Improving the Performance of Variable Reluctance Resolver Against Short Circuit Using Physical Parameters

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***Abstract*— Variable reluctance resolver is one of the popular sensors used in the industry. Because they can operate at high temperatures, withstand shock and less expensive and easier to manufacture. Despite the mentioned advantages, the variable reluctance resolver may suffer from faults that lead to inaccurate position. The paper aims to reduce position error under short circuit fault by changing parameters such as excitation frequency, number of signal and excitation poles, shape of the air gap, slot opening width and the number of teeth. The effect of each parameter on reducing the position error is examined to determine whether it has a positive, a negative or zero effect. Finally, the optimal case is introduced by selecting the best value for each parameter, which significantly reduces the position error.**

***Index Terms*—resolver, Variable Reluctance (VR), Short Circuit Fault, Finite Element analysis, Position Error**

I. INTRODUCTION

Resolvers are electromagnetic sensors that can measure the position and speed of rotating machinery with high accuracy and precision. They are widely used in various industrial applications such as robotics, aerospace, automotive, and manufacturing industries [1]-[2]. Resolvers are classified into two kinds of Variable Reluctance (VR) Resolvers and Wound Rotor (WR) ones [3]-[4]. Among them, VR resolvers attract more attentions due to their easier manufacturing process and lower cost.

Resolvers have a function similar to synchronous machine, therefore they may suffer from electrical and mechanical faults interrupting their performance. mechanical faults are considered in [5]- [11]. In [5] a multi-turn VR resolver is presented and its performance against static and dynamic eccentricity and run out fault is improved. In [6] by using the damper winding, the position error of WR resolver under mechanical fault is reduced. In [7] a VR resolver with toroidal windings is introduced and

Magnetic Equivalent Circuit (MEC) model is used to investigate its performance in healthy condition and under misalignment. Also, the influence of rotor saliencies on the performance of toroidal winding resolver is examined considering 1-X, 3-X, 5-X, and 7-X rotors. In [8] a parametric MEC model is developed for performance evaluation of a permanent magnet VR resolver with five, seven and 11 saliencies on the mover in fully-aligned and misaligned conditions. The presented results depict good accuracy of the proposed model. In [9] the effect of axial eccentricity, rotating eccentricity, radial eccentricity on axial flux VR resolver is investigated using finite element method. In [10], a non-overlapping configuration is proposed for the winding of VR resolver, which makes the resolver winding process easier. Then, the performance of the resolver is studied in healthy condition and under mechanical fault. In [11] by injecting harmonics into the rotor contour, the performance of the VR resolver is improved in a healthy condition. Then, the effect of assembling eccentricity on optimal sensor's accuracy is examined.

Another fault of resolver is inter-turn Short Circuit (SC) fault. This type of fault occurs when there is an unintended low-impedance connection between two points in the electrical circuit. When a short circuit fault occurs in the resolver, it can lead to a high position error and possible instability of the motion control system. Therefore, reducing the position error of resolver under short circuit fault is crucial in maintaining the reliability and safety of the motion control.

In [12] and [13], the effect of eccentricity and short circuit faults on the accuracy of a VR resolver is studied using finite element simulation. In [14] and [15] the electrical and mechanical faults in WR and VR resolvers are predicted by identifying specific harmonics as indicators in the envelope of signal voltages. In [16], the performance of the variable area resolver under fault with three different winding configurations has been investigated. In [17] the effect of short circuit fault and eccentricity of the disk type VR resolver has been studied using the finite element model. In [18] and [19] the magnetic equivalent circuit model is presented for linear and rotary VR resolvers, respectively, and the performance of the resolvers under eccentricity and short circuit faults with overlapping and non-overlapping windings is studied. In [20] inter-turn short circuit fault in WR resolver is modeled with dq-axis theory. In [21] WR resolver with and without damper winding under short circuit fault is modeled using Winding Function (WF) theory.

In [22] and [23] the influence of the geometrical parameters on resolver's accuracy in the healthy condition is discussed. In [22] the effect of slot opening width, number of poles, number of slots per pole and number of rotor slots on position error of disk type WR resolver is investigated. In [23] the rotor shape of VR resolver was optimized using Taguchi method and finite element analysis.

Despite all the mentioned valuable researches, there is a research gap that comprehensively examines the effect of resolver parameters on the position error under short circuit and provides a guide line for designer. In fact, most of the articles have dealt with the design of the resolver for proper performance in a healthy condition [24], but this article has dealt with the process of designing for better performance under short circuit fault. Therefore, the effect of the parameters of a variable air-gap resolver is discussed and finally a structure with better performance against the SC fault is presented. All simulations have been done by ANSYS Electromagnetics Suite 2020.

II. The Studied Resolver

The studied resolver is a VR, variable air-gap length resolver with three rotor saliencies and eight stator tooth. The stator and its expected windings are shown in Fig. 1-a, and the winding-less rotor is given in Fig. 1-b. Each stator tooth equipped with three coils so-called sine, cosine and excitation coils. the coils' distribution and the turn number of each coil are shown in Fig. 2. First the studied resolver is simulated in the healthy condition. The output voltages and position error are given in Figs. 3-a, and -b, respectively. It can be seen that the position error of the resolver in a healthy condition is low, which indicates the proper operating of the resolver in a healthy condition.

To apply the SC fault, 10 turns of the cosine winding on the first tooth are shorted and the resolver is simulated in finite element software. The obtained signal voltages are shown in Fig. 4-a, and the calculated position error based on the inverse tangent of the envelopes' ratio is given in Fig. 4-b. In this case, as depicted in Fig. 4-b, the maximum position error is increased 62.6 degrees. In the following, we try to reduce the position error under short circuit fault. It should be noted that all the simulations in the following sections have been performed for 10 turns short circuit on the first tooth of cosine winding.

III. The Air Gap Length of The Resolver

The air gap length is the first parameter whose effect on resolver position error is investigated. The outer radius of the rotor can be written as:

$$r(\varphi) = r_s - \frac{1}{a + b\cos(X\varphi)} \tag{1}$$

where φ is the rotor mechanical coordinate, r_S is internal radius of the stator core, X is number of saliencies, a and b are constant coefficients that $a>b$.

The air gap length of the resolver is equal to:

$$g(\varphi) = r_s - r(\varphi) = \frac{1}{a + b\cos(X\varphi)} \tag{2}$$

The air gap of the resolver consists of two terms, AC and DC. The issue to be investigated is whether the value of the position error under short circuit fault is a function of the average (DC) value of the air gap length, its AC value, or Root Mean Square (RMS) value of the air gap length. Therefore, different scenarios are examined in the following sections.

A. Constant DC Term and Variable AC Term

In this study the DC term of the air-gap length is kept constant and its AC value is increased/deceased with respect to its initial value. The two investigated cases are a=1.7, b=1.47 (case I) and a=1.08, b=0.64 (case II). The variations of the air-gap length for the different cases are given in Fig. 5. The AC value of the air gap length in case I is higher than that of initial case, while in case II it is lower. Then, the resolver is simulated in the mentioned cases and the position error is shown in Fig. 6. It reveals that the position error of the resolver under short circuit is related to the AC value of the air gap length and not independent of it. A higher AC value of the air gap length results in a lower position error of the resolver.

B. Constant AC Term and Variable DC Term

In the previous section, it was determined that the position error under short circuit fault is related to the AC terms of air gap length. Now, we should check whether the DC term has any effect on the position error or not. To investigate this issue, we consider the AC term of the air gap length to be constant while its DC value is increased or decreased compared to that of the initial case. The two investigated cases are a=0.94, b=0.57 (case III) and a=2.11, b=1.71 (case IV). The variation of air gap length for these studied cases are shown in Fig. 7. The DC value of the air gap in case III/IV is higher/lower than that of the initial value.

The position error of the sensor considering the studied conditions is shown in Fig.8. It can be seen that the position error of the resolver under inter-turn short circuit fault is related to the DC value of the air gap length and is not independent of it. The higher the DC value of the air gap length, the lower the position error, and vice versa.

C. Constant RMS Value

The results of sections II-A, and II-B show that the position error is dependent on the AC and DC values, but the issue that should be checked is whether the position error value under short circuit is dependent on the RMS value of the air-gap length or not. It means for equal RMS values of the air gap length, are the position errors equal? To investigate this issue, two cases a=2.43, b=2.04 (case V) and case a=1.02, b=0.61 (case VI) are simulated in finite element software. The variation of air gap in these two case and the initial case are shown in Fig. 9. The RMS value for all three cases are kept equal. The results of finite element simulation are given in Fig. 10. It can be seen that the position error is different in these three cases. Therefore, the same RMS value does not mean the same position error under short circuit fault.

From the simulation results, it is found that increasing the AC value of the air gap length and decreasing its DC value will improve the position error under short circuit fault. However, the limitation in the minimum air gap length does not allow a large decrease in DC value and a large increase in AC value. In addition, the relationship between the coefficients *a* and *b* with AC term and DC term of the air gap length is complicated. Therefore, it is recommended to study the effect of the minimum and the maximum air gap length on the resolver's performance under short circuit, too. Then, by determining g_{min} and g_{max} the value of *a* and *b* can be easily calculated.

This study is carried out in two sections: a) fixed minimum air gap length (g_{min}), variable maximum air gap length (g_{max}), and b) fixed maximum air gap length (g_{min}) and variable minimum air gap length (g_{min}).

D. Fixed g_{min} and Variable g_{max}

In this section, the minimum air gap length, $g_{min,}$ is considered equal to the initial case, and the maximum air gap length, g_{max}, is set higher/lower than its initial value. The two investigated cases are *a*=1.21, *b*=0.72 (case VII) and *a*=1, b=0.92 (case VIII). The schematics of resolver in case VII and case VIII are shown in Figs. 11-a, and 11-b, respectively. Also, the variation of air gap in these two case and the initial case are shown in Fig. 12. The position error of the studied cases is shown in Fig. 13. It can be observed that by increasing g_{max}, the position error of the resolver under short circuit fault decreases. Therefore, it’s recommended to increase the g_{max} as much as possible.

E. Fixed g_{max} and Variable g_{min}

Here g_{max} is set equal to its initial value, and g_{min} is considered higher/lower than its initial value. The two investigated cases are *a*=1, *b*=0.61 (case IX) and *a*=1.92, *b*=1.54 (case X). The variation of air gap length in these two cases and the initial case are shown in Fig. 14. The calculated position error of the studied cases is shown in Fig. 15. It can be seen that by reducing the g_{min}, the position error under short circuit fault decreases. Therefore, it is recommended to set g_{min} equal to the smallest possible value.

F. Determining the Value of a and b

It was mentioned that the lower value of g_{min} and the higher value of g_{max} cause the better performance against the short circuit fault. However, the minimum of the g_{min} is limited by the mechanical considerations and the maximum of the g_{max} is determined from:

$$\max imum\,airgap = r_s - r_{shaft} - m\arg in \qquad (3)$$

where r_{shaft} is radius of the shaft and margin is constant value for mechanical consideration.

From the equation (2) the value of g_{min} and g_{max} are equal to:

$$g_{\min} = \frac{1}{a+b} \qquad (4)$$

$$g_{\max} = \frac{1}{a-b} \qquad (5)$$

By solving the equations (4) and (5), the value of *a* and *b* is equal to:

$$a = \frac{\alpha+\beta}{2} \qquad (6)$$

$$b = \frac{\alpha-\beta}{2} \qquad (7)$$

where

$$\alpha = \frac{1}{g_{\min}} \qquad (8)$$

$$\beta = \frac{1}{g_{\max}} \qquad (9)$$

Therefore, after determining the g_{min} from the mechanical limitations and g_{max} from (3), the value of *a* and *b* can be determined from the equations (6) - (9).

IV. Slot Opening Width

In this section, the effect of the slot opening width on the position error of the resolver under short circuit fault is investigated. In the case XII, the minimum width of the slot opening is considered, and in the case XI, the slot opening width is increased compared to case XII. The schematics of Case XI and Case XII and initial design are shown in Figs. 16-a to 16-c, respectively. The position error obtained from the simulation of different cases are given in Fig. 17. It can be seen that despite the healthy condition, increasing the slot opening width leads to reduce the position error of the resolver under short circuit fault.

V. Increasing the number of stator tooth

The number of stator tooth is increased to 16, 20, 28, 32 tooth. The schematic of studied cases is shown in Figs. 18-a to 18-d, respectively. In each case, short circuit fault is applied to the 10 turns of the first cosine coil and the simulations are repeated. The influence of stator's number of tooth on position error of the 3-X resolver is shown in Fig. 19. It can be seen that increasing the number of stator teeth reduces the position error under short circuit fault. However, supposing a practical value for the slot's space factor, the number of tooth cannot be increased arbitrarily. Also, increasing the number of stator tooth more than a certain limit has less effect on the position error. Therefore, the designer should determine the number of tooth according to these issues. It should be mentioned that in the resolver, due to the low operating flux density, there is no concern of saturation and the minimum width of the tooth is determined by mechanical strength of the ferromagnetic material.

VI. The number of signal-excitation pole

In a resolver with three saliencies, the number of signal and excitation poles is n and n+3, respectively. It means the number of signal-excitation poles can be 1-4, 2-5, 3-6 and so on. Therefore, in this section, the effect of the number of poles on the position error is investigated. Since the number of tooth affects the position error under short circuit fault, it is necessary to change the number of poles in a fixed number of tooth. In this section, 32 tooth is considered for the stator and the combinations of the possible signal-excitation poles are 1-4, 2-5, 3-6 and 4-7. The number of turns per tooth for the sine, cosine and the excitation windings are given in the Table I. Finite element analysis of the studied configurations leads to the position errors of Fig. 20. It can be seen that increasing the number of signal-excitation poles, leads to higher position error of the sensor under short circuit fault. Hence, the number of signal-excitation poles should be set to its minimum value.

VII. Excitation Frequency

The next parameter whose effect on the position error under short circuit fault is investigated is the excitation frequency. The excitation frequency of the resolver must be much higher than the mechanical frequency of the rotor. In the studied resolver, the rotation speed of the resolver is 300 rpm and the excitation frequency is 4 kHz. To investigate the effect of the excitation frequency, once the frequency is increased to 8 kHz and once the frequency is decreased to 2 kHz. The position error obtained from the finite element simulations is shown in Fig. 21. It can be seen that the frequency variation has a very small effect on the resolver position error, which can be ignored. Therefore, the excitation frequency does not affect the resolver performance under inter-turn short circuit fault.

VIII. The Optimal Case

Using the results of previous simulations, the optimal case is as follows: the number of stator tooth is 32, the number of signal poles is 1, the number of excitation poles is 4, the minimum air gap is 0.5 mm and the maximum air gap is 13 mm. The schematic of the optimal resolver is shown in Fig. 22. The optimal resolver is simulated in a healthy condition and under short circuit fault, and their output voltages are given in 23-a and 23-b respectively. also, the Position error of optimum case in healthy condition and under SC fault with the position error of initial case under SC fault is shown in fig 23-c. It can be seen that as a result of short circuit, the position error of the resolver has increased compared to the healthy condition. so even in the optimal resolver, the short circuit has a destructive effect on the position error, but the amount of position error is less than the initial case. The maximum position error of the initial resolver is 62.6 degrees and the maximum position error of the optimal resolver is 11.9 degrees. Therefore, the position error is reduced by 81 percent.

Finally, to guarantee that the improvement of the resolver performance against the SC fault is not limited to the SC fault on the first cosine coil, and it is general, 10 turns short circuit fault is assigned to the second tooth of the sine winding of the initial resolver and the optimal one. The induced voltages are given in Figs. 24-a, and 24-b for the initial design and the optimal ones, respectively. Position error of the sensors are compared in Fig. 24-c It can be seen that the position error of the optimal case is significantly less than that of the initial case. Therefore, the presented method for choosing the optimal case is general and using the optimal configuration the performance of the resolver under short circuit fault on different tooth of different signal windings will improve.

IX. CONCLUSION

In this paper, the effect of different parameters such as number of stator tooth, number of excitation/signal winding’s poles, excitation frequency, air gap length, and slot opening width on the performance of the resolver under short circuit was investigated and the results are as follows:

- The minimum air gap length should be set to its lowest possible value, which is determined by mechanical considerations.
- The maximum air gap length should be set as large as possible.

- Higher number of stator tooth leads to higher accuracy under short circuit fault.
- The number of signal and excitation poles should be set equal to the lowest values.
- Open slot configuration leads to higher accuracy under short circuit fault and therefore, the slot opening width should be the largest amount.
- Changing the excitation frequency has no effect on the position error of the resolver under short circuit fault.

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BIOGRAPHIES

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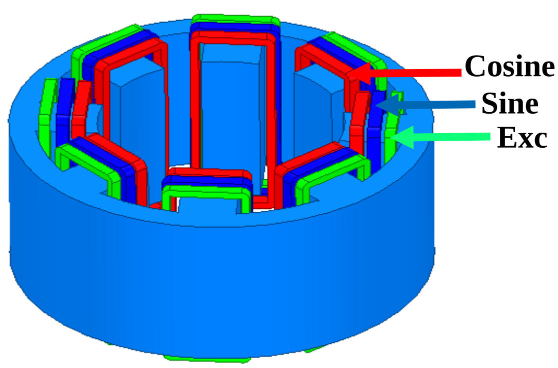

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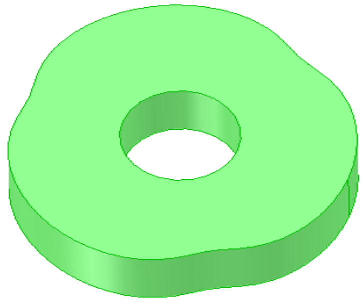


(b)

Fig. 1. Finite the image of the studied resolver: (a) The stator and winding, (b) The rotor.

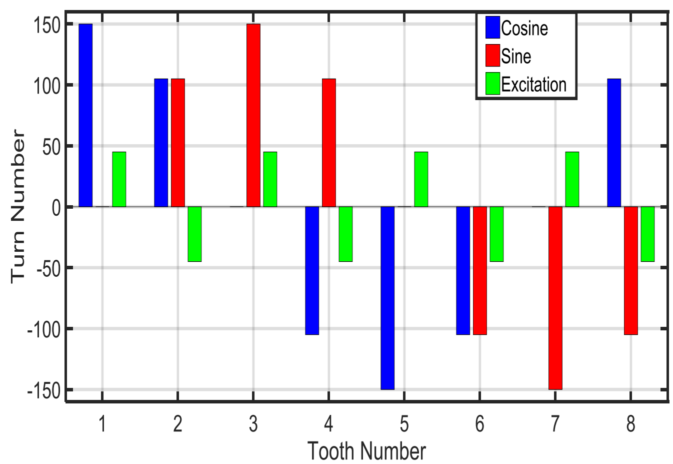
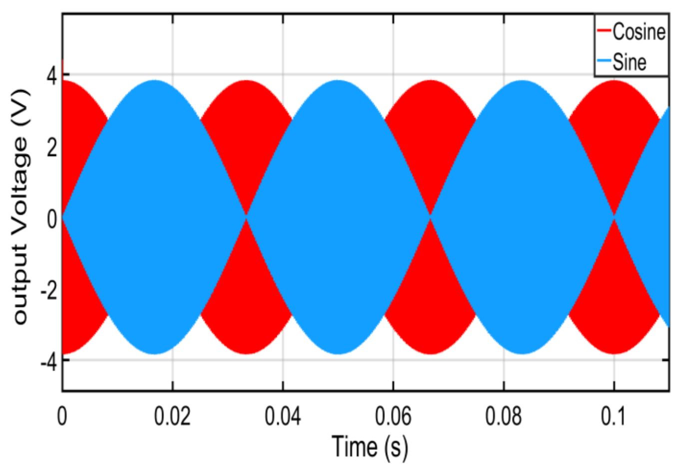


Fig. 2. the number of turns per tooth for the sine winding, cosine winding and excitation winding



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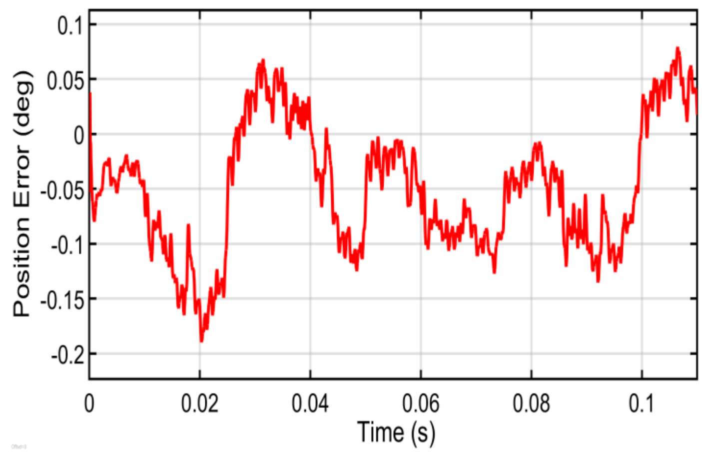
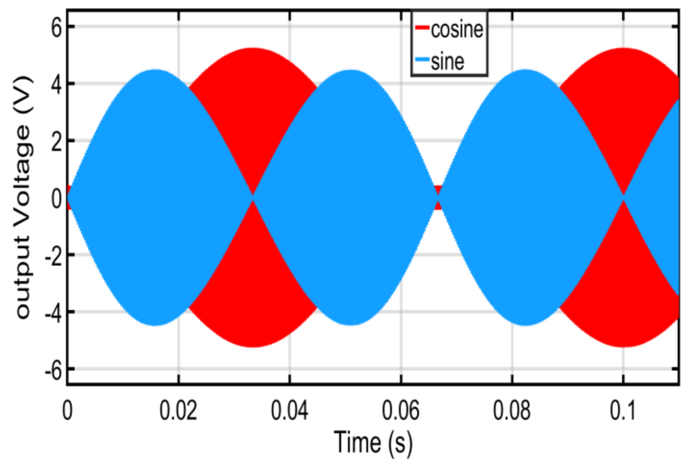


(b)

Fig. 3. Finite element simulation results in healthy condition: (a) signal voltages, (b) the position error



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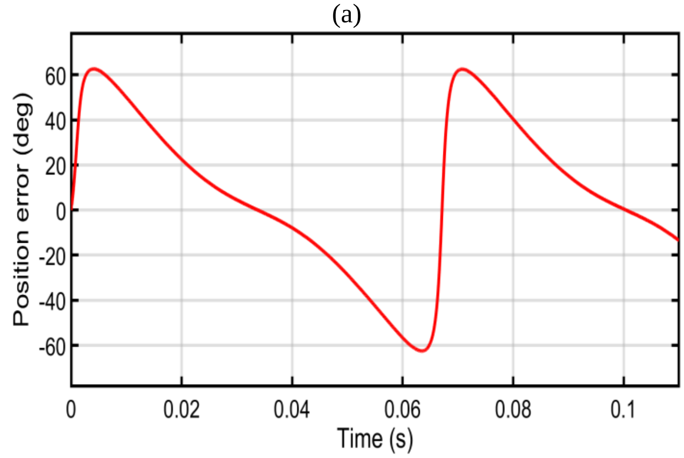


(b)

Fig. 4. Finite element simulation results under short circuit fault: (a) signal voltages, (b) the position error

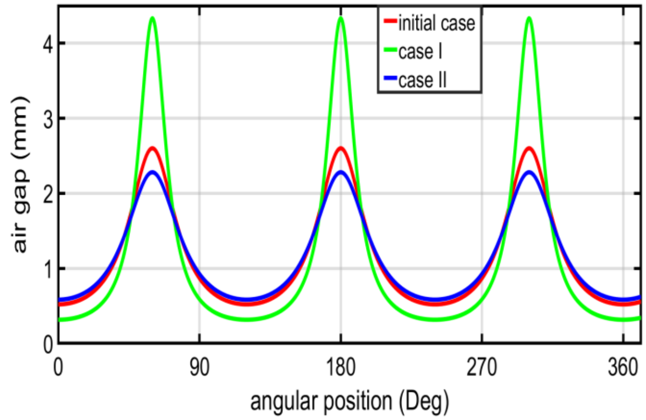


Fig. 5. Variation of air gap in case I, case II and the initial case

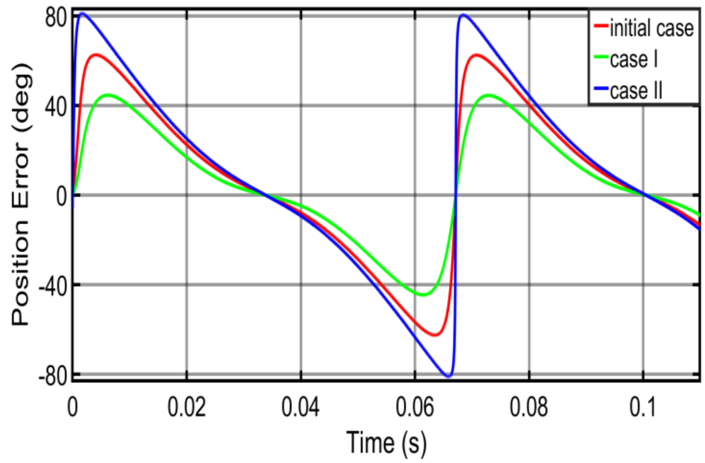


Fig. 6. Position error of resolver under short circuit fault in case I, case II and the initial case

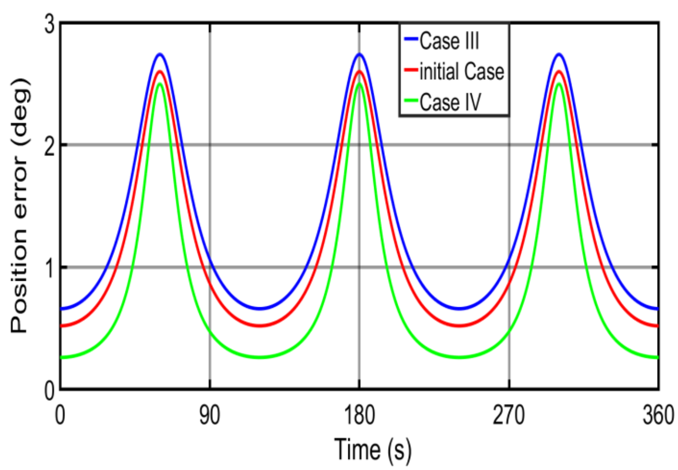


Fig. 7. Variation of air gap in case III, case IV and the initial case

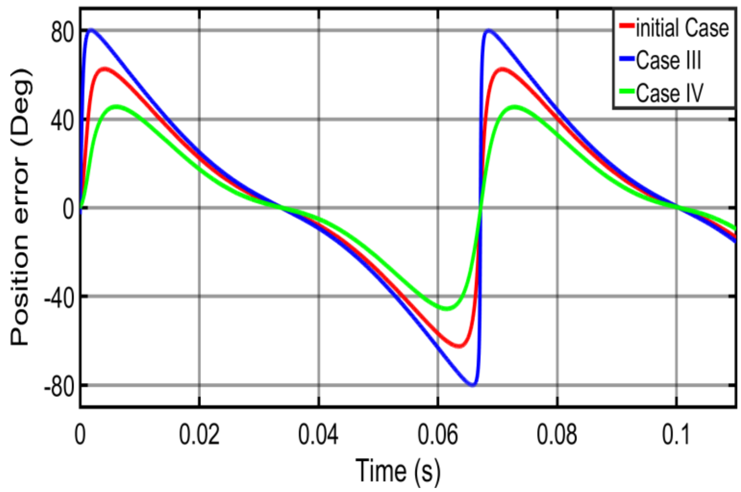


Fig. 8. Position error of resolver under short circuit fault in case III, case IV and the initial case

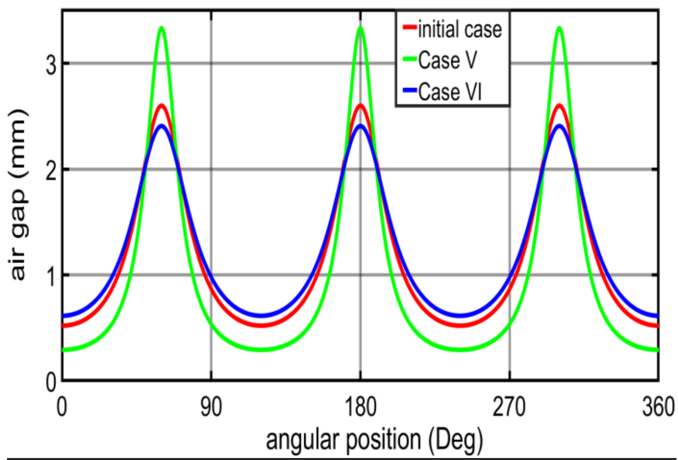


Fig. 9. Variation of air gap in case V, case VI and the initial case

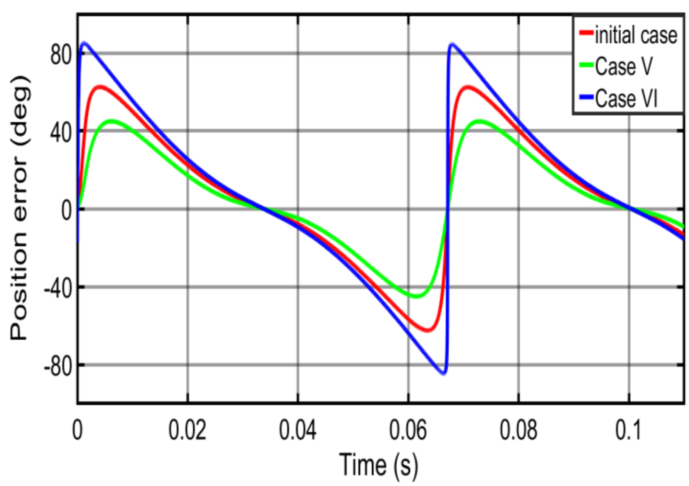


Fig. 10. Position error of resolver under short circuit fault in case V, case VI and the initial case

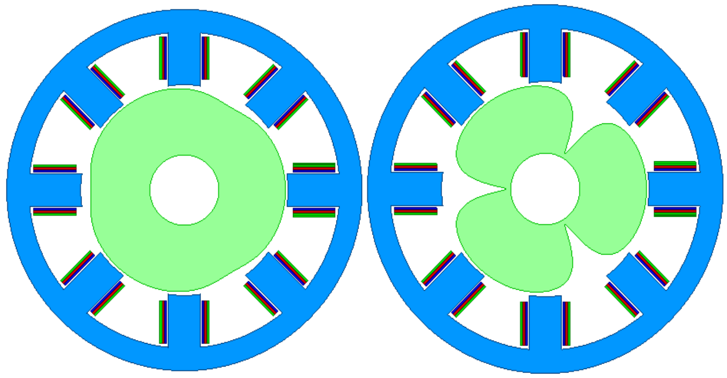


Fig. 11. The schematics of resolver: (a) Case VII, (b) Case VIII

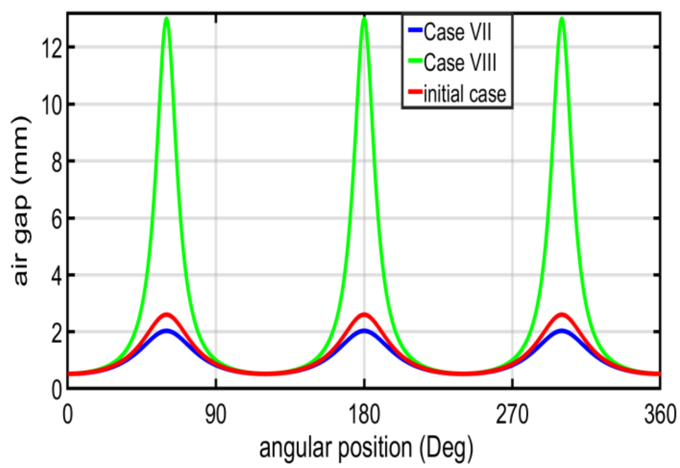


Fig. 12. Variation of air gap in case VII, case VIII and the initial case

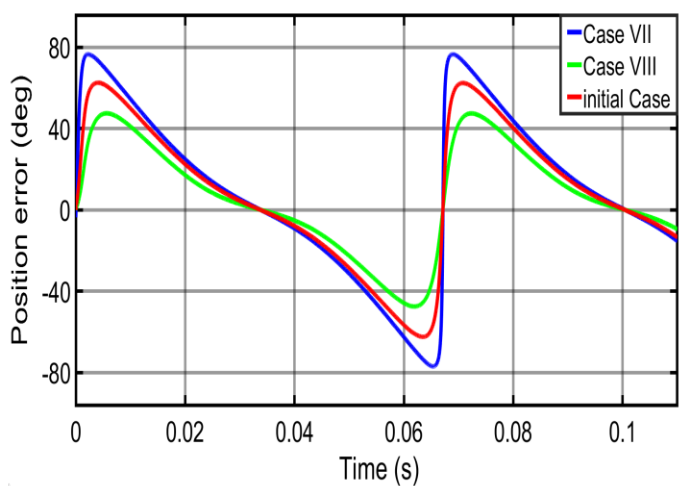


Fig. 13. Position error of resolver under short circuit fault in case VII, case VIII and the initial case

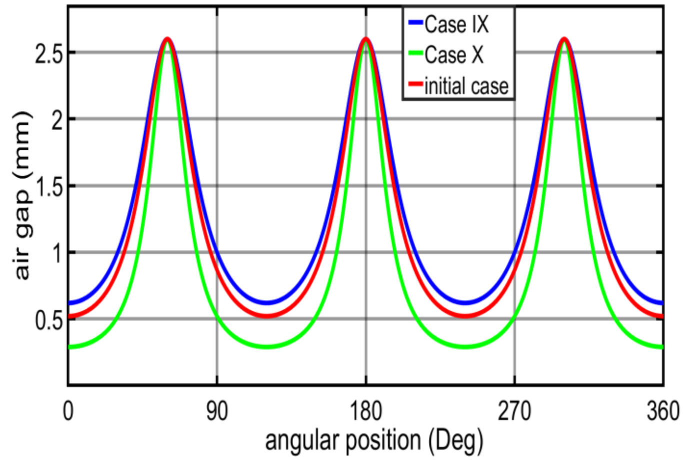


Fig. 14. Variation of air gap in case IX, case X and the initial case

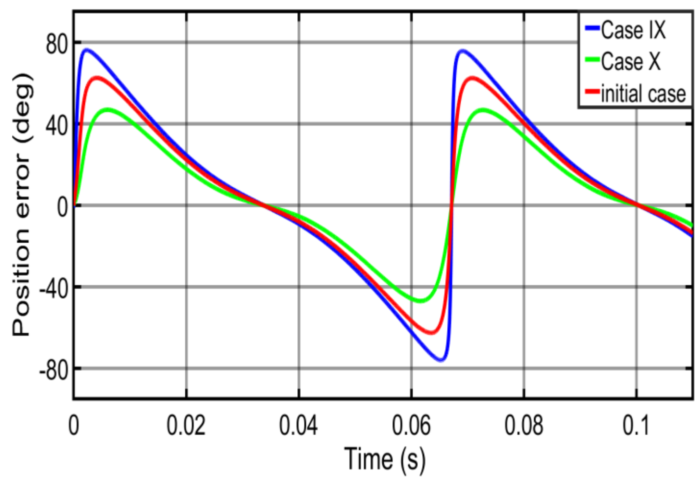
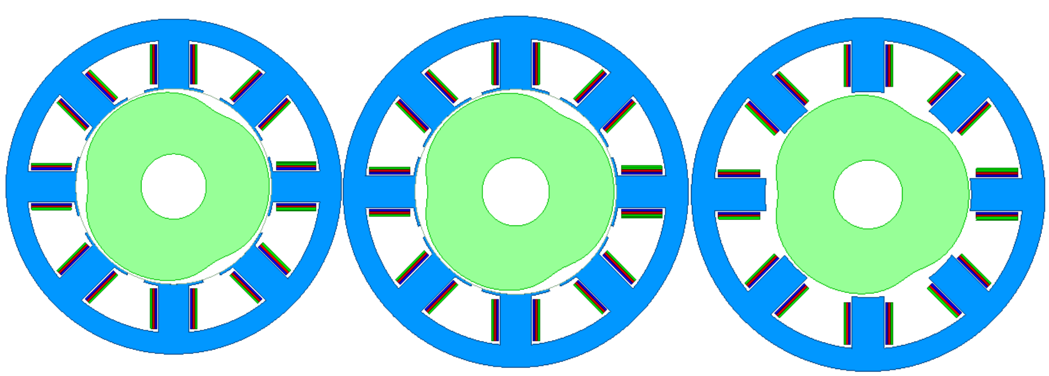


Fig. 15. Position error of resolver under short circuit fault in case IX, case X and the initial case



(a) (b) (c)

Fig. 16. The schematics of resolver: (a) Case XI, (b) Case XII, (c) Case study

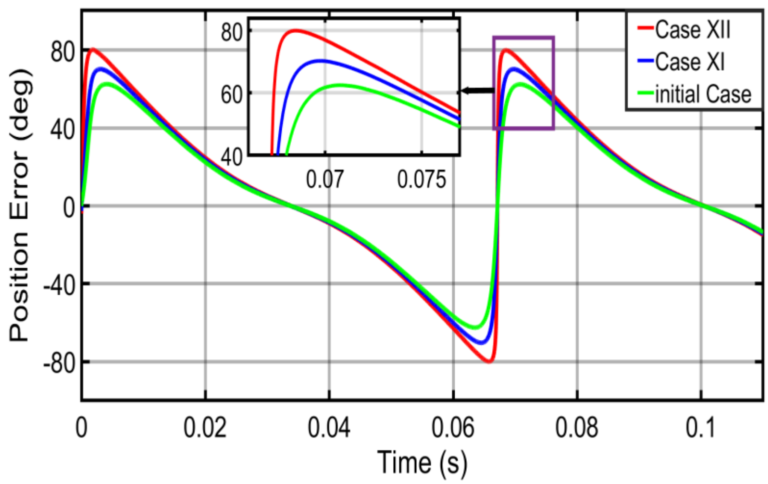
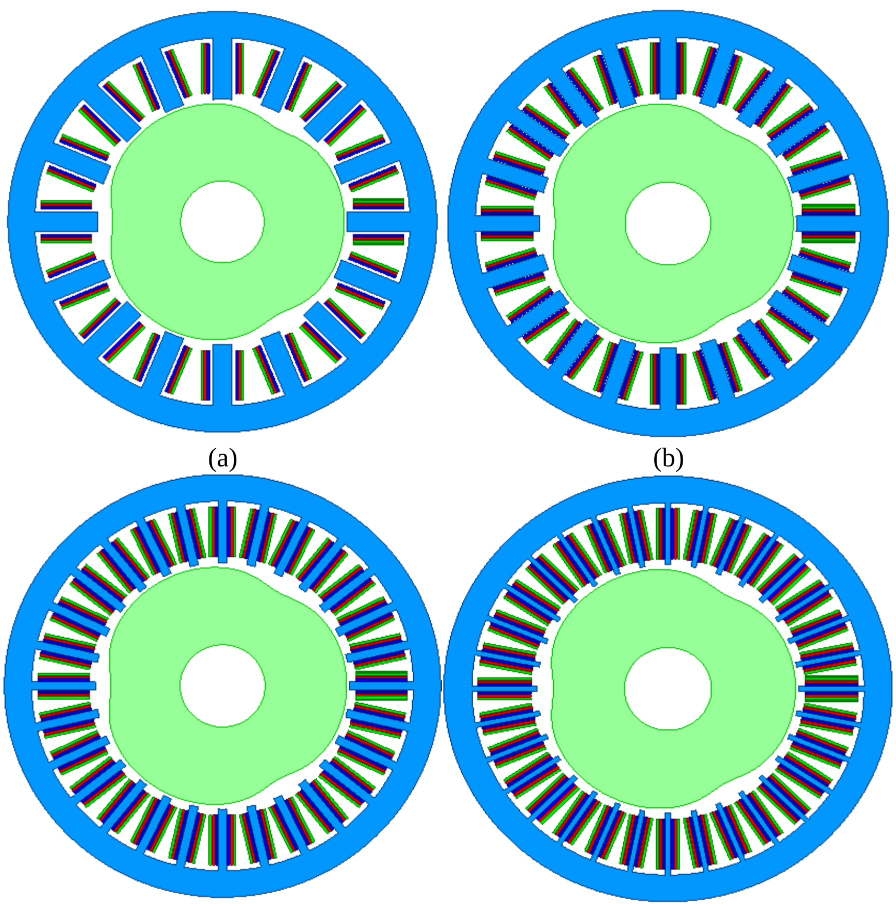


Fig. 17. Position error of resolver under short circuit fault in case XI, case XII and the initial case



(a) (b) (c) (d)

Fig.18 The schematics of resolver with different tooth: (a) 16 tooth, (b) 20 tooth, (c) 28 Tooth, (d) 32 Tooth

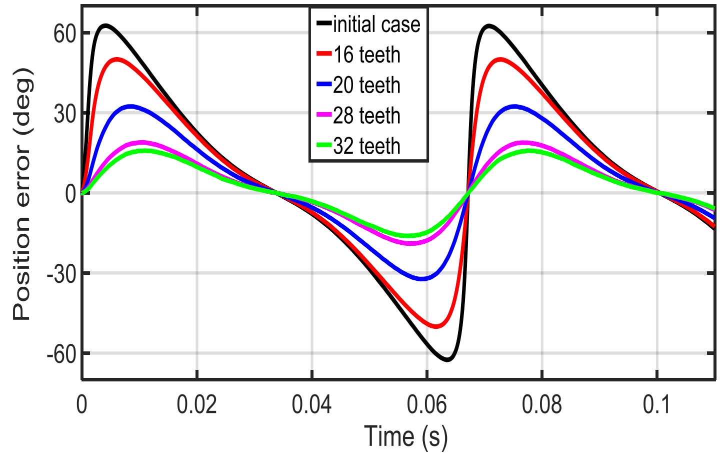


Fig. 19. Position error of resolver with different tooth under short circuit fault

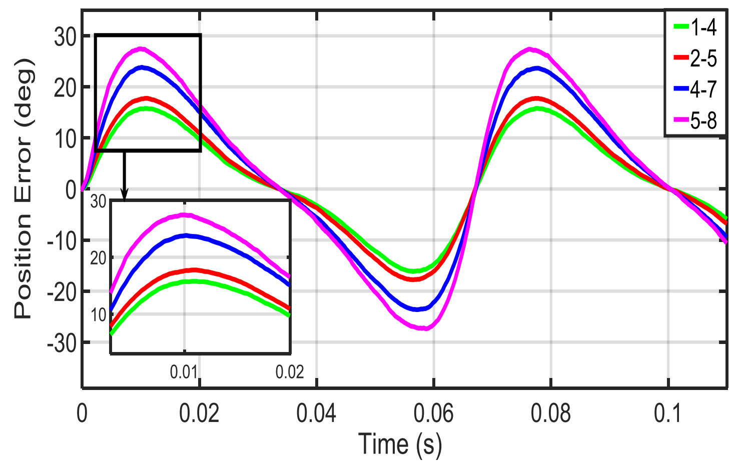


Fig. 20. Position error of resolver under short circuit fault with different combination of poles

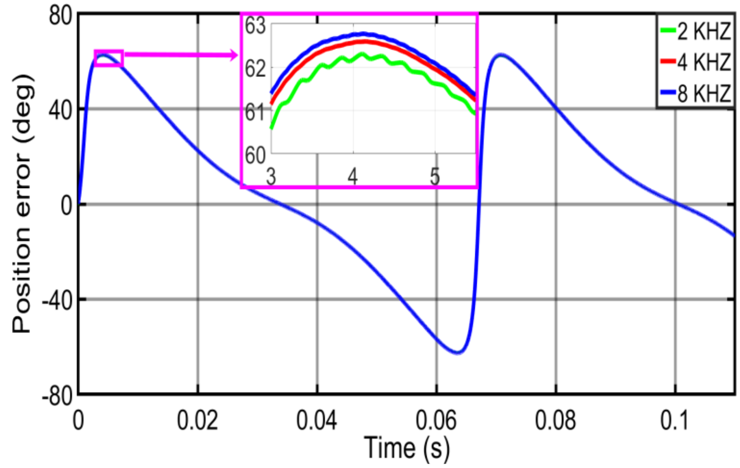


Fig. 21. Position error of resolver under short circuit fault in 2 KHZ, 4 KHZ and 8 KHZ

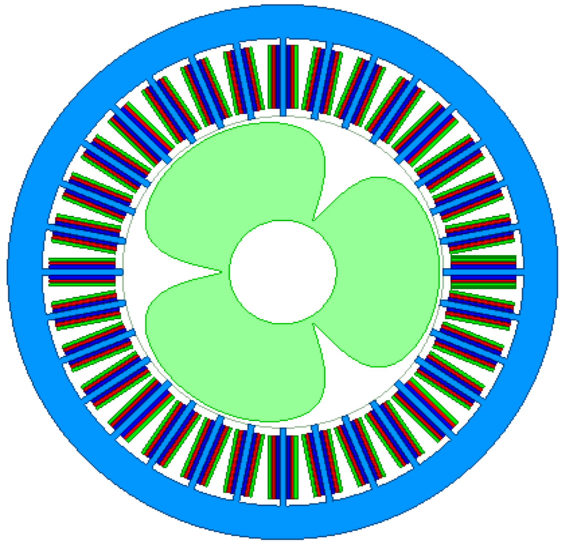
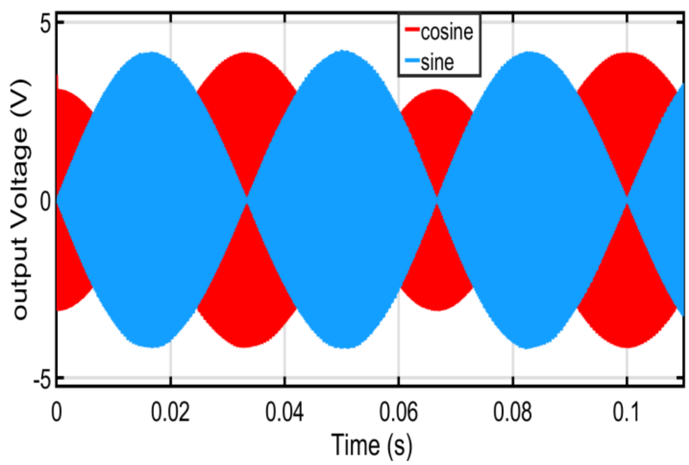
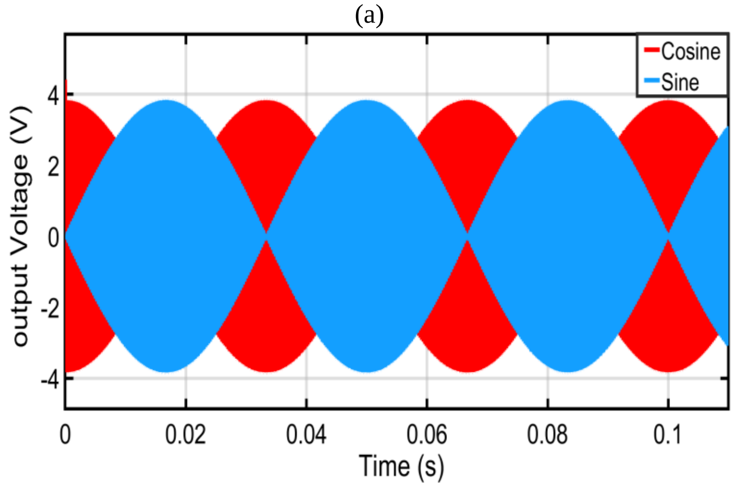


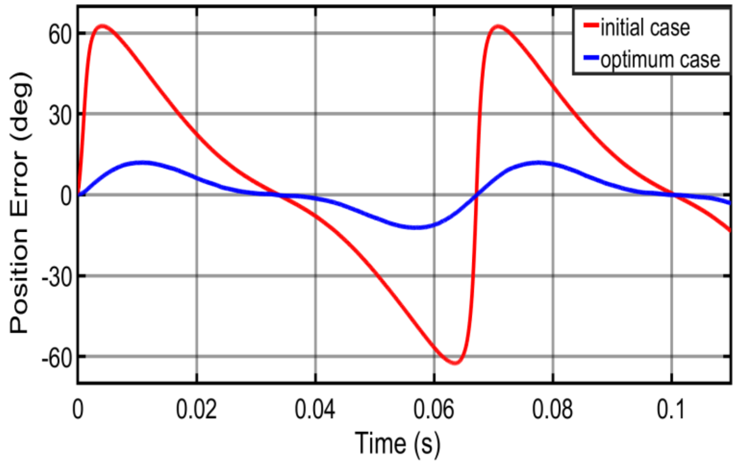
Fig. 22. The schematics of optimum case



(a)

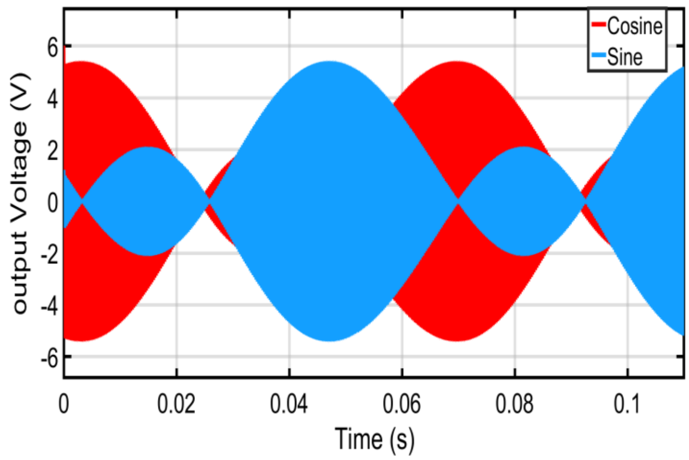


(b)

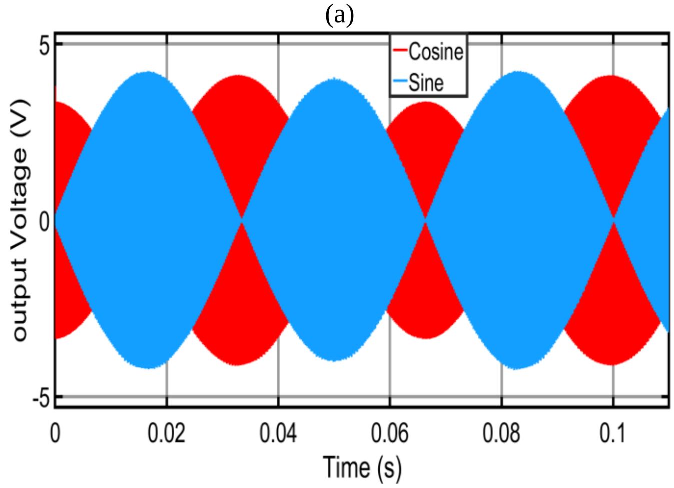


(c)

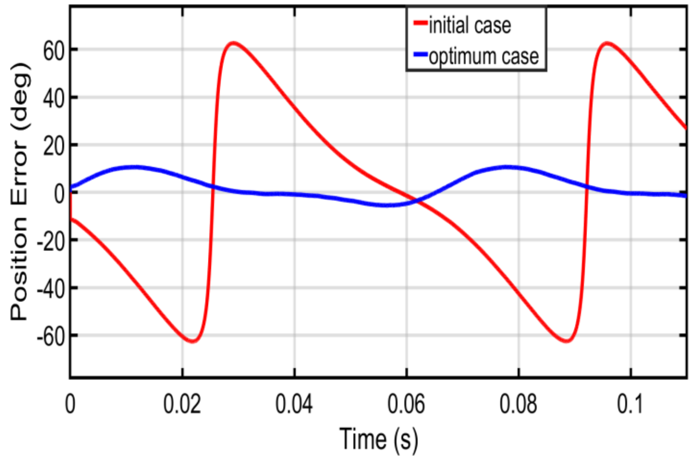
Fig. 23. Finite element simulation results for optimum case: (a) signal voltage under short circuit fault on first tooth, (b) signal voltage in healthy condition (c) the position error



(a)



(b)



(c)

Fig. 24. Finite element simulation results for short circuit on the second tooth of sine winding: (a) signal voltage of initial case, (b) signal Voltage of optimum case (c) the position error of initial case and optimum case

Table I. The number of turns per tooth for the sine, cosine and the excitation winding with different combination of pole

Tooth	1-4			2-5			4-7			5-8		
	cos	sin	exc	cos	sin	exc	cos	sin	exc	cos	sin	exc
1	150	0	45	150	0	45	150	0	45	150	0	45
2	147	29	32	139	57	25	106	106	9	83	125	0
3	139	57	0	106	106	-17	0	150	-42	-57	139	-45
4	125	83	-32	57	139	-44	-106	106	-25	-147	29	0
5	106	106	-45	0	150	-32	-150	0	32	-106	-106	45
6	83	125	-32	-57	139	9	-106	-106	37	29	-147	0
7	57	139	0	-106	106	42	0	-150	-17	139	-57	-45
8	29	147	32	-139	57	37	106	-106	-44	125	83	0
9	0	150	45	-150	0	0	150	0	0	0	150	45
10	-29	147	32	-139	-57	-37	106	106	44	-125	83	0
11	-57	139	0	-106	-106	-42	0	150	17	-139	-57	-45
12	-83	125	-32	-57	-139	-9	-106	106	-37	-29	-147	0
13	-106	106	-45	0	-150	32	-150	0	-32	106	-106	45
14	-125	83	-32	57	-139	44	-106	-106	25	147	29	0
15	-139	57	0	106	-106	17	0	-150	42	57	139	-45
16	-147	29	32	139	-57	-25	106	-106	-9	-83	125	0
17	-150	0	45	150	0	-45	150	0	-45	-150	0	45
18	-147	-29	32	139	57	-25	106	106	-9	-83	-125	0
19	-139	-57	0	106	106	17	0	150	42	57	-139	-45
20	-125	-83	-32	57	139	44	-106	106	25	147	-29	0
21	-106	-106	-45	0	150	32	-150	0	-32	106	106	45
22	-83	-125	-32	-57	139	-9	-106	-106	-37	-29	147	0
23	-57	-139	0	-106	106	-42	0	-150	17	-139	57	-45

24	-29	-147	32	-139	57	-37	106	-106	44	-125	-83	0
25	0	-150	45	-150	0	0	150	0	0	0	-150	45
26	29	-147	32	-139	-57	37	106	106	-44	125	-83	0
27	57	-139	0	-106	-106	42	0	150	-17	139	57	-45
28	83	-125	-32	-57	-139	9	-106	106	37	29	147	0
29	106	-106	-45	0	-150	-32	-150	0	32	-106	106	45
30	125	-83	-32	57	-139	-44	-106	-106	-25	-147	-29	0
31	139	-57	0	106	-106	-17	0	-150	-42	-57	-139	-45
32	147	-29	32	139	-57	25	106	-106	9	83	-125	0