Signal Processing and Renewable Energy
December 2018, (pp. 23-36)
ISSN: 2588-7327
eISSN: 2588-7335

Study of Reduce Harmonic and Increasing Positioning Determination in Variable Reluctance Resolver with Area Couplings

Roya Shamsali [1], Hamid Lesani[2*]

[1] Electrical Engineering Department, South Tehran Branch, Islamic Azad University, Tehran, Iran
[2] Electrical Engineering and Computer Science Department, Tehran University

Received: 19-Apr-2018, Accepted: 20-Aug-2018

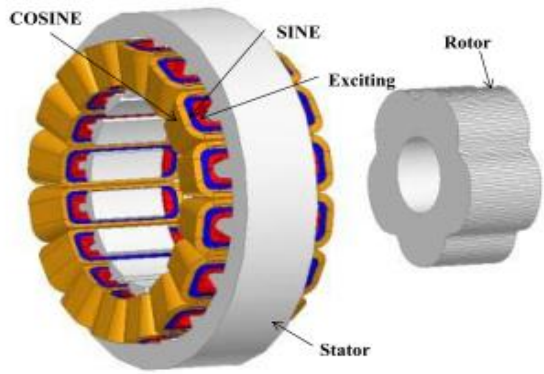
Abstract
Variable reluctance (VR) resolvers are widely used in industrial applications such as aerospace, military, robotic, control of hybrid motors, and navigation for solar systems. Variable reluctance resolvers are preferred because of simplified structure and affordable prices in many applications in comparison with to the coiled rotor resolvers. In this study, effect of variation of physical parameters including skewing and opening slots of stator is investigated. The performance of the proposed structure is simulated by using a 3-D time stepping finite element method.

Keywords: Variable reluctance resolver, accuracy, physical parameters, time steps, finite element method.

1. INTRODUCTION

Among different magnetic sensors, the encoder and resolver are commonly used as the position and speed sensors for an inverter-driven electric motors and motion control systems. Resolvers are positioned sensors that are increasingly used in many industrial applications. The rival of resolver for obtaining the position is optical encoders. Although accuracy of encoders is very high and they are not expensive, they are not suitable in dirty and environmentally-sensitive environments, such as high temperature variation and continuous vibration environments. Although, the encoders output is digital, the resolvers output is analog. However, the

*Corresponding Author's Email: lesani@ut.ac.ir



(a) (b)

Fig. 1. Variable reluctance resolver with sinusoidal air gap: a) rotor b) stator [12].

ability to work in harsh environments is the most advantages of resolvers in contrast with encoders [1-3].

Resolver electromagnetic sensors that determine the position offers advantages like the optical encoder [5] which listed in following.

1. Ability of working with the wide range of frequency, temperature and vibration.
2. Low volume and adequate cost and robust structure.
3. The ability of usage in the polluted environments.

In general, resolvers are two-phase synchronous generators that their excitation circuit instead of DC current is fed by an AC current. So, there are two-types of resolvers; the rotor wounded and the variable reluctance [7].

The first generation of resolvers (rotor wounded) due to use of brush and slip rings has decreased mechanical reliability, and it needs to repair and maintenance [4-5]. In this regard, the second generation of rotor wound resolvers has been developed. These resolvers are breathless and for inducing voltage, it uses the rotary transformer [18].

The primary coil of rotary transformer is placed on the stator and fed by a high frequency voltage. The voltage induced in secondary coil of the rotary transformer, which is located on rotor, feeds the excitation winding [10].

The presence of a rotary transformer in the radial flux resolver increases the sensor length, and in the axial flux resolver, in the inner diameter of the sensor, the sensor diameter increases, which is not suitable for both models [4]- [7]. Another problem with rotating transformers is being two coils (primary and secondary rotary transformers) to a set of sensor, which in addition to phase shift error, reduces the thermal stability of the sensor [6].

Despite these disadvantages, due to the high precision of two-pole rotary transformers, they are used in many applications [4], and many studies have been done to reduce the impact of electrical and mechanical errors on the accuracy of these resolvers [3]- [7].

In order to overcome the problems of rotary transformer resolver, the new resolver which called variable veluctance (VR) vesolver has been developed, which is non-coil rotor [6]- [10].

The base of VR resolver operation is the sinusoidal variable reluctance in the air gap, and both of excitation and signal windings are on the stator [2].

According to $R = \iota/\mu A$, there are two types of VR resolvers. The first one works based on the sinusoidal flux variation of air gap length and the second type works based on the sinusoidal flux variation of the coupling area between stator and rotor [2].

The conventionally types of VR resolvers that works based on the sinusoidal flux variation of air gap length consists of saliency rotor without windings, see Fig. 1(a). The excitation and signals windings are concentric located on stator slots according to Fig. 1.

In usual type of VR resolver that works based on a sinusoidal flux variation of air gap length, both the signal (SIN and COS windings) and excitation windings are wounded in each slot of the stator with different turn numbers, that make a complicate winding process. Increasing the number of poles of VR resolver can increase the VR resolver accuracy but the manufacturing and installation process is very complicated [4], [12]. Hence, many studies have been done to solve the mentioned problems in recent years [9],[11], [12],[14], [16], [17], [19].

The last generation of VR resolver works based on the sinusoidal flux variation of the coupling area between stator and rotor [21-23]. Authors in [21] calculated the optimal length of the rotor ring and the length of the stator teeth to reduce the harmonics of output voltages. The result of the proposed optimization recommended choosing the rotor ring length the same as the stator length. In [22], effect of increasing the number of poles on performance of variation of resolver reluctance with coupling was investigated in the case of eccentricity error. Comparison of total harmonic distortion (THD) of the output voltages for two- poles and four- poles pairs VR resolvers in [22], showed that the THD of induced voltages of VR resolver with four poles pairs rotor is smaller than two-poles pairs rotor.

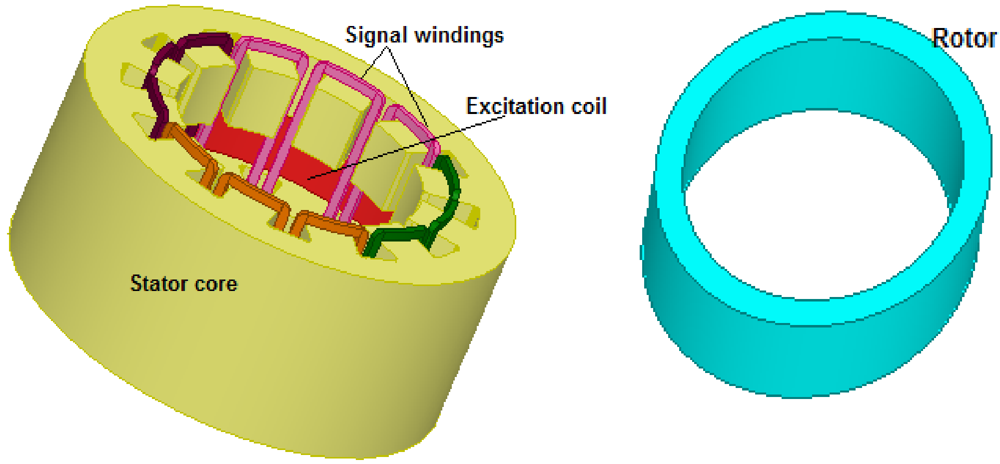
In [20], effect of mechanical errors, including static and dynamic eccentricity, rotor tilting and run-out has been investigated.

In [23], distribution of flux lines and flux density of VR resolver was shown by using three dimensional finite element method. Authors [23] have shown that the zero error of the reluctance resolver flux variation with coupling area is less than the amount of resolver variable variation with the change in the air gap length.

In [2], for the first time, VR resolver disk was provided with variable coupling area. Authors [2] have shown that the disc structure increases the resilience of variable reluctance resolver by coupling the area to the run-out error.

The harmonic contents of output voltages of variable reluctance resolver with area coupling indicates that the third harmonic is the largest harmonic component, that in healthy conditions, affects the accuracy of the resolver.

In this paper, two methods of skewing and opening the stator slots are used to reduce the harmonic component. For this purpose, the 3D finite element method is used in the transient state to simulate resolver. After calculating the output voltages by the finite element method, induce voltages are called in MATLAB software and the envelope of these voltages is calculated. The harmonic content of the pointer is determined and then



(a) *(b)*

Fig. 2. Structure of tow pole-pairs of VR resolver, a) stator, signals and excitation windings on the stator, b)sinusoidal rotor shape.

the output position is obtained. In this study the four- and eight-poles stator VR area coupling resolver is introduced and THD of VR resolvers is determined and compared.

2. STRUCTURE OF VARIABLE RELUCTANCE RESOLVER

The proposed resolver is a variable reluctance resolver with variation flux coupling area between rotor and stator. Stator consists twelve axial slots, with concentric SIN and COS windings, with a fixed number of turns and a radial groove in the middle of the stator height that the excitation winding is on it. This groove divided stator to 3 parts; upper slots, lower slots, and middle groove, with equal height. Rotor of this VR resolver is a ferromagnetic sinusoidal shape with two non-ferromagnetic holder. Fig. 2 shows the stator and rotor of VR resolver as well.

Table 1 shows the geometric dimensions and excitation parameters of the proposed resolver.

3. FINITE ELEMENT ANALYSISI OF VR RESOLVER

For the performance evaluation of sensors, a 3-D time stepping nonlinear finite element method is used. Although, VR resolver with varying air gap flux can be simulated with 2-D, it is recommended to simulate in 3-D because the flux variation in length is increased and variation flux of area coupling should see the sinusoidal by teeth. Therefore, the model should have volume, and 2-D model does not have the accuracy required for this simulation.

Accuracy of finite element method depends on the mesh size and problem solving step. Therefore, choosing the mesh dimensions and problem solving step small is equivalent with more accurate results, but the problem solving time goes up. So, obtaining the optimal values of these parameters in order to have proper accuracy is necessary.

Fig. 3 shows the schematic of VR Resolver mesh where the meshes density increase near the air gap to improve the simulation precision.

Table1. ***Parameters of studied VR resolver.***

Parameter	unit	value
voltage	volt	5
frequency	Hz	400
rotor pole pair	-	1
Stator core outer/inner diameters	mm	70/40
Rotor core outer/inner diameters	mm	36/30
air gap length	mm	2
number of stator slots	-	12
Tooth width	mm	7.46
Slot height	mm	10
number of turn for	-	100
excitation winding number of turn for signal windings	-	50
winding method		concent rated

To make sure that there is no magnetic saturation; magnetic flux density distribution is shown on proposed VR resolver in Fig.4. As seen in Fig. 4, the maximum flux density is about 0.3 m-Tesla at time of 0.8 T = m-seconds, which is more less than the allowable maximum flux density of the employed steel.

Fig. 5 shows induced voltages and harmonic contents of envelopes of induced voltages. The amplitude of the third harmonic related to peak value of envelope is 3% of main component. The THD value of the signals envelops is 3.63%. The average absolute error and maximum error are 1.21 and 3.25 degrees, respectively.

Moreover, effect of changing parameters on accuracy of estimate position is given in following.

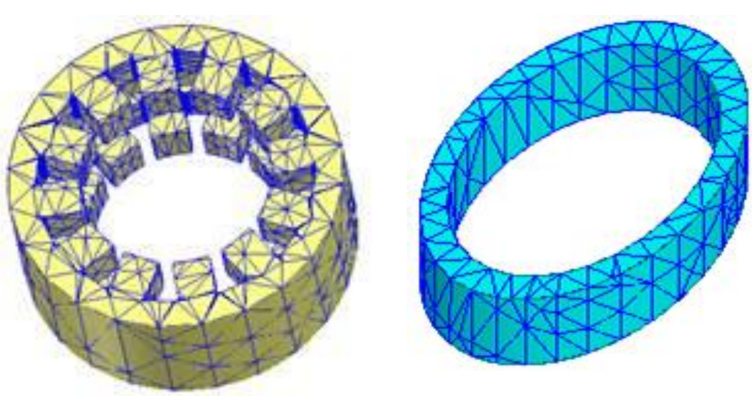


Fig. 3. Mesh schematic of VR resolver (rotor and stator).

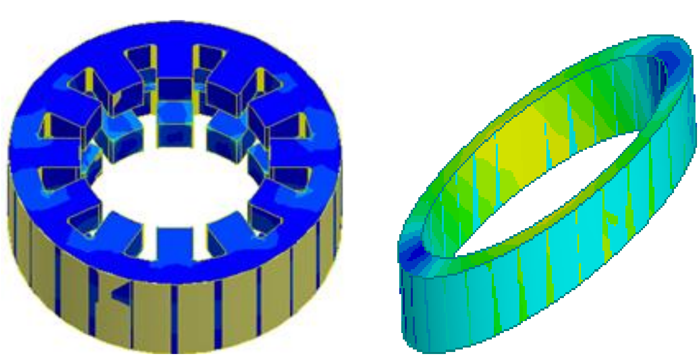
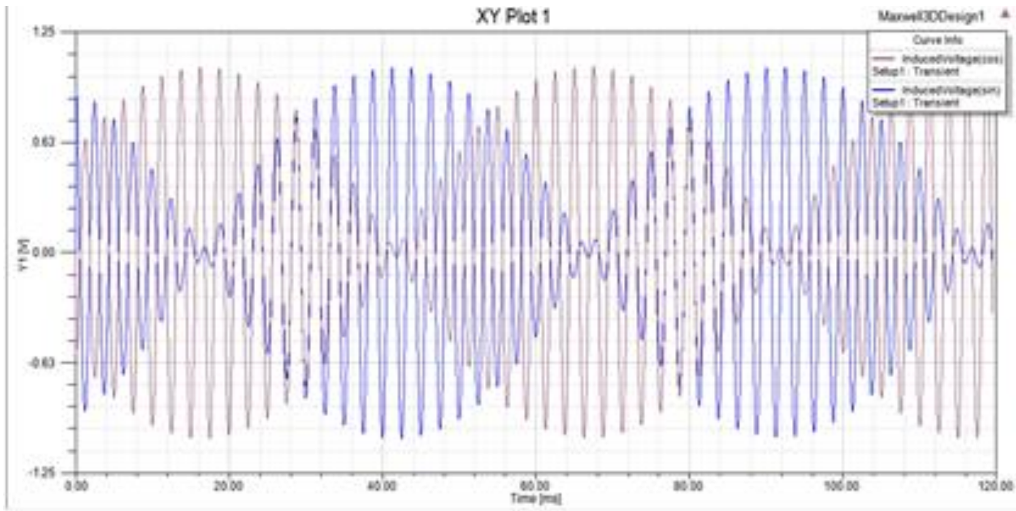
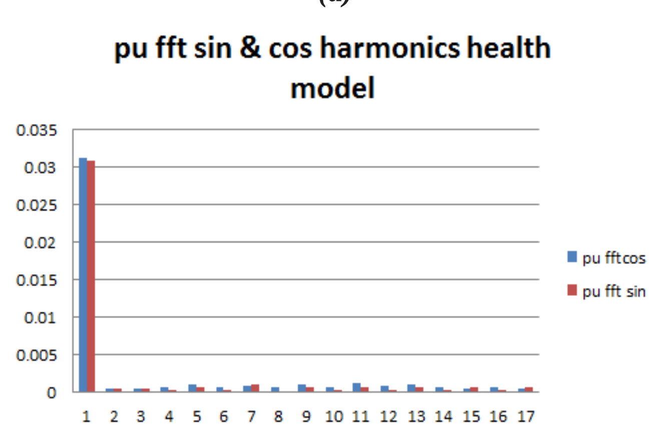


Fig.4. Distribution of flux density on VR resolver.



(a)



(b)

Fig. 5. (a) Induced voltages in signal windings, (b) Harmonic contents for envelopes of induced voltages.

4. EFFECT OF PHYSICAL PARAMETERS ON PERFORMANCE

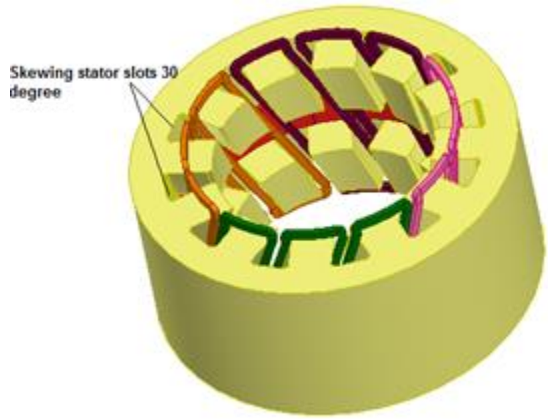
Using resolvers' design parameters to attenuate the error is an expensive solution. An appropriate tool to evaluate the accuracy of a resolve is analyzing the harmonic contents of the air–gap's magneto motive force (MMF) [7].

In this Section, effect of skewing and slot opening, on THD induced voltages and estimate position error, are studied:

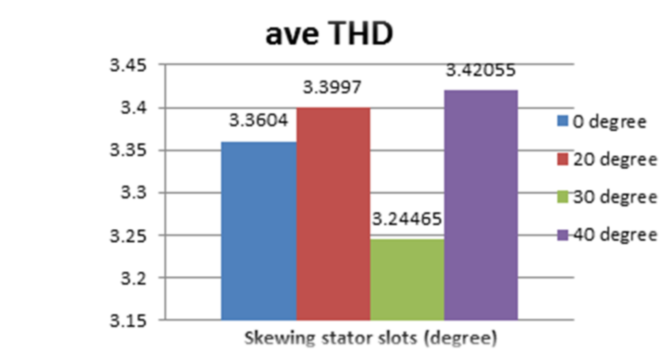
4.1. Effect of Stator Slots Skewing

In electrical machines, slots of rotor, stator and sometimes both of them, are skewed to reduce slot harmonics. This is achieved by causing a linear rise in the flux distribution in the air-gap. Besides, by harmonic contents reduction, skewing reduces the induced voltage in the windings.

Fig. 6(a) shows schematic of VR resolver with skewing slots. Three different angles, including 20, 30 and 35 degrees are considered. THD of induced voltages of various skewing slots of VR resolver is shown in Fig. 6(b).This leads to better position estimation with small



(a)



(b)

Fig. 6. Effect of skewing slots, (a)stator schematic with skewing slots (skewing 30 °), (b) THD of induced voltages for different skewing.

error. It is observed that the lowest THD is related to VR resolver with a skewing angle of 30 degrees by 3.24 that is less than VR resolver without skewing, where THD is 3.36.

4.2. Effect of Slot Opening

In previous Section, the lowest THD of induced voltage is obtained with angle of 30 degrees skewing. In order to increase the precision of estimation of VR resolver, the width of slot opening is done.

4.2.1. Reduce the Slots Opening Width

Reducing opening width of slots causes,

1- Change of reluctance the air gap decreases with the rotor rotation, therefore, the resolver error should be reduced.

2- Leakage flux increases, as a result of resolver error.

Therefore, VR resolver with 30 degrees skewing, is investigated by slots opening in five dimensions 1, 2, 2.5, 3, 3.5 and 4 mm. THD of induced voltages for different values of the slot opening is shown in Fig. 7. It should be noted that the best result based on the simulation results and obtained THD is for VR resolver with a width of 3 mm.

As seen in Fig. 7, increasing slot opening up to 3 mm, with a constant slot width, makes the

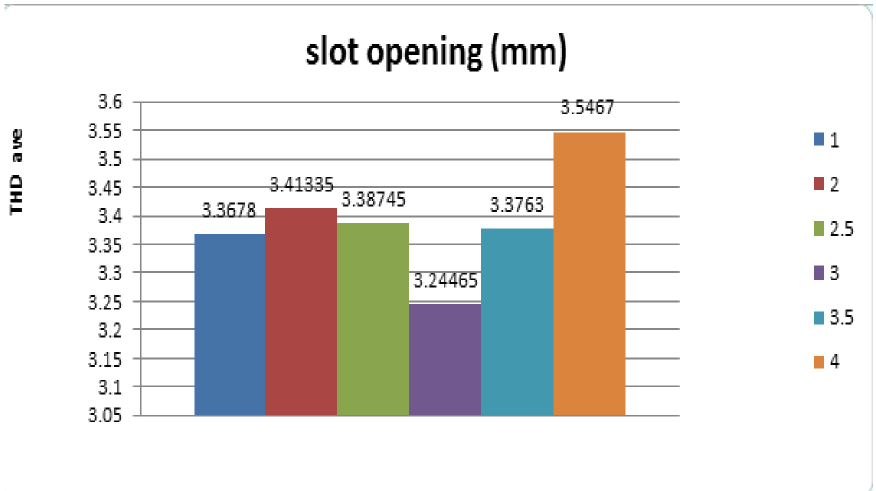
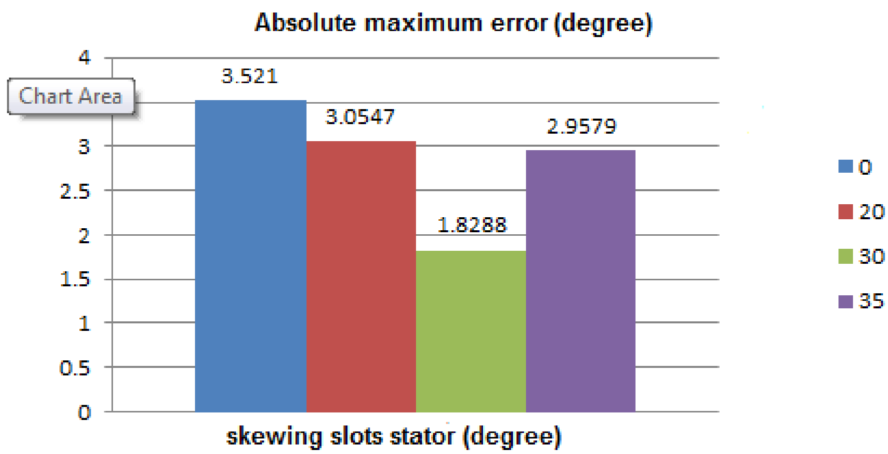
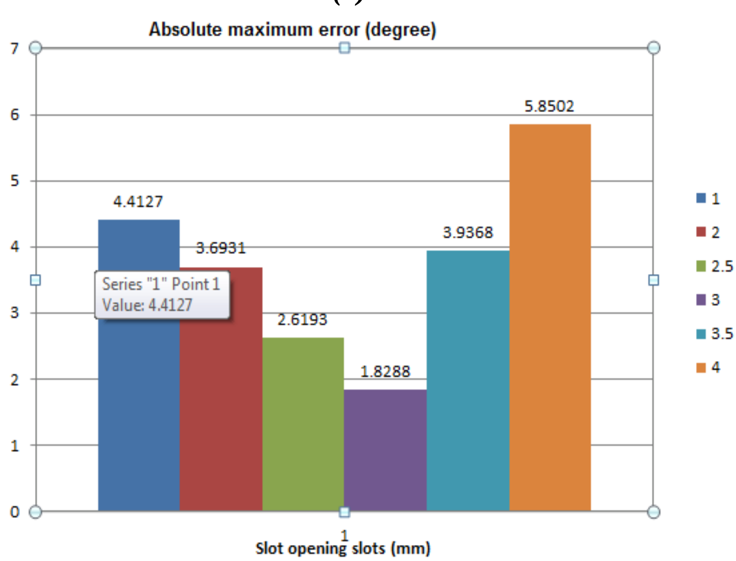


Fig. 7. THD of induced voltages for different slot opening of stator.

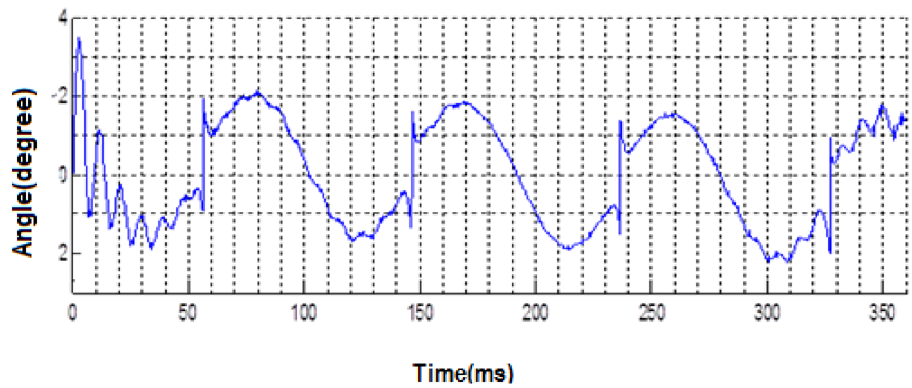


(a)

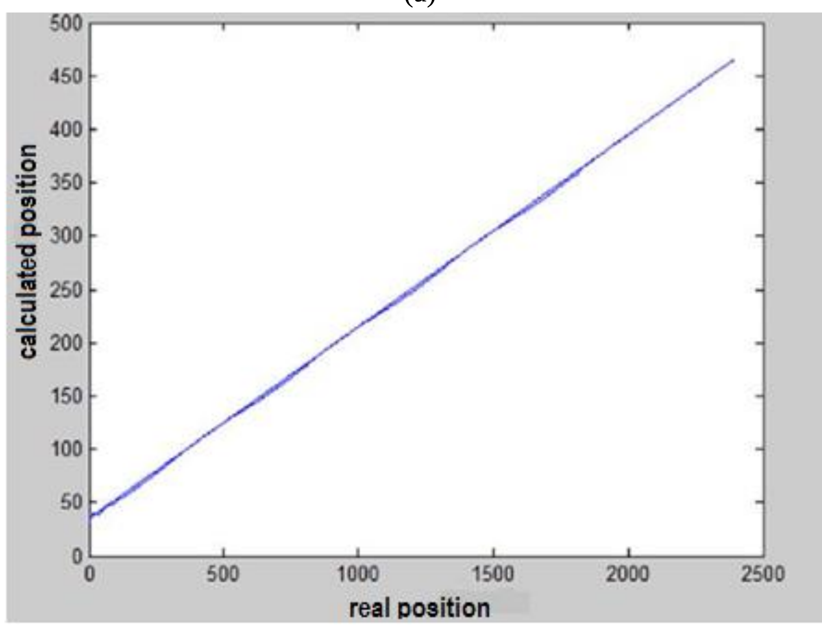


(b)

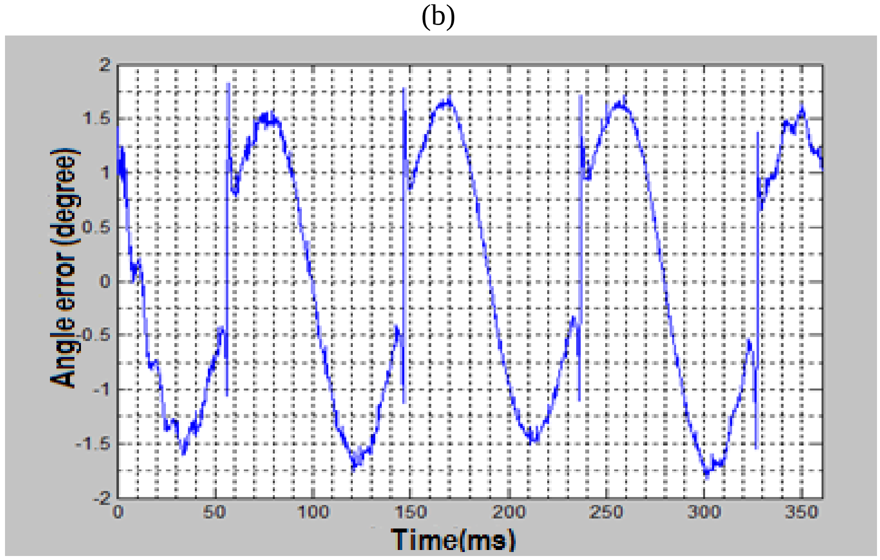
Fig. 8. Absolute maximum error charts under VR resolver study is shown, (a) skewing of 20, 30 and 35 degrees, (b) slot opening 1, 2, 2.5, 3, 3.5 and 4 mm.


Angle(degree)
Time(ms)

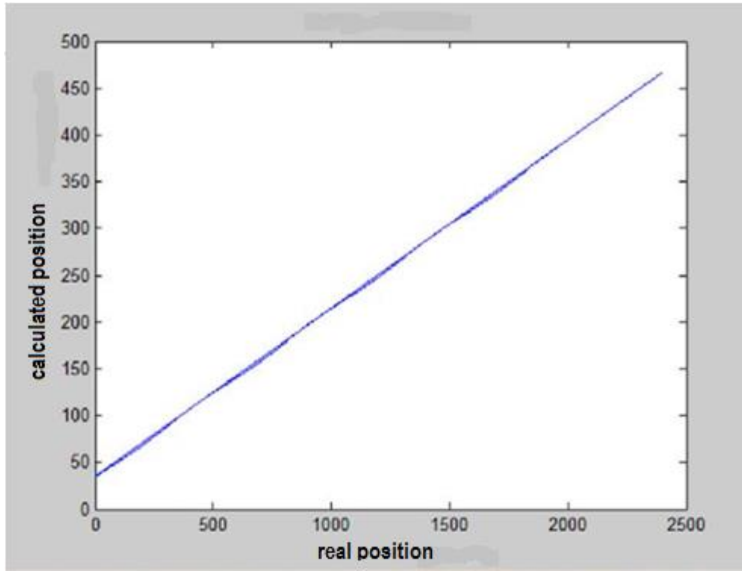
(a)


calculated position
real position

(b)


Angle error (degree)
Time(ms)

(c)



(d)

Fig. 9. (a,b) The position error and estimation of error signal of not skewing VR resolve respectively are shown. (c,d) The position error and estimation of error signal of VR resolver with 30 degrees skewing and 3mm slot opening are shown respectively.

output signals' THD's decreased from 3.36 to 3.24.

4.3. Absolute Maximum Error Position and the Best THD

So far, THD was the main criterion for determining the accuracy of inductive voltages of resolvers, but the fact is that THD is not perfect because,

1- THD is not sensitive to harmonic.

2- The phase shift is not affected.

Therefore, it is necessary to ensure that the extracted position is correct through obtaining the position error.

The best indicator of comparing the accuracy of resolvers is absolute maximum error value of the mean resolver error. Fig. 8(a) shows the maximum absolute error of studied VR resolver under skewing of 20, 30 and 35 degrees.

Fig. 8(b) shows the maximum absolute error diagram for the stator slots under opening slots of 1, 2, 2.5,3, 3.5, 4 m.

4.3.1. Signals of calculated position to real position

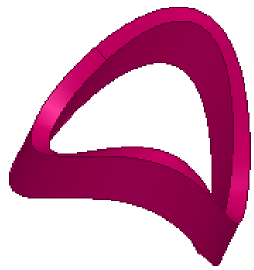
The estimate position error signals and calculated position diagram of VR resolver without skewing and under skewing of 30 degrees and slot opening 3 mm is shown in Fig. 9(a,b) and Fig. 9(c,d) respectively .

5. MULTIPOLAR VR RESOLVER

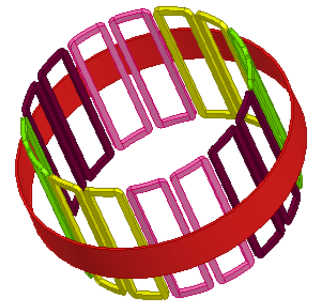
By increasing number of poles and phases, the VR resolvers accuracy is increased, also the number of stator slots and signal windings varies. Hence in this Section, multipolar VR resolver and induced voltages had been simulated.

5.1. Four-Pole Pairs VR Resolver

Four-poles pairs VR resolver has a rotor with 4 sinusoidal arcs magnetic without any windings. Its' stator consists of 16 vertical teeth, in this way wounding both signal (SIN,

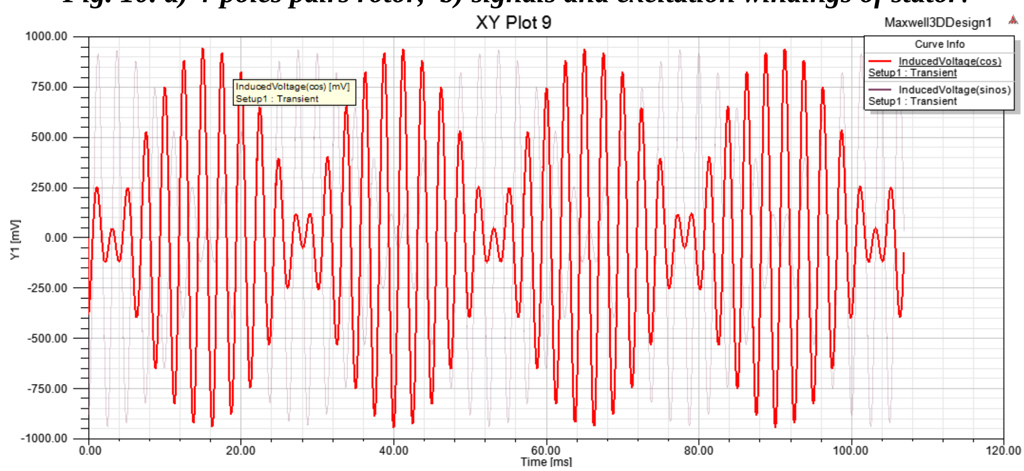


(a)

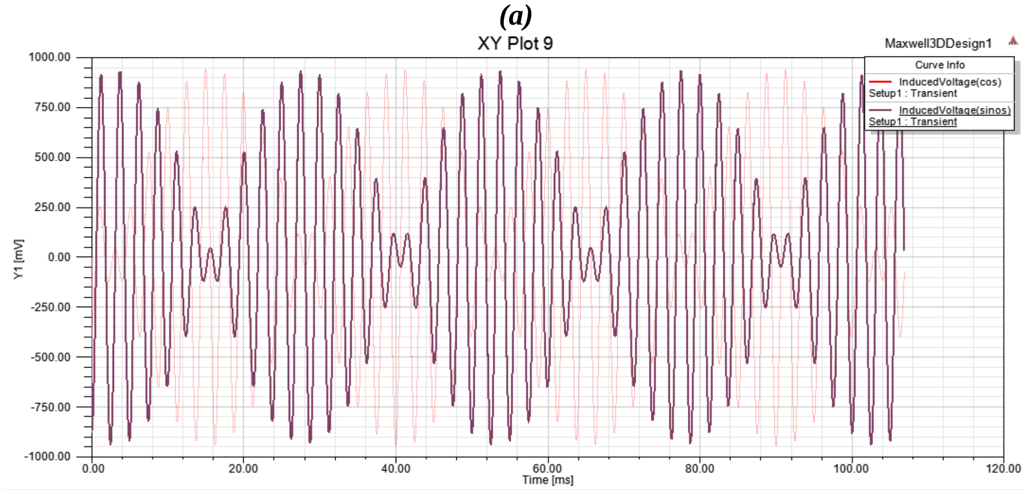


(b)

Fig. 10. a) 4-poles pairs rotor, b) signals and excitation windings of stator.



(a)



(b)

Fig. 11. a) Cosine induced voltage signal, b) Sinusoid induced voltage signal

COS windings) on each stator teeth is changed because of polar stator is to be changed, too, and other specification is like as two-poles pairs VR resolver.

Fig. 10(a, b) shows rotor, signals and excitation windings of stator teeth of 4-poles pairs VR resolver respectively.

The simulation results of induced voltages (SIN and COS) of 4-poles pairs VR resolver are shown in Fig. 11. (a, b) respectively.

Sinusoid and cosine THD of 4-poles pairs VR resolver is 2.9 and 3.7 respectively.

Average THD of 4-poles pairs is about 3.3 without changing other physical parameters

(a) *(b)*

Fig.12. a) 6-poles rotor, b) Signals and excitation windings of stator.

such as skewing and opening slots, if there is an insult the situation will get better.

5.2. Six-Pole Pairs VR Resolver

Fig. 12 (a, b) shows rotor, signals and excitation windings of stator teeth of VR resolver.

As seen in Fig. 12, rotor has 6 sinusoidal magnetic arc and stator has 12 teeth. Stator winding is changed and other parameters are the same as 2-poles pairs VR resolver.

Increasing number of poles could improve the accuracy of resolver. In this way the number of stator slots increased and wounding of signals windings is very complicated.

Of course, in this study, only the simulation of multipolar VR resolver, is investigated, and obtaining THD and determining the accuracy of position error is postponed to subsequent studying.

6. CONCLUSION

In this paper, the effect of different designing parameters, such as, skewing and opening slots of VR resolver on the THD of the output signals and consequently the position estimation error, has been studied. It was shown that as the skewing increases, up to 30 degrees harmonic content of output signals decrease. It was also shown that, increasing the slot opening up to 3mm also helps to obtaine the proper THD in comparison with the previous VR resolver(without skewing). Whereas THD is not the best criterion for determining the state of affairs, we tried to calculate the position error of VR resolver. Changing the physical parameters by obtaining the position error, which again yields the same results. In other words, by skewing the slots of 30 degrees and opening 3 mm of slots, there is the lowest harmonic in the output signals, which will increase the accuracy of the position.

REFERENCES

[1] Zahra Nasiri-Gheidari , and Farid Tootoonchian , “An Optimized Axial Flux Variabble Reluctance Resolver with Concentric Winding “ IEEE 2016.

[2] Zahra Nasiri-Gheidari , and Farid Tootoonchian , and Fateme Zare “ Design oriented technique for mitigating position error due to shaft run-out in sinusoidal-rotor variable reluctance resolvers” IET 2016.

[3] F.tootoonchian, K. Abbaszadeh and , M. Ardebili "A New Technique for Analysis of Static Eccentricity in Axial Flux Resolver" IEEE 2012.

[4] Z. Nasiri-Gheidari " Design Analysis, and Prototyping of a New Wound-Rotor Axial Flux Brushless Resolver" IEEE 2016.

[5] Zahra Nasiri-Gheidari , and Farid Tootoonchian "Axial flux resolver design techniques for minimizing position error due to static eccentricities" IEEE 2015.

[6] Farid Tootoonchian "Design, Performancing , and Testing of a Brushless Axial Flux Resolver Without Rotor Windings" IEEE 2016.

[7] R. Alipour-Sarabi, Z.Nasiri-Gheidari, F. Tootoonchian " Effects of Physical Parameters on the Accuracy of Axial Flux Resolvers" IEEE 2016.

[8] G. Kronacher "Design , Performance and Application of the Vernier Resolver" 1957.

[9] Chang-Sung Jin , Ik-Sang , Jae-Nam Bae , and Won- Ho Kim "Proposal of Improved Winding Method for VR Resolver" IEEE 2015.

[10] O.A.Tolstykh , A.P.Balkovoi, M.G.Tiapkin, A.S. Markov " Research and Development of the 4X-Variable Reluctance Resolver" IEEE 2016.

[11] Ki-Chan Kim "Analysis on the Charateristics of Variable Reluctance Resolver Considering Uneven Magnetic Field" IEEE 2013.

[12] X.Ge , Z. Q. Zhu, r.Ren, and J.T.Chen " Analysis of Windings in Variablr Reluctance Resolver" IEEE 2015.

[13] Yoshimi Kikuchi , Hiromi Makiuchi , Hisashi Mimura ,Akira Kojima , Hiroyuki Wakiwaka , Kunihisa Tashiri , "Reduction Method of External Magnetic Field Effect on VR Resolver" , IEEE 2009.

[14] Sung-In Park , and Ki-Chan Kim "Study on the Optimal Design of a Novel Slotless Resolver by FEM" IEEE 2014

[15] Duane C. Hanselman " Resolver Signal Requirements for High Accuracy Resolver-to- Digital Conversion" IEEE 1990.

[16] Cui Shui-Mei , Ge-Hao " Stator Structure Design and Analysis of Variable Reluctance Resolver for Hybrid-Vehicle Motor Drive "IEEE 2012.

[17] Joao Figueiredo "Resolver Models for Manufacturing" IEEE 2010.

[18] Lizhi Sun " Analysis and Improvement on the Structure of Variable Reluctance Resolvers" IEEE 2008.

[19] K. Masaki , K. Kitazawa , H.Mimura , M. Nirei , K. Tsuchimichi , H. Wakiwaka , H. Yamada " Magnetic field analysis of a resolver with a skewed and eccentric rotor" Elsevier Science 2000.

[20] Jing Shang , Hao Wang, Mimi Chen , Ning Cong, Yong Li, Chengjun Liu, "The Effects of Stator and Roor Eccentricities on Measurement Accuracy of Axial Flux Variable – Reluctance Resolver with Sinusoidal Rotor" IEEE 2014.

[21] Shang Jing , Zou Jibib " The Analysis for New Axial Flux Variable Reluctance Resolver with Air-gap Complementary Structure" IEEE.

[22] Shang Jing , Wang Hao , Wang Weiqiang , " The Analysis of Multipole Axial Flux Reluctance Resolver with Sinusoidal Rotor" IEEE 2012.

[23] Shang Jing , Hu Jianhui, Xu Yongxiang " The Parameter Design and Calculation for Axial-Flux Resistance Resolver" IEEE .

[24] Shang Jing , Zhao Meng , Jiang Shalan,” The Principle of Reluctance Resolver and EMF Waveform Optimization Based on FEM” IEEE 2011.