (D_o) \)   | mm   | 40      |
| Stator Inner Diameter \( (D_i) \)   | mm   | 24      |
| Total Height                        | mm   | 10      |
| Excitation Winding’s Coil Number    | -    | 50      |
| Signal Winding’s Coil Number        | -    | 50      |
| **Supply Characteristics**          |      |         |
| Excitation Voltage                 | V    | 5       |
| Excitation Current                 | mA   | 50      |
| Excitation Frequency (for AC supply)| kHz | 3.2     |

TABLE VII. THE OUTPUTS OF THE AC AND DC SUPPLIED RESOLVERS WITH VOLTAGE/CURRENT SOURCE

| Excitation Type   | Supply Type    | AAPE (Deg.) | MPE (Deg.) |
|-------------------|----------------|-------------|------------|
| AC Excitation     | Voltage Source | 0.1139      | 0.1978     |
|                   | Current Source | 0.1265      | 0.3055     |
| DC Excitation     | Voltage Source | 4.6935      | >10        |
|                   | Current Source | 0.0316      | 0.0947     |

TABLE VIII. THE OUTPUTS OF THE AC FLUX AND DC FLUX RESOLVERS IN DIFFERENT CONSTANT SPEEDS

| Excitation Type | Speed (rpm) | AAPE (Deg.) | MPE (Deg.) | THD (%) |
|-----------------|-------------|-------------|------------|---------|
| AC Excitation   | 600         | 0.1139      | 0.1978     | 0.3338  |
|                 | 1200        | 0.1153      | 0.1983     | 0.3310  |
|                 | 2400        | 0.1247      | 0.2280     | 0.4625  |
|                 | 4800        | 0.2176      | 0.2823     | 0.7052  |
| DC Excitation   | 600         | 0.0316      | 0.0947     | 0.0762  |
|                 | 1200        | 0.0317      | 0.0998     | 0.0762  |
|                 | 2400        | 0.0317      | 0.1059     | 0.0766  |
|                 | 4800        | 0.0331      | 0.1113     | 0.0770  |
TABLE IX. THE OUTPUTS OF BOTH AC AND DC FLUX RESOLVERS WITH DIFFERENT ANGULAR ACCELERATIONS

| Excitation Type | Angular Acceleration (rad/s²) | AASE (rpm) | MSE (rpm) |
|-----------------|-------------------------------|------------|-----------|
| AC Excitation   | 628                           | 2.56       | 12.91     |
| DC Excitation   | 1256                          | 2.54       | 12.33     |
| AC Excitation   | 2 kA/m-16 kHz                 | 2.61       | 26.92     |
| DC Excitation   | 1256                          | 2.62       | 23.01     |

TABLE X. THE PERFORMANCE OF THE RESOLVERS IN THE PRESENCE OF EXTERNAL ELECTROMAGNETIC FIELDS

| External Magnetic Field | Resolver Type | AAPE (Deg.) | MPE (Deg.) |
|-------------------------|---------------|-------------|------------|
| AC field                | AC flux       | 1.58        | 2.83       |
| 2 kA/m-16 kHz           | DC flux       | 0.34        | 0.96       |
| DC Excitation           | AC flux       | 0.13        | 0.32       |
| 2 kA/m                  | DC flux       | 0.56        | 0.98       |