Marine Current Turbine System Post-Fault Behavior under an Open Circuit Fault

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Abstract. *This paper describes the modeling and simulation of a Permanent Magnet Synchronous Generator (PMSG) based Marine Current Turbine (MCT) under converter faulty conditions. The modeling of the generator is represented in the d-q reference frame. The Proportional Integral (PI) controllers are used for the direct current, the quadratic current, and the speed Control. The faulty mode describes an open-circuit fault in the generator-side converter. Simulations results show that the dynamic performances and the power generation of the MCT are highly degraded due to the fault.*

Keywords

Generator-side converter, marine current turbine, MPPT, open-circuit fault, permanent magnet synchronous generator, PI control.

1. Introduction

Nowadays, new renewable resources are developed such as wave energy, thermal energy, and marine tidal energy. In fact, the production of electric power from marine tidal energy is interesting; 48 % is in the UK, 8 % in Ireland, and 42 % in France [1].

However, marine current turbine systems are exposed to ecological constraints because of the severe weather conditions (immersed systems). Due to these constraints, the performance of the MCT system can be degraded [2] and [3]. That leads to several faults, which can be related to the PMSG, to the blades, and to the converters [4] and [5]. Indeed, industrial surveys have shown that 70 % of converter faults are related to the switches.

This paper describes the modeling of the MCT system under switchs fault conditions (open circuit fault). The control of the MCT system is achieved by using the Maximum Power Point Tracking (MPPT) to extract the optimal power and the PI controllers are designed to control the dq-axis currents and the speed.

This paper is composed as follows: in Sec. 2. , the MCT system modeling is given. In Sec. 3. , MCT system control is developed. In Sec. 4. , post-fault behavior of the generator-side converter and performance evaluation are analyzed. Section 5. gives the conclusion.

2. Marine Current Turbine Modeling

Figure 1 represents the MCT basic structure. It contains the turbine, the PMSG, the three-phase converter and the DC-bus.

2.1. Resource Description

The gravitational interaction of Moon, Earth, and Sun creates the marine currents [6]. Marine currents are resulted about 32 % from the Sun and 68 % from the Moon.

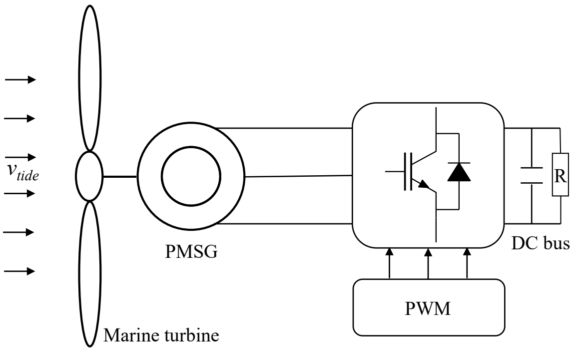


Fig. 1: Marine current turbine basic structure.

In fact, this interaction makes the ocean swell on different places. This fact makes an increase of the altitude of the water in the aligned places with the moon and a decrease in the level of the water between those two places. A horizontal movement is resulted from the increase in water level; this movement is called tidal current.

2.2. Marine Turbine Model

A marine turbine mechanical power is given by Eq. (1) [7].

$$P_m = \frac{1}{2} C_p(\lambda, \beta) \rho \pi r^2 v_t^3, \tag{1}$$

where ρ is the fluid density in (kg·m^{-3}), r is the turbine radius in (m), v_t is the tidal velocity in (m·s^{-1}), C_p represents the rate of mechanical power extracted by the turbine from the fluid, λ is the tip speed ratio, and β is the blade pitch angle in (°). For typical MCTs and under normal operation, the maximum value of C_p is in the range of 0.35–0.5. In fact, for a given turbine, the power coefficient is represented using λ (Eq. (2)) and β [8].

$$\lambda = \frac{r\Omega}{v_t}, \tag{2}$$

where Ω is the mechanical turbine speed in (rpm).

2.3. Generator Model

The PMSG was chosen for the system [9] thanks to its high efficiency, its compactness, and the possibility to remove gearbox in case of a direct-drive system. This reduces maintenance and makes the PMSG as a candidate of choice for immersed systems. The modeling of PMSG in the d-q reference is given by Eq. (3) as follows:

$$\begin{cases} \dfrac{\mathrm{d}i_{sd}}{\mathrm{d}t} = \dfrac{v_{sd}}{L_s} - \dfrac{R_s}{L_s} i_{sd} + p\Omega i_{sq}, \\ \dfrac{\mathrm{d}i_{sq}}{\mathrm{d}t} = \dfrac{v_{sq}}{L_s} - \dfrac{R_s}{L_s} i_{sq} - p\Omega i_{sd} - p\dfrac{\Phi_a}{L_s}, \\ T_{em} = \dfrac{3}{2} p \Phi_a i_{sq}, \\ J_t \dfrac{\mathrm{d}\Omega}{\mathrm{d}t} = T_m - T_{em} - f\Omega, \end{cases} \tag{3}$$

where J_t is the total inertia in (kg·m^{-2}), T_m is the mechanical torque in (N·m), T_{em} is the electromagnetic torque in (N·m), f is the viscosity coefficient in (N·m·s^{-1}) tidal velocity in (m·s^{-1}), v_{sd} and v_{sq} are the $d-q$ components of the stator voltages respectively in (V), i_{sd} and i_{sq} are the $d-q$ components of the stator currents respectively in (A), R_s is the phase resistance of the stator winding in (Ω), L_s is the stator cyclic inductance in (H), Φ_a is the permanent magnet flux in (Wb) and p is the pole pair number.

2.4. Converter Model

The generator-side converter contains three legs (Fig. 2). Every leg is composed by two switches (T_k, T_k+3, $k=1$, 2, 3) and two freewheeling diodes (D_k, D_k+3) called IGBT. These IGBTs are controlled by a block of a PWM using gate signals S_k ($k = 1, 2, 3$) [10]. The kth gate signal denoted S_k switch is defined by Eq. (4) as follows:

$$S_k = \begin{cases} 1 & \text{if} \quad T_k \quad \text{on} \quad \text{and} \quad T_{k+3} \quad \text{off}, \\ 0 & \text{if} \quad T_{k+3} \quad \text{on} \quad \text{and} \quad T_k \quad \text{off}. \end{cases} \tag{4}$$

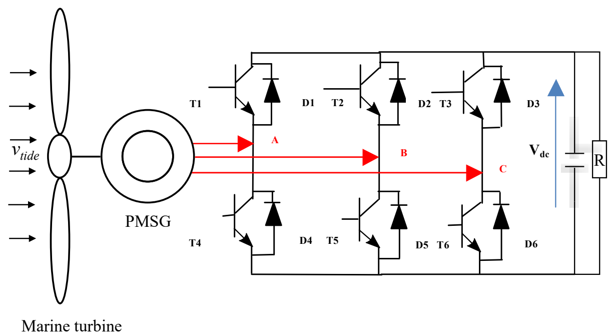


Fig. 2: Generator-side converter topology.

3. Marine Current Turbine Control

The marine current turbine control system is based on a PI controller, which is used in conventional field-oriented control technique. It is illustrated by Fig. 3.

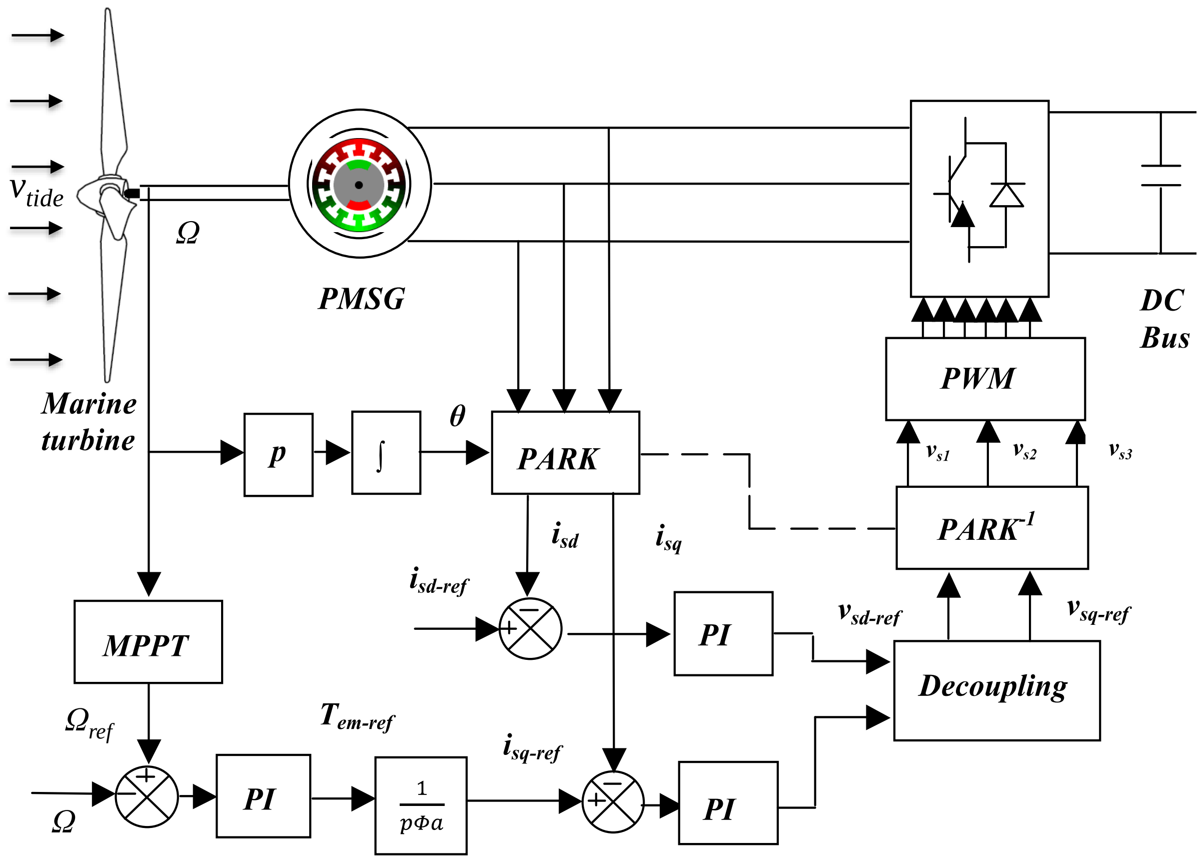


Fig. 3: The proposed control structure.

3.1. Maximum Power Point Tracking

The control system is defined by Eq. (5) as follows:

$$\begin{cases} i_{sd} = \dfrac{1}{R_s + L_s s}(v_{sd} + \omega\psi_{sq}) \\ i_{sq} = \dfrac{1}{R_s + L_s s}(v_{sq} - \omega\psi_{sd}) \\ T_{em} = \dfrac{3}{2}p\Phi_a i_{sq} \end{cases}, \tag{5}$$

where $(\omega = p\Omega)$ is the electrical speed, ψ_{sd} and ψ_{sq} are the $d-q$ components of the stator flux, respectively, defined by Eq. (6) as follows:

$$\begin{cases} \psi_{sd} = L_s i_{sd} + \Phi_a, \\ \psi_{sq} = L_s i_{sq}. \end{cases} \tag{6}$$

The MPPT strategy is based on a variable speed [11]. Indeed, the rotor speed is controlled using a PI controller to obtain the value of λ that corresponds to the maximum value of the power coefficient C_p and finally achieve the expected maximum power by the MCT.

The speed controller is given by Eq. (7) as follows:

$$R(s) = b_1 + \frac{b_0}{s}, \tag{7}$$

where b_1 is the controller proportional coefficient and b_0 is the controller integral.

The placing poles technique is used to compute the parameters of this controller. The reference of the speed is expressed by Eq. (8). It is used in order to make the function of the turbine is around the maximum power for different current tidal velocities.

$$\Omega_{ref} = \frac{v_t \lambda_{opt}}{r}. \tag{8}$$

If the tidal velocity exceeds 2.3 m·s^{-1} [12], the power is restricted to 7.5 kW. The power of the turbine for different tidal velocities is determined by Eq. (1).

3.2. Current PI Controller

The PI currents controllers are given by Eq. (9) as follows:

$$R(s) = k_p \left(1 + \frac{1}{k_i s}\right), \tag{9}$$

where k_p is the controller proportional coefficient and k_i is the controller integral. The division compensation technique is used to complete the parameters of these controllers. To reduce resistive losses, the reference of the d-axis current is zero, so, the q-axis current is the only current which control the electromagnetic torque.

The reference of the quadratic current is determined via the controller of the speed. The converter voltage vector is given by the two PI currents controllers. The control signal is generated by the PWM block to implement the vector control of the generator.

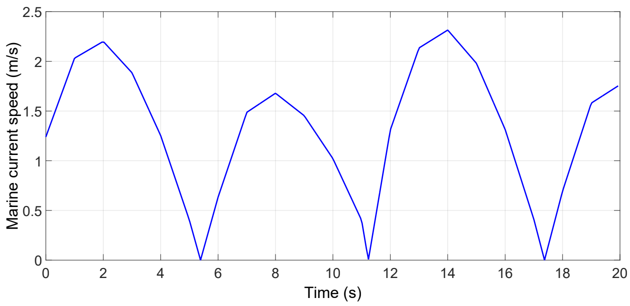
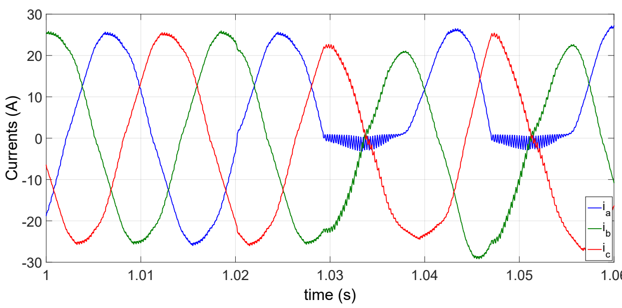


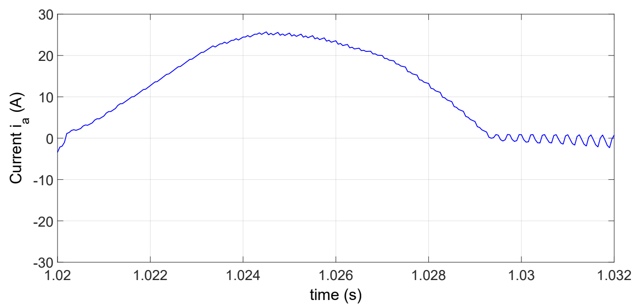
Fig. 4: Marine current turbine basic structure.

4. Marine Current Turbine Post-Fault Behavior and Results Analysis

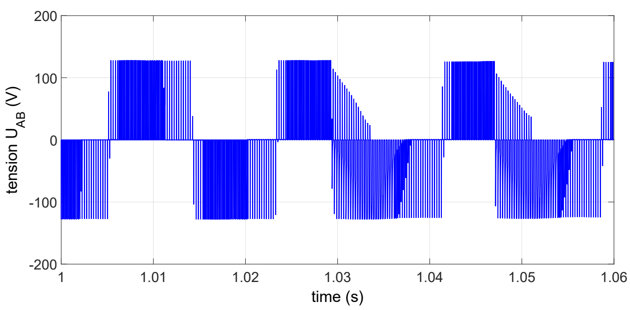
In this section, the influence of an open-circuit fault on the PMSG phase currents and the MCT dynamic performances will be studied on a PMSG-based MCT whose parameters are given in the Appendix. Simulations are carried out using MATLAB/Simulink environment. Figure 4 represents an example of marine current velocity in the Raz de Sein (potential site for the MCT project of the coast of Brittany in France) during 20 s based on tidal current data given by the French Navy Hydrographic and Oceanographic Service (SHOM). The marine current velocity can reach 2.3 m·s^{-1}.



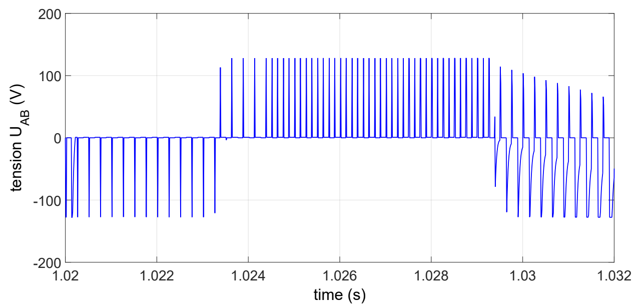
(a) Current.



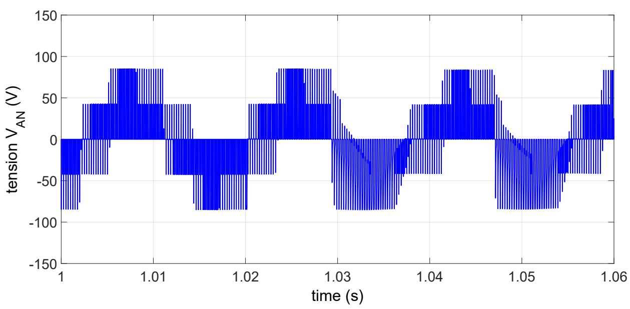
(b) Current.



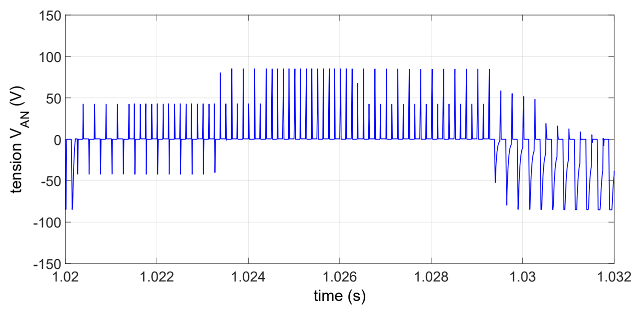
(c) Line-to-line voltage.



(d) Line-to-line voltage.



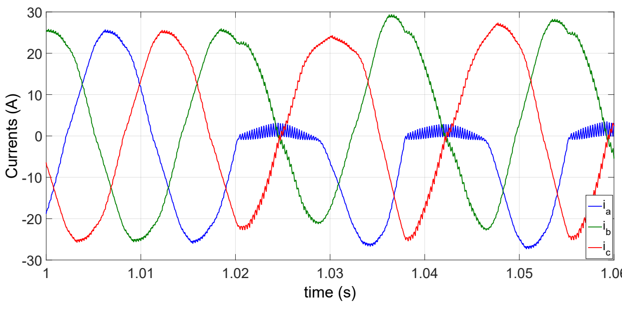
(e) Load voltage.



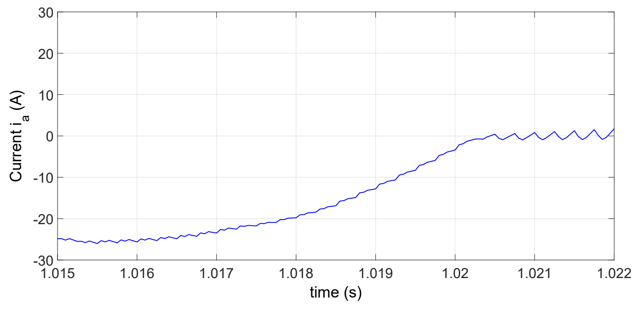
(f) Load voltage.

Fig. 5: Simulation Results of (T1) open-circuit fault: (a, b) currents, (c, d) line-to-line voltage U_{AB}, (e, f) load voltage V_{AN}.

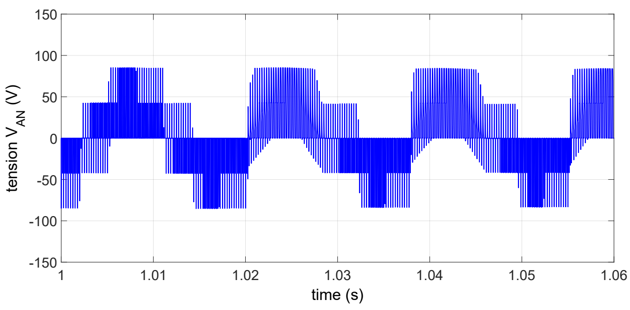
Waveforms given by Fig. 5 and Fig. 6 shows the three phase currents, the line-to-line voltage U_{AB}, and the load voltage V_{AN}, respectively. In Fig. 6, a fault state is introduced at $t = 1.02$ s and applied to the switch (T1). It is observed that the phase current ia is no more negative (Fig. 5(a)). The line-to-line voltage U_{AB} (Fig. 5(c)) and the load voltage V_{AN} (Fig. 5(e)) exhibit a great drop from the positive level to the negative one. Figure 5(b), Fig. 5(d), and Fig. 5(f) shows that the Fault detection is accomplished



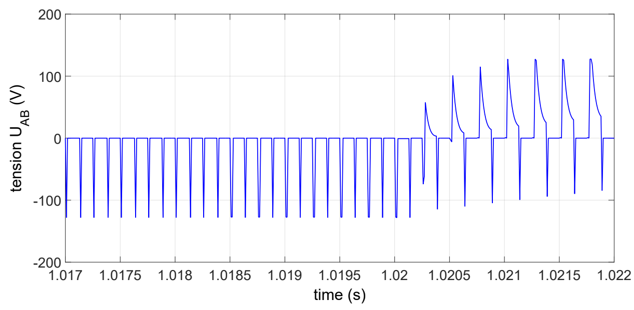
(a) Current.



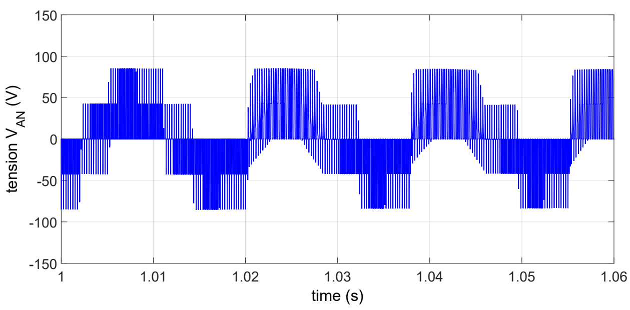
(b) Current.



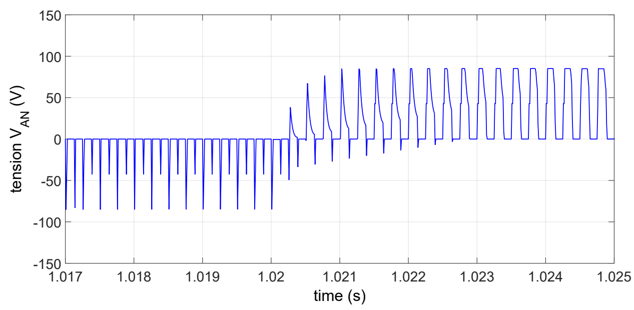
(c) Line-to-line voltage.



(d) Line-to-line voltage.

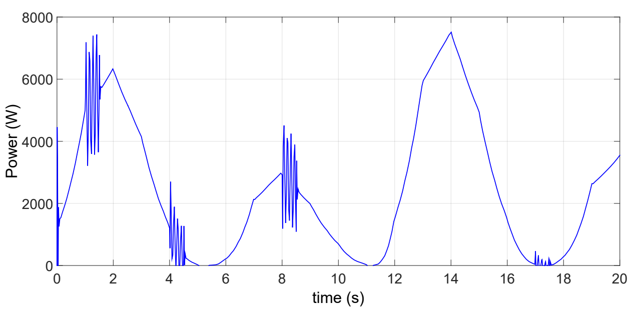


(e) Load voltage.

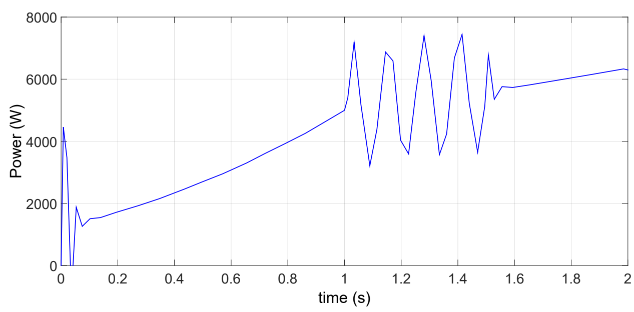


(f) Load voltage.

Fig. 6: Simulation Results of (T4) open-circuit fault: (a, b) currents, (c, d) line-to-line voltage U_{AB}, (e, f) load voltage V_{AN}.

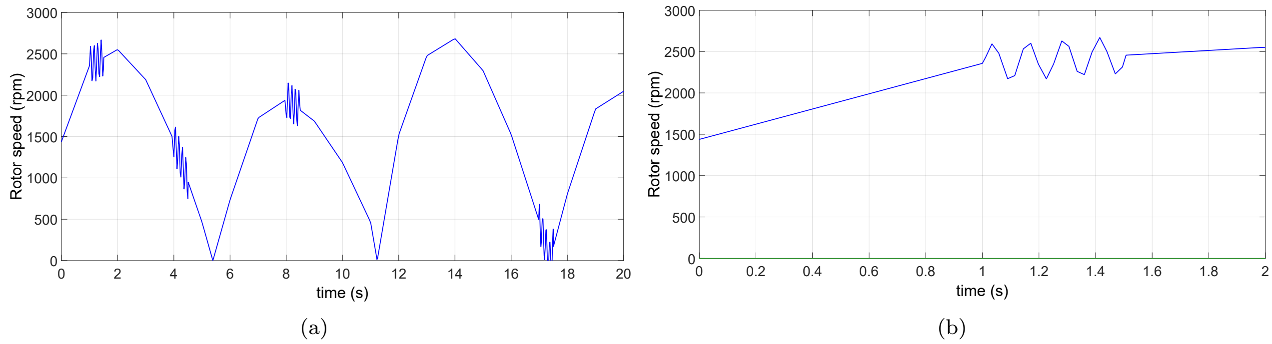


(a)



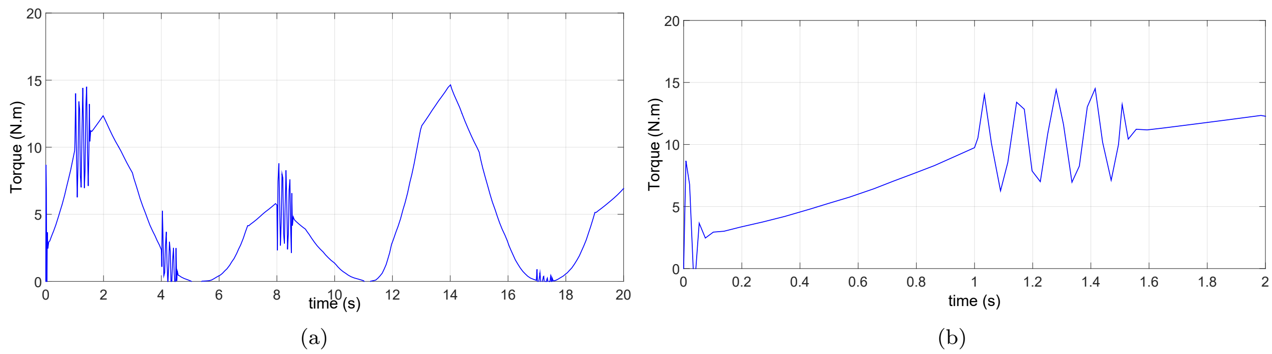
(b)

Fig. 7: PMSG generated power.



(a) (b)

Fig. 8: PMSG rotor speed.



(a) (b)

Fig. 9: PMSG torque.

at $t = 1.0295$ s, taking 9.5 ms as fault detection time. In Fig. 6, the fault is now applied to the switch (T4), the reverse effect is observed on the phase current ia (Fig. 6(a)), the line-to-line voltage U_{AB} (Fig. 6(b)), and the load voltage V_{AN} (Fig. 6(c)) exhibit a great drop from the negative level to the positive one. Figure 7, Fig. 8, and Fig. 9 represent the generated power, the rotor speed, and the torque with its version. It should be noticed that these results are achieved for an open-circuit in switch T1 occurring at $t = 1$ s, $t = 4$ s, $t = 8$ s and $t = 17$ s. As shown in these figures, by using PI control, the power, the speed, and the torque have some ripples at the faults occurrence.

Figure 10 gives a histogram which shows the range of variation in speed, torque, and power in (%) at $t = 1$ s. This proves that this technique is not useful and does not present any robustness against faults, therefore leading to the MCT system performances degradation.

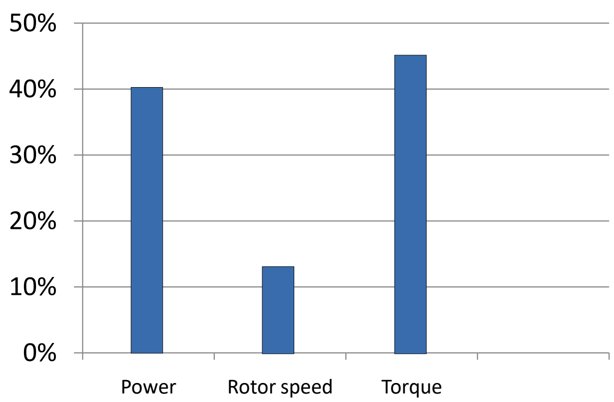


Fig. 10: Range of variation in speed, torque and power in (%) at $t = 1$ s.

5. Conclusion

The paper described the simulation of a PMSG-based marine current turbine experiencing open-circuit fault in power switches of its generator-side converter. PI controllers have been adopted for the MCT control. These results evidently show that PI control is very sensitive to faulty conditions and does not present any robustness. Therefore a fault-tolerant rectifier with specific redundancy or an advanced robust control techniques such as a high order sliding mode control are required.

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Appendix A
PMSG-Based MCT Parameters

MCT Parameters	
Turbine blade radius	0.87 m
Number of blades	3
Fluid density	1027.68 kg·m^{-3}
PMSG Parameters	
Rated Power	7.5 kW
Rated Speed	3000 tr·mn^{-1}
Rated Torque	17 N·m
Stator resistance	0.173 mΩ
Stator inductance	0.951 mH
Permanent magnets flux	0.112 Wb
System total inertia	1.3131 106 kg·m^{-2}
Viscosity coefficient	8.5 10-3 Nm·s^{-1}
Converter Parameters	
Turn-on time	0.13 µs
Turn-off time	0.445 µs
Dead-time	4 µs
Duty-cycle frequency	5 kHz
DC-bus voltage	600 V
PI Controller parameter	
Turbine speed loop (b0, b1)	(0.56, 1.7)
Generator dq-axis current loop (kp, ki)	(0.0173, 5.49)