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Performance Comparison of Three- and Five-Phase Permanent Magnet Generators for Marine Current Turbine Applications Under Open-Circuit Faults

Seifeddine Benelghali, Fatiha Mekri, Mohamed Benbouzid and Jean Frédéric Charpentier

***Abstract*—Multiphase generators seems to be an interesting solution for variable-speed drive applications and particularly attractive for renewable energy generation. In this context, the performance of a five-phase permanent magnet synchronous generator are evaluated within a marine current turbine and compared to a classical three-phase generator. For both topologies, a robust nonlinear control strategy, namely high-order sliding mode control, is adopted. Hence, the generators performances are analyzed, during open-circuit faults, and conclusions are derived regarding multiphase generators key features marine applications.**

***Index Terms*—Marine Current Turbine MCT), five-phase Permanent Magnet Synchronous Generator (PMSG), open-circuit fault, high-order sliding mode control.**

I. Introduction

Marine energy has become an issue of significant interest achieving a spectacular increase in the last years. It is currently the focus of much industrial and academic research around the world [1-3]. Indeed, the astronomic nature of this resource makes it predictable, to within 98% accuracy for decades, and independent of prevailing weather conditions. This predictability is critical to a successful integration of renewable energy in the electrical grid.

Nevertheless, several marine energy projects over the world are facing difficulties delaying their complete achievement. These difficulties mainly concern installations high-cost and maintenance [4].

As marine current turbines are similar in many aspects to wind turbine technologies, their theoretical and experimental studies are essentially based on wind turbine experiences. Therefore, critical aspects, as availability and reliability, are emphasized by the analysis of the collected data from wind turbine farms.

S. Benelghali is with the University of Aix-Marseille 3, UMR CNRS 6168 LSIS, Avenue Escadrille Normandie-Niemen, 13397 Marseille Cedex 20, France (email: seifeddine.benelghali@lsis.org).

F. Mekri and J.F. Charpentier are with the French Naval Academy, EA 3634 IRENav, Lanveoc-Poulmic, CC 600, 29240 Brest Cedex 9, France (e-mail: fatiha.mekri@ecole-navale.fr).

M.E.H. Benbouzid is with the University of Brest, EA 4325 LBMS, Rue de Kergoat, CS 93837, 29238 Brest Cedex 03, France (e-mail: Mohamed.Benbouzid@univ-brest.fr).

In this context, it has been shown that electrical and control system failures account for the highest percentage of failures [5]. Such failure high rate is not tolerable for MCTs due to site intervention and maintenance high-costs. Furthermore, the marine environment harsh nature requires a long term planning beforehand to investigate human intervention periods [4].

In this context, multiphase generators seem to be interesting alternative to classical three-phase generators [6]. Indeed, multiphase generators offer additional degrees of freedom that can be used for fault-tolerant operation. In fact, under fault conditions, their remaining healthy phases can be used to compensate the faults and continue the MCT operation [7-8].

This paper deals then with a detailed analysis and a comparative study of three- and five-phase PMSG within the context of a marine current turbine application in normal and faulty conditions (an open-circuit fault). First, a method is proposed for the determination of the PMSG optimal currents leading to copper losses minimization under an open-circuit mode. Then, these currents are associated to a high-order sliding mode control approach for robustness purposes.

Using a previously developed MCT simulator, the generators performances are analyzed under an open-circuit mode for the same hydrodynamic input torque and the same extracted power [3].

II. MCT Modeling Briefly [3]

A. MCT Simulator

The Matlab/Simulink®-based MCT simulator has adopted a multiphysics approach to model the whole system, including the resource, the rotor, the gearbox, and the generator (Fig. 1). This simulator can evaluate marine current turbine performances and dynamic loads over different operating conditions. Currently, it incorporates all types of horizontal-axis turbines. Due to its modularity, the five-phase PMSG has been easily incorporated and investigated.

B. Five-Phase PMSG Model

The three-phase PMSG mode is already described in [3]. A five-phase PMSG electric model in a natural base is given for the kth phase by

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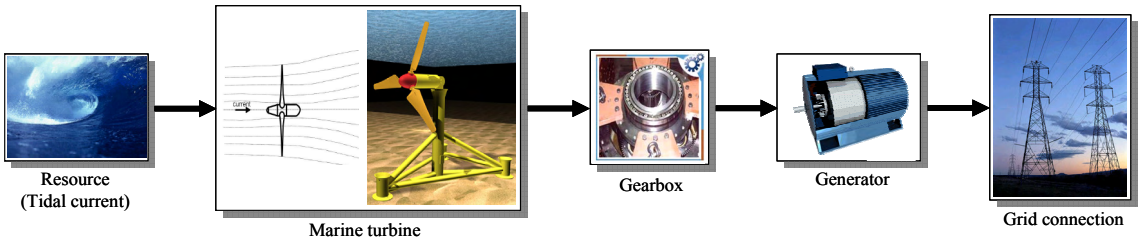

Fig. 1. Marine current turbine global scheme.

$$v_k = R_s i_k + \frac{d\phi_{sk}}{dt} + e_k \tag{1}$$

where R_s is the stator resistance, ϕ_{sk} is the stator flux, and e_k is the *emf* induced in this phase by the permanent magnets.

Assuming that the k phases are regularly shifted and there is no saturation and no saliency effects. Therefore, the following can be obtained [9-10]

$$\begin{cases} \vec{\boldsymbol{\phi}}_s = \lambda\left(\vec{\boldsymbol{i}}\right) \\ \left[L_s^n\right] = mat\left(\lambda, B^n\right) = \begin{bmatrix} L & M_1 & M_2 & M_2 & M_1 \\ M_1 & L & M_1 & M_2 & M_2 \\ M_2 & M_1 & L & M_1 & M_2 \\ M_2 & M_2 & M_1 & L & M_1 \\ M_1 & M_2 & M_2 & M_1 & L \end{bmatrix} \end{cases} \tag{2}$$

where L is the phase inductance, M_1 is the mutual inductance between two adjacent phases ($\pm 2\pi/5$ electrical shift), and M_2 is the mutual inductance between two phases shifted of $\pm 4\pi/5$.

Phase magnetic couplings make multiphase generators control more complex [6]. To achieve a simpler control, it is possible to work in a base in which the phases are magnetically decoupled. Using Concordia transform, (1) can be rewritten in this new base [11]. Hence, the three-phase generators (*z*ero sequence, ***p***rimary, and ***s***econdary) model is deduced in the [z,α,β] plane.

$$\begin{cases} \vec{\boldsymbol{v}}_z = R_s \vec{\boldsymbol{i}}_z + \Lambda_z \dfrac{d\vec{\boldsymbol{i}}_z}{dt} + \vec{\boldsymbol{e}}_z \\ \vec{\boldsymbol{v}}_{\alpha\beta-p} = R_s \vec{\boldsymbol{i}}_{\alpha\beta-p} + \Lambda_p \dfrac{d\vec{\boldsymbol{i}}_{\alpha\beta-p}}{dt} + \vec{\boldsymbol{e}}_{\alpha\beta-p} \\ \vec{\boldsymbol{v}}_{\alpha\beta-s} = R_s \vec{\boldsymbol{i}}_{\alpha\beta-s} + \Lambda_s \dfrac{d\vec{\boldsymbol{i}}_{\alpha\beta-s}}{dt} + \vec{\boldsymbol{e}}_{\alpha\beta-s} \end{cases} \tag{3}$$

As the generator is wye-coupled, the current zero sequence component is null.

It is possible to control the main and the secondary generator independently, since both of them are magnetically decoupled. Indeed, the system behaves as if there are two different generators mechanically coupled. If the main generator has p pole pairs and the secondary one has $3p$. The five-phase PMSG control is therefore achieved using the appropriate Park transform to each generator (3). This transform leads to define two *d-q* rotating frames: The first one corresponds to the first harmonics and rotates at ω, and the second one corresponds to the third harmonics and rotates at –3ω. An homopolar frame is also obtained. It corresponds to the fifth order harmonics. In this context, the stator voltage can be expressed as

$$\begin{cases} V_{dp} = R_s I_{dp} - \omega \Lambda_p I_{qp} + E_{dp} + \Lambda_p \dfrac{dI_{dp}}{dt} \\ V_{qp} = R_s I_{qp} + \omega \Lambda_p I_{dp} + E_{qp} + \Lambda_p \dfrac{dI_{qp}}{dt} \\ V_{ds} = R_s I_{ds} - 3\omega \Lambda_s I_{qs} + E_{ds} + \Lambda_s \dfrac{dI_{ds}}{dt} \\ V_{qs} = R_s I_{qs} + 3\omega \Lambda_s I_{ds} + E_{qs} + \Lambda_s \dfrac{dI_{qs}}{dt} \end{cases} \tag{4}$$

where $$\begin{cases} \Lambda_p = L - 2\left[M_1 \cos\left(\dfrac{2\pi}{5}\right) + M_2 \cos\left(\dfrac{\pi}{5}\right)\right] \\ \Lambda_s = L - 2\left[M_1 \cos\left(\dfrac{\pi}{5}\right) + M_2 \cos\left(\dfrac{3\pi}{5}\right)\right] \end{cases} \tag{5}$$

The five-phase PMSG electromagnetic torque is given by

$$T_{em} = \frac{\vec{\boldsymbol{e}}\vec{\boldsymbol{i}}}{\Omega} = \frac{\vec{\boldsymbol{e}}_p \vec{\boldsymbol{i}}_p + \vec{\boldsymbol{e}}_s \vec{\boldsymbol{i}}_s}{\Omega} \tag{6}$$

and its dynamics by

$$T_{em} = J\frac{d\Omega}{dt} + f\Omega = T_{em_p} + T_{em_s} \tag{7}$$

where Ω is the generator speed, J the inertia, and f the viscous friction coefficient

III. PMSG-Based MCT Control

A. Problem Formulation

High-order sliding mode has been adopted for the control of the PMSG-based marine current turbine. This robust control approach has been chosen mainly due to the tidal

resource characteristics such as turbulence and swell effects and the inevitable uncertainties inherent in PMSG-based marine current turbines [3]. Indeed, although many modern techniques can be used for this purpose, sliding mode control has proved to be especially appropriate for nonlinear systems, presenting robust features with respect to system parameter uncertainties and external disturbances [12-13].

Figure 2 illustrates the proposed PMSG-based MCT control scheme.

B. Reference Current

In normal operation, minimizing copper losses for a constant given torque T_{max} leads to express the optimal reference current of each phase as [9], [14-15]

$$\vec{i}_{ref} = A\frac{\vec{e}}{\Omega} \quad \text{with } A = \frac{T_{\max}}{\left\|\frac{\vec{e}}{\Omega}\right\|^2} \tag{8}$$

If an open-circuit fault occurs, torque ripples appear if the above classical control remains adopted. Indeed, torque ripples are due to interactions between the currents nonsymmetrical system with the *emf* symmetrical system. To avoid these ripples an adaptive control method is proposed to determine current references.

To ensure the multiphase generator operation continuity with minimum copper losses when an open-phase fault occurs, an adaptive control strategy has been previously proposed in [14]. In this method the faulty phases are firstly detected. Then a new system is considered. This new system only comprises the healthy phases. For example, in case of one or two faulty phases the new *emf* vector for each healthy phase (here the first phase) is given by

$$e_1' = e_1 - \frac{1}{q'}\sum_{k=1}^{q} h_k e_k \tag{9}$$

where q' is the active phase number and $h_k = 1$ for an active phase and $h_k = 0$ for a faulty one.

Therefore (8) is rewritten as follows

$$\vec{i}_{ref} = A'\frac{\vec{e}'}{\Omega} \quad \text{with } A = \frac{T_{\max}}{\left\|\frac{\vec{e}'}{\Omega}\right\|^2} \tag{10}$$

This strategy remains valid in normal and faulty operations to achieve a constant and filtered torque at minimum copper losses.

C. High-Order Sliding Mode Control

The PMSG-based MCT proposed control strategy has been previously applied and tested in [3].

It is based on a step-by-step procedure:

1) First, the speed reference ω_{ref} is generated by a Maximum Power Point Tracking (MPPT) strategy.

2) Then, an optimal electromagnetic torque, which ensures the rotor speed convergence to ω_{ref} is computed using the following equation.

$$T_{em_ref} = T_m + f\omega - \alpha(\omega - \omega_{ref}) + J\dot{\omega}_{ref} \tag{11}$$

Where α is a positive constant. Afterwards, current references are derived to ensure the PMSG torque convergence to the optimal one and to minimize the error between the current and its reference Let us define the following sliding surfaces for the first *d-q* frames (A similar approach is done for the second *d-q* frame).

$$\begin{cases} S_{1p} = I_{dp} - I_{dp_ref} \\ S_{2p} = I_{qp} - I_{qp_ref} \end{cases} \tag{12}$$

It follows that $\begin{cases} \dot{S}_{1p} = \dot{I}_{dp} - \dot{I}_{dp_ref} \\ \ddot{S}_{1p} = \varphi_1(t,x) + \gamma_1(t,x)\dot{V}_{dp} \end{cases}$ (13)

and $\begin{cases} \dot{S}_{2p} = \dot{I}_{qp} - \dot{I}_{qp_ref} \\ \ddot{S}_{2p} = \varphi_{2p}(t,x) + \gamma_2(t,x)\dot{V}_{qp} \end{cases}$ (14)

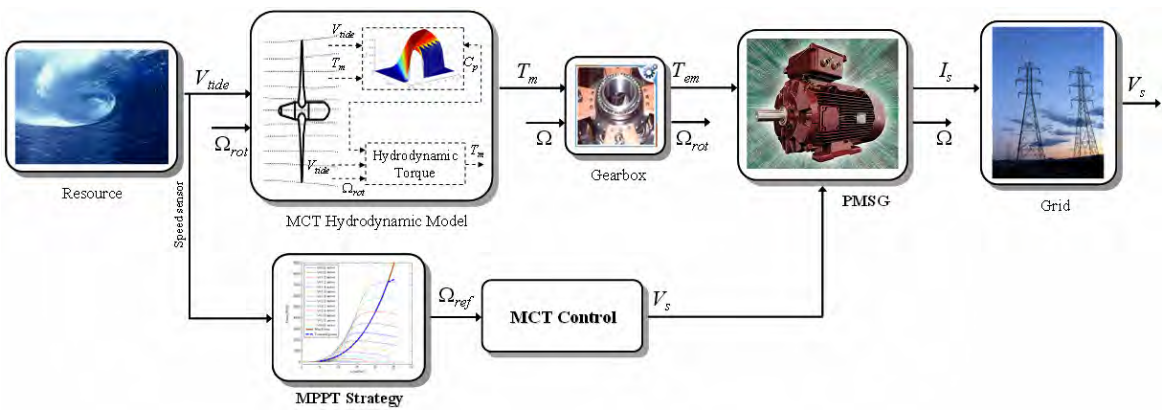

Fig. 2. The proposed PMSG-based MCT control scheme.

Where $\varphi_1(t,x)$, $\varphi_2(t,x)$, $\gamma_1(t,x)$, and $\gamma_2(t,x)$ are uncertain bounded functions that satisfy

$$\begin{cases} \varphi_1 > 0, \quad |\varphi_1| > \Phi_1, \quad 0 < \Gamma_{m1} < \gamma_1 < \Gamma_{M1} \\ \varphi_2 > 0, \quad |\varphi_2| > \Phi_2, \quad 0 < \Gamma_{m2} < \gamma_2 < \Gamma_{M2} \end{cases}$$

The proposed high-order sliding mode control, which is in fact a second-order one, has been designed using the super twisting algorithm. The controller contains two parts:

$$\begin{cases} V_{dp} = u_1 + u_2 \\ V_{qp} = w_1 + w_2 \end{cases} \tag{15}$$

where $\begin{cases} \dot{u}_1 = -\alpha_1 sign(S_1) \\ u_2 = -\beta_1 |S_1|^{\rho} sign(S_1) \end{cases}$ and $\begin{cases} \dot{w}_1 = -\alpha_2 sign(S_2) \\ w_2 = -\beta_2 |S_2|^{\rho} sign(S_2) \end{cases}$

To ensure the sliding manifolds convergence to zero in finite time, the gains can be chosen as follows [13].

$$\begin{cases} \alpha_i > \dfrac{\Phi_i}{\Gamma_{mi}} \\ \beta_i^{\,2} \geq \dfrac{4\Phi_i}{\Gamma_{mi}^{\,2}} \dfrac{\Gamma_{Mi}(\alpha_i + \Phi_i)}{\Gamma_{mi}(\alpha_i - \Phi_i)}; \quad i = 1,2 \\ 0 < \rho \leq 0.5 \end{cases}$$

IV. Comparative Study using the MCT Simulator

The three- and five-phase PMSG comparative study has have been carried-out using the above cited MCT simulator. In this case, simulations are based on 2-kW PMSG-based MCT with a constant tidal resource for comparison simplification in contrary to [7]. Moreover, generator comparisons were made for the same torque and the same generated power.

The control strategy, for the five-phase PMSG, is based on the second-order sliding mode simultaneous control of the main and secondary generators in the two *d-q* frame as above presented.

A. Healthy Condition Operation

The three- and five-phase PMSG-based MCT control performances in healthy conditions are shown in Figs. 3 to 7, respectively illustrating the rotor speed, the generated power, the mechanical torque, and the PMSG currents. These simulation results lead to the following main conclusions:

- The five-phase PMSG-based MCT generated power is very smooth (Fig. 4).
- The peak-to-peak torque ripples are significantly reduced in the five-phase PMSG (Fig. 5).

It is therefore obvious that a multiphase generator is more appropriate for MCTs normal operation than a classical three-phase generator.

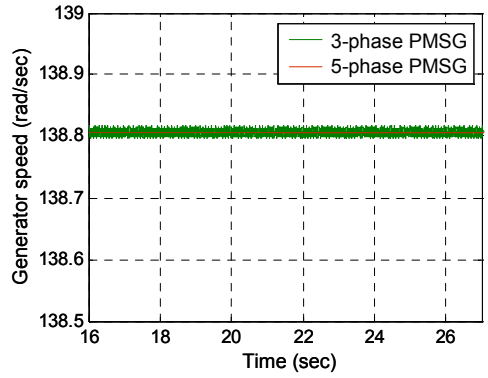

Fig. 3. Marine current turbine generator speed under normal conditions.

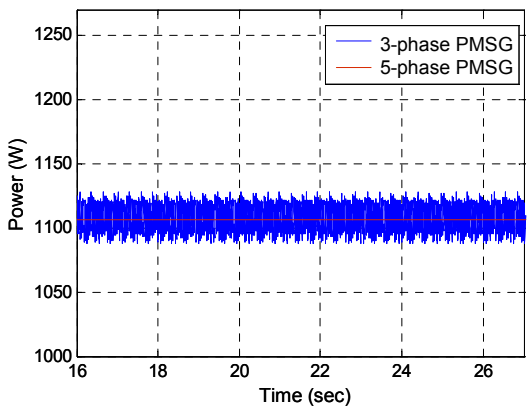

Fig. 4. Marine current turbine power under normal conditions.

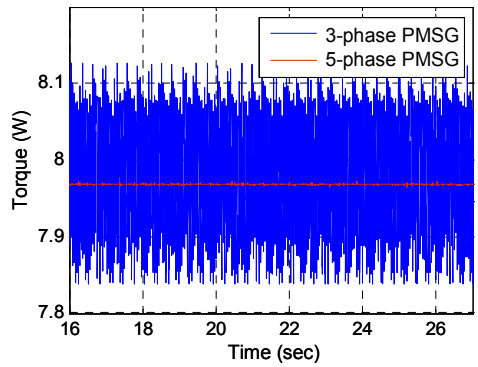

Fig. 5. Marine current turbine mechanical torque under normal conditions.

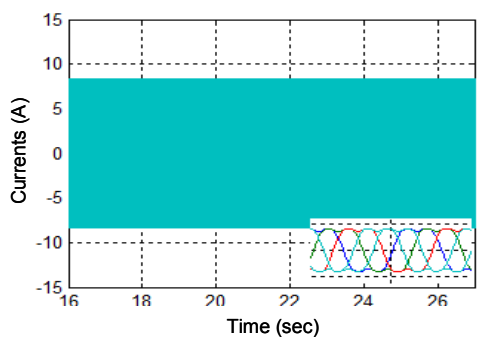

Fig. 6. Five-phase PMGS currents under normal conditions.

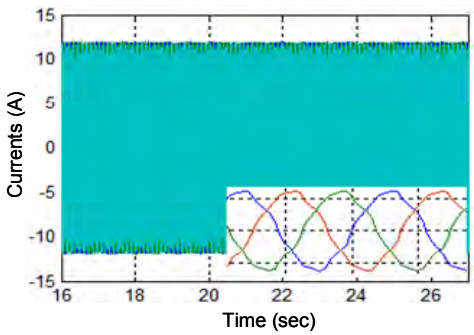

Fig. 7. Three-phase PMSG under normal conditions.

B. Operation under Open-Circuit Fault Conditions

The two generators performances are now evaluated under an open-circuit in the first phase. In this case, a reference current is now on-line determined under faulty conditions to achieve a constant and smooth torque, equals to the one under normal conditions, and leading to minimum copper losses.

Simulation results are shown in Figs. 8 to 11, the generated power, the mechanical torque, and the PMSG currents. These simulation results lead to the following main conclusions:

– The five-phase PMSG-based MCT generated power is still quiet smooth even in faulty conditions (Fig. 8).

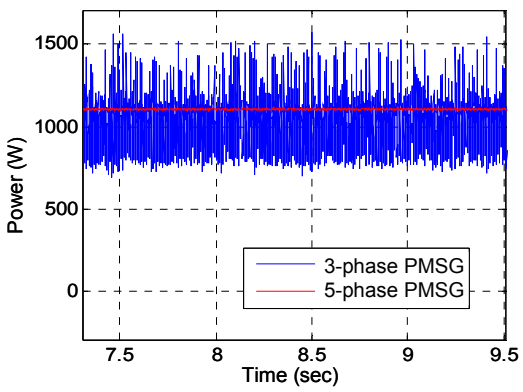

Fig. 8. Marine current turbine power under open-circuit fault conditions.

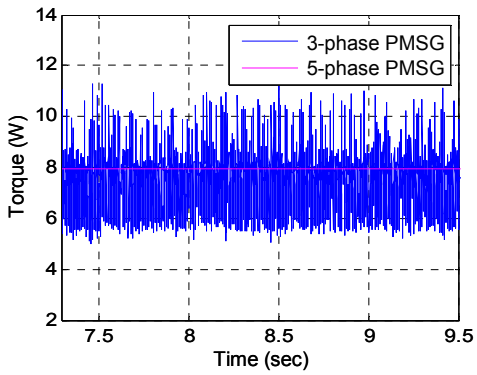

Fig. 9. Marine current turbine torque under open-circuit fault conditions.

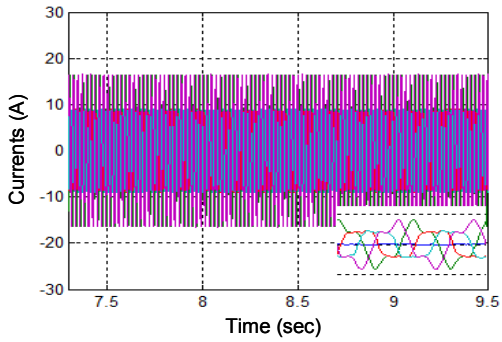

Fig. 10. Five-phase PMGS currents under open-circuit fault conditions.

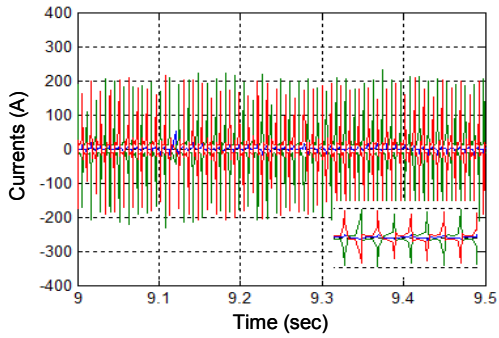

Fig. 11. Three-phase PMGS currents under open-circuit fault conditions.

– The torque ripples are significantly reduced in the five-phase PMSG thanks to the proposed procedures (Fig. 9) [15]. Indeed, the torque remains quiet smooth. Therefore, no extra stresses are induced in the MCT torque.

– The three-phase PMSG currents increase is quiet huge compared to the five-phase one.

The analysis of the above performances under faulty conditions confirms the fact that a multiphase generator is clearly a candidate of choice for a marine current turbine.

V. Conclusion

This paper dealt with a comparative study of three- and five-phase PMSG within the context of a marine current turbine application in normal and faulty conditions. The PMSG control strategy was based on a high-order sliding mode approach using a super twisting algorithm. In faulty conditions, a reference current is on-line determined to achieve a constant and smooth torque, equals to the one under normal conditions, and leading to minimum copper losses.

The obtained results clearly show that, even in normal operation, a multiphase generator is clearly a candidate of choice for marine current turbine applications, in comparison to a classical three-phase generator.

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