European Association for the Development of Renewable Energies, Environment and Power Quality (EA4EPQ)	International Conference on Renewable Energies and Power Quality (ICREPQ'11) Las Palmas de Gran Canaria (Spain), 13th to 15th April, 2010

Thermal design and analysis of a direct-water-cooled permanent-magnet synchronous generator for high-power direct-drive wind turbine applications

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Abstract. As the wind turbines become larger and larger each year, more powerful and reliable generators must be designed for them. The increase of the rated power implies higher current density to achieve the acceptable dimensions for the generator. A direct-water cooling system for the stator winding of the synchronous generator ensures removal of heat losses and therefore safe temperature of the stator winding.

The aim of this paper is determine the performance attributes of the cooling system of the stator winding. The design and evaluation of the cooling system are executed on the basis of analytical calculations and by using Finite Element Method.

Key words

Electrical machines, wind turbine generator, direct-drive, direct water cooling, thermal analysis

1. Introduction

Despite all wind power becomes more and more popular globally as power generation by wind does not need fuel. Wind energy is considered as environmentally friendly and its development is supported by governments. Almost all famous energy technology companies are involved in the race of creating the most reliable, efficient and high power wind generators. The new tendency of the current market is shifting towards the direct drive systems coupled with low-speed permanent magnet synchronous generators (PMSG).

Direct drive PM generators are considered as more reliable than the medium-speed gear based PM generator drives and high-speed induction generators as they are free from the gearbox unreliability. For high power machines (>3 MW) the gearbox becomes more complex and fragile, as it requires an additional stage to the common gearbox and has some temperature problems [8]. Direct drive PMS generators are notable for their high energy yield and low operation and maintenance costs. The gearbox creates about 40 % of the total system losses and it requires routine maintenance during the operation period [2]. However, among the existing generator types the direct drive PMSG is the most expensive one because of the impressive dimensions and weight. As the produced torque is proportional to the square of the air gap diameter the outer radius of the machine should be large for high torque production. This fact causes the main disadvantage of the high-power low-speed gearless PMSG - its large dimensions and big mass that imply high cost.

The problem of impressive dimensions and weight of PMSG can, in principle, be solved by increasing the machine linear current density and the stator winding current density to no less than 8-10 A/mm^2. Such a high current density imposes high ohmic heating within the conductor. It can cause overheating of the copper and damage the winding insulation if specific measures are not used to cool the copper conductor. Also in terms of the permanent magnet rotor, the high temperature heat flux from the stator can cause damage on the permanent magnets' operation as their working temperature is limited to 120-150 $^{\circ}$C (NdFeB).

The above mentioned problems can be solved through the direct cooling of the stator winding. Despite the existence of the air and hydrogen based solutions for internal cooling of the stator, the direct water based cooling system is the most effective way to remove the heat losses mainly because of high heat capacity of water (4200 J/m^{3}K). However the use of the demineralised water implies additional systems for filtering and cleaning.

The objective of this study is to analyze and evaluate the direct-water cooling system for the stator copper winding of the direct-drive permanent magnet synchronous generator. We have used analytical and Finite Element Method (FEM) based analyses to solve the formulated problems.

2. Description of Thermal Model

A. A Studied Generator

The studied machine is a low-speed, concentrated pole winding, three-phase, rotor-surface-magnet synchronous generator with rated power of 6 MW. The main application of such a generator can be found in wind