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Impact of a multi-star winding on the reliability of a permanent magnet generator for marine current turbine

Christophe Olmi, Franck Sculler *, Jean-Frédéric Charpentier

Naval Academy Research Institute, BCRM Brest – EN/GEP, CC 600, FR-29240, Brest Cedex 9, France

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ABSTRACT

For Marine current turbine (MCT), low speed Surface-mounted Permanent Magnet generator is a solution to satisfy the efficiency and fault tolerant requirements. This is supposed to be true if the winding is made with several non-shifted three-phase stars that could be supplied with standard modular voltage source inverters. This paper investigates the impact of the star number on the MCT energy yield if the system is conceived to operate with disconnected inverters. For this purpose, a method to calculate the extracted power according to the tidal speed for a given star number and a given activated star number is detailed. A rainflow counting method is used to account the stress due to the tidal speed change on the star converter: the impact of the star number on the resilience capability of the MCT is then quantified. By assuming a ten-year period without converter repair, according to the introduced probabilistic approach, the star number increase improves the reliability and three-star configuration appears as a trade-off.

1. Introduction

Among the various possible technologies to capture the kinetic energy from tidal currents, horizontal axis marine current turbine (MCT) appears as one the most studied solution. This can be explained by the similarities with wind turbine (WT) even if ressource characteristics [1], turbine blade design and mechanical stress are different [2]. For the grid operator, the main advantage of marine current energy is the high predictability: marine currents are mostly driven by the tide thus making this resource predictable over long time scales.

However, due to harsh environment and low accessibility, the economic development of MCT requires to consider the reliability and efficiency of the overall system. Again experiences from WT exploitation can help the designer to choose the right solution for MCT. According to [3], for off-shore WT, gearbox, yaw and pitch appear as the most faulty components. The choice of low speed generator directly driven by a non-pitchable turbine is thus justified. For example, in [4] where large MCT at the industrial development stage are reviewed, it appears that non pitchable blades are often chosen. It should be highlighted that non pitchable blades suggest to implement a particular flux weakening (FW) control of the machine at high tidal speed that really differs from the solutions used in large WT [5].

Regarding the generator choice, robust machines suitable for direct-drive should be selected. Switched-reluctant generator is an attractive solution, especially regarding the fault-tolerant ability in so far as the phase-to-phase magnetic couplings are usually low [6]. However, mechanical vibrations and electrical losses can be both reduced by choosing a

* Corresponding author.
E-mail address: franck.scuiller@ecole-navale.fr (F. Scuiller).

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Nomenclature

BBC	Back-to-Back Converter
CPR	Constant Power Range
DD	Direct Drive
FW	Flux Weakening
MCT	Marine Current Turbine
MPPT	Maximum Power Point Tracking
MTPA	Maximum Torque Per Ampere
SC	Semiconductor
WT	Wind Turbine
C_p	Turbine power coefficient
ν	Tip speed ratio
λ	Failure rate
υ_C	Cut-in tidal speed
υ_R	Rated tidal speed (base)
υ_F	Cut-out tidal speed
z	p.u. tidal speed
y	p.u. mechanical and electrical speed
e	p.u. back-emf
r	p.u. armature resistance
x	p.u. synchronous inductance
(i_d, i_q)	p.u. d-axis, q-axis currents
S	Total star number
s	Activated (i.e. used) star number
$F_{c,s/S}$	Capacity factor if using s stars among S
$R_S(t)$	Reliability (survivor) function with S stars
$\Sigma_S(t)$	Reliability-performance function with S stars
τ_S	Reliability-performance criterion with S stars

Surface-mounted Permanent Magnet (SPM) machine [7]. High phase number machine can inherently improves the availability of the drive [8]. In safety–critical applications as in aerospace, the regulation imposes that a single fault should not reduce the performance [9]. In this case, each phase must be overrated by a rating factor depending on the healthy state phases number [10]. MCT is not a safety–critical application: thus the first fault can lead to a degraded state where the captured power is reduced. In this context, the right phase number should be determined by quantifying the phase faults consequences on the energy yield. In [11,12], the fault tolerant ability of a five-phase SPM machine for MCT is evaluated. Modular generator-converters where phase coils are individually connected to the grid with their own boost converter are presented and tested in [13,14] for example. All these solutions require specific converters and fault detections are necessary.

In this paper, the possibility of using a multi-star SPM generator is explored. Multi-star machine are equipped with several electrically independent three-phase wye-coupled windings, each winding terminal being connected to the grid with its own three-phase back-to-back converter (BBC). The dual 3-phase machine (two 3-phase windings with 30 degrees shift angle) is probably the more common solution [15]. With the multi-star three-phase machines here considered, standard three-phase converters can be used thus offering the advantage of modularity, lower cost and easier maintenance. The study focuses on non shifted (i.e. magnetically aligned) stars since this solution allows to avoid circulating current between star windings and reduce the star-to-star magnetic couplings [16]. In addition, the pulsating torque frequencies (in electrical angle) do not change even in case of star losses or disconnections (the reason is that the considered non shifted multi-star machines are magnetic three-phase machines [17]). Thereby, the first fault in one phase is assumed to lead to the disconnection of the corresponding 3-phase BBC. Finally, the control of the machine is virtually the same in normal or faulty operation.

The performances of modular multi-star machines are discussed in [18] that focuses on a nine-phase generator for Direct Drive (DD) WT and in [19] that evaluates a particular four-star motor for marine propulsion. For high power machine, the star number can be considered as a design parameter that should be optimized with regard to efficiency and resilience objectives. The studied structures are close to the ones evaluated in [20] where it is claimed that industrial companies are trying to develop WT generators with 2 to 6 modular 3-phase converters.

Divided into four parts, the paper aims to investigate the impact of the star number on the MCT energy yield. The starting idea is to design a MCT that must continue to operate even in case of open-circuit fault: this ability is the resilience. It is then considered that any converter fault will be ended by disconnecting the converter, the initial fault finally becoming an open-circuit fault. In the first section, from typical tidal speed record over one year, the turbine and generator adaptation issue is