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A Fault-Tolerant Multiphase Permanent Magnet Generator for Marine Current Turbine Applications

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

Abstract—**Tidal currents are being recognized as a resource for sustainable electrical power generation. However, the main challenge for marine current energy development is to minimize the operation costs and maintenance operations in the marine harsh environment. These worries are justified by the incident high rates on offshore wind turbine systems. Marine current turbines are characterized by a very difficult access for regular or emergency maintenance operations. This is why the development of fault tolerant system is a key feature. This paper deals with the use of a PM multiphase marine current turbine generator. With this kind of system, it is possible to maintain the power production even if an electrical fault appears in the power converter. This system is associated with an optimal strategy of torque/speed control using a high-order sliding mode control which is particularly adapted to the healthy or faulty operation mode.**

Index Terms—**Marine Current Turbine (MCT), Permanent Magnet Synchronous Generator (PMSG), multiphase generator, modeling, fault-tolerance, high-order sliding mode.**

I. INTRODUCTION

Nowadays, the attraction of tidal currents for renewable energy developers is obvious. Seawater is more than 800 times denser than air. So, typical marine current turbine (MCT) are more compact than wind turbines, for the same rated power. Moreover, the astronomic nature of the tidal phenomenon results essentially in predictable resource. As a renewable resource, tidal current flow is very predictable, to within 98% accuracy for decades. Tidal current is mainly independent of prevailing weather conditions such as fog, rain, and clouds that can impact other renewable generation forecasts. This predictability is critical to successful integration of renewable resources into the electrical grid. Therefore, the marine renewable sector is currently the focus of industrial and academic research around the world [1]. Nevertheless, many difficulties have met the complete successful achievement of several projects over the world, especially in what concerns the installations high-cost and their maintenance operations [2].

In a first approach, marine current turbine is not always considered as a new technology, because it seems similar in many aspects to wind turbines, which are already well developed and commercialized. For that reason, marine current turbine theoretical and experimental studies are mainly based on wind turbines experiences. Therefore, worries about the availability and reliability of marine current system are emphasized by the analysis of the collected data from wind turbine farms. Many studies show that electrical and control system failures account for the highest percentage of failures. For the year 2000, failures of electrical and controls systems accounted for around 50% of the need for wind turbine repairs [3]. This failure high rate is not tolerable for MCTs due to site intervention and maintenance high-costs.

For that reasons, the use of a multiphase system seems to be an interesting candidate for marine current energy generation. Indeed, multiphase generators present many advantages over traditional three-phase generators. These advantages are higher torque density, higher reliability, smoother torque and possibilities of minimizing the constraints on the converter switches by dividing power. However, the drives high phase order are currently limited to specialized applications where these advantages are a key feature such as aerospace, automotive, and ship propulsion applications [4-6].

This paper deals then with robustness and efficiency evaluation of marine current turbines based on a multiphase generator. The generator performances are evaluated using an MCT simulator environment which has been developed in previous works [7]. In this paper, an optimal control strategy for healthy and open-circuit fault operation mode is proposed and associated with a high order sliding mode control. The proposed topology and the associated control strategy advantages are highlighted and discussed regarding an open-circuit fault conditions for a 5-phase permanent magnet synchronous generator.

II. MARINE CURRENT TURBINE MODELING

The global scheme for a grid-connected marine current turbine is given by Fig. 1.

A. Marine Current Turbine Simulator

In previous works, a Matlab/Simulink®-based simulation tool for marine current turbines has been proposed [7-8].

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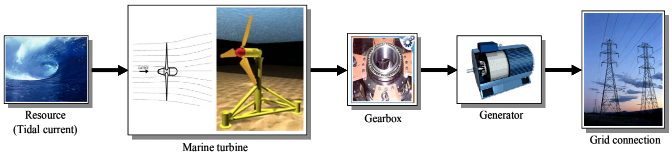

Fig. 1. Marine current turbine global scheme.

A multiphysics approach has been adopted to model the whole system, including the resource, the turbine rotor blades, the gearbox, and the generator. The developed tool can evaluate marine current turbine performances and dynamic loads over different operating conditions. Moreover, it should be used to quantify the potential for generating electricity from various sites and various technology choices and therefore evaluate their cost-effectiveness. Currently, the marine current turbine simulator incorporates several types of turbines models. The various components of the simulator (marine current resource, turbine hydrodynamics, generator, and converter models) have been tested and experimentally validated in terms of models and speed control performances [7-8]. Due to its modularity, numerous improvements can be considered. In this work, the generator and converter blocks are replaced by a 5-phase permanent magnet generator to evaluate its performances in such application.

B. The Generator Electric Model

A 5-phase PMSG electric model in a natural base is given for the k^{th} phase by:

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

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.

The following assumptions are assumed: the k phases are regularly shifted and there is no saturation and no saliency effects. Therefore, the following relations can be obtained [9].

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

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 $\pm 4\pi/5$.

Magnetic coupling between phases make multiphase generators control complex [5]. The model (1) is interesting in terms of simulation. However, the analytical expression of dynamic regimes is difficult to formulate. To simplify the dynamic control, it is possible to work in a base in which the phases are magnetically decoupled. Using a generalization of the Concordia transform, (1) can be rewritten in this new base [10]. Hence, (1) can be decomposed in three independent 2D and 1D subsystems which can be assimilated to three 2-phase and one-phase machines. These three machines are respectively called ***z***ero sequence machine (1D space, (z)), ***p***rimary, and ***s***econdary machines (PrM, SdM) These two machines are associated with two 2D planes: (α_p,β_p) and (α_s,β_s).

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

where $\Lambda(z,p,s)$ and $e(z,p,s)$ are respectively the inductance and the emf for zero sequence, primary and secondary machines.

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

As the generator is wye-coupled, the current zero sequence component is null. So the generator electromagnetic torque is given by:

$$\begin{cases} T_{em} = \dfrac{\vec{e}\,\vec{i}}{\Omega} = \dfrac{\vec{e}_z \vec{i}_z + \vec{e}_p \vec{i}_p + \vec{e}_s \vec{i}_s}{\Omega} \\ T_{em} = \dfrac{\vec{e}_p \vec{i}_p + \vec{e}_s \vec{i}_s}{\Omega} \\ T_{em} = T_p + T_s \end{cases} \tag{4}$$

where T_p, T_s, Ω are respectively: the torque of main machine, the torque of secondary one and the generator speed.

It is possible to control the main and the secondary machines independently, since both of them are magnetically decoupled, the system behaves as if there are two independent machines mechanically coupled. Each of these two 2D machines is characterized by a particular harmonic family. PrM harmonic family contains the 1^{st}, 9^{th} and 11^{th} harmonics and SdM family contains the 3^{rd}, 7^{th} and 13^{th} ones [5], [17]. We can then consider that the main machine has p pairs of poles and the secondary machine has 3p pairs of poles. The 5-phase PMSG control is therefore achieved using two appropriate Park transform for each machine (main and secondary) (3). This transform leads to define two *d-q* rotating frames: The first frame is associated with the first harmonics and rotates at ω, and the second one, with the third harmonics and rotates at -3ω:

$$\begin{cases} v_{dp} = R_s I_{dp} - \omega \Lambda_p I_{qp} + E_{dp} + \Lambda_p \dfrac{dI_{dp}}{dt} \\ v_{qp} = R_s I_{qp} + \omega \Lambda_p I_{dp} + E_{qp} + \Lambda_p \dfrac{dI_{qp}}{dt} \\ v_{ds} = R_s I_{ds} - 3\omega \Lambda_s I_{qs} + E_{ds} + \Lambda_s \dfrac{dI_{ds}}{dt} \\ v_{qs} = R_s I_{qs} + 3\omega \Lambda_s I_{ds} + E_{qs} + \Lambda_s \dfrac{dI_{qs}}{dt} \end{cases} \tag{5}$$

In this two *d-q* frames, currents and voltage values remains constant in steady state which leads to an easier control.

The above set of equations (4) and (5) allows then to model the 5-phase PMSG electromechanical behavior.

III. CONTROL OF THE 5-PHASE PMSG-BASED MARINE CURRENT TURBINE

A. Control Principle

A variable speed control based on the MPPT strategy has been applied for the marine current turbine control. This strategy aims generally at regulating the power harvested from the tidal currents by modifying the electrical generator speed; in particular, the MPPT strategy leads to capture the maximum power available from the tidal current in the actuator disk. For each given tidal current speed, there is a corresponding rotational speed at which the power curve of a given MCT is maximum (C_p reaches its maximum value). In such a control MPPT speed control of the system an external speed loop is associated to an internal torque control loop (current control). In the next paragraph this torque control loop is detailed.

B. Reference Currents

In normal operation, minimizing Joules losses for a constant given torque T_{max} leads to express the optimal reference current of each phase as [16].

$$\vec{i}_{ref} = A \frac{\vec{e}}{\Omega} \quad \text{with } A = \frac{T_{\max}}{\left\| \dfrac{\vec{e}}{\Omega} \right\|^2} \tag{6}$$

To ensure the multiphase generator operation continuity with minimum copper losses when an open phase fault occurs, a new adaptive control strategy has been proposed in [16-17]. In this method the faulty phases are firstly detected. Then a new system is considered. The new system only comprises the healthy phases. For example, in case of one or two faulty phases the new *emf* vector ($\vec{e}'$) for each healthy phase (here the first phase) is given by:

$$e_1' = e_1 - \frac{1}{q'} \sum_{k=1}^{q} h_k e_k \tag{7}$$

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

Therefore (6) is rewritten as follows:

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

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

A common practice in addressing PMSG control problem is to use a classical linear control approach [11]. However, in fault mode, the current references have a high dynamic behavior in the natural frame and even in the rotating *d-q* frames. Linear controller based on the association of the generalized park transform presented previously and the use of PI or PID can not provide a correct tracking of these current references [17]. Moreover MCT are characterized by inevitable uncertainties such as turbulence and swell effects. Hence nonlinear and robust control is needed to take into account these control problems. 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 [12]. So in the case of a fault tolerant MCT linear control methods come at the price of poor system performance and low reliability.

Sliding mode control copes with system uncertainty keeping a properly chosen constraint by means of high-frequency control switching. Featuring robustness and high accuracy, the standard (first-order) sliding mode usage is restricted due to the chattering. High-order sliding mode approach suggests treating the chattering effect using a time derivative of control as a new control, thus integrating the switching [13]. Up to now, a few second-order sliding mode control approaches have been introduced for wind and marine applications [7], [14-15].

Therefore, high-order sliding mode has been adopted for the control of a 5-phase PMSG-based marine current turbine. Figure 2 illustrates the proposed control scheme.

C. Second-Order Sliding Mode Control [7]

As the chattering phenomenon is the major drawback of practical implementation of sliding mode control, the most efficient ways to cope with this problem is higher order sliding mode. This technique generalizes the basic sliding mode idea by acting on the higher order time derivatives of the sliding manifold, instead of influencing the first time derivative as it is the case in the standard (first order) sliding mode. This operational feature allows mitigating the chattering effect, keeping the main properties of the original approach.

The proposed control strategy 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.

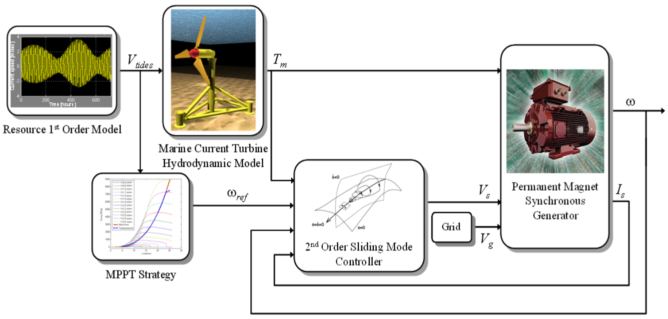

Fig. 2. The proposed control scheme.

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

$$T_{em\_ref} = T_m + f\Omega - \alpha(\Omega - \Omega_{ref}) + J\dot{\Omega}_{ref} \tag{9}$$

Where α is a positive constant. Afterwards, current references are derived to ensure the 5-phase 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 main machine in *d-q* frames (A similar approach is done for the secondary machine in *d-q* frame).

$$\begin{cases} S_{1p} = I_{dp} - I_{dp\_ref} \\ S_{2p} = I_{qp} - I_{qp\_ref} \end{cases} \tag{10}$$

It follows that
$$\begin{cases} \dot{S}_{1p} = \dot{I}_{dp} - \dot{I}_{dp\_ref} \\ \ddot{S}_{1p} = \varphi_1(t,x) + \gamma_1(t,x)V_{dp} \end{cases} \tag{11}$$

and
$$\begin{cases} \dot{S}_{2p} = \dot{I}_{qp} - \dot{I}_{qp\_ref} \\ \ddot{S}_{2p} = \varphi_2(t,x) + \gamma_2(t,x)V_{qp} \end{cases} \tag{12}$$

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

$$\begin{cases} \varphi_1 > 0, \quad |\varphi_1| > \Phi_1, \quad 0 < \Gamma_{m1} < \gamma_1 < \Gamma_{M1} \\ \varphi_2 > 0, \quad |\varphi_2| > \Phi_2, \quad 0 < \Gamma_{m2} < \gamma_2 < \Gamma_{M2} \end{cases} \tag{13}$$

The main problem with high-sliding mode algorithm implementations is the increased required information. Indeed, the implementation of an nth-order controller requires the knowledge of $\dot{S}$, $\ddot{S}$, $\dddot{S}$, …, $S^{(n-1)}$. The exception is the super twisting algorithm, which only needs information about the sliding surface *S*. Therefore, the proposed control approach has been designed using this algorithm. The proposed second-order sliding mode controller contains two parts:

$$\begin{cases} V_{dm} = u_1 + u_2 \\ V_{qm} = w_1 + w_2 \end{cases} \tag{14}$$

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

In order to ensure the convergence of the sliding manifolds to zero in finite time, the gains can be chosen as follows [14].

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

IV. SIMULATION RESULTS USING THE MCT SIMULATOR

Simulations of the whole system in healthy and fault operation modes are presented to evaluate the fault-tolerant capabilities of a 5-phase PMSG-based MCT using the presented control approach. In this case, simulations are based on a PMSG-based MCT with a typical tidal resource cycle. Simulation scale has been reduced from two tidal cycles (approximately 24 hours) to 100 seconds for simulation time reason. The control strategy under healthy and faulty conditions is based on the control of the two fictitious generators in the above presented two *d-q* frames. It consists in the combination of three strategies: an MPPT, an adaptive current generation, and high-order sliding modes.

A. Normal Condition Operation

The 5-phase PMSG-based MCT control performances in healthy conditions are shown in Figs. 3 to 8 respectively illustrating the rotor speed, the generated power, the mechanical torque and the currents.

The obtained results show good tracking performances of the 5-phase PMSG rotor speed and currents and clearly illustrate the effectiveness of the proposed control strategy in healthy conditions.

B. Operation under Open Circuit Fault Conditions

The fault-tolerant capabilities are now evaluated under open circuit fault conditions. Simulation results are given in Figs. 9 to 14 respectively illustrating the rotor speed, the generated power, the mechanical torque and the currents when one phase of generator is open (1st phase).

In this case good tracking performances are achieved in terms of speed and currents which prove that the proposed second-order sliding mode control approach is really efficient for fault-tolerant operations. Indeed in this faulty mode, the 5-phase PMSG-based MCT generated power and EM torque remains smooth as in the healthy mode (Fig. 10). Moreover, no mechanical extra stresses are induced in the MCT (Fig. 11) However, it has been noticed an increase of the current of the 5-phase PMSG from 1 to 1.5 pu compared to the healthy mode.

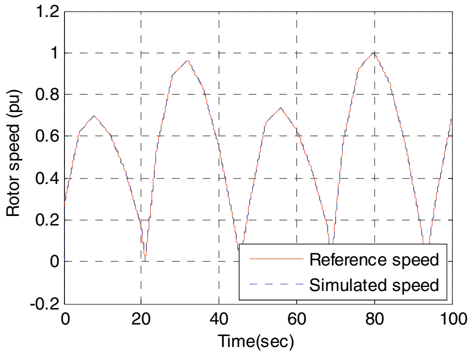

Fig. 3. 5-Phase PMSG speed and its reference in healthy mode.

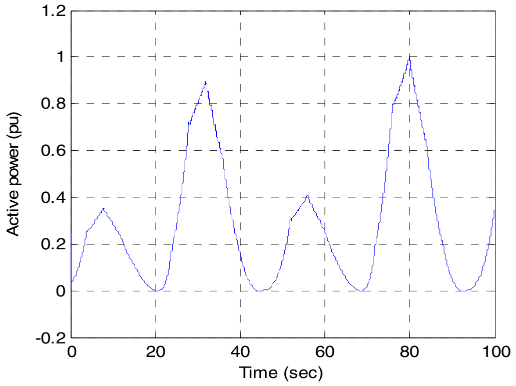

Fig. 4. MCT generated active power in healthy mode.

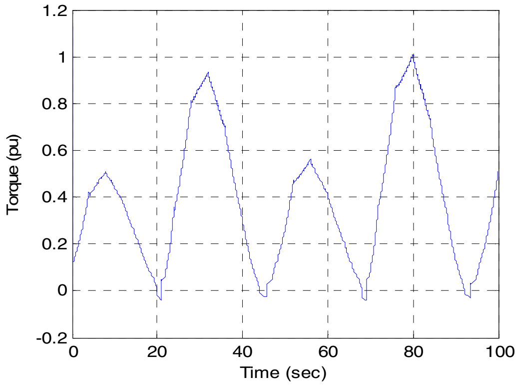

Fig. 5. MCT mechanical torque in healthy mode.

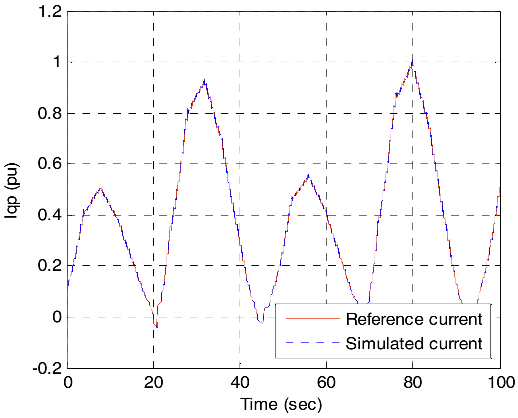

Fig. 6. Primary virtual generator I_{qp} current in healthy mode.

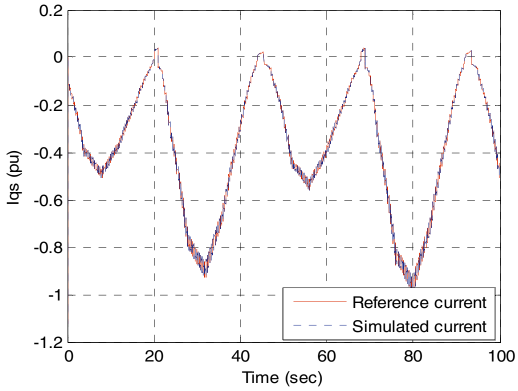

Fig. 7. Secondary virtual generator I_{qs} current in healthy mode.

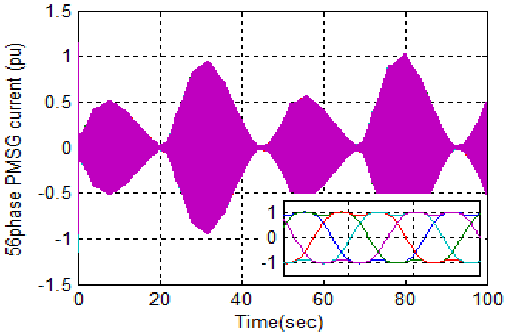

Fig. 8. 5-Phase PMSG current in healthy mode.

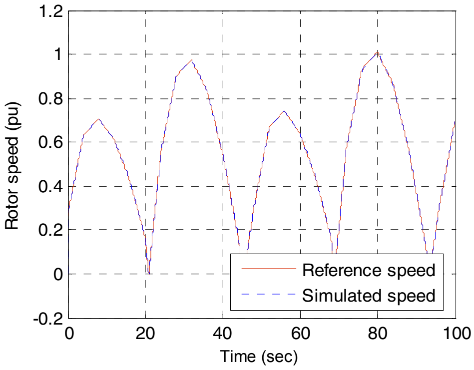

Fig. 9. 5-Phase PMSG speed and its reference in faulty mode.

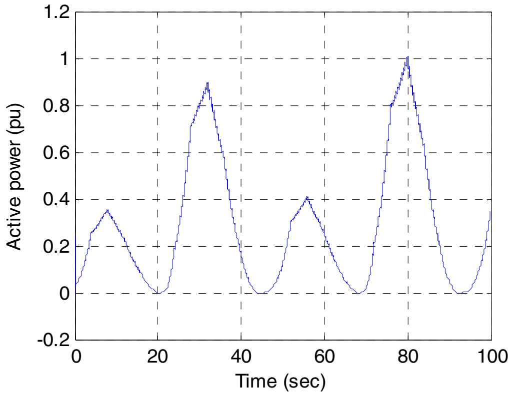

Fig. 10. MCT generated active power in faulty mode.

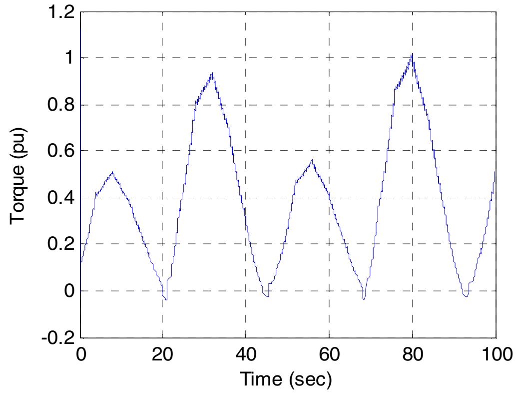

Fig. 11. MCT mechanical torque in faulty mode.

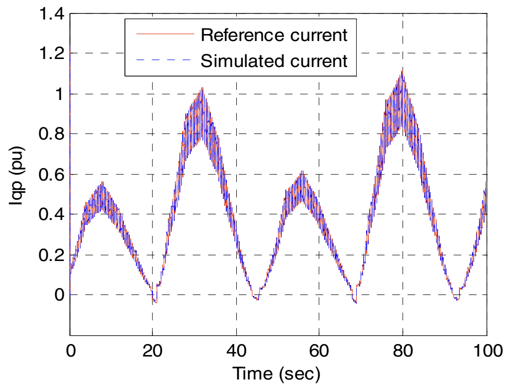

Fig.12. Primary virtual generator I_{qp} current in faulty mode.

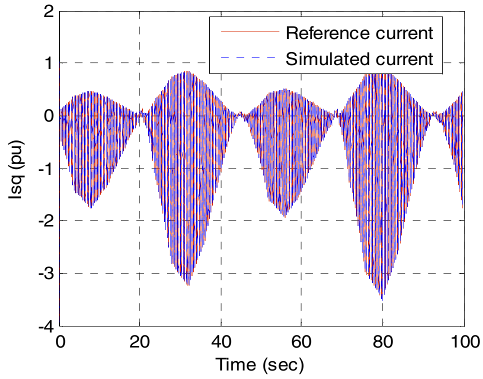

Fig.13. Secondary virtual generator I_{qs} current in faulty mode.

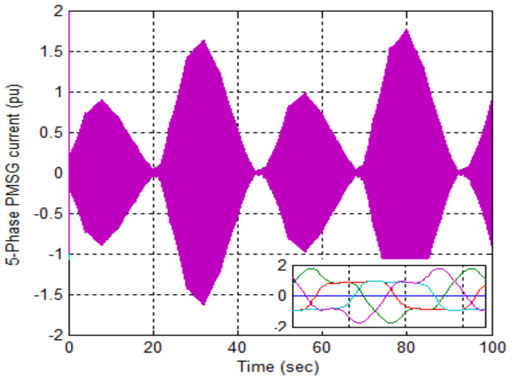

Fig.14. 5-Phase PMSG current in faulty mode.

V. CONCLUSION

This paper dealt with the evaluation of the fault-tolerance capabilities of marine current turbine using a multiphase generator. The proposed 5-phase PMSG-based MCT associated with an adaptive control approach that combines three strategies: an MPPT, an optimal fault-adaptive current reference generation and high-order sliding modes. This approach has been successfully tested using an MCT simulator in healthy and faulty conditions. The obtained results clearly show that the proposed topology is effective for achieving electrical fault-tolerant operation in an MCT. This will obviously increase the system reliability.

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