# Permanent magnet and wound salient pole synchronous generator design comparison

CH. PATSIOS, A. G. KLADAS[*]

*Electric Power Division, Faculty of Electrical & Computer Engineering, National Technical University of Athens*
*9, Iroon Polytechneiou Street, 15780 Athens, Greece*

The paper presents the optimization procedure, and comparison of salient pole with field winding and of peripheral winding synchronous electrical machines, presenting important advantages in wind power generation and traction applications. Neodymium alloy magnet rotor structure has been considered and compared to the salient rotor case. Design optimization has been performed based on the finite element method and sensitivity analysis techniques.

## 1. Introduction

Permanent magnets have been extensively used to replace the excitation winding in synchronous machines with the well known advantages of simple rotor design without field windings, slip-rings and exciter generator, avoiding heat dissipation in the rotor and providing higher overall efficiency.

The rotor design can be distinguished in three main types according to the magnet position, namely the "interior", the "peripheral" and the "claw pole" type. For wind power applications in particular, multipole permanent magnet generators have become very attractive especially in small ratings. Recent advances in power electronics enabling energy efficient drives have aroused the interest in using permanent magnet generators in small and medium systems for both autonomous and parallel operation with the electrical grid.

## 2. Permanent magnet machine design

At the design stage, Neodymium alloy magnets with "peripheral" machine construction merits to be considered. The main generator dimensions of the machine configuration are derived by using classical formulae while the optimization of the permanent magnet dimensions is performed through a finite element modeling procedure.

A first estimation of the generator structure can be obtained by using standard formulae for the machine considered. The preliminary design of main dimensions is performed by means of the following procedure: the magnetic flux per pole is determined by considering the permanent magnet characteristics and the air gap geometry while the appropriate number of turns of the stator windings by applying the flux cutting rule in order to ensure the desired voltage level with respect to the rotor speed; the loading current is then derived by the machine output characteristics while the flux per pole under nominal loading is determined by taking into consideration the demagnetization effects of the stator currents on the no load flux.

Once the basic structure of the machine has been determined the second step of the shape optimization is performed by introducing a finite element model. A 2D model is implemented enabling the performance determination of the machine through a detailed field analysis including the torque variation with the rotor rotation as well as the design improvement by means of the permanent magnet shape modification.

The optimization of the permanent magnet shape is performed by using a perturbation technique of the magnet main dimensions at the final design stage. Sensitivity analysis techniques enable fast and robust cost function extremum research. For the sake of simplicity only rectangular magnet cross sections have been considered here. The cost function used involves torque maximization for a given volume of permanent magnet by adopting the magnet cross-section, length and width as optimizing variables.

## 3. Salient pole synchronous machine design

A first estimation of the salient pole generator structure and determination of important parameters is achieved by considering classical machine design techniques. After determining the basic structure of the machine according to this procedure, 2D finite element model has been introduced for detailed design optimization. A stator winding involving one slot per pole and phase has been considered in the 2D finite element model. One pole part of the machine has been modeled by using appropriate anti-periodic lateral boundary conditions.

The same solution domain has been implemented in the case of the model used for the permanent magnet machine.

## 4. Results and discussion

The two models are compared regarding flux density distribution under maximum torque conditions. Fig. 1a depicts the magnetic flux for permanent magnet machine while Fig. 1b gives the same result in the salient rotor machine case. The comparison of the field calculation shows that both models are in quite good agreement and the main difference is that in the permanent magnet machine case the flux density distribution is less affected by the machine loading. Fig. 2 displays the magnetic flux density in the airgap against the airgap length. In the case of the synchronous machine the flux distribution at the airgap appears to involve less high harmonics content.
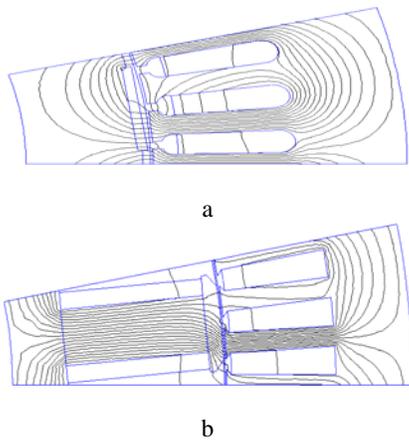


*Fig. 1 Magnetic flux lines for maximum torque conditions.*
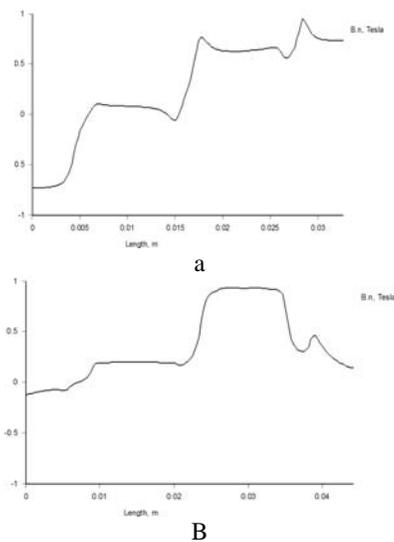***a:*** *Permanent magnet machine.* ***b:*** *Salient pole synchronous machine.*



*Fig. 2 Magnetic flux density B against airgap length. Full load conditions.* ***a:*** *Permanent magnet machine.* ***b:*** *Salient pole machine.*
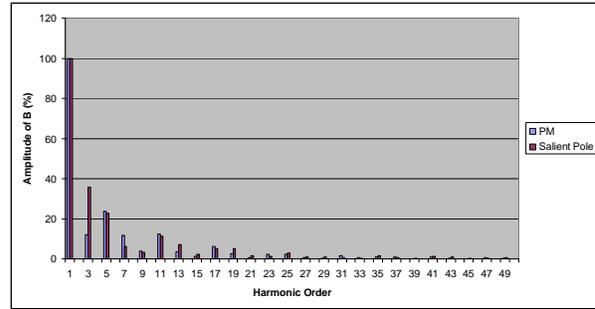


*Fig. 3. Harmonic content comparison of PM and Salient Pole Synchronous machine airgap flux density B. Full load conditions.*

However, an FFT analysis of the magnetic flux density for both machine types under full load conditions, displayed in Fig. 3, shows that the salient pole machine exhibits a stronger third harmonic component. Higher harmonics seem to be in agreement.

Respective to Fig. 1 and 2, Fig. 4 and Fig. 5 display magnetic flux lines and density B, for no load conditions. In this case, as shown in Fig. 6, the permanent magnet machine displays a higher third harmonic component compared to the salient pole structure, nevertheless, the latter shows a stronger $5^{th}$, $11^{th}$ and $13^{th}$ component.
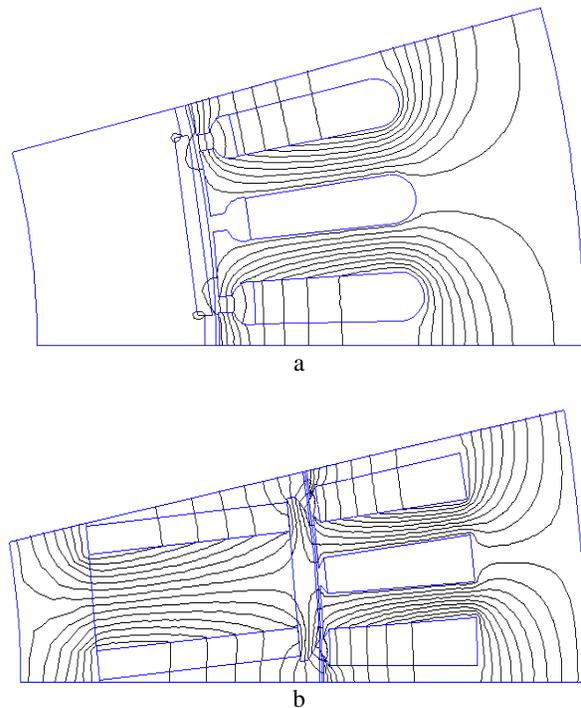


*Fig. 4 Magnetic flux lines for no load conditions.*
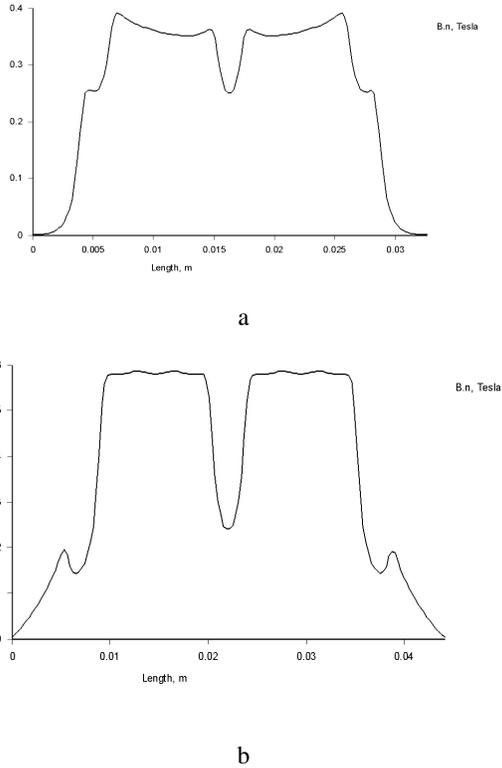***a:*** *Permanent magnet machine.* ***b:*** *Salient pole synchronous machine.*

a



b

Fig. 5 Magnetic flux density B against airgap length. No load conditions. **a:** Permanent magnet machine. **b:**Salient pole machine.
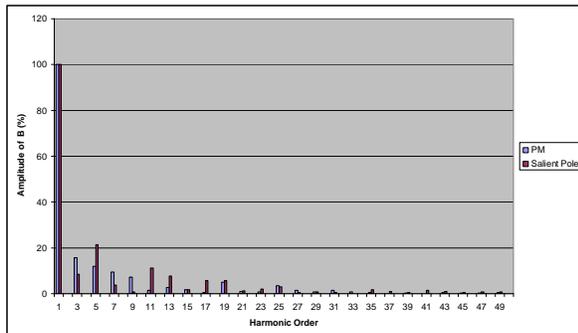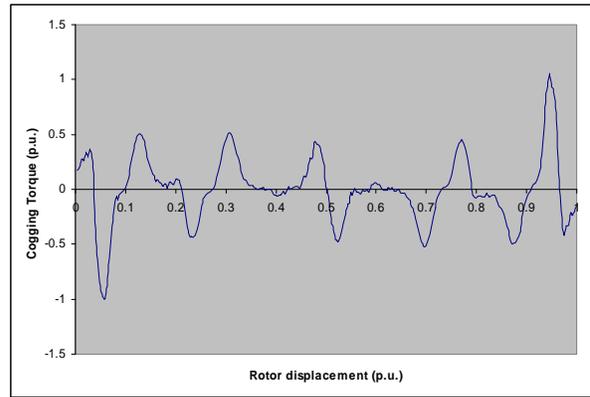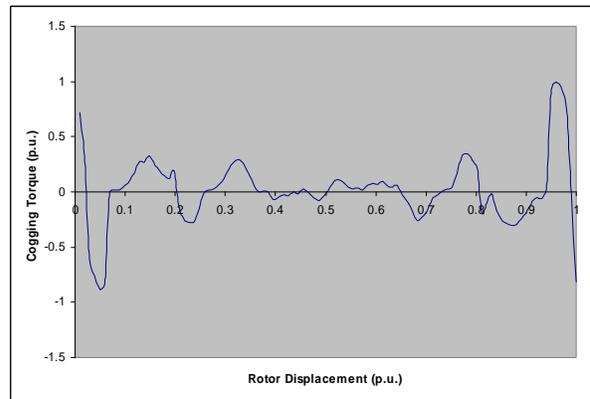


Fig. 6 Harmonic content comparison of PM and Salient Pole Synchronous machine airgap flux density B. No load conditions.



a



b

Fig. 7. Cogging torque for one pole displacement of the rotor under no load conditions. **a:** Permanent Magnet machine **b:** Salient Pole machine.

## 4. Conclusion

A comparison of peripheral permanent magnet machine configuration with salient pole machine structure has been performed. The proposed design technique comprises a preliminary design stage by means of standard formulae and an optimization stage involving finite element models.

## References

[1] A. G. Kladas, J. A. Tegopoulos: IEEE Transactions on Magnetics **28**(2), 1103 (1992).

[2] P. Di Barba, A. Kladas, P. Neittaanmaki, M. Rudnicki, A. Savini, Advances in Engineering Software, No 19, Elsevier Science Ltd, pp. 121-125, 1994.

[3] T. Higuchi, J. Oyama, E. Yamada, E. Chiricozzi, F. Parasiliti and M. Villani, "Optimization procedure of surface permanent magnet synchronous motors", IEEE Transactions on Magnetics **33**(2), 1943 (1997).

Simulations are also undertaken in order to measure the cogging torque of both machines under no load conditions. Fig. 7 exhibits p.u. simulation results for the cogging torque measured at the airgap against a rotor displacement of one pole. It is clear that in the case of the salient pole machine the cogging torque is notably smaller.

[4] A. G. Kladas, M. P. Papadopoulos, J. A. Tegopoulos, "Multipole permanent magnet generator design for gearless wind power applications", Proceedings ICEM'98, Istanbul,  pp. 2055-9, 1998.

[5] S. B. Yoon , I. S. Jung, D. S. Hyun, J. P. Hong, Y. J. Kim, IEEE Transactions on Magnetics **35**(3), 1710 (1999). A. G. Kladas, J. A. Tegopoulos: IEEE Transactions on Magnetics **28**(2), 1103 March 1992.

[6] A. G. Kladas, M. P. Papadopoulos and J. A. Tegopoulos, "Multipole permanent magnet generator design for gearless wind power applications", Proceedings ICEM'98, Istanbul,  pp. 2055-9, 1998.

[7] B. Chalmers, W. Wu, E. Spooner, IEEE Transactions on Energy Conversion, **14**, (2), 251 (1999).

[8] A. J. G. Westlake, J. R. Burnby, E. Spooner, IEE Proceedings - Electric Power Applications **143**(3), 269 (1996).

[9] P. Lampola, J. Perho, J. Väänänen, Proceedings of the European Union Wind Energy Conference, Goteborg, Sweden, 20-24 May 1996.

[10] A. G. Kladas, J. A. Tegopoulos Proceedings of the 3rd International Workshop on Electric and Magnetic Fields, Liege, 1996, pp. 165-169.

[11] A. G. Kladas, M. P. Papadopoulos, J. A. Tegopoulos Compel, **17**, (1/2/3), 151 (1998).

[12] A. Grauers, O. Carlson, E. Hogberg, P. Lundmark, M. Johnsson, S. Svenning  Proceedings of the European Union Wind Energy Conference, Dublin, Ireland, 5-9 October 1997.

[13] S. Kiartzis, A. Kladas, Elsevier, Journal of Materials Processing Technology, pp. 232-236, 2001.

[14] O. Honorati, F. Caricchi, F. Crescimbini and G. Noia, Elsevier Science Publisher, pp. 814-818, 1991.

[15] P. Rasmussen, N. Vilsboell and A. Larsen, European Community Wind Energy Conference, pp. 643-645, 1993.

_____
*Corresponding author: kladasel@central.ntua.gr