Magnetic Field Analysis Using Magnetic Equivalent Circuit for the Initial Design of Toroidal Winding Switched Reluctance Motor

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Abstract—**In this paper, a Magnetic Equivalent Circuit (MEC) of Toroidal Winding Switched Reluctance Motor (TSRM) is proposed. In this MEC, one can get the flux of TSRM easily and rapidly. And then the phase inductance can be calculated according to that flux. The results are compared with those of 2-D FEA, which shows good agreements and presented analysis method can be effectively applied to initial design of TSRM.**

I. INTRODUCTION

Due to a simple and robust structure without permanent magnet, Switched Reluctance Motor (SRM) has been widely used in many industry devices and home-appliances. Since the uneconomical asymmetrical converter of conventional SRM (CSRM) drive device, Toroidal Winding Switched Reluctance Motor that is drived by universal full bridge converter is proposed and becoming popular [1]. In [1], the dynamic characteristics and advantages of TSRM have been introduced. Especially in low applied voltage and high speed case, TSRM behaves high torque and efficiency.

A cross-section of TSRM shows in fig 1. For driving TSRM in 6-step switching sequence like BLDC motor as shown in fig 2, the winding is toroidally wound in stator yoke, while there is remarkable coupling inductance between each two phases. The existence of strong coupling inductance can generate more powerful torque for TSRM. However, it means that phase flux linkage depends not only on the rotor position but also the currents in two phases, which makes the design and analysis of TSRM complicated. Certainly, Finite Element Method (FEM) can solve TSRM model and get an accurate solution [2]. But a great deal of time and computation resource reduces design efficiency and increases design cost.

The Magnetic Equivalent Circuit (MEC) has been used to model the nonlinear magnetic field in various electromagnetic devices including CSRM [3]. In MEC method, the calculation process without Laplace's equation and the numerable elements result in shortening design time and saving computation resource. Due to similar structures of the rotor and stator of CSRM and TSRM, both MECs of these two kinds of motors are analogous. In this paper, a MEC of TSRM each is proposed. Depending upon numerical analysis techniques, the flux of each part can be solved. And then based on the flux, the phase inductance can be calculated. The results are compared with those of 2-D FEA, which shows good agreements and presented analysis method can be effectively applied to initial design of TSRM.

II.DESCRIPTION OF MAGNETIC CIRCUIT

The MEC is based on the lumped representation of magnetic material with a series of permeance elements. Each element is a flux tube just as an electrical resistance. The Kirchhoff's current and voltage laws of electrical circuits are valid in magnetic circuits.

Fig 3 shows the flux pattern of a TSRM. It is evident that the major difference between CSRM and TSRM is just the position of stator winding. The position of CSRM winding is on each stator pole, while the winding of TSRM is wound on stator yoke. Hence, in MEC the MMF source of CSRM is placed in series with the permeances of stator pole stem, while that of TSRM is placed in series with the permeances of stator yoke.

In addition, it is observed that there are four flux flowing cycles produced by two pairs of symmetrical MMF sources. Therefore, each rotor pole connects with adjacent one or two stator poles though air reluctance in every sequence step. The general MEC is shown in fig 4 where the air permeances will be described in detail in the next section.

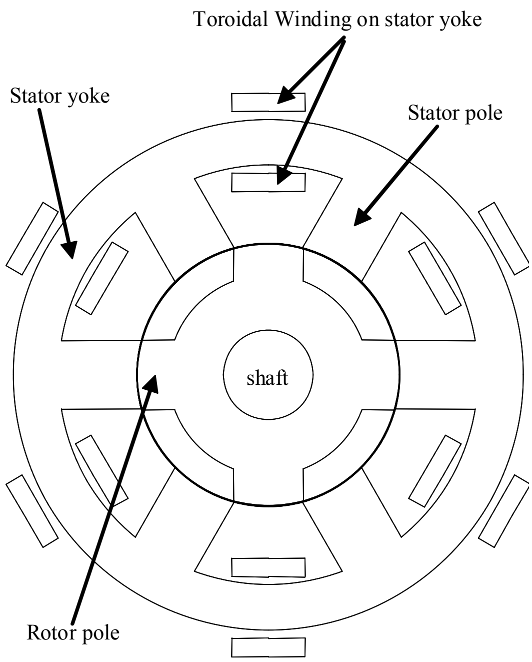
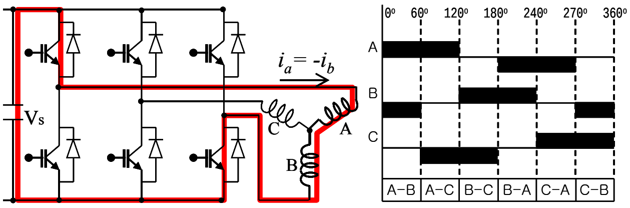


Fig. 1 cross-section of a TSRM



(a) 6-switch converter (b) switching sequence

Fig. 2 Topology and switching sequence of the TSRM

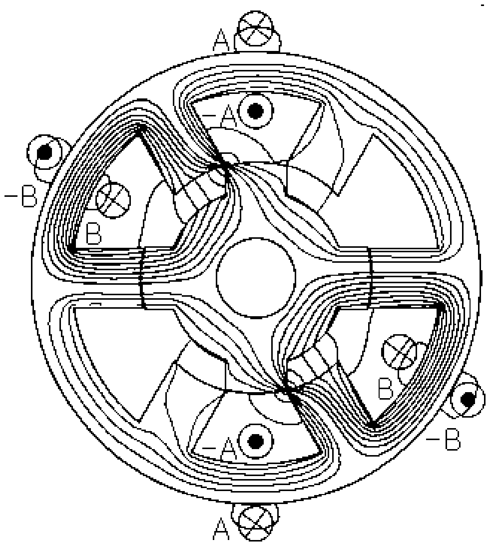


Fig. 3 the flux pattern of a TSRM

In fig. 4, where P_{syn}, P_{spn}, P_{rpn} and P_{rbin} are the permeances of partial stator yoke, stator pole, slot, rotor pole and partial rotor back iron, respectively; and P_{slotn}, P_{ptpn}, $P_{overlapmn}$ and $P_{fringingmn}$ are the permeances of slot air permeance, pole-to-pole air permeance, overlap air permeance and fringing air permeance, respectively.

III. PERMEANCES

Due to the structure without permanent magnet, there are only two kinds of permeances in a TSRM.

A Iron Permeances

The Iron permeances, namely is just the permeance of each part of stator and rotor. For TSRM, they are identified to CSRM. In [4] a conception of pole tip permeance is proposed to solve "saturable pole tip." Here it is different to [4] that the tip permeance is not connected with every stator pole, but every overlap air permeance.

B Air Permeances

In the MEC of TSRM, the iron permeances are constants, while the air permeances are variational with rotor rotating and phase changing. Therefore the air permeances become more complicated and important. Generally there are four different air permeances, such as overlap air permeance, fringing air permeance, slot air permeance and pole-to-pole air permeance [4]. In [4], each permeance has been presented in detail. So this paper simply introduces their conceptions, equations and main differences.

1) *Overlap air permeance*: The overlap air permeance is the air-gap permeance between a stator pole and a rotor pole when they are overlapped. Its maximum value occurs when they are completely overlapped. The function of overlap air permeance with overlap angle is

$$P = \left(\frac{\theta_{overlap}}{\theta_{\max}}\right) P_{\max} \tag{1}$$

Where P_{max} is the maximum permeance when a rotor pole and a stator pole are completely overlapped; $\theta_{overlap}$ and θ_{max} are overlap angle and possible maximum overlap angle, respectively.

2) *Fringing air permeance*: There are two kinds of fringing air permeance that occurs when a stator pole and a rotor pole are partially overlapped and completely overlapped, respectively. Their equations are given by

$$P_{partially} = \frac{4\mu_0 l}{\pi} \tag{2}$$

$$P_{completely} = \frac{2\mu_0 l}{\pi} \tag{3}$$

3) S*lot air permeance*: The slot air permeance occurs between two stator poles. It should pay attention to that it dose not exist between any two stator poles. In this MEC of TSRM, slot air permeance only appears between the adjacent two poles of excited MMF source. And the slot air permeance is given by

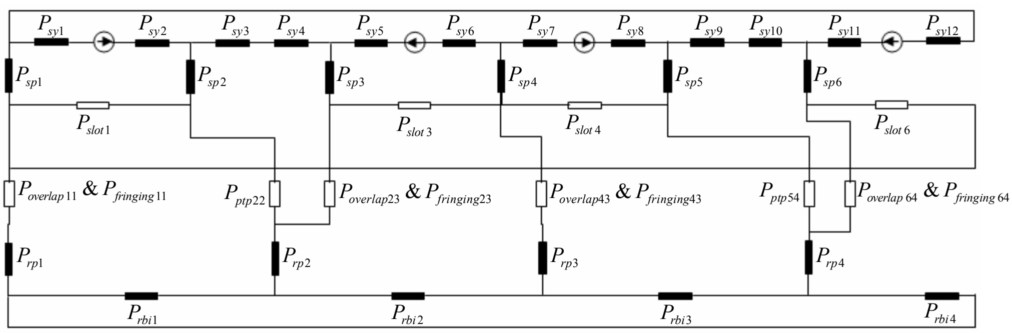


Fig. 4 the general MEC of TSRM during one step of switching sequence

$$P_{slot} = \frac{\mu_0 l}{r_{sp}\theta_{slot}}(r_{sy} - r_{sp}) \quad (4)$$

Where r_{sp} is the radius of the stator pole face circle; r_{sy} is the radius of the stator yoke inner circle; θ_{slot} is the included angle between two adjacent stator poles.

4) Pole-to-pole *air permeance*: The pole-to-pole permeance occurs when two adjacent stator pole and rotor pole is not overlapped. In this MEC of TSRM, there exist only two pole-to-pole air permeances in any step of switching sequence.

$$P_{ptp} = \frac{2\mu_0 l}{\theta_{space}} \quad (5)$$

Where θ_{space} is the included angle between the stator pole and rotor pole.

IV. NUMERICAL SOLUTION

Similar to solving electric circuit, the MEC can be solved by node scalar potential method based on (6). First set a reference node to be negative potential and assume the potential of other nodes are positive. And then according to KVL and KCL, establish n equations, where n is the number of nodes.

$$[P][F] = [\phi] \quad (6)$$

Where Φ is the vector of fluxes of elements, F is vector of MMF, and P is the matrix of permeances. Since the permeability is a function of flux density, elements are function of flux, and the set of equations is nonlinear.

Generally, Newton's or Gauss-Siedel methods are used to solve the set of nonlinear equations. In this case, permeances are not explicit function of flux, so it is impossible to obtain analytical expressions for necessary jacobian matrix of elements in Newton's method.

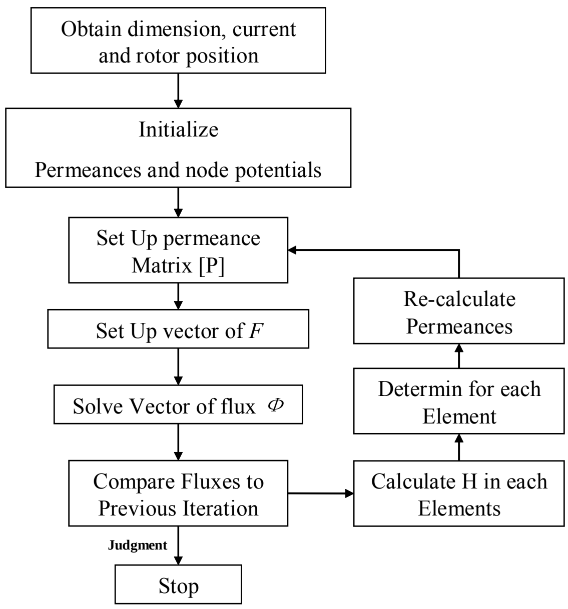
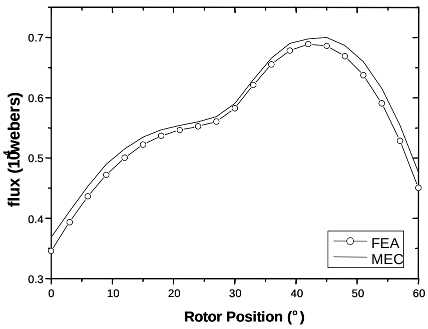


Fig. 5 the nonlinear solution procedure

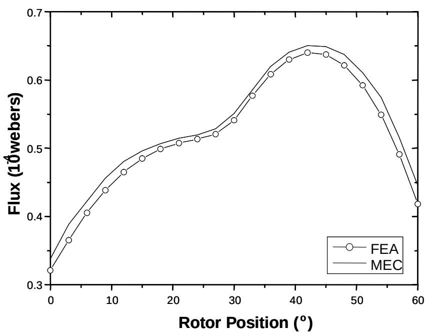
Therefore, in order to solve nonlinear equations, [4] presents an iterative approach to solve node potentials based on Gauss-Siedel method. In this paper, the solution procedure has a difference with [4]. In [4], in each process of iteration, the node potentials are solved and compared, while the fluxes of elements are solved and compared in this paper.

V. RESULTS

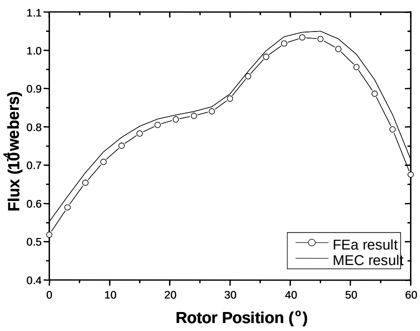
The dimension of TSRM is given in Table I. In order to get complete inductance pattern, the excited MMF sources are kept in two steps of switching sequence, and namely the rotor rotates 60 mechanical degrees. According to the results of numerical solution, the phase flux density and inductance are obtained and shown in fig. 6.



(a)

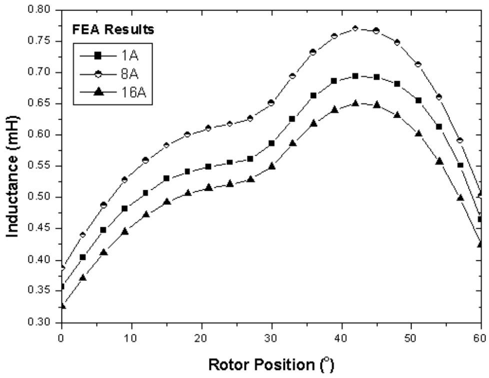


(b)

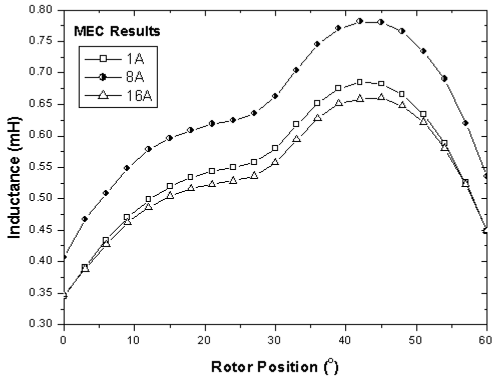


(c)

Fig. 6 the flux patterns: (a) applied 1A current; (b) applied 8A current; (c) applied 16A current



(a)



(b)

Fig. 7 the inductance pattern of TSRM:
(a) the FEA results; (b) the MEC results

It is shown that the flux obtained by MEC is very similar to those from FEA. Especially near the 30 mechanical degrees, two results are almost same. It is due to the flux leakage is the least when a stator pole and a rotor pole are completely overlapped, which weakens effects generated by unconsidered air permeance.

IV. CONCLUSION

MEC model is suit for any geometry and avoids the Laplace's equations in FEA. Hence it is an efficient analysis method. In this paper, a MEC for TSRM is proposed. In order to get flux and then the phase inductance, a nonlinear solution based on node potential equations is utilized. Compared with the results obtained by 2-D FEA, the MEC can get very good accuracy. It means this MEC can be a tool of initial design for TSRM.

TABLE I
THE DIMENSION OF THE TSRM

stator yoke outer diameter (mm)	140
stator yoke inner diameter (mm)	116
rotor yoke outer diameter (mm)	54
rotor yoke inner diameter (mm)	24
Stator pole face diameter (mm)	74
air gap length (mm)	1
stator/rotor pole arc (degrees)	30/32
Number of turns	10

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