A Synchronous/Permanent Magnet Hybrid AC Machine

Xiaogang Luo, Member, IEEE
TransDimension International Corporation
Riverside, CA 92507 USA

Thomas A. Lipo, Fellow IEEE
Department of Electrical and Computer Engineering
University of Wisoconsin-Madison
Madison, WI 53706 USA

Abstract: In this paper, a synchronous/permanent magnet hybrid(SynPM) machine is presented. It is shown that the machine has good power density and efficiency, and that the machine has true field regulation capability. The principle of operation, finite element analysis and simulation of this new machine are investigated in the paper.

I. Introduction

In this paper, a new electric machine termed the SynPM Hybrid machine is presented. This new machine is a combination of a PM machine and a wound field synchronous machine. It has both PM poles and excitation poles on the rotor, retaining the conventional multi-phase machine stator winding. It has both the features of both PM and synchronous machines. The PM poles provide the air gap with major part of air gap flux. The excitation poles act as the flux regulator to adjust the air gap flux distribution. By proper connection the of stator windings, field weakening/strengthening operation is achieved by picking up the EMF changes caused by the change of flux density under the excitation poles. Although the slip rings and brushes are still present in this kind of electric machine, failure of the brush rigging will not cause as severe a problem as it would for the conventional wound field synchronous machine since the PM poles still produce fairly large air gap flux even with the field winding out of service.

II. Principle of Operation

The structure of the SynPM machine is shown in Figure. 1. The machine has six poles in which 4 of the rotor poles are PM poles and the remaining 2 poles are excitation poles. In general, the operation of this type of machines is quite similar to that of the permanent magnet synchronous machine except that this new structure possesses field regulation characteristics.

For easy understanding of the operation principle, an ideal magnetic circuit analysis is helpful. In this analysis, the following points are assumed

1. The iron has infinite permeance.
2. Fringing and leakage fluxes are neglected.
3. Even distribution of flux under a pole.
4. Even distribution of flux in the region between poles.

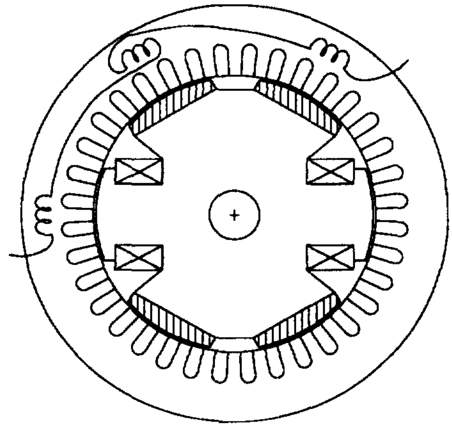

Fig. 1. Structure of SynPM Machine

5. Smooth surfaces on both stator bore and rotor poles.

Based on the above assumption and "Norton" equivalent circuit for magnet [1], A magnetic circuit model of SynPM machine can be constructed and is shown in Figure 2. The circuit model has two rings, representing stator core and rotor core, twelve magnetic reluctances, and six MMF sources. In this model R_g is the air gap reluctance of the excitation poles, R_{pm} is the reluctance of the PM poles and R_s is the reluctance of the slot between two poles. F_{ex} is the MMF of the field winding of excitation pole, assuming that the 2 poles have the same MMF value but in opposite direction.

The circuit is described by the following equation:

$$\sum_{i=1}^{12} \frac{1}{R_i} \cdot P = \sum_{i=1}^{12} \frac{F_i}{R_i} \qquad (1)$$

where P is the magnetic potential of the rotor core (taking stator core as zero reference), F_i is the MMF of branch i, R_i is the reluctance of the branch i.

Since the magnets and field windings are present in pairs and thus cancel each other, $\sum_{i=1}^{12} \frac{F_i}{R_i}$ is always zero. Solving equation (1) yields

$$P = 0 \qquad (2)$$

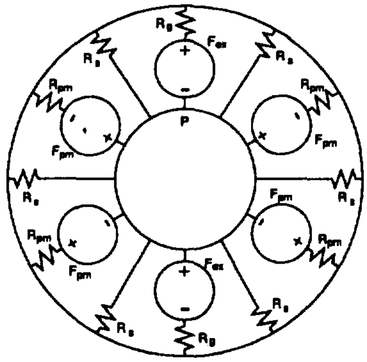

Fig. 2. Magnetic Circuit Model of 6 pole SynPM Machines

Thus the flux of a branch i is

$$\Phi_i = \frac{1}{R_i} \cdot F_i \tag{3}$$

So, the flux of an excitation pole is

$$\Phi_{ex} = \frac{F_{ex}}{R_g} \tag{4}$$

and the flux of a PM pole is

$$\Phi_{pm} = \frac{F_{pm}}{R_{pm}} \tag{5}$$

From equation (4) it is apparent that changing F_{ex} can easily change the flux of the excitation poles, since the air gap reluctance R_g is normally very small. However, the flux of the PM pole is difficult to change due to the typically large value of reluctance R_{pm}.

when field current changes, it can change the back EMF of a circuit, assuming that speed is maintained constant. Figure 1 shows an example of the connection.

III. Coupled Circuit Simulation

A magnetic circuit analysis is used to calculate the parameters for coupled circuit simulation [2] [3]. Figure 3 shows the calculated circuit self inductance versus rotor angular position curve. There are six positions where the inductance reaches its maximum as a result of the series connection of the member coils of the circuit.

The flux linkage of circuits produced by PM poles is another important issue in the simulation. The circuit flux linkage can also be calculated by magnetic circuit analysis [4] and is shown in Figure 4. From the curve it is clear that from the terminals of the circuit, the number of poles is six, which is achieved by connecting the coils of same phase under all poles in series.

A simulation study has been made to determine the performance of the SynPM machine. The simulation results are shown in Figures 5 and 6. From these plots, it should be clear that the SynPM machine with field current regulation capability has much higher constant power speed range with considerably improved torque capability than an equivalent PM machine. In

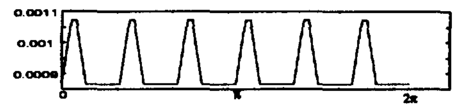

Fig. 3. Calculated Circuit Inductances

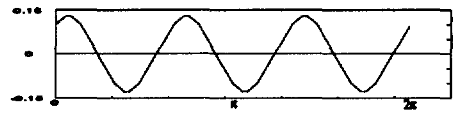

Fig. 4. Calculated Flux Linkages of One Circuit

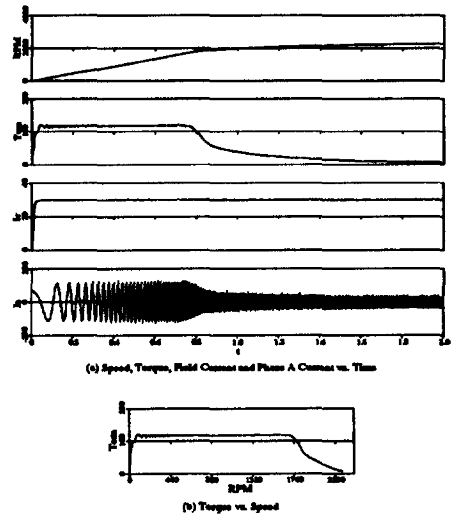

Fig. 5. Simulation of SynPM Machine Without Field Current Regulation

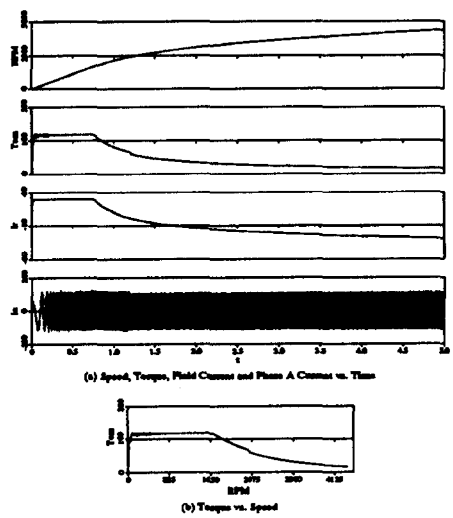

Fig. 6. Simulation of SynPM Machine with Field Current Regulation

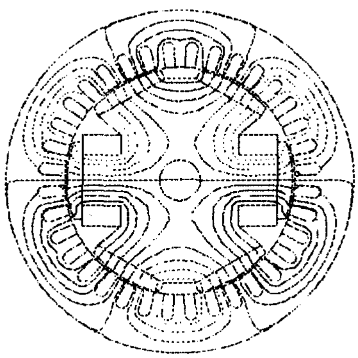

Fig. 7. Flux Lines of a 6 Pole SynPM Machine with Full Positive Field Current

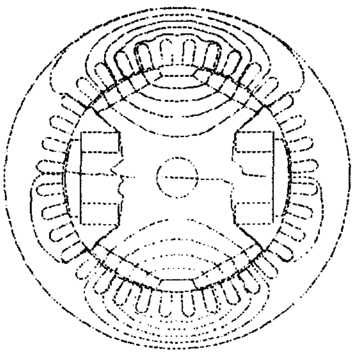

Fig. 8. Flux Lines of a 6 Pole SynPM Machine with Zero Field Current

these computer traces current regulated pulse width modulation was used to control the stator and rotor current. The field weakening range has been extended from 1.3 to 2.7 per unit or greater compared to a machine without current regulation.

IV. Finite Element Analysis

To verify the results of the ideal magnetic circuit analysis, an FEM analysis was also conducted. Figure 7 shows the flux lines of the SynPM machine with positive field current. Figure 8 shows another case of the SynPM machine with zero field current, and, finally, Figure 9 shows the case where the field current is negative, or the field weakening case. From these FEM resulting plots it is apparent that a change of field current does indeed change the flux pattern in the SynPM machine as predicted.

V. Conclusion

A new synchronous/permanent magnet hybrid machine has been presented in this paper and its working principle has been demonstrated. It can work as a generator or a motor. Although a 6 pole version is discussed here, an 8 pole version functions in a similar manner with 4 PM poles and 4 excitation poles.

The SynPM machine has true field regulation. The machine can operate at high speed with field weakening capability. It has

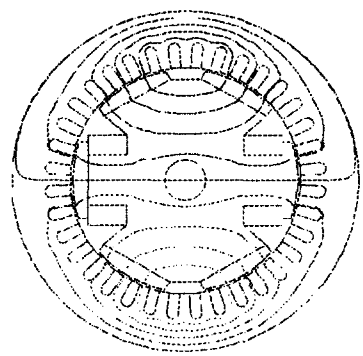

Fig. 9. Flux Lines of a 6 Pole SynPM Machine with Full Negative Field Current

potentials of achieving high efficiency and high power density due to the use of PM material. The ability to operate as pure PM machine increases its reliability. However, the slip ring and brushes are still present. Also there is high flux density present in the stator core region between two adjacent PM poles at high speed when weakening the field, which may cause high iron loss in the stator core.

Considering the gains in power density, efficiency and reliability, it can be concluded that the SynPM drive has potential to compete with conventional AC induction motor drives in higher horsepower applications where the added cost of the rotor structure is offset by the improvement gains in size and weight of the machine and by reduced cost in the power converter.

VI. Acknowledgment

This work was supported primarily by the ERC Program of the National Science Fundation under Award Number EEC-9731677. The authors thank the National Science Foundation for their support of this research project.

References

[1] T. J. E. Miller, *Brushless Permanent-Magnet and Reluctance Motor Drives,* Clarendon Press, Oxford, 1989 .

[2] X. Luo, Y. Liao, H. Toliyat, A. El-Antably, T. A. Lipo, *Multiple Coupled Circuit Modeling of Induction Machines,* IEEE Trans. Ind. Applic., Vol. IA-31, No. 2, pp. 311-318, March/April 1995.

[3] X. Luo, A. El-Antably, T. A. Lipo, *Multiple Coupled Circuit Modeling of Synchronous Reluctance Machines,* IEEE Industry Applications Soc. Conf. Rec., Vol. 1, pp. 281-289, 1994.

[4] T. A. Lipo, *Theory and Control of Synchronous Machines* Course Notes for ECE 511, ECE Department, University of Wisconsin-Madison, 1995.