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Substitution Analytical Model for Finite Element Method to Predict Distribution of Flux density for Flux Switching Permanent Magnet with E-Core Shape of Stator at no load

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Abstract

In this essay, a two-dimensional analytical model for switched flux machines without permanent magnet brushes with E-shape of stator is presented. This machine is a suitable choice for use in hybrid vehicles, due to high power density of this configuration. The radial and tangential components of the magnetic flux density in the presence of only magnets are calculated based on Maxwell's equations and the subdomain method for different areas of the machine, including air gaps. Finally, in order to validate the proposed model of the essay, the results extracted from the analytical model are compared with the results obtained from the finite element method.

Keywords: Flux-switching; Analytical model; Finite element method; Sub-domain; Boundary conditions; E-core

NOMENCLATURE

AMagnetic vector potential (V.s/m)

BMagnetic flux density vector (T)

B rem Permanent magnet residual flux density (T)

H Magnetic field intensity vector (A/m)

J Armature current density vector (A/m2)

MMagnetization vector (A/m).

μ0 Free space permeability (H/m).

μr Relative permeability.

μrpm Relative permeability of permanent magnet

NsiNumber of inner stator slots

Nri Number of inner rotor slots

Npmi Number of inner permanent magnets (PM)

Rsi Inner radios of stator

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RyiOuter radios of stator slot

RriOuter radios of rotor

RnmiOuter radios of PM

RryiInner radios of rotor slot

wsiWidth of stator slot

wriWidth of rotor slot

wpmiWidth of PM

wpmoWidth of PM

αiCentral angle of ith slot of rotor

βiCentral angle of ith slot of stator

σiCentral angle of ith PM

Introduction

The permanent magnet switched flux machine is known as a high-efficiency machine with high power density, which can receive adequate power on a small scale. The operation of this machine is such that with the movement of the rotor, the flux produced by the magnets placed on the stator teeth chooses the path with the least magnetic resistance according to Figures 1[1], which causes a sinusoidal induced voltage on It is on the stator winding (generator view) and due to the synchronous nature of this machine, there is no starting torque and with the initial rotation of the rotor and applying a balanced voltage to the three-phase winding, a continuous torque can be obtained (view motor). Machines brushless permanent magnet are usually designed in such a way that permanent magnets are mounted on the rotor, but in the machine examined in this project, the magnets are mounted inside the stator tooth, which has two advantages: first The reason is because of the convenience of the cooling process, and the other reason is that the magnet is not subjected to any force due to rotation due to its placement in the fixed parts of the machine. There are different designs for a permanent magnet square-switched machine, as shown in Figure 2[2] is a multi-tooth structure. In Figure 3[3], the magnets are placed under the stator shoe (reversing flux machine), therefore, in this type of design, we will have an increase in the length of the air gap, which will reduce the amount of air gap flux and, as a result, reduce the produced torque. In another type of permanent magnet switched flux machine structure, the magnets are mounted one in the middle of the stator teeth and can be seen in Figure 4[4]. But in some proposed structures, in addition to the magnet, they use a coil with a constant voltage, which will increase the copper loss of the system, but the production flux will be changeable, which is shown in Figure 5[5] of the design of this type of machine. There are other structures according to Figure 6[6] for the permanent magnet switched flux machine, which are defined as C-core, and the permanent magnet switched flux machine with one-to-one winding can also be seen in Figure 7[7]. Many works were done in past that an overview of the design and application of permanent magnet square-switched machine is presented in [8]. Also, in recent years, two-rotor permanent magnet machines have attracted the attention of many researchers. One of the characteristics of such engines is their four-quadrant performance which has increased the interest in working on this structure. In a new structure of the permanent magnet flux-switched machine with combined winding is proposed, with the help of the magnetic equivalent circuit, the quantities of linked flux and the average torque of the positive, negative and zero direct current are calculated. In the structure of a reversing flux machine with antimagnetic material on the rotor is described, and with the help of the finite element method, the quantities of cog torque, mutual torque and link flux are calculated. In a basic model of a single-phase permanent magnet flux-switched machine, which has an asymmetric rotor in order to create self-starting torque, is presented and the quantities of linked flux, average torque, induced voltage, tooth torque are calculated. Based on three positive, negative and zero currents, the electromagnetic torque is analyzed with the help of the finite element method. In the proposed permanent magnet square-switched machine with different structure in terms of the number of rotor poles and the number of stator poles provides better conditions for the tooth torque (due to the diagonalization of the rotor tooth), induced voltage harmonics, core hysteresis losses, copper losses, average torque, Sharpening, induction voltage and no-load current calculation have been done with the help of analytical method and finite element method. In the flux-switched machine of a permanent magnet with a single rotor and a single stator with multiple teeth of one pole is introduced, and in different numbers of rotor poles and different numbers of additional stator teeth for each pole, the quantities of linked flux, average torque, inductance are calculated with the help of the finite element method and with the limitation of the volume of the structure discusses about the new structure of the reversing flux machine and the quantities of induced voltage, average torque, tooth torque, leakage flux and core losses are calculated both by analytical model and finite element method, and then compared with each other. become In a permanent magnet flux-switched machine is studied magnetically and thermally, and the quantities of linked flux, inductance, copper losses, core losses due to eddy current, induced voltage and temperature are calculated throughout the machine by considering the effect The temperature is calculated on the magnetic curve of the magnet and with the help of the finite element method. In the structure of permanent magnet square-switched machine is modeled with both magnetic equivalent circuit and Fourier series, and in a more complete review, a new method that is a combination of Fourier model and magnetic equivalent circuit model is proposed and compared with each other. have been Also, in this study, the effect of the magnet and the reaction of the armature have been observed, and finally, various quantities of torque, flux density, including the flux density in the tangential and radial direction, and tooth torque are calculated. In a single-rotor and single-stator permanent magnet flux-switched machine is proposed, and with the help of the Fourier analytical model of electromagnetic torque quantities, the flux density in the radial and tangential directions at the center of the air gap is also calculated by considering the armature reaction. And finally, it is compared with the finite element method. In the new structure of the permanent magnet flux-switched machine with combined winding is introduced and it is studied from the point of view of different winding methods for direct current, and the quantities of average torque, link flux, induced voltage, calculation of the harmonic order of volts The inductance and self-inductance are compared with the conventional.

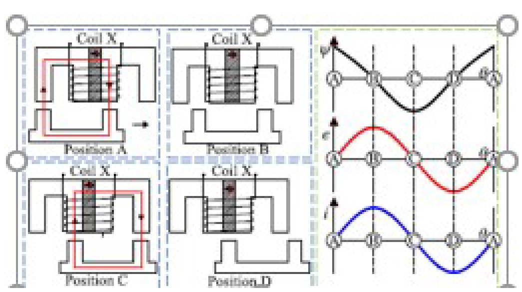

Fig.1 **Instruction of permanent magnet switched flux machine**

view of the placement of the stator teeth, also the average torque of each base structure of different currents is calculated along the minimum inductance and the ability to weaken and strengthen the flux with the help of current winding. It is checked directly and considering saturation. In a combined switched flux machine is proposed and with two different types of magnets, from the point of view of residual flux and under different direct currents, the effects of the flux on the machine are investigated, and the quantities of the flux density caused by only the magnet are proportional to the movement. Rotor under two magnets with residual flux density 1.2 and 0.4 Tesla, calculation of flux under positive and negative direct current of 5 amps, mutual and self-inductance are calculated by nonlinear network model and finite element method. In a semi-switched permanent magnet machine is proposed, which has core sheets in the direction of the axis, and this type of design is compared with the conventional semi-switched permanent magnet machine, which has core sheets in the radial direction. And the quantities of torque, tooth torque, link flux, efficiency and losses are calculated by the finite element method. In a comparison is made between the permanent magnet square-switched machine and the permanent magnet internal magnet machine, and the quantities of induced voltage, losses, average torque, tooth torque and pulsating torque are calculated with the help of the finite element method. In the structure of the two-rotor axial flux permanent magnet flux-switched machine, which has a two-way stator, is described, and the parameters of the torque, induced voltage, tooth torque, flux distribution in the air gap and link flux are calculated with the help of the finite element method. It is bent. In a linear permanent magnet square-switched machine with combined winding is proposed and the important parameters of tooth force, force pulse, thrust force, induced voltage and harmonic are calculated with the help of finite element method. In a linear permanent magnet flux-switched machine is proposed, and in order to control this system, its mathematical model is extracted, and with the finite element model, the quantities of linked flux, inductance, harmonics of induced voltage, induced voltage, Tooth torque is comparable. In two permanent magnet four-switched machine structures are proposed, and they are first optimized from the point of view of the width of the magnet, and then a comparison is made from the point of view of torque. In this study, the effects of the number of deviation steps on the tooth torque are also seen, and the torque quantities, torque pulses, and tooth torque are calculated with the help of the finite element method. In analysis, by Fourier series method for reluctance switch machine and permanent magnet flux switched machine, the presence and absence of direct current winding is discussed and the distribution of flux density, tangential and radial component of flux density and induced voltage, It is calculated and compared with the finite element method. It should be noted that in this article the effectiveness of the iron bridge has been studied and the general purpose of this study is to predict the magnetic potential vector and the flux density under any number of phases and under any number of grooves for each sub-area (area).This method has assumptions of infinite magnetic permeability coefficient for the iron core, ignoring the effect of eddy current, ignoring the end effect, infinite axial length, existence of current density only along the axis. In the semi-switched permanent magnet machine with a combination of winding in terms of the dimensions of the magnet and the amount of direct current excitation, the machine is optimized and the magnetic circuit model is formed from different working aspects and its results are compared with the finite element method. In the external rotor permanent magnet four-switched machine is introduced, in this structure, two magnets are mounted on the stator tooth, which is compared with the conventional single magnet external rotor machine (magnet on the stator) and the quantity Different connected flux, induced voltage, output torque and efficiency (losses) and harmonic induced voltage are calculated with the help of finite element method.

In three different modes of tooth, groove and magnet in the stator structure are discussed for the two-stator axial flux permanent magnet flux-switched machine and the effects of changes in the structure on the quantities of average torque, tooth torque, flux distribution in the air gap, voltage Induction is observed with the help of finite element method. In permanent magnet semi-switched machines in different structures are compared in terms of winding (based on the number of layers and winding coefficient) and the harmonic quantities of induced voltage, losses, average torque, torque pulsations, The induced voltage and eddy current losses in the magnet are calculated using the finite element method. In a permanent magnet flux-switched machine with combined winding is proposed, and in that the output torque, tooth torque and flux density in three direct current winding modes without magnet, only magnet and in the presence of both with the help of the method Finite components are calculated and in addition, the link flux is also obtained for different current densities. In the permanent magnet square-switched linear machine was investigated and thrust force analysis was obtained by combining the response surface analytical model and the finite element method. In the permanent magnet flux-switched machine is compared with the internal magnet machine and based on the type of sheet and the degree of rotor misalignment, the induced voltage parameters, the flux density at different frequencies and the torque with the help of the finite element method and considering the effect Finally, the saturation of the core and the dependence of the magnetic saturation of the magnet on the temperature are calculated. In torque and link flux parameters are calculated using the magnetic equivalent circuit model for a permanent magnet flux-switched machine and are compared with the results of the finite element method. In the structure of permanent magnet flux-switched machine is built for different excitations (armature winding only, armature winding with magnet and combined winding) and the important parameters of flux distribution in the air gap, induction voltage, Tooth torque is calculated with the help of finite element method. In a permanent magnet flux-switched machine is proposed, and its torque and harmonic model are extracted with the help of an analytical model, and the results of the parameters (torque and its harmonics, radial component of the flux density in the air gap caused only by the magnet) are This model is compared with the finite element method. In the permanent magnet square-switched machine was investigated in two single three-phase and double three-phase modes, and a comparison was made between the analytical model and the finite element method in terms of the values of the parameters of sharp coupling, induced voltage, torque, torque pulsations and tooth torque. It can be in a permanent magnet short-switched machine with two ports is proposed, where each port is separated from the other port by an anti-magnetic material. In this type of structure, to transfer power from the motor to the rotating part, the common axis and bearing are not used, and the power transfer is done through magnetic bearing. Quantities of magnetic distribution of flux density, induction voltage for internal and external machine, and torque for internal and external rotor are finally calculated with the help of finite element method. In three square-switched permanent magnet machines are proposed from the perspective of the stator tooth structure and together with each other in terms of tooth torque, induced voltage, average torque, induced voltage harmonics and with the help of finite element method and shape analysis, the pole is done, and they are compared with each other. In the permanent magnet semi-switched machine with combined winding is investigated, where the direct current winding is placed on the pole of the rake. Its performance is checked by considering the effect of saturation and different current densities for direct current winding, and finally, the flux distribution quantities under different current densities, the connection flux with different current densities, the induced voltage under current densities different, losses under different speeds and current under short circuit are calculated with the help of finite element method.

This paper consists of some chapters, the first chapter is the current chapter and it deals with the introduction, definition of the problem, generalities. In the second chapter, a review of past works is done, then, the types of modeling for the investigated machine are described in the next chapter, thereafter, the governing relations based on Maxwell's equations for the permanent magnet switched flux machine are implemented with the desired structure, Finally, the results obtained from the stated method will be shown, and the conclusions and suggestions will be presented.

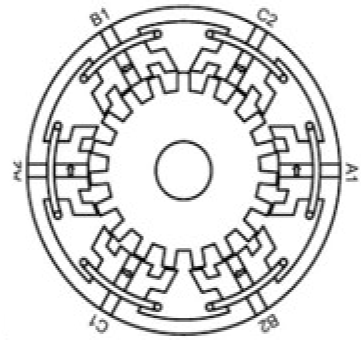

Fig.2 **Permanent magnet switched flux machine with multi-tooth stator**

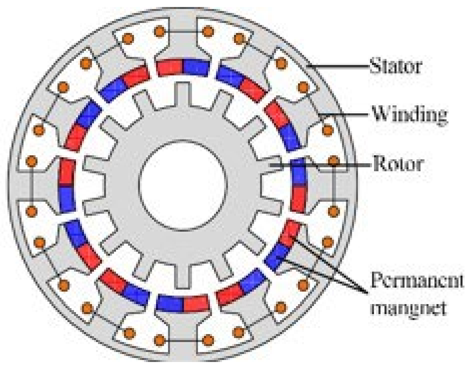

Fig.3 **Placing the magnet in the air gap**

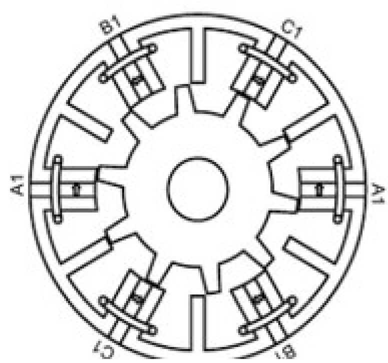

Fig.4 **Permanent magnet switched flux machine with one in between magnet structure (E-core)**

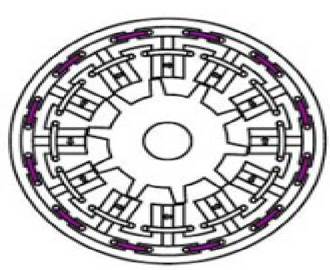

Fig.5 **Design of magnet and excitation winding**

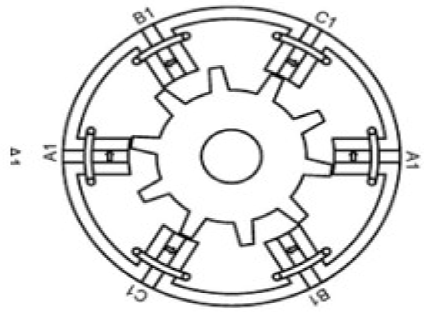

Fig.6 **C-core stator of flux switching permanent magnet machine**

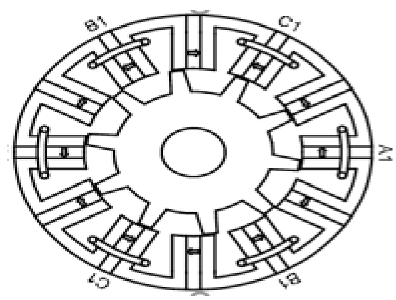

Fig.7 **Permanent magnet switching flux machine with one-way winding**

PROBLEM FORMULATION

For obtaining the PDEs in each sub-region in the FSPMM with E-core stator (Fig. 8) the investigated algorithm is demonstrated as follows:

- Make a set of assumptions to enable the analytical solution.
- Dividing the motor area to the appropriate sub-domain.
- By Poisson and Laplace equation, PDEs of system are introduced.
- For obtaining the unknown constants coefficients in the magnetic flux density, boundary conditions are applied.
- Calculating the expansion Fourier for the current density in the winding sub-region and PM magnetization pattern for obtaining the Poisson equations.
- After knowing constant coefficient for each sub-region, the magnetic flux density is able to be calculated.
- Comparison between the obtained analytic method results and FEM results to validate the model.

Assumptions

At the first step of solution some assumptions are considered as follows:

1. End effects are ignored, and then the motor is assumed to have infinite radial length.

2.The magnetic flux density is a 2-D vector with radial and tangential components. Therefore the magnetic vector potential has only z-component.

3.The magnetic flux density vector and the magnetic vector potential are independent of z.

4.All materials are isotropic.

5.The stator and rotor teeth have no tooth-tip.

6.The rotor/stator iron is infinitely permeability; therefore the saturation effects are neglected.

7.The slots and rotor poles have radial sides.

8.Eddy current reaction field is neglected.

Subdomains

The active subdomains consist of stator slots, rotor slots, PM, air-gap, and exterior due to the infinite permeability assumption of the stator and rotor back-iron therefore; there are Ns+Nr+Npm+2 regions to be solved as shown in Fig.8.

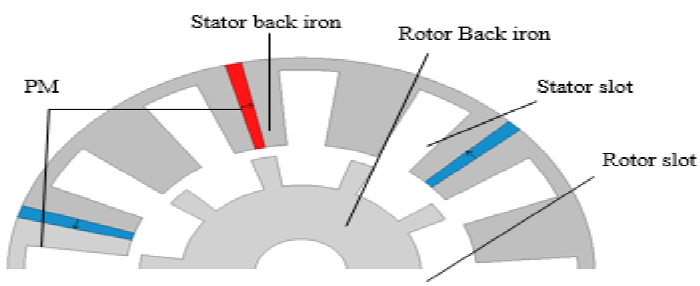

Fig.8. **Cross section of FSPMM with inner rotor**

Fig.8. Cross section of FSPMM with inner rotor

Governing equations

Based on the stated assumptions, Maxwell's equations for each sub-field considering the excitations, i.e. wiring and magnets, are in the form of equation (1).

$$-\Delta^2 A_z^i = \mu_0 \mu_r J_z^i + \frac{\mu_0}{r}\left(\frac{\partial M_r}{\partial \theta} - r\frac{\partial M_\theta}{\partial r}\right) \quad (1)$$

In the winding area, there is no magnetic vector of the magnet, so its value is equal to zero, that is, Mr = Mθ = 0, and in the area of the magnet, the magnetic current density is zero, that is, Jz = 0. Equation (2) is the equation extracted from Maxwell's equation for the areas of rotor slots and air gap where there is no energy production in those areas.

$$-\frac{1}{r^2}\frac{\partial^2 A_z^i}{\partial z^2} - \frac{\partial^2 A_z^i}{\partial z^2} = 0 \quad (2)$$

Magnetic flux density is obtained for each sub-region by using curl from magnetic vector potential( ), component of tangential and normal are obtained and magnetic field strength is calculated by

$$H = \frac{B}{\mu_r \mu_0} \quad (3)$$

Boundary conditions

The magnetic vector potential is continuous at the interface between two adjacent media. If the interface is source-free, then the parallel component of the magnetic field intensity vector on one side of the boundary is equal to that of the other side. Also, the parallel component of the magnetic field intensity vector is zero at the interface of those media adjacent to infinitely permeable domains. Therefore the following boundary conditions are expressed for E- core FSPM with inner rotor in table 2.

TABLE 1. **Boundary Conditions for Intersection of Regions for FSPM with E-core stator.**

$$A_z^{airgap} = A_z^{rotor\ slot}\ ,\ R=R_{ri},\ \alpha_i - w_r/2 < \theta < \alpha_i + w_r/2$$

$$A_z^{airgap} = A_z^{stator\ slot}\ ,\ R=R_{si},\ \beta_i - w_{si}/2 < \theta < \beta_i + w_{si}/2$$

$$A_z^{airgap} = A_z^{PM}\ ,\ R=R_{si},\ \sigma_i - w_{pmi}/2 < \theta < \sigma_i + w_{pmi}/2,\ i=odd\ slots$$

$$A_z^{exterior} = A_z^{pm}\ ,\ R=R_{nmi},\ \sigma_i - w_{pmi}/2 < \theta < \sigma_i + w_{pmi}/2,\ i=odd\ slots$$

$$\frac{\partial A_z}{\partial \theta} = 0\ ,\quad \theta = \alpha_i - w_{ri/2}\ ,\ \theta = \alpha_i + w_{ri/2}\ ,\ R_{ryi} < R < R_{ri}$$

$$\frac{\partial A_z}{\partial \theta} = 0\ ,\quad \theta = \beta_i - w_{si}/2,\ \theta = \beta_i + w_{si}/2,\ R_{si} < R < R_{yi}$$

$$\frac{\partial A_z}{\partial \theta} = 0\ ,\quad \theta = \sigma_i - w_{pmi}/2,\ \theta = \sigma_i + w_{pmi}/2,\ R_{si} < R < R_{nmi},\ i=odd\ slots$$

$$\frac{\partial A_z}{\partial r} = 0\ ,\quad R=R_{ryi},\ R=R_{yi}$$

$$H_\theta^{airgap} = \sum_{i=1}^{i=Nri} H_\theta^{rotor\ slot},\ R=R_{ri}, \alpha_i - w_{ri}/2 < \theta < \alpha_i + w_{ri}/2$$

$$H_\theta^{airgap} = \sum_{i=1}^{i=Nsi} H_\theta^{stator\ slot},\quad R=R_{si},\ \beta_i - w_{si}/2 < \theta < \beta_i + w_{si}/2$$

$$H_\theta^{airgap} = \sum_{i=2k+1}^{i=Npmi} H_\theta^{i\ PM},\ R=R_{si},\ \sigma_i - w_{pmi}/2 < \theta < \sigma_i + w_{pmi}/2$$

$$k=1,2,3,4,\ldots$$

$$H_\theta^{exterior} = \sum_{i=2k+1}^{i=Npmi} H_\theta^{i\ PM},\ R=R_{nmi},\ \sigma_i - w_{pmi}/2 < \theta < \sigma_i + w_{pmi}/2$$

$$K=1,2,3,4,\ldots$$

CASE STUDY

To demonstrate the efficacy of proposed method, a prototype machine of FSPMM with specified geometric is assessed that Dimension of this machine is placed in table 3. Rotor pole/stator 10/12 that only PM states considered for this sample geometric to prove our claim.

TABLE 2. **Specifications of prototype FSPMBM with inner rotor**

Items	Value
Number of phases, N_{phi}	3
Number of rotor slots, Nri	10
Number of stator slots, Nsi	12
Relative permeability of permanent magnet, μ_{rpm}	1
Residual flux density, B_{rem}	1.2T
rotor yoke radius, R_{ryi}	26mm
stator yoke radius, R_{yi}	60mm
radius of inner stator, R_{si}	38mm
radius of inner rotor, R_{ri}	35mm
radius of exterior, R_{nmi}	63.63mm
Width of rotor slot, w_{ri}	26.99 π/180 rad
Width of stator slot, w_{si}	12.5 π/180 rad
Width of PM, w_{pmi}	3.24 π/180 rad

In fig.9 FSBPMM with E-core stator at initial position with angle equal to zero is shown for inner rotor structure that distribution of flux density for this structure for both normal and tangential component in fig.10 and fig.11 is brought moreover distribution of flux density for inner rotor structure for both normal and tangential component.

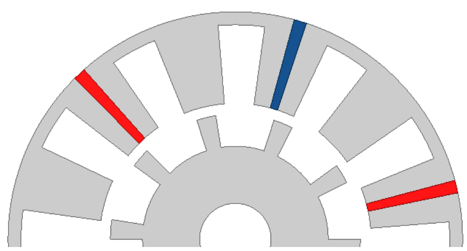

FIG. 9. **Situation of different part of FSBPM at angular position equal to zero**

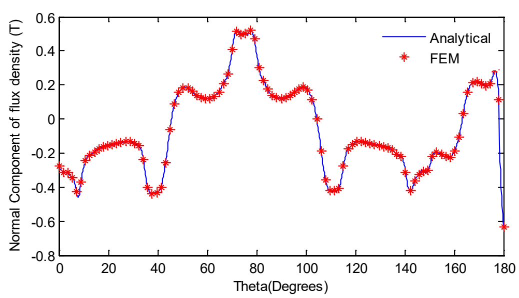

FIG.10. **Airgap radial flux density at 35.6mm**

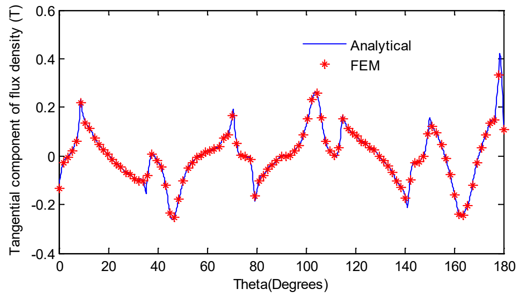

FIG. 11. **Airgap tangential flux density at 35.6mm**

CONCLUSION

In this paper, by introducing and comparing different structures of switched flux machine and stating the advantages of this type of machine, the reasons of interest for research on this type of synchronous machine were stated. The ability to operate this type of machine at high speeds provides the basis for the use of this type of machine in hybrid cars and wind turbines, therefore according to past studies, switched flux machines without permanent magnet brushes with E-core stator is a suitable option to receive energy from two sets of 3-phase winding in a compact structure.In order to quickly extract the information of this type of machine for the purpose of construction and design, we need a suitable and accurate modeling, which two-dimensional analytical modeling based on the Fourier series is a suitable model for extracting information, so in this essay, two-dimensional analytical modeling was chosen and By solving Maxwell's equations and using the boundary conditions, a suitable model for extracting the information of this type of machine with any number of stator and rotor teeth and with any dimensions was extracted, which has the ability to calculate the magnetic flux density along the air gap, the combined magnetic flux. Finally, to prove the correctness of the stated model, the results of this two-dimensional analytical model were compared with the results of the finite element method.

Declarations

Ethical Approval

I hereby declare that this thesis represents my own work which has been done after studying at university of Bojnourd, and has not been previously included in a thesis or dissertation submitted to this or any other institution for a degree, diploma or other qualifications. I have read the research ethics guidelines, and accept responsibility for the conduct of the procedures in accordance with Springer journal. We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property. We further confirm that any aspect of the work covered in this manuscript that not has involved either experimental animals or human patients. We understand that the Corresponding Author is the sole contact for the Editorial process (including Editorial Manager and direct communications with the office). We confirm that we have provided a current, correct email address which is accessible by the Corresponding Author.

Competing interests

This research is sponsored by [Bojnourd University] and may lead to development of products.

Authors' contributions

The authors confirm contribution to the paper as follows: all of the works are done by Ehsan Shirzad.

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Availability of data and materials

No datasets were generated or analyzed during the current study.

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