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Geometry optimization of solid rotor eddy current brake by using sensitivity analysis and 3D finite elements

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Abstract

The paper presents an optimization procedure for eddy current brakes, considering both copper and solid iron rotors. The rotor geometry optimization has been performed based on analytical solutions and 3D finite elements combined to sensitivity analysis technique. Optimum dimensions of copper parts and solid iron slots have been investigated.

Keywords: Eddy currents; Finite element methods; Optimization methods; Rotating machines

1. Introduction

Eddy current brakes can be attractive rivals of mechanic brakes used for over-speed protection of wind turbines in cases of disturbances. They provide important advantages such as good reliability, low cost and involve no maintenance requirements. Especially for wind turbines equipped with permanent magnet generators, they can provide reliable braking operation in cases of loss of the grid connection due to faults. In such situations the decelerating torque provided by the generator connected to dump loads, can be substantially increased by the parallel connection of an eddy current braking machine connected on the same shaft. The configuration of a wind turbine system operating under such disturbance conditions is shown in Fig. 1.

This work is related to a project concerning the design and construction of a 25 kW grid connected, stall regulated, variable speed wind turbine, equipped with a permanent magnet (PM) generator. The PM generator has already been optimized and tested through a prototype [1].

In order to enable braking operation the number of poles of the induction machine brake must be greater than the one of the PM generator. Moreover, in order to obtain a simple structure only solid rotor machine configurations have been considered.

The design of the brake as well as the evaluation of the equivalent circuit parameters can be obtained by using finite element techniques [2,3]. However, the optimization of the rotor geometry may require laborious and expensive numerical schemes especially when 3D configuration should be considered [4,5]. Although both stochastic [6] and deterministic optimization algorithms can be implemented [7–9], the sensitivity analysis technique combined with finite element methods enables robust and fast convergence [1].

2. Methodology

The geometry optimization of the eddy current brake is based on solid rotor configuration for construction simplicity purposes. The analysis problem has been solved either by using existing solutions of closed form (case of rotating field around non-salient rotor) or by 3D finite elements (slotted stator and rotor case). A particular reduced scalar potential formulation necessitating no source field calculation has been adopted to develop the 3D finite element model [11]. The analysis methods as well as the optimization procedure are developed hereafter.

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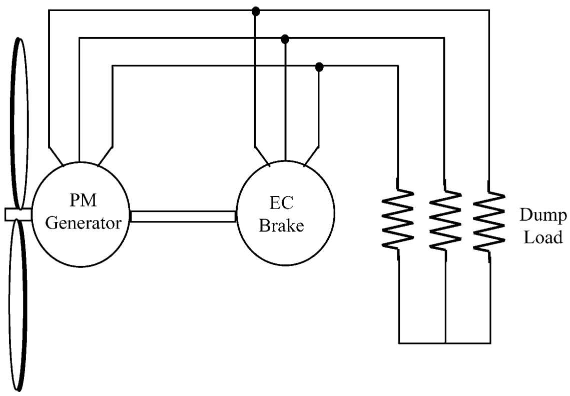

Fig. 1. Configuration of the wind turbine electric part in case of grid connection loss due to fault (PM generator supplying the eddy current brake and the resistive dump load).

2.1. Analytical solution for solid rotor brake

The case of a non-salient rotor structure surrounded by a uniform air-gap has been considered, as shown in Fig. 2. The stator presence has been represented by a sinusoidal rotating magnetic field. The rotor is consisted of concentric cylindrical layers of conducting materials. The analytical solution of Laplace equation in the air gap takes the form in terms of the complex magnetic vector potential:

$$\bar{A}_a(r,\theta) = \left[(C_1 + jC_2)r^k + (C_3 + jC_4)\left(\frac{1}{r^k}\right)\right] \times \exp[-jk(\theta - \omega t)] \quad (1)$$

where C_1, C_2, C_3, C_4 are real constants, k is the number of pole pairs and ω the angular velocity.

In a cylindrical conducting layer the analytical solution of diffusion equation for the complex magnetic vector potential is of the form:

$$A_c(r,\theta) = \{[D_1 + jD_2][\mathrm{ber}_k(\lambda r) + j\mathrm{bei}_k(\lambda r)] + [D_3 + jD_4][\mathrm{ker}_k(\lambda r) + j\mathrm{kei}_k(\lambda r)]\} \times \exp[-jk(\theta - \omega t)] \quad (2)$$

where D_1, D_2, D_3, D_4 are real constants, ber_k, bei_k, ker_k, kei_k are kth order Kelvin functions of first and second kind, while

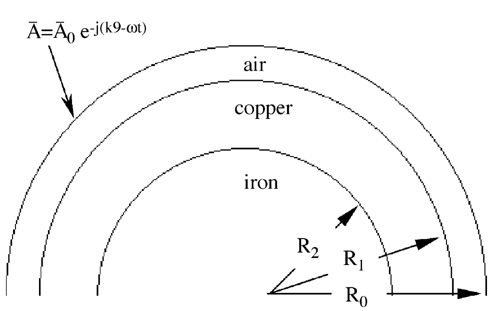

Fig. 2. Geometry of the non-salient solid iron rotor structure surrounded by a sinusoidal rotating magnetic field.

$\lambda^2 = (\sigma\,\omega\,\mu)$, with σ denoting the electrical conductivity and μ the magnetic permeability.

The constants in these solutions are calculated by applying the boundary conditions and the continuity relations across the material boundaries.

2.2. Scalar potential 3D FEM technique

The use of scalar potential formulations in 3D configurations usually necessitates a prior source field calculation by using Biot-Savart's Law, which presents the drawback of considerable computational effort. We have developed a particular scalar potential formulation enabling treatment of 3D magnetostatics. It permits one to model efficiently laminated iron cores with or without air-gaps and needs no prior source field calculation.

According to our method the magnetic field strength $\mathbf{H}$ is conveniently partitioned to a rotational and an irrotational part as follows:

$$\mathbf{H} = \mathbf{K} - \nabla\mathbf{\Phi} \quad (3)$$

where $\mathbf{\Phi}$ is a scalar potential extended all over the solution domain while $\mathbf{K}$ is a vector quantity (fictitious field distribution), defined in a simply connected subdomain comprising the conductor, that satisfies Ampere's law and is perpendicular on the subdomain boundary.

This technique has been extended for cases involving eddy currents in well-defined paths [10]. In cases of thin skin effect depth however, it is possible to express the corresponding induced surface current density $\mathbf{J}_\mathrm{I}$ as follows [11]:

$$\mathbf{J}_I = \left(\frac{\partial}{\partial t}\right)(\mathrm{grad}\,Tx\mathbf{n}) \quad (4)$$

where T is a scalar quantity existing only on the surface where eddy currents are developed while $\mathbf{n}$ is the unit normal to the above-mentioned surface.

2.3. Optimization procedure

The optimization of the rotor shape is performed by using a perturbation technique of the slot dimensions as well as copper parts. When combined with the analytical solution procedure as design variables are considered the copper layer width $(R_1 - R_2)$ the machine loading (A_0 value) as well as the number of pole pairs (k value). When combined with the 3D FEM model in the case of slotted rotor machine, for the sake of simplicity only rectangular slot cross-sections have been considered. In that case the design variables are the slot number and dimensions as well as the machine loading represented by:

$$\mathbf{x} = x_1, x_2, x_3, x_4 \quad (5)$$

where x_1 is the number of slots, x_2 the slot height, x_3 the slot width and x_4 the current in stator slots. These variables make maximum the objective function $F(x)$ representing the