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# Analytical analysis of sleeve permeability for output performance of high speed permanent magnet generators driven by micro gas turbines

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ABSTRACT

An alloy sleeve is often used to prevent the damage to rotor magnets caused by the large rotational centrifugal forces within a high speed permanent magnet generator (HSPMG). It should be thick enough to satisfy the mechanical strength needed. The generator main reluctance mainly focuses on the rotor sleeve, so sleeve permeability has much influence on the magnetic circuit and generator performance. Since a finite element simulation for every machine is time consuming and complicated, a simple analytical model of general surface-mounted permanent magnet machines has been established within this paper. Additionally, an analytical method is also given in full, so that optimal sleeve permeability can be obtained for a set of parameters for a given machine. In order to accurately establish the variation of the pole-to-pole leakage flux in the air gap and rotor sleeve of the generator with different permeability sleeves, an iterative method is proposed. The leakage flux, main flux, magnet performance and their relationships with the generator have been studied further, and the influence mechanism of sleeve permeability on the generator performance has been determined. Based on the research of the above influence factors, the optimal sleeve permeability is obtained by using the analytical method. Comparing the results of the analytical method and finite element method, they are in close agreement; hence the rotor sleeve with optimal permeability can improve the generator performance.


## 1. Introduction

Micro gas turbine generation systems are considered an efficient alternative to costly generation and transmission of electricity [1,2]. Due to their small size, high efficiency, high power density, simple mechanical construction, easy maintenance and good reliability, high speed permanent magnet generators (HSPMG) are fit for use, and play a key role in the electricity systems of micro gas turbines [3,4]. In such a generator, a rotor sleeve is often used to prevent damage to permanent magnets (PM) caused by the large rotational centrifugal forces. These sleeves can provide pre-stress for permanent magnets, since the tensile strength of permanent magnets is very poor. The rotor sleeves can be made of an alloy or carbon

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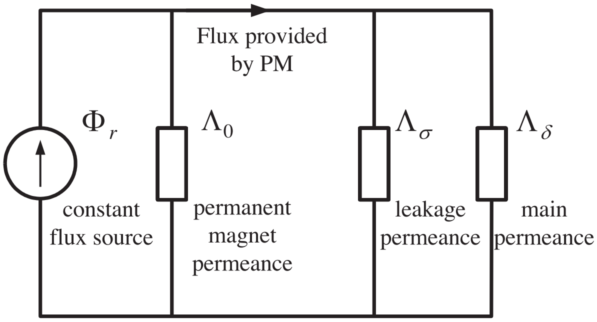


**Fig. 1.** Equivalent magnetic circuit of the permanent magnet generator.

fiber. Alloy sleeves are relatively superior to the carbon fiber sleeves for heat conductivity and processing technique, and are used extensively [5–9].

In HSPMG, the rotor sleeve should be thick enough to satisfy the mechanical strength. Hence, its thickness is much larger than the air-gap length. The generator reluctance mainly focuses on the rotor sleeve. The reluctance in the rotor sleeve can reduce the permanent magnet excitation performance and lower the operating point of permanent magnets. Therefore, material with some permeability used as the rotor sleeve could effectively reduce the generator reluctance and improve its performance. However, material with too large permeability could excessively increase the pole-to-pole leakage flux, resulting in the permanent magnet excitation flux which goes through the stator core being reduced. Therefore, the sleeve permeability optimization is very important.

Some researchers have proposed using a semi permeable sleeve in high speed permanent magnet generators [10], but the influence mechanism has not been clarified in depth. Furthermore, the permanent magnet performance variation with sleeves of different permeability was ignored. The finite element method is often used for studying HSPMG. However, the analytical method, which is suitable for optimal design and appropriate for industry with its advantages of simple analysis and fast computing, is not widely used. Refs. [11,12] present the two-dimensional analytical expressions of machines, and only focus on motor design and rotor loss reduction.

This paper is based on the equivalent magnetic circuit of the permanent magnet generator and the flux provided by permanent magnets. The main flux and leakage flux have been researched using the analytical method. In order to determine the leakage permeance both in the rotor sleeve and air gap, an iterative method was proposed in this paper. Using this method, the main flux and the leakage flux could be calculated more accurately. Finally, the influence factors and mechanism were determined. Based on the above analyses, an analytical method for surface-mounted permanent magnet machines is proposed to achieve optimal sleeve permeability. Comparing the analytical results, the finite element calculation results and the test data, this paper proves that the analytical method is appropriate for analyzing general surface-mounted permanent magnet machines.

## 2. Analysis of the high speed permanent magnet generator

For investigating the influence of sleeve permeability on the generator performance and trying to establish the influence mechanism, the excitation performance of permanent magnets is a key factor. In this section, the factors that affect permanent magnet excitation performance are analyzed. By using the analytical method, the performance of generators with different permeability sleeves is studied, and the relationship between rotor sleeve permeability and generator performance is researched. Based on the analysis of the variation of the generator main flux and leakage flux, the influence mechanism of the sleeve permeability on the generator performance is determined.

### *2.1. Equivalent magnetic circuit of the permanent magnet generator*

Since the reluctance of the magnetic circuit in the generator has much influence on the permanent magnet excitation performance, and also affects the generator output performance further, the analysis on the magnet circuit in the generator is very important.

Based on the relationship between the permanent magnet performance and the permeance in the generator, Fig. 1 shows the equivalent magnetic circuit of the permanent magnet generator. In this equivalent magnetic circuit, the permanent magnet is equivalent to a constant flux source in parallel with a permanent magnet permeance. The generator main permeance and the leakage permeance change with sleeve permeability. In order to obtain the main flux which induces the electromotive force, every permeance in Fig. 1 needs to be determined. The permanent magnet permeance ($\Lambda_0$) and the generator main permeance ($\Lambda_\delta$) can be calculated by:

$$\Lambda_0 = \frac{\mu_p A_m}{h_{mp}}, \tag{1}$$

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