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A Simplified Power Regulation Strategy for Grid-tied PMSG-based Marine Current Turbine System in High-speed Marine Current Conditions

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Abstract: Marine current turbine systems (MCTSs) play a crucial role in harnessing renewable energy from ocean currents. These systems are designed with specific rated values of marine current speed, dictating their optimal operational parameters. However, the dynamic nature of marine currents can lead to fluctuations, occasionally exceeding the rated values for which these systems are designed. This poses significant challenges to the efficient and safe operation of MCTSs, necessitating the development of effective power regulation strategies. In response to these challenges, this paper presents a simplified power regulation strategy to address the complexities of high-speed marine current conditions. The strategy focuses on constraining the reference torque command, a pivotal parameter governing power generation within MCTS. By precisely managing the reference torque command, the strategy aims to ensure that power output remains within designated limits, thereby safeguarding the MCTS despite high-speed marine current conditions. The proposed strategy leverages a computational approach to determine the generator's reference torque command, utilizing key parameters such as the rated power of the MCT and the mechanical angular rotor speed. It facilitates seamless transition between unconstrained reference torque command (URTC) and constrained reference torque command (CRTC) modes, enabling precise power regulation. This flexibility empowers the MCTS to respond promptly to changes in marine current conditions, facilitating precise and responsive power regulation. To validate the effectiveness of the proposed strategy, the paper conducts a comprehensive analysis of MCTS performance across both URTC and CRTC modes utilizing Typhoon HIL604 real-time simulator. Through detailed examinations of MCT speed responses, generator torque, output power, and grid-side parameters, the study provides valuable insights into the dynamics of MCTS operation. This comprehensive understanding enhances the stability and adaptability of MCTSs across diverse operating conditions, thereby advancing their potential as a sustainable energy solution.

Keywords: Constrained reference torque command (CRTC), high-speed marine current, marine current turbine (MCT), marine current turbine system (MCTS), real-time simulation, unconstrained reference torque command (URTC).

I. INTRODUCTION

Generating electricity from coal, gas, and oil releases a lot of carbon dioxide, which is harmful to the environment and health. To address this issue, cleaner energy sources such as wind, solar and tidal powers, are being considered [1]. These changes aim to increase the use of renewable energy in the future [2]. An intriguing option is harnessing energy from the ocean, including waves and tides, which could offer significant global power potential [3, 4]. Overall, utilizing the ocean's energy has the potential to play a substantial role in shaping a cleaner energy future.

The operational principles of marine current turbine systems (MCTSs) share similarities with wind energy systems but face unique challenges due to the marine environment such as water density, fluid dynamics, and corrosion [5, 6]. Despite higher running costs compared to offshore wind, marine energy offers distinct advantages like higher energy density and reliable power generation [6]. The governments of several countries are proactively advocating for marine energy to reduce dependence on fossil fuels, alleviate the effects of climate change, and stimulate innovation within the renewable energy industry [7]. Despite facing challenges, the increasing investment in marine energy signifies a growing confidence in its capacity to play a significant role in propelling the global energy transition forward.

The tides on earth are influenced by the gravitational forces of the moon and the sun, leading to spring tides when their forces align and neap tides when they partially cancel each other [8]. Methods for converting tidal energy encompass tidal barrages, dynamic tidal installations, and tidal stream converters [4–6]. A horizontal-axis tidal turbine showcases advancements in efficiently harnessing tidal currents to generate electricity [9]. Optimizing MCTS with permanent magnet synchronous generators (PMSGs) entails refining turbine designs and implementing advanced control strategies to effectively respond to fluctuating tidal flows, thereby maximizing power output [6]. While PMSGs are known for their efficiency and reliability in marine power generation,

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comprehensive studies are essential to evaluate the control aspects of PMSG-based MCTSs. Exploring cost-effective solutions and energy storage options, along with ongoing research endeavors, are crucial for enhancing the overall performance and reliability of MCTSs [10]. Various control theories and strategies have been extensively researched to optimize power extraction and ensure reliability in PMSG-based MCTSs [11, 13]. Among these, sliding mode control [14, 15], adaptive control [16], passivity-based control [17, 18], and fault-resilient control [19] stand out. By incorporating these advanced control theories and strategies, alongside state-of-the-art monitoring and fault detection techniques, into PMSG-based MCTSs, significant improvements in power extraction efficiency, continuous operation assurance, and overall system reliability can be achieved in challenging marine conditions. Furthermore, fostering collaboration among researchers, industry experts, and regulatory bodies is essential for advancing these technologies and accelerating their integration into renewable energy applications.

MCTSs are usually engineered to align with a specific rated value of marine current speed for practical and efficiency reasons [20]. However, they encounter challenges in regulating power when marine current speeds surpass these ratings, unlike pitchable marine current turbines (MCTs). This underscores the importance of implementing a power regulation strategy to optimize energy extraction from marine currents. This paper proposes a control strategy that emphasizes constraining the reference torque command to effectively manage and regulate generated power. This approach ensures efficient and safe operation, even under challenging high-speed marine current conditions.

The structure of the remaining paper is as follows: Section II provides an overview of the MCTS and presents the modeling equations. Section III offers a description of the control strategy employed. Real-time simulation results and accompanying discussions are outlined in Section IV. Finally, Section V encapsulates the conclusions drawn from this paper.

II. System Description and Modelling

A. Marine Current Turbine (MCT)

The power (P_{marine}) extracted by the MCT can vary widely depending on factors such as the turbine's radius R_T, marine current velocity V_c, marine water density ρ , and power coefficient C_p as represented by following equations:

$$P_{marine} = \frac{1}{2}\rho C_p(\pi R_T^2)V_c^3 \tag{1}$$

$$C_p = 0.73\left[\frac{151}{\lambda_k} - 0.002\theta^{2.14} - 0.58\theta - 13.2\right]\exp\left(-\frac{18.4}{\lambda_k}\right) \tag{2}$$

$$\frac{1}{\lambda_k} = \frac{1}{\lambda + 0.08\theta} - \frac{0.035}{\theta^3 + 1} \tag{3}$$

where θ represents the pitch-angle of the MCT blades. Symbol λ denotes the tip-speed-ratio (TSR), which is the ratio of the mechanical angular speed ω_m of the MCT to the marine current speed V_c . This relationship is expressed in equation (4).

$$\lambda = \omega_m R / V_c \tag{4}$$

Here C_p is a function of the TSR λ. Within the context of this non-pitchable MCT, there exists an optimal TSR (λ_{opt} = 5.66) at which the MCT achieves maximum power output under the rated marine current speed. This paper focuses on a single MCT with a capacity of 1.5 MW. To achieve maximum power extraction at a rated speed (3.2 m/s) of marine current, a maximum turbine speed of 21.6 rpm is required, corresponding to a mechanical angular rotational speed of 2.26 rad/s.

B. PMSG Model

The d-and q-axes stator voltage equations of PMSG [14, 16, 22] are given as

$$v_{ds} = R_m i_{ds} + L_m \frac{d}{dt} i_{ds} - \omega_r L_m i_{qs} \tag{5}$$

$$v_{qs} = R_m i_{qs} + L_m \frac{d}{dt} i_{qs} + \omega_r L_m i_{ds} + \omega_r \lambda_m \tag{6}$$

where, R_m represents the stator resistance of PMSG; L_m denotes the stator inductance of PMSG, ω_r stands for the electrical angular speed of the PMSG; λ_m signifies the permanent magnet rotor flux; and i_{ds} and i_{qs} refer to the stator currents along the d-axis and q-axis, respectively.

The electromagnetic torque of P-pole surface-mounted PMSG is given as

$$T_e = \frac{3}{2} \cdot \frac{P}{2} \cdot \lambda_m \cdot i_{qs} \tag{7}$$

C. Grid-Voltage Equations

The equations for grid voltage are expressed [15, 16, 22] as shown below

$$e_{dg} = Ri_{dg} + L\frac{di_{dg}}{dt} - \omega L i_{qg} + v_{dg} \tag{8}$$

$$e_{qg} = Ri_{qg} + L\frac{di_{qg}}{dt} + \omega L i_{dg} + v_{qg} \tag{9}$$

where, e_{dg} and e_{qg} denote the components of grid voltage along the d-axis and q-axis, respectively; R represents the coupling resistance; L stands for coupling inductance; v_{dg} and v_{qg} are the d-axis and q-axis line-side converter (LSC) voltage components, respectively; and ω signifies the grid angular frequency.

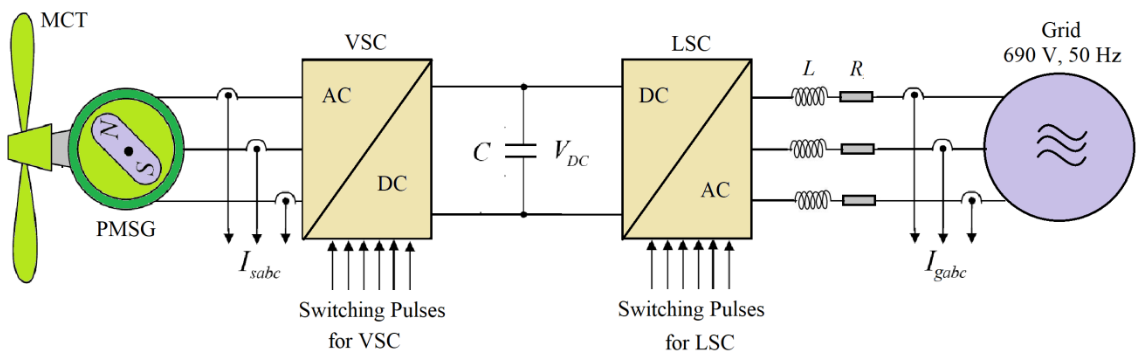


Fig.1. The proposed grid-tied PMSG-based MCTS.

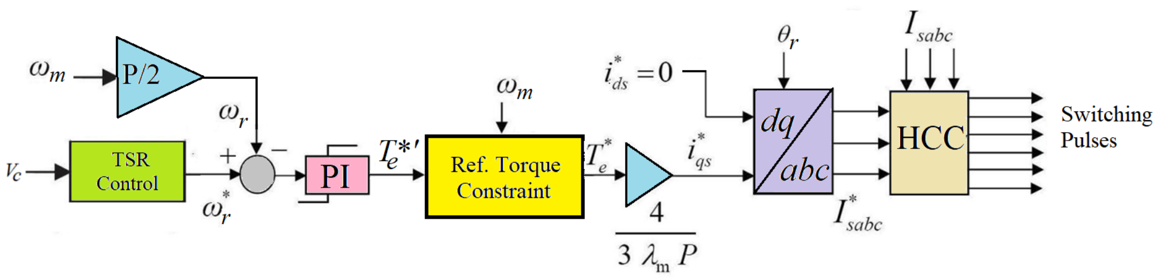


Fig.2. The proposed control for the generator-side VSC.

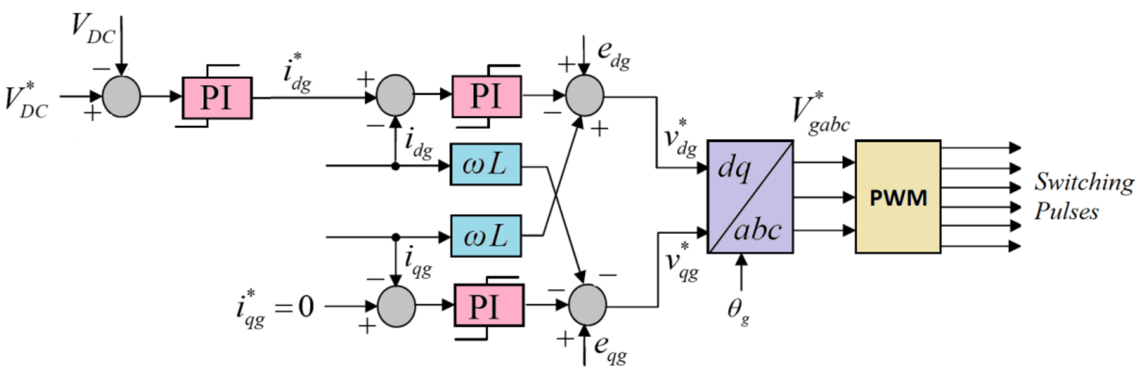


Fig.3. The voltage-oriented control for the LSC.

III. CONTROL DESCRIPTION

Typically, a grid-tied MCTS operates in maximum power extraction mode. The control structure is realized via field-oriented control of the PMSG using the generator-side voltage source converter (VSC), as illustrated in Figure 1. When the speed of the marine current stays under the rated value, the TSR control algorithm [22, 24] for maximum power extraction estimates the reference mechanical angular rotor speed based on λ_{opt} and R_T, which is then used to determine the reference electrical angular rotor speed using equations (10)–(11).

$$\omega_m^* = \frac{\lambda_{opt} V_c}{R_T} \tag{10}$$

$$\omega_r^* = \frac{P}{2}\omega_m^* \tag{11}$$

The speed PI controller compares the actual electrical angular rotor speed ω_r with the reference electrical angular rotor speed ω_r^* and utilizes the speed error to compute the torque command i.e. $T_e^*{'}$ using the following equation:

$$T_e^*{'} = K_{ps}\left(\frac{1+pT_{is}}{pT_{is}}\right)\cdot(\omega_r^* - \omega_r) \tag{12}$$

where K_{ps} represents the proportional gain and T_{is} represents the integral-time constant of the outer PMSG speed PI controller.

On the other hand, in conditions of high marine current speeds (*i.e.* speeds exceeding the rated value), the reference torque for the generator can be computed by dividing the rated MCT power by the mechanical angular rotor speed. This approach ensures that the generator torque is appropriately adjusted to uphold the power output at the designated limit when marine current speeds surpass the rated value. To effectively control generated power, the proposed method enables a transition between the unconstrained reference torque command (URTC) mode and the constrained reference torque command (CRTC) mode. This transition can be implemented as follows:

$$T_e^* = \begin{cases} \dfrac{P_{MCT}^{rated}}{\omega_{\mathrm{m}}} & \text{if } V_c > V_c^{rated} \quad : \quad \text{CRTC Mode} \\ T_e^*{'} & \text{Otherwise} \quad : \quad \text{URTC Mode} \end{cases} \tag{13}$$

Notably, this CRTC mode operates independently of information regarding marine current speed or MCT power-speed characteristics, offering a straightforward and efficient means of achieving power limitation requirements. Moreover, the proposed control approach ensures optimal performance and adaptability of the MCTS across varying operating conditions. The obtained reference electromagnetic torque command, denoted as T_e^*, is subsequently utilized to compute the *q*-axis reference stator current, i_{qs}^*. To attain a high torque-to-current ratio, the reference *d*-axis stator current i_{ds}^*, is typically put to zero [22, 24]. The inner hysteresis current controller (HCC) compares the measured stator currents with the three-phase reference stator currents, producing switching signals for the generator-side VSC.

On the other hand, the voltage-oriented control (VOC) is applied for the control of the LSC where, the DC-link voltage PI controller compares the reference and actual values of the DC-link voltages and addresses any voltage deviation to determine the reference *d*-axis grid current i_{dg}^*.

$$i_{dg}^* = K_{pv}\left(\frac{1+pT_{iv}}{pT_{iv}}\right)\cdot(V_{DC}^* - V_{DC}) \tag{14}$$

where K_{pv} and T_{iv} represent the proportional gain and the integral time constant, respectively, of the outer voltage PI controller.

To ensure that the LSC operates with a power factor of unity, the reference grid current along the *q*-axis i_{qs}^*, is put to zero [22, 24]. These reference commands for the *d-q* axes grid currents are then incorporated into the inner current control loop. Inside this loop, PI controllers for current compare the actual *d-q* axes grid currents i_{dg} and

i_{qg}, with their respective reference values, and handle any deviations to calculate the reference values of the *d-q* axis LSC voltages v^*_{dg} and v^*_{qg}. By inversely transforming the *d-q* axes reference LSC voltages, the three-phase reference LSC voltages V^*_{gabc}, are derived. These values are then utilized by the pulse width modulator (PWM) to generate switching signals for the LSC.

IV. Real-time Simulation Results

This study assumes that positioning the MCT at an appropriate depth beneath the sea surface will mitigate the influence of local wind-generated waves, thereby creating calm sea conditions with minimal swell waves. Furthermore, it attributes the high marine current speeds to strong tidal currents during spring tides, which are reliably predictable across different areas.

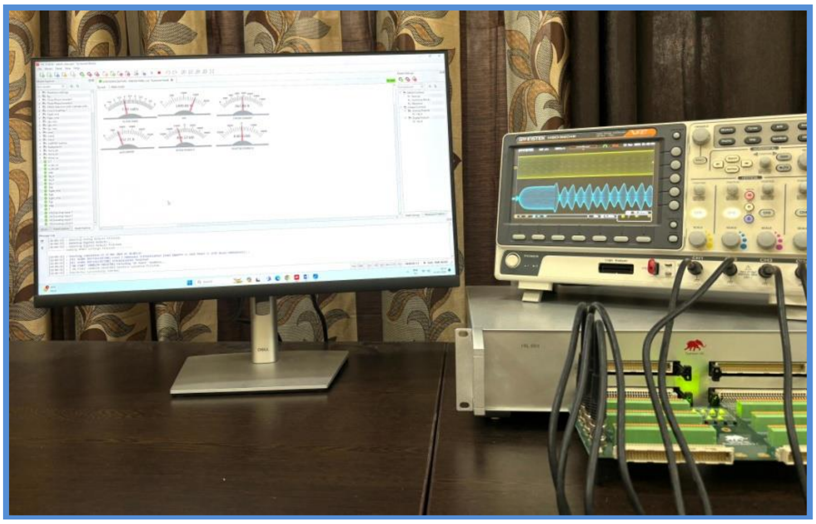
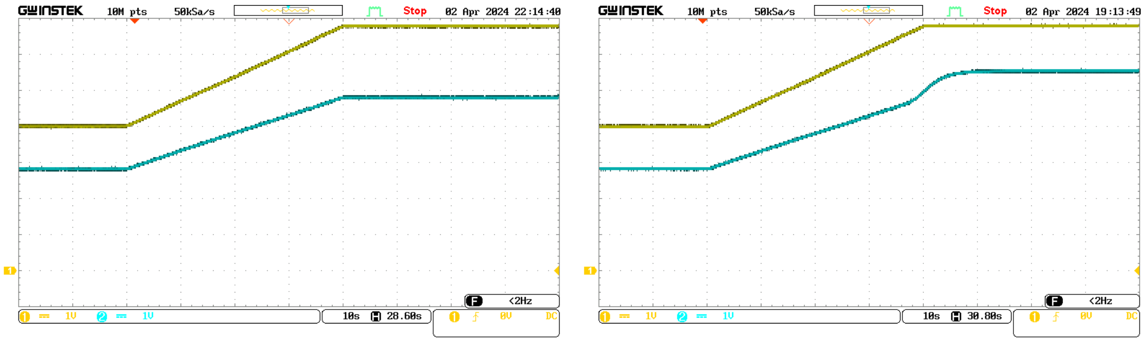


Figure 4. The real-time simulation test setup, utilizing the Typhoon HIL604 real-time simulator.

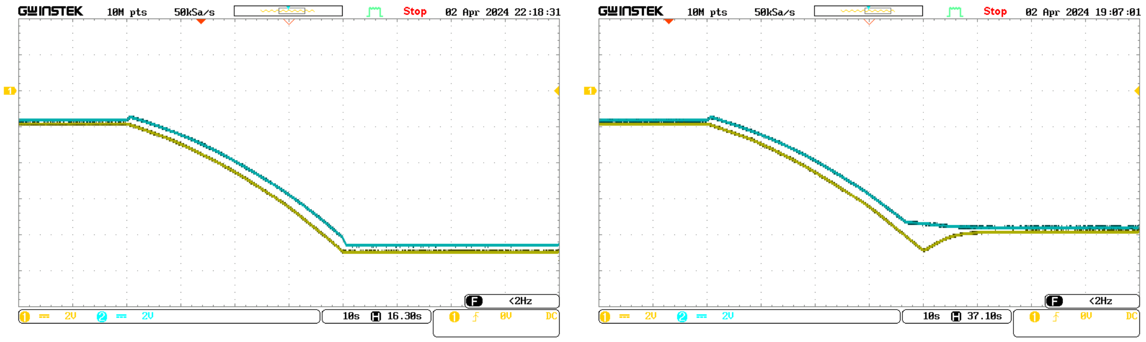
The maximum tidal speed plays a critical role in devising an effective control strategy for MCTs and their power generation. In the operation of marine current turbines (MCTs), the turbine's performance across two different modes, such as URTC and CRTC, entails achieving precise objectives related to power generation and torque production. This involves sustaining nominal generator output power, especially in instances of marine currents surpassing rated speeds, while ensuring the stability and reliability of the system. Examining MCT speed responses, MCT and generator torques, MCT and generator output powers, generator currents, grid-side active and reactive powers, and grid-side voltage and currents across two modes (URTC and CRTC) provides valuable insights into the performance characteristics of MCTSs. The real-time simulation setup, portrayed in Fig. 4, utilizes the Typhoon HIL604 real-time simulator. The aforementioned responses are dynamically illustrated in real-time, as depicted in Figures 5–10. The MCTS parameters [25] used for real-time simulation are listed in Appendix.

In this study, the initial speed of the marine current is put as 2.0 m/s, gradually increasing to 3.4 m/s within the timeframe of 20 s to 60 s, as depicted in Fig. 5. After 54 s, the marine current speed surpasses the defined rated value of 3.2 m/s, prompting the shift from URTC mode to CRTC mode. Both the maximum extractable power (under URTC mode) and the need for power regulation (under CRTC mode) are critical considerations. Without power regulation (i.e., under URTC mode), the MCT could potentially generate over 1.8 MW of power at the maximum marine current speed of 3.4 m/s, as shown in Fig. 6. The decrease in generator torque as rotor speed surpasses the rated speed (2.26 rad/s), as depicted in Fig 7, suggests efficient control under CRTC mode. Of particular significance is the capability of the CRTC mode to consistently regulate generator power at 1.5 MW, ensuring efficient and safe operation, even in high-speed marine current conditions where the speed of the marine current surpasses the rated value.



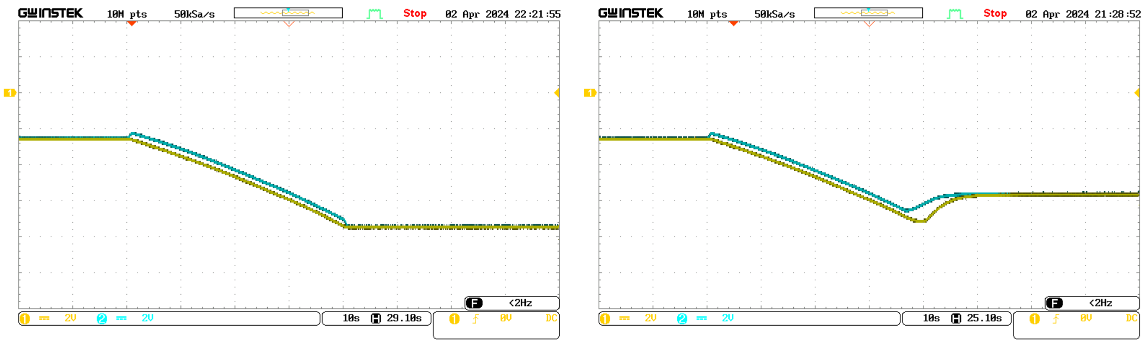
(a) (b)

Fig. 5. Real-time results under (a) URTM and (b) CRTM—Ch.1: Marine current speed (0.5 m/s per div); Ch.2: Generator rotational speed (0.5 rad/s per div).



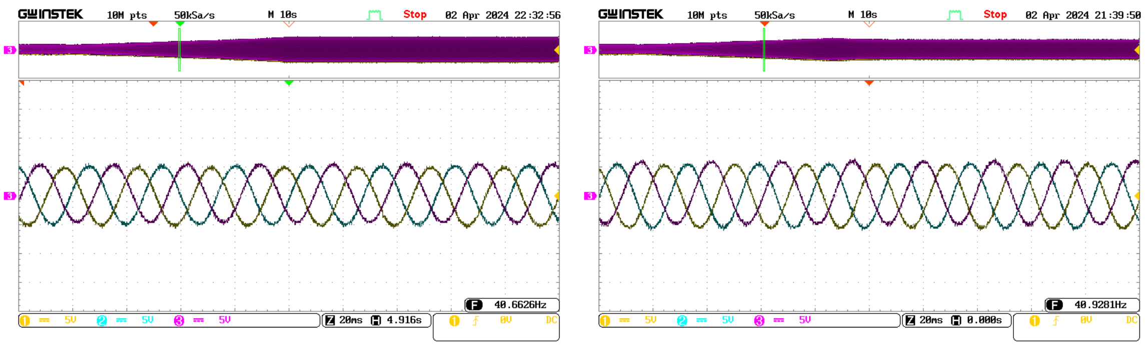
(a) (b)

Fig. 6. Real-time results under (a) URTM and (b) CRTM—Ch.1: MCT power (400 kW per div); Ch.2: Generated power (400 kW per div).



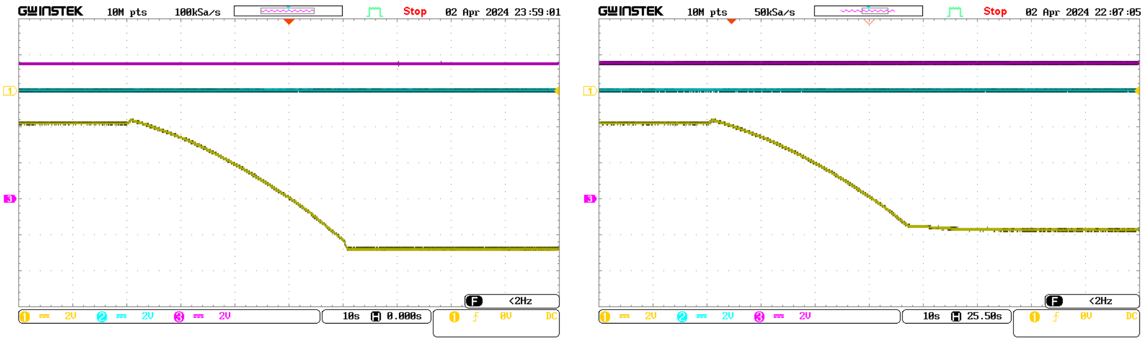
(a) (b)

Fig. 7. Real-time results under (a) URTM and (b) CRTM—Ch.1: MCT torque (200 kN per div); Ch.2: Generator torque (200 kN per div).



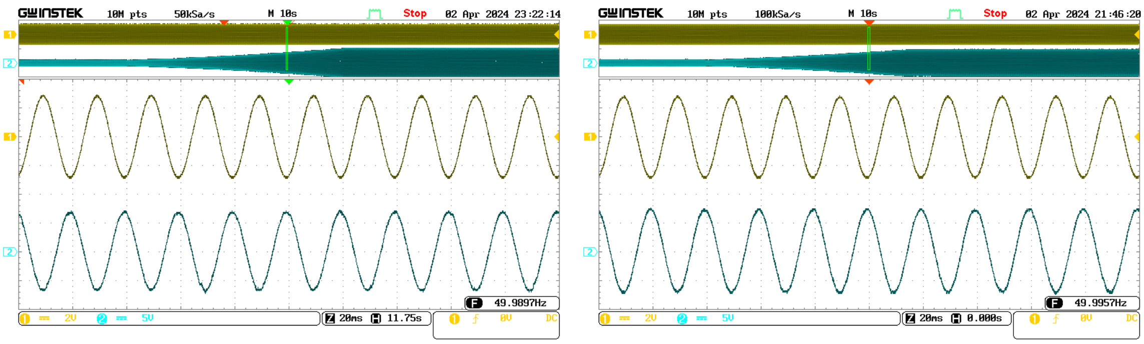
(a) (b)

Fig. 8. Real-time results (zoomed view) under (a) URTM and (b) CRTM—Ch.1: Phase-a generator current (2000 A per div); Ch.2: Phase-b generator current (2000 A per div); Ch.3: Phase-c generator current (2000 A per div).



(a) (b)

Fig. 9. Real-time results under (a) URTM and (b) CRTM—Ch.1: Grid-side active power (400 kW per div); Ch.2: grid-side reactive power (400 kVAR per div); Ch.3: DC-link voltage (400 V per div).



(a) (b)

Fig. 10. Real-time results (zoomed view) under (a) URTM and (b) CRTM demonstrating unity power factor operation—Ch.1: Phase-a grid voltage (400 V per div); Ch.2: Phase-a grid current (1000 A per div).

Additionally, Fig. 8 depicts the three-phase stator current profile of the PMSG. Although the increase in marine current speed simulated in real-time may not precisely mimic real-world scenarios, where marine currents typically evolve more gradually over tidal cycles spanning approximately half a day, it provides a valuable opportunity to assess the effectiveness of CRTC mode under high-speed marine current conditions.

Furthermore, Figure 9 indicates that the DC link voltage remains stable at 1500 V, even when the speed of the marine current exceeds the rated value of 3.2 m/s. The active power injection profiles into the grid under two modes, URTC and CRTC, are depicted in Figure 9. It is evident from the graph that the injected active power closely aligns with the respective generated power for both modes. Additionally, the reactive power remains approximately 0 MVAr, indicating unity power factor operation of the system. This observation is further supported by examining the grid voltage and grid current profiles for Phase–a, as depicted in Figure 10 for both modes.

V. Conclusions

This paper addresses critical aspects of MCTSs and presents a simplified power regulation strategy aimed at optimizing energy extraction across varying marine current speeds. The proposed approach seamlessly transitions between unconstrained reference torque command (URTC) and constrained reference torque command (CRTC) modes, effectively regulating power output and ensuring system stability, even in high-speed marine current conditions. Real-time simulation results demonstrate the efficacy of the strategy in regulating power generation while maintaining safe operation. Furthermore, the stability of the DC link voltage and the achievement of unity power factor operation serve as additional validations of the practical applicability of the proposed strategy. Despite inherent limitations in real-time simulation accuracy compared to real-world scenarios, the study provides valuable insights into MCTS performance across different operating conditions. Overall, the findings presented herein significantly contribute to advancing the understanding and practical implementation of efficient and reliable MCTS.

APPENDIX

Rated MCT power	:	$P_{MCT} = 1.5\,\text{MW}$
MCT Blade radius	:	$R_T = 8.0\,\text{m}$
Tip-speed ratio	:	$\lambda_{opt} = 5.66$
Power coefficient	:	$C_{p\max} = 0.4412$
Rated marine current speed	:	$V_c = 3.2\,\text{m/s}$
Marine density	:	$\rho = 1027\,\text{kg/m}^2$
PMSG stator resistance	:	$R_m = 0.0081\Omega$
PMSG stator inductance	:	$L_m = 1.2\,\text{mH}$
PMSG poles	:	$P = 240$
PM flux	:	$\lambda_m = 2.458\,\text{Wb}$
MCT Inertia	:	$J = 1.313\times10^6\ \ \text{kg-m}^2$
DC link capacitance	:	$C = 60\,\text{mF}$
DC link voltage	:	$V_{DC} = 1500\,\text{V}$
Grid voltage (r.m.s.)	:	$V_{LL} = 690\,\text{V}$
Grid frequency	:	$f = 50\,\text{Hz}$
Coupling resistance	:	$R = 0.1\text{m}\Omega$
Coupling inductance	:	$L = 0.6\,\text{mH}$

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