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Comparison between rare-earth and ferrite permanent magnet flux-switching generators for gearless wind turbines

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Abstract

Flux switching generators with permanent magnets (PMs) on the stator is a good alternative to traditional synchronous generators for gearless wind turbines. This paper is dedicated to the comparison of the 3-phase rare-earth and ferrite PM flux switching generators considered in gearless wind generator application (332 rpm, 1784 W). The machines are designed and optimized using the Nelder–Mead algorithm coupled with 2D FEM model. The objective function is built taking into account the following objectives: the average efficiency of the generators over the wind turbine profile, the required power of the AC–DC converter, the quantity of the magnets and the torque ripple. It is found that the ferrite PM flux switching generator can be an attractive alternative to the rare-earth one. The averaged efficiency of the generator with ferrite PM is higher by 4.1% than that of the rare-earth one. The active power of the ferrite generator is also higher in a wide range of powers. Although the mass of the ferrite PM generator is 2.4 times higher, the costs of the generators are approximately similar since the rare-earth magnets are much more expensive than ferrite ones.

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1. Introduction

Synchronous machines (SM) with permanent magnets on the rotor have been widely used in gearless generators of low-power wind turbines. However, flux switching machines with permanent magnets on the stator provide several advantages over SM in this application [1]. Designing flux switching generators (FSG) with rare-earth magnets on the stator is presented in [1,2]. However, rare-earth magnets have a high cost and the process of obtaining rare-earth elements from raw ore is associated with significant harmful environmental impacts. Further, in the current situation in the market, the prices of rare-earth elements are unstable and can change by several times within several years.

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These problems force all manufacturers of electric machines with magnets to search for an alternative to rare-earths [3]. Therefore, a good alternative to the FSG with rare-earth magnets is FSG with ferrite magnets. Ferrite magnets are several times cheaper than rare-earth ones and the extraction of raw materials for their production as well as their production exist in many countries of the world [3].

Many works have been presented on design of FSG with rare-earth magnets [2,4–6]. Some studies also are dedicated to design of FSG with ferrite magnets [3,7,8]. However, only several works were dedicated to comparison of the of rare-earth and ferrite flux switching machines (FSM). The following is an overview of these several works dedicated to the comparison of rare-earth and ferrite FSM. For traction applications with the maximum torque of 30 N m and the speed of 1200–6700 rpm, the rare-earth FSM has been compared with the ferrite FSM in [9]. In paper [9], a comparison of similar rare-earth and ferrite FSGs is presented; both generators have 12/10 teeth on the stator/rotor with an external diameter of 134 mm and stack length of 90 mm. The specific torque of the rare-earth FSG is 1.48 times higher and the active material cost is two times higher compared to the ferrite FSG. However, in that paper, a comparison of such important characteristics as torque ripple, efficiency and power factor affects the required power of the frequency converter are not presented. The efficiency underload conditions in which wind generators operate most of the time is also not considered. Moreover, the comparison is carried out without design optimization techniques of electric machines. Therefore, the discussed comparison of the machines is to be concluded as incomplete.

In paper [10], optimized designs of rare-earth and ferrite FSGs are compared in geared wind turbine applications. The rated performances of these FSGs are 10 kW, 259 N m and 360 rpm. The total mass of active materials and the mass of permanent magnets are chosen as the optimization criteria. Efficiency is, however, not included in the optimization function. A non-gradient multi-objective algorithm is applied to accomplish the optimization process. It was reported that the specific torque and active material cost of the rare-earth FSG is 1.63 and 1.65 times higher than those of the ferrite FSG respectively. Besides, the specific characteristics of the ferrite FSG with respect to the rare-earth FSG are better than those reported in [9]. Furthermore, the efficiency of the rare-earth and ferrite FSGs are 94.01% and 95.18% respectively. Moreover, both the FSGs under analysis have a quite low power factor of 0.79 and high torque ripple. The torque ripple of the rare-earth and ferrite FSGs are 7.84% and 9.42% respectively.

This paper compares 3-phase rare-earth and ferrite FSGs in gearless wind generator application (332 rpm, 1784 W). The machines are designed and optimized using the Nelder–Mead algorithm coupled with 2D FEM model. The objective function is built taking into account the following objectives: the average efficiency of the generators over the wind turbine profile, the required power of the AC–DC converter, the quantity of the magnets and torque ripple. Additionally, optimization is carried out using substituting two-mode load profile that considerably reduces computational time.

2. Geometry of the flux switching generator

Two 3-phase FSG gearless wind generators are investigated in this study. General structure of both generators is shown in Fig. 1. Unlike traditional synchronous generators with magnets on the rotor, the FSM' magnets are inserted between each stator tooth. The magnets located in the nearest slits are magnetized oppositely. Each second stator tooth is wound with a concentrated coil.

Both generators have similar geometrical design: the numbers of the stator and rotor teeth are 24 and 22 respectively; the air gap is 0.35 mm; concentrated winding is used. However, there are some differences: (1) Remanent flux density of the rare-earth and ferrite magnets are 1.2 T and 0.4 T respectively; (2) Thin ribs provide mechanical integrity of the rare-earth FSG while they are eliminated in the ferrite FSG to compensate the decreased remanent flux density of the ferrite magnets; (3) The same reason, the outer diameter and the stack length of the ferrite FSG are increased compared to those of the rare-earth FSG (the stack lengths are 100 and 110 mm respectively, the outer diameters of the stator are 160 and 220 mm respectively); (4) Each magnet of the rare-earth FSG consists of three electrically-insulated segments to suppress the eddy current in the magnets. Dividing the ferrite magnets into segments is not necessary because their electric conductivity is too low. More information on design parameters of these generators can be found in [2,3].

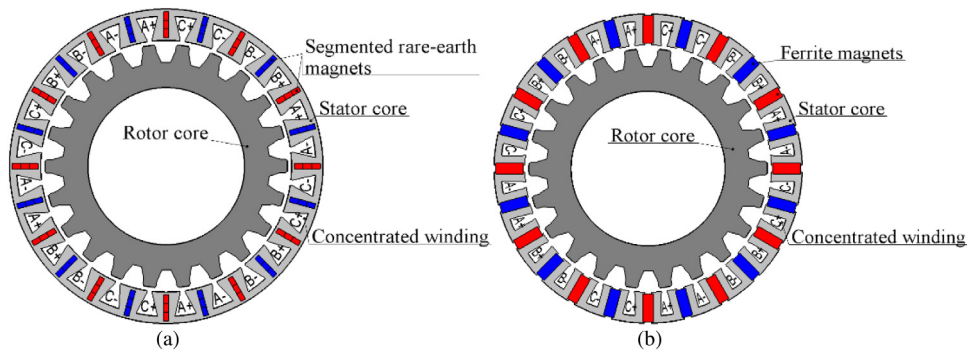


Fig. 1. FSG designs sketches: (a) with rare-earth magnets; (b) with ferrite magnets.

3. Optimization of the flux switching generator

A multi-objective optimization (MOO) of electric machines is aimed to compromise between several objectives determined by preferences of a user. Some MOO methods are based on creating the Pareto front. Then, a user chooses the most appropriate solution. In other MOO methods, a user defines an objective function determining the merits of the objectives. Then objective function is minimized by a one-criterion optimization algorithm. This strategy is effective in obtaining the optimal values with less iteration number and time as presented in [2,3]. In this work, to optimize the generators' geometrical parameters, the objective function has been selected and minimized with the Nelder–Mead optimization method.

The generators' design optimization is made for the load profile determined by the maximum power points of the wind turbine [2]; the wind speed was assumed to be distributed according to the Rayleigh distribution. The initial profile described in [2] has 9 points. Instead, in the work [2], the two-mode substituting profile is used which reduces the efforts at the objective function call by 4.5 times. This profile is chosen so that the averages of any value over the two-mode substituting profile and over the nine-mode initial profile coincide if the dependence of this value on the generator mechanical power can be accurately approximated by quadric trinomial. The two mode profile consists of the rated mode (the mode of maximum power) and the mode of decreased power (further in the paper underload mode).

The general form of the objective function used in the optimization of both motors is as follows:

$$F = K_1 \cdot K_2^n \cdot K_3^m \cdot K_4^k, \quad (1)$$

where K_1 , K_2 , and K_3 are the optimization objectives; K_1 is the averaged losses of the FSG; K_2 is the required AC–DC converter power; $K_2 = 0.5 \cdot \sqrt{3} \cdot I_{\text{ampl, rated, 0}} \cdot U_{\text{DC, rated, 0}}$; $K_3 = L \cdot (h_{\text{magn}} + 0.001 \text{ m}) \cdot l_{\text{mag}}$, where $l_{\text{mag}} = (R_1 - R_3 - 2 \cdot \Delta_3)$ is the radial length of the magnets. The thickness of the magnets was increased by 1 mm when calculating the K_3 to take into account that thin magnets are more expensive. K_4 is the average of the relative value of the peak-to-peak torque ripple. Parameters n , m and k determine how many percent decrease in K_1 is as valuable as a decrease in K_2 , K_3 , and K_4 by 1% respectively.

4. Results and discussions

The optimization strategy is coupled with 2D finite element method (FEM) to obtain the optimal values of the geometrical parameters. Initial designs and many details of optimization are not included here. Nevertheless, these aspects are described in [2,3] in more details. The rare-earth FSG was optimized with the following parameters: $n = 2$, $m = 0.5$, $k = 0$. K_4 is absent because the torque ripple of the rare-earth FSG is very small. At optimization of the ferrite FSG, although the torque ripple of the ferrite FSG is rather small, it is higher than that of the rare-earth FSG generator. Hence, a small merit of objective K_4 is introduced ($k = 0.1$). Also, m is reduced to 0.1 because ferrite magnets are much chipper than rare-earth ones. The problem of the optimization of the ferrite FSG was to obtain the acceptable level of the required converter power K_3 . K_3 was 3.7 kW at initial design, which is more than 2 times the rated (maximum) mechanical power. Therefore, optimization was started with $n = 2$ and then n

was increased to 3 and to 4 until K_3 achieves an acceptable value. Thus, optimization was implemented in three stage. At second and third stages, the best design found in previous stage was taken as the initial design.

Figs. 2a and 2b show the flux density plot of the optimal FSGs with rare-earth and ferrite magnets at the rated condition. Several parameters of optimized design of both generators are reported in Table 1. The active power of the FSG with ferrite magnets is higher in a wide range of powers. (Fig. 3a). The averaged efficiency of the FSG with rare-earth magnets is higher by 4.1% than that of the FSG with ferrite magnets (the efficiency at the rated mode and at the underload is higher by 5% and 2.5% respectively).

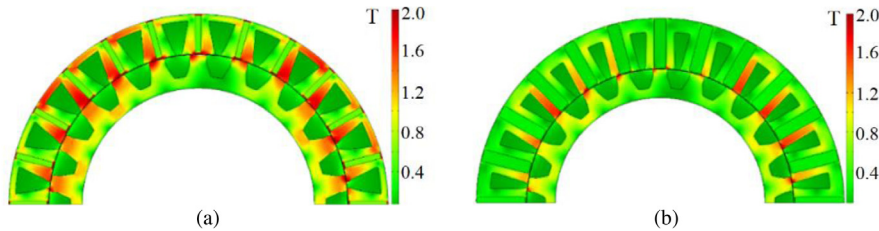


Fig. 2. Flux density plot of FSGs at the rated condition: (a) rare-earth; (b) ferrite.

Table 1. Parameters and characteristics of two flux switching generators.

Parameter	Rare-earth FSG	Ferrite FSG
Rotor and stator cores length, mm	100	110
Outer diameters of the stator, mm	160	220
Rated input mechanical power (rotational speed 332 rpm, torque 51.4 N m), W	1784	1784
Rated output real electrical power, W	1488	1577
Required AC–DC converter power, V A	1973	2093
Input mechanical power at underload (rotational speed 194 rpm, torque 17.8 N m), W	362	362
Output real electrical power at underload, W	318	327
Efficiency in the rated mode, %	0.834	0.884
Efficiency in the underload mode, %	0.878	0.903
Average efficiency, %	0.854	0.895
Average losses, K_1 W	79	56.9
Torque ripple at the rated mode, %	1.3	1.8
Torque ripple at the underload, %	2.4	2.7
Mass of the magnets, kg	0.674	4.19
Mass of the copper, kg	1.06	1.66
Mass of the stator core, kg	3.26	7.96
Mass of the rotor core, kg	2.46	4.13
Active material mass, kg	7.45	17.94
Area of the stator slot filled with the copper wire, mm ²	98	139
Active material cost, \$	98.5	101.2

This is because of reducing the losses throughout power range in case of the FSG with ferrite magnets (Fig. 3b). The losses reduction in the FSG with ferrite magnets is obtained due to decreasing the copper losses. The decrease in the copper loss is about 1.4 times thanks to the increased stator slot area. Although the mass of the FSG with ferrite magnets is 2.4 higher than that of the FSG with rare-earth magnets, the costs of the generators are approximately similar since the rare-earth magnets are much more expensive than ferrite magnets. When calculating the cost of active materials, the following prices were assumed: \$1/kg for steel, \$7/kg for copper, \$126.6/kg for rare-earth permanent magnets (42SH) and \$18.46/kg for ferrite permanent magnets (Y30H-2) [11,12].

5. Conclusions

This paper has presented the comparison between two flux switching machines based on rare-earth and ferrite magnets for a direct-driven wind turbine. The optimization algorithm is coupled with the 2D finite element model to obtain the optimal geometry of both machines for the maximum power profile of the turbine. It is found that the ferrite FSG can be attractive alternative to the rare-earth FSG. The averaged efficiency of the FSG with ferrite

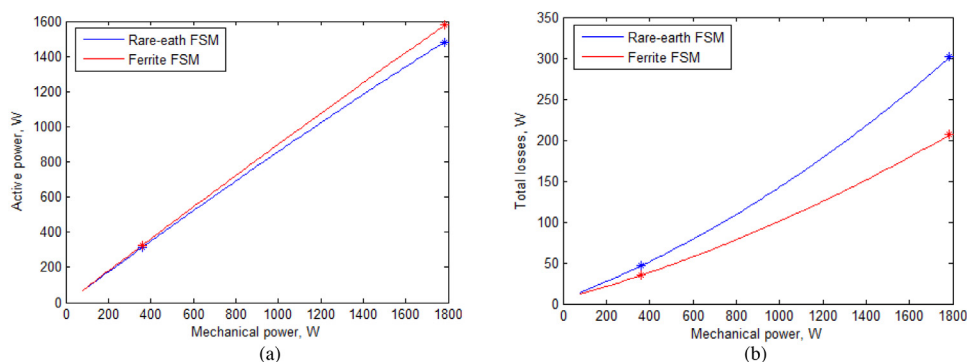


Fig. 3. Characteristics of FSGs: (a) active power; (b) total losses.

magnets is higher by 4.1% than that of the FSG with rare-earth magnets. The active power of the FSG with ferrite magnets is also higher in a wide range of powers. Although the mass of the FSG with ferrite magnet is 2.4 higher than that of the FSG with rare-earth magnet, the costs of the generators are approximately similar since the rare-earth magnets are much more expensive than ferrite magnets.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

- [1] Shao L, Hua W, Soulard J, Zhu ZQ, Wu Z, Cheng M. Electromagnetic performance comparison between 12-phase switched flux and surface-mounted pm machines for direct-drive wind power generation. *IEEE Trans Ind Appl* 2020;56(2):1408–22. <http://dx.doi.org/10.1109/TIA.2020.2964527>.
- [2] Dmitrievskii V, Prakht V, Kazakbaev V. Design optimization of a permanent-magnet flux-switching generator for direct-drive wind turbines. *Energies* 2019;12(19):1–15.
- [3] Prakht V, Dmitrievskii V, Kazakbaev V. Optimal design of gearless flux-switching generator with ferrite permanent magnets. *Mathematics* 2020;8(2):1–14. <http://dx.doi.org/10.3390/math8020206>.
- [4] Vahedi A, Meo S, Zohoori A. An AHP-based approach for design optimization of flux-switching permanent magnet generator for wind turbine applications. *Int Trans Electr Energy Syst* 2016;26:1318–38. <http://dx.doi.org/10.1002/etep.2149>.
- [5] Wang Y, Deng Z. Comparison of switched-flux permanent magnet machines with non-overlapping concentrated winding for open-winding generator system. *IET Electr Power Appl* 2017;11(2):242–51. <http://dx.doi.org/10.1049/iet-epa.2016.0321>.
- [6] Zohoori A, Vahedi A, Noroozi M, Meo S. A new outer-rotor flux switching permanent magnet generator for wind farm applications. *Wind Energy* 2017;20:3–17. <http://dx.doi.org/10.1002/we.1986>.
- [7] Akuru U, Kamper M. Intriguing behavioral characteristics of rare-earth-free flux switching wind generators at small- and large-scale power levels. *IEEE Trans Ind Appl* 2018;54:5772–82. <http://dx.doi.org/10.1109/TIA.2018.2848979>.
- [8] Ojeda J, Simões M, Li G, Gabsi M. Design of a flux-switching electrical generator for wind turbine systems. *IEEE Trans Ind Appl* 2012;48:1808–16. <http://dx.doi.org/10.1109/TIA.2012.2221674>.
- [9] Fasolo A, Alberti L, Bianchi N. Performance comparison between switching-flux and IPM machines with rare-earth and ferrite PMs. *IEEE Trans Ind Appl* 2014;50(6):3708–16. <http://dx.doi.org/10.1109/ICEIMach.2012.6349955>.
- [10] Akuru U, Kamper M. Design and investigation of low-cost PM flux switching machine for geared medium-speed wind energy applications. *Electr Power Compon Syst* 2018;46(9):1084–92. <http://dx.doi.org/10.1080/15325008.2018.1485789>.
- [11] NdFeB magnets, price list of standard block magnets, ChenYang. 2020, Available online: <http://www.ndfeb magnets.de/CY-PriceList-NdFeB-Block.pdf> (accessed on 22 2020).
- [12] Hard ferrite magnets, product information, IBSMagnet. 2020, Available online: <https://ibsmagnet.com/products/dauermagnete/hartferrit.php> (accessed on 22 2020).