Analysis of Permanent Magnet Hybrid Excitation Machine

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***Abstract*—It is a general perception that the interior permanent magnet machines will have different values of inductances along d-axis and q-axis and hence they are salient pole machines. Though it is true in most of the cases, some interior permanent magnet machines may turn out to be non-salient pole machines. Hence an accurate modeling of magnetic equivalent circuit is very much required in order to estimate the inductance values along d-axis and q-axis. A hybrid excitation machine with an interior configuration of permanent magnets and field winding is proposed in the literature. Though it appears to be a salient pole machine from rotor configuration view point, the actual analytical inductance analysis on this machine proves that it is a non-salient pole machine. A simpler analytical approach is carried out through approximate linear magnetic equivalent circuit. The analytical analysis is validated with analysis carried out through FEM software.**

***Keywords*—Flux regulation, Hybrid excitation, Permanent magnet machine, Air gap inductance.**

I. INTRODUCTION

The salience ratio which is the ratio between q-axis inductance and d-axis inductance of a permanent magnet machine plays a key role in its operation. Substantial research has been carried to improve the saliency of the permanent magnet machine for its own advantages. The utilization of saliency effect for sensorless control technique of permanent magnet machine is well described [1-4]. The saliency effect of a machine may arise due to structure configuration or saturation effects. Simulation of permanent magnet machines has been carried out taking structural and saturation saliencies into account [5-6].

Different rotor configurations are proposed in the literature to improve the saliency of permanent magnet machine. A multilayer permanent magnet machine is analyzed with multilayer magnet structure in the rotor for achieving large saliency [7]. Rotor with internal flux barriers designed for a permanent magnet machine shows considerable increase in the saliency ratio [8]. The torque characteristic of interior permanent magnet machine is improved by increasing the saliency ratio and thereby reluctance torque through ribs and air barriers in the rotor[9]. Concentrated flux interior permanent magnet machine is designed to improve the efficiency range and operation range by increasing the saliency ratio. The increase in saliency ratio has been achieved by shaping the rotor optimally [10]. A single-phase line-start permanent magnet motor is designed by improving rotor structure to reduce the cost of permanent magnets. The reduction of magnet torque due to less permanent magnet utilization is compensated by increasing the reluctance torque through high saliency ratio. Double layer structure of interior permanent magnet rotor is proposed to achieve high saliency ratio of single-phase line-start permanent magnet motor [11]. Saliency ratio of interior permanent magnet rotor is optimally designed for high efficiency and low cost application [12]. The average torque of interior permanent magnet machine is improved by shaping the rotor for optimal third harmonic which also results in increase in saliency ratio [13].

The inductances were analyzed and compared for two different rotor structures of interior permanent magnet machine [14]. An interior permanent magnet machine with fractional slot concentrated winding has been analyzed for self and mutual inductances [15]. The q-axis inductance and d-axis inductance are numerically modelled and estimated using recursive least square method [16].

The saliency of permanent magnet machine is also widely used in estimating the position through sensorless control techniques. The improved position sensorless control of interior permanent magnet machine is proposed using current prediction method for low cost application. The proposed sensorless control uses saliency based position with a single current sensor [17]. The sensorless position estimation of permanent magnet machine is proposed with improved accuracy by using saliency tracking that combines both resistance and inductance of machine [18]. The performance of saliency based position sensorless control of various permanent magnet machines have been studied and compared. The saliency shift equations and per unit scale shift equations are used to predict the sensorless control performance of machines [19].

Thus the estimation of saliency ratio of a permanent magnet machine is very much required to understand its operation. Analysis of permanent magnet machines carried out on the assumption of saliency ratio may lead to substantial error in the performance characteristics. In the present paper, it is proved that an interior permanent magnet hybrid excitation machine is a non-salient pole machine though it looks like salient pole machine from rotor configuration point of view.

II. ESTIMATION OF AIR GAP INDUCTANCE

A 4-pole, 18-slot hybrid excitation alternator with series type rotor excitation topology proposed in the literature achieves 83% flux regulation ability. The cross section perpendicular to the axis of rotation of this series hybrid excitation machine proposed in the literature is shown in Fig. 1 [20]. Generally the permanent magnet slots are provided in the rotor just below the outer diameter of the rotor in order to have maximum air gap flux density. But in the considered rotor configuration, the permanent magnet slots are made across the circumference which is approximately 10 mm away from the outer diameter of the rotor. In addition to this, around 10 mm of space in between permanent magnet slots is also provided. Twelve permanent magnet slots are made in the rotor to allocate three permanent magnet slots for one pole. Exploiting the periodicity of hybrid excited synchronous machine, only half of the rotor cross section of series hybrid excitation alternator is shown in Fig. 1. The excitation winding slots are provided below the permanent magnet slots with slot openings in between the poles.

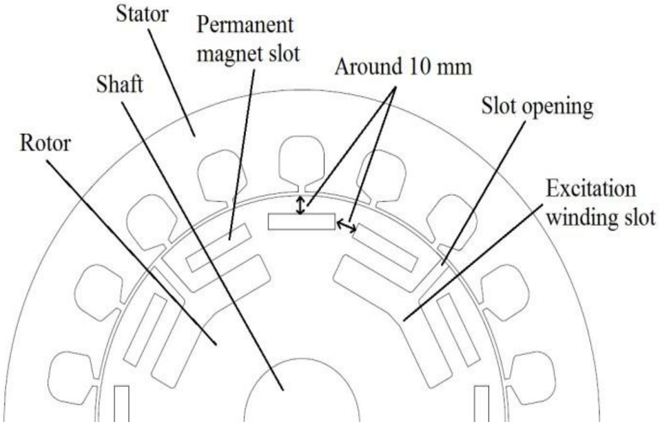
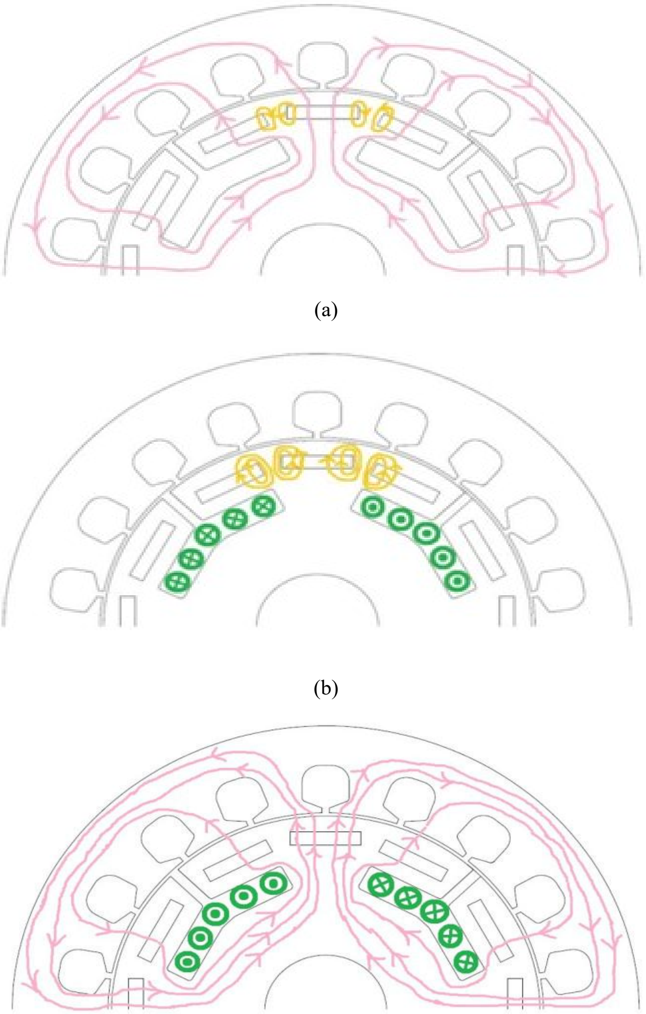


Fig. 1 Cross section of hybrid excitation machine

This peculiar kind of interior permanent magnet arrangement is to serve the purpose of wide flux regulation in the hybrid excitation machine. The flux regulation operation can easily be understood from the conceptual drawings shown in Fig. 2. When the field windings are not excited, some of the magnetic flux will leak within the rotor and only some of the magnetic flux will pass through the air gap and link the stator winding as shown in Fig. 2(a). When the field windings are given maximum negative excitation (electromagnet pole and permanent magnet pole are different), the field winding mmf increases the leakage flux within the rotor to the maximum value and hence the magnetic flux will hardly be there in the air gap as shown in Fig. 2(b). Similarly when the field windings are given maximum positive excitation (electromagnet pole and permanent magnet pole are same), the field winding mmf increases the magnetic flux to the maximum value in the air gap and the leakage flux will hardly be there within the rotor as shown in Fig. 2(c).



(a)

(b)

(c)

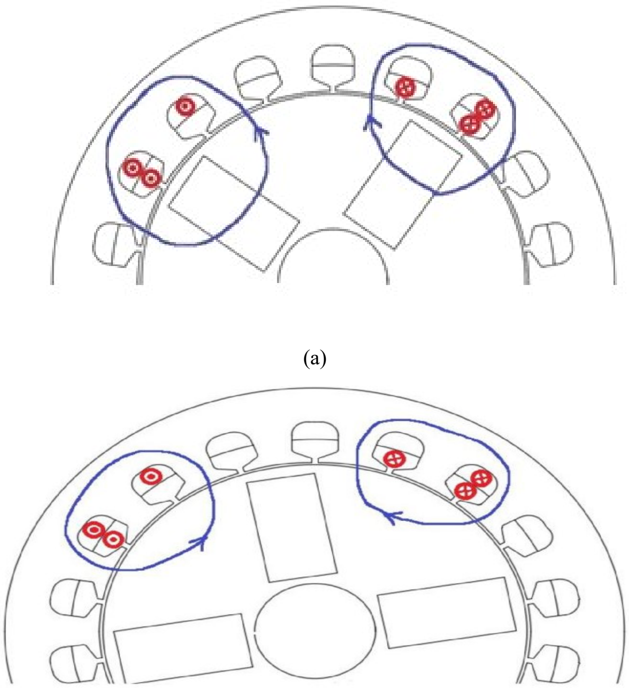
Fig. 2 Flux regulation.

(a) Under zero excitation; (b) Under maximum negative excitation;

(c) Under maximum positive excitation.

This unusual kind of interior permanent magnet arrangement for serving the purpose of wide flux regulation in the hybrid excitation machine has iron material around each permanent magnet unlike in usual interior permanent magnet machine where the permanent magnets are arranged ensuring minimal leakage flux within the rotor and maximum magnetic flux in the air gap. The iron material that is present around each permanent magnet in the hybrid excitation machine makes it non-salient pole type.

To understand the saliency of machine from fundamental view point, the spoke type rotor cross-section of interior permanent magnet machine is considered and compared with rotor cross section of interior permanent magnet hybrid excitation machine. The permanent magnet machine with spoke type rotor configuration is shown in Fig. 3 for two different rotor positions, one along d-axis and the other one along q-axis.



(a)

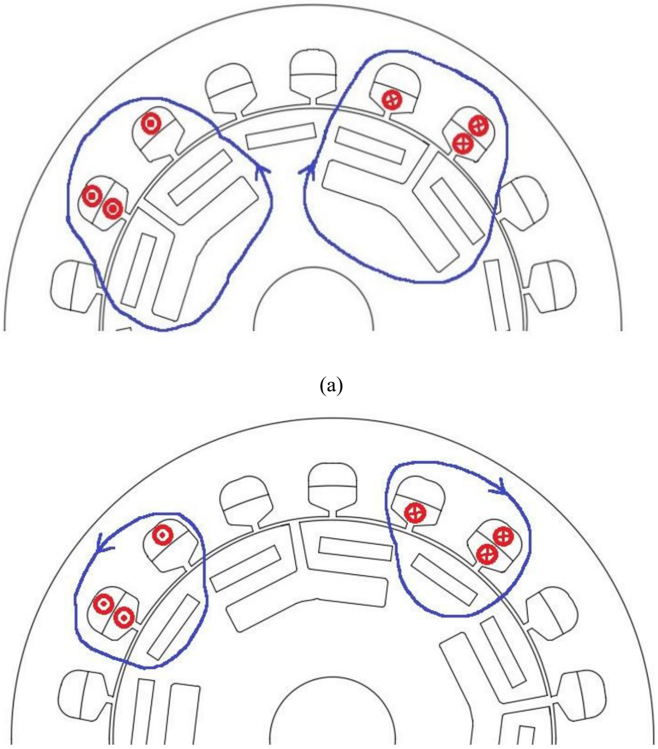
(b)

Fig. 3 Stator coil magnetic flux closed path of spoke type PMM.

(a) for d-axis rotor position; (b) for q-axis rotor position;

The magnetic flux closed loop paths are shown assuming that the rotor without permanent magnets is inserted into the stator and the stator coil is excited with dc current. Fig. 3(a) shows the magnetic flux closed loop path when the rotor position is such that the d-axis of rotor coincides with the center line of the stator coil. The magnetic flux closed loop path for this rotor position is such that it will pass through the permanent magnet slot. The reluctance seen by the magnetic flux of stator coil for this rotor position is the highest and hence the inductance along d-axis is the least. Fig. 3(b) shows the magnetic flux closed loop path when the rotor position is such that the q-axis of rotor coincides with the center line of the stator coil. The magnetic flux closed loop path for this rotor position is such that it will not pass through the permanent magnet slot. The reluctance seen by the magnetic flux of stator coil for this rotor position is the lowest and hence the inductance along q-axis is the highest. Thus it is clear from the conceptual drawings shown in Fig. 3 that interior permanent magnet machine with spoke type rotor configuration is salient-type.

The rotor cross-section of interior permanent magnet hybrid excitation machine discussed in Fig. 1 is redrawn for two different rotor positions, one along d-axis and the other one along q-axis as shown in Fig. 4. The magnetic flux closed loop paths are shown assuming that the rotor without permanent magnets is inserted into the stator and the stator coil is excited with dc current. Fig. 4(a) shows the magnetic flux closed loop path when the rotor position is such that the d-axis of rotor coincides with the center line of the stator coil. The magnetic flux closed loop path for this rotor position is such that it will not pass through the permanent magnet slot but rotor iron only. The reluctance seen by the magnetic flux of stator coil for this rotor position is air gap reluctance only. Fig. 4(b) shows the magnetic flux closed loop path when the rotor position is such that the q-axis of rotor coincides with the center line of the stator coil. The magnetic flux closed loop path for this rotor position is also such that it will not pass through the permanent magnet slot. The reluctance seen by the magnetic flux of stator coil for this rotor position also is air gap reluctance only. Since the reluctance seen by the magnetic flux of stator coil is same for both rotor positions, the inductance along d-axis and q-axis will be same. Thus it is clear from the conceptual drawings shown in Fig. 4 that interior permanent magnet hybrid excitation machine is non-salient type as the reluctance seen by stator coil magnetic flux is same for any rotor position.



(a)

(b)

Fig. 4 Stator coil magnetic flux closed path of interior permanent magnet hybrid excitation machine.

(a) for d-axis rotor position; (b) for q-axis rotor position;

This non-saliency of hybrid excitation machine is also verified by estimating air gap inductance of hybrid excitation machine for different positions of rotor. In order to simplify the analysis of estimation of air gap inductance, the magnetic system of hybrid excitation machine is considered to be linear which means the saturation effects are neglected. The magnetic equivalent circuit of hybrid excitation machine when one of the stator coils is excited with dc power supply is as shown in Fig. 5. The permanent magnet reluctance is modeled as RPM, the magneto motive force of coil with N equivalent turns is modeled as FC, the stator iron reluctance is modeled as RS, the reluctance of rotor iron bridge between permanent magnets is modeled as R_{R1}, the reluctance of rotor back iron is modeled as R_{R2} and the air gap reluctance is modeled as RG.

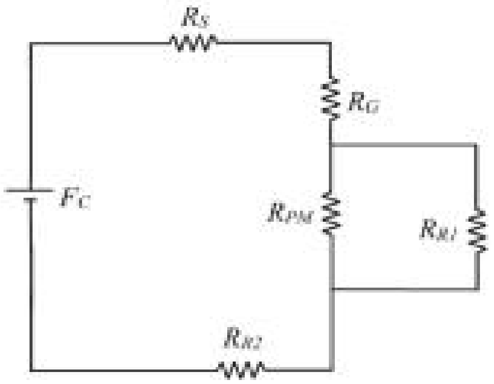


Fig. 5 Magnetic equivalent circuit

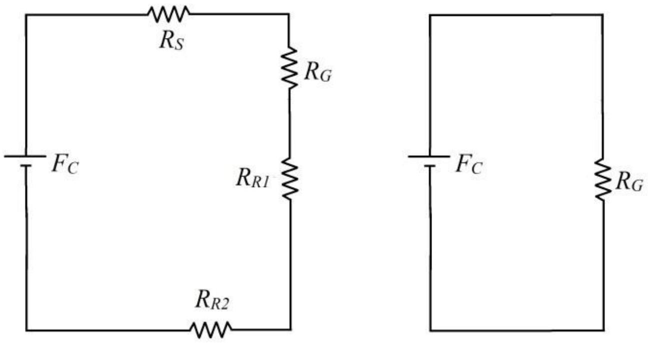
The approximations are to be considered for simplification of magnetic equivalent circuit because the iron permeability is more than 1000 times the permanent magnet permeability and air permeability.

It means the permanent magnet reluctance can be neglected in the parallel branch of magnetic equivalent circuit.

The magnetic equivalent circuit that is obtained after removing the high reluctance path in the parallel branch is as shown in Fig. 6(a).

Now it is very obvious that the stator and rotor iron reluctances can be neglected in comparison with the air gap reluctance as the iron reluctance is very small with respect to air gap reluctance.

The magnetic equivalent circuit is further simplified as shown in Fig. 6(b) by neglecting the stator and rotor iron reluctances.



(a) (b)

Fig. 6 Simplified magnetic equivalent circuit. (a) Permanent magnet reluctance is neglected; (b) Iron reluctance is neglected.

The simplification made in the magnetic equivalent circuit is true for all rotor positions because the flux passes though the rotor iron only and not through the permanent magnet for any rotor position. It means that the inductance along d-axis and q-axis are same and the hybrid excitation alternator is non-salient hybrid excitation alternator. The analytical value of air gap inductance is found to be 32 mH. The required parameters of the considered hybrid excitation machine model for estimation of air gap inductance are given in Table I.

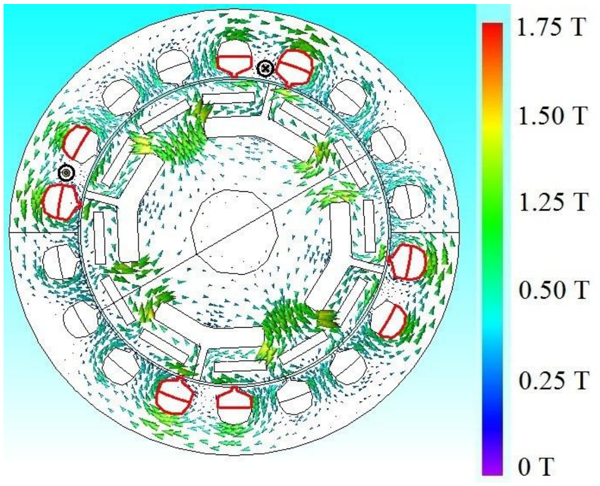
TABLE I

Parameters of Hybrid Excitation Machine Model

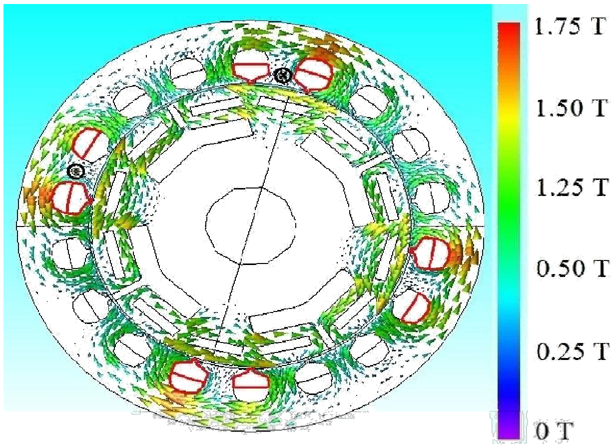
Parameters	***Value***
Stator Inner Diameter	250 mm
Stator Outer Diameter	360 mm
Rotor Inner Diameter	100 mm
Rotor Outer Diameter	246 mm
Equivalent Turns	320
Length of the core	40 mm
No. of poles	4
No. of stator slots	18

III. FEM ANALYSIS

Finite Element Method (FEM) analysis is helpful in analyzing the magnetic flux distribution and characteristics of electrical machine. FEM analysis makes it possible to study, optimize and design prior to the prototyping [21]. The finite element method analysis has been carried out on hybrid excitation machine to validate the inductance values estimated through magnetic equivalent circuit approach. The flux plots are plotted by exciting one of the stator phases with dc power supply to capture the magnetic flux path of the coil.



(a)



(b)

Fig. 7. Stator coil flux line plot. (a) for coil position along d-axis; (b) for coil position along q-axis.

The flux plots shown in Fig. 7 correspond to two different rotor positions, one along d-axis and the other one along q-axis. Fig. 7(a) shows the flux plot when the rotor position is such that the d-axis of rotor coincides with the center line of the stator coil. Most of the flux vectors flow through the iron part only in the rotor. The magnetic flux closed loop path for this rotor position is such that it will enclose the excitation winding slot. Hence the magnetic flux vectors are present at the inner diameter of the rotor also. Fig. 7(b) shows the flux plot when the rotor position is such that the q-axis of rotor coincides with the center line of the stator coil. Most of the flux vectors flow through the iron part only in the rotor. The magnetic flux closed loop path for this rotor position is such that it will not enclose the excitation winding slot. Hence the magnetic flux vectors are not present at the inner diameter of the rotor. The approximations that are considered for simplification of magnetic equivalent circuit can also be understood from these flux plot diagrams. Both the flux plots show that the flux passes through the rotor iron and not through the permanent magnet because the iron reluctance is much lower than the permanent magnet reluctance.

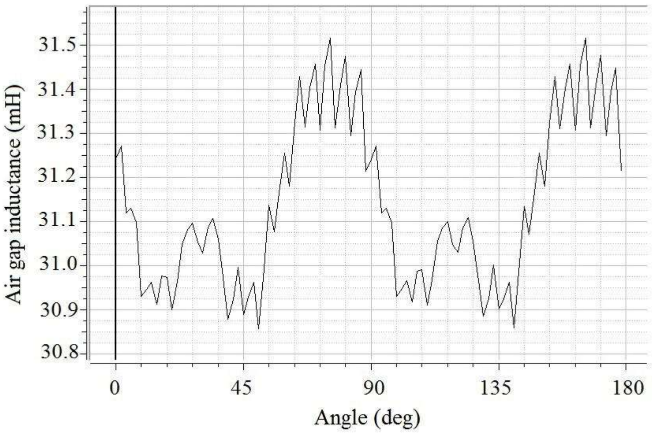


Fig. 8. Inductance plot for different rotor positions

The air gap inductance plot for different positions is also shown in Fig. 8. Though the air gap inductance varies as the rotor position varies, the variation in the air gap inductance is small and it is in the first decimal place when the units are in mH. The d-axis inductance is 31.1 mH while the q-axis inductance is 31.5 mH as shown in the flux plot. The deviation of analytical value of air gap inductance from the inductance values obtained through FEM method is 2% and this may be due to the simplification made in the magnetic equivalent circuit.

IV. CONCLUSION

The inductance analysis has been carried out on a hybrid excitation machine which comprises of permanent magnets arranged in the interior portion of rotor. It is proved that the interior permanent magnet hybrid excitation machine considered in the analysis is non-salient machine through magnetic equivalent circuit approach. The values of inductances estimated through analytical approach are validated with FEM software analysis. It is found that the approximations considered in analytical approach are very much valid and it is also observed that the FEM software results and analytical results are in good agreement with 2% deviation between them.

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