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Research Article

Research on Low Power Marine Current Power Generation System

Dongkai Peng, Jingang Han, Lianbin Xie and Tianhao Tang
Department of Electrical Engineering, Shanghai Maritime University, Shanghai 201306, China

Abstract: This study proposes a simple topological structure and power control method for a small scale stand alone marine current system, in which a diode rectifier, DC/DC boost converter for the maximum power control, battery as a storage element and a single phase inverter to link with load. The study establishes the steady-state mathematical model of marine current power generation system and derives the formula between the maximum power point and dc battery voltage. Then use the measurements of DC voltage and DC current to obtain Maximum Power Point Tracking (MPPT) by controlling the duty cycle of the boost converter switch in order to simplify the system structure and the control strategies. In this case, the hill climbing searching algorithm is employed to get maximum power point and the double closed loops control strategy is used to improve the dynamic and static performance of single phase inverter. The simulation model is developed in MATLAB/Simulink. And the control method is executed in dSPACE1104 real-time platform. The simulation and experimental results demonstrate the feasibility and validity of the proposed control strategies.

Keywords: dSPACE, marine current generator, Maximum Power Point Tracking (MPPT) control, steady state model

INTRODUCTION

Nowadays, marine currents and waves are being recognized as a resource to be exploited for the sustainable generation of electrical power. Marine current energy, which is the clean energy source and the predictable resource characteristics, is arousing more and more attention (Ben Elghali *et al*., 2007a).

The research of marine current power generation system mainly focus on two kinds of Variable Speed Constant Frequency (VSCF) system which are permanent magnet synchronous type (Ben Elghali *et al*., 2007b) and permanent magnet synchronous type doubly-fed induction type (Ben Elghali *et al*., 2010). Permanent magnet synchronous type current power generation system including three-phase bridge controlled rectifier and three-phase bridge inverter constitutes a back-to-back circuit, by controlling the output power in PWM rectifier side and controlling grid connection in inverter side, but this control method of the topological structure is complex and the switch loss is high.

Considering a low power stand alone marine current power generation system, this study proposes a simple topological structure including diode rectifier, a DC/DC boost converter, battery and a single phase inverter to get maximum power of the small power marine current system by controlling the duty cycle of the boost converter switch so as to simplify the system structure and control strategies. Moreover, the study establishes the steady mathematical model of marine current system and deduces the formula between the maximum power point and battery voltage. In order to obtain the maximum power point tracking and improve the dynamic and static performance of single phase inverter, the hill-climbing searching algorithm and the double closed loops control strategy are employed respectively.

The proposed system has been modeled and simulated using MATLAB/Simulink software. A prototype has been developed on dSPACE1104 real-time platform in order to demonstrate the feasibility and validity of the proposed control strategies.

SYSTEM STRUCTURE AND MODELING

Figure 1 shows the power circuit topology and control strategies of a low power marine current system proposed in this study. The whole system consists of marine current turbine connected to a Permanent Magnetic Synchronous Generator (PMSG), diode rectifier which is used to convert the AC output waveforms of the PMSG to a DC voltage, DC/DC boost convert which is used to obtain the maximum marine current power, where a MPPT control algorithm is employed to do so, battery as a storage element, H-bridge single phase inverter which is used to improve the quality of the output voltage, where a double closed

Corresponding Author: Dongkai Peng, Department of Electrical Engineering, Shanghai Maritime University, Shanghai 201306, China

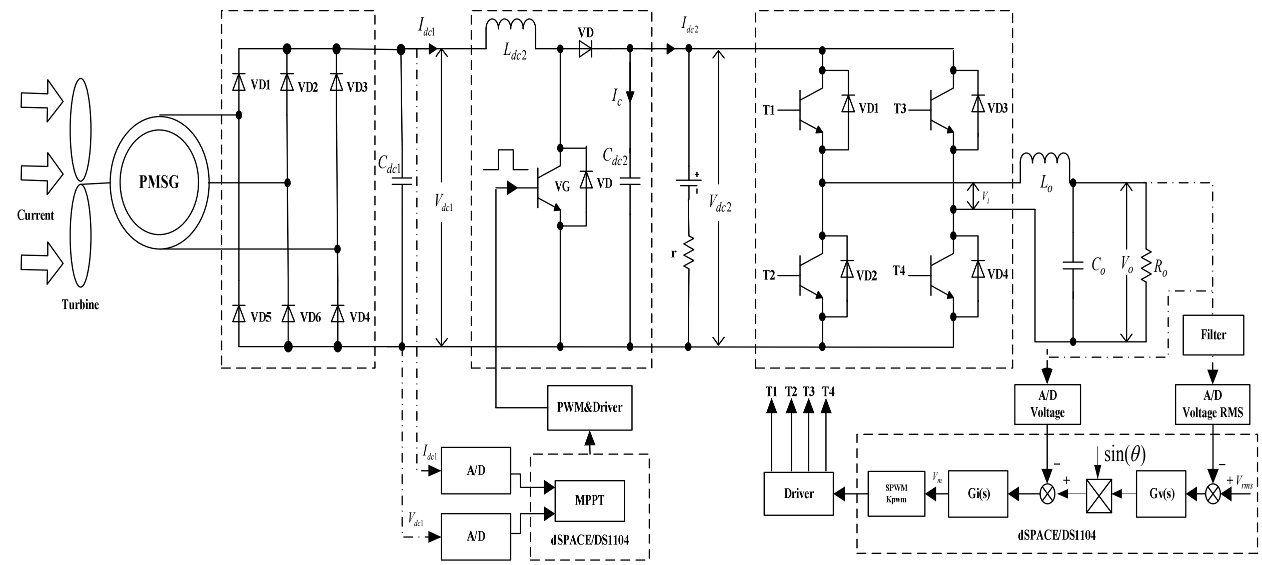

Fig. 1: Configuration of the proposed marine current power generation system

loops control algorithm is employed to control the inverter.

Model of permanent magnet synchronous generator: The rotor structure of a permanent magnet synchronous generator is a permanent magnet which does not need to provide external excitation. The electromagnetic torque equation for a PMSG is shown like the following (Ben Elghali *et al*., 2009):

$$T_e = \frac{3}{2} \cdot n_p i_q \cdot \left[\left(L_d - L_q \right) \cdot i_d + \phi_f \right] \quad (1)$$

where,

- T_e = Electromagnetic torque
- n_p = The number of poles
- L_d, T_q = The equivalent inductor in the dq frame respectively
- i_d, i_q = The equivalent current in the dq frame respectively
- ϕ_f = The constant flux due to the permanent magnets

It is assumed that permanent magnet uses radial surface distribution type. The electromagnetic torque equation for a PMSG can be described as:

$$T_e = \frac{3}{2} \cdot n_p i_q \phi_f \quad (2)$$

If the turbine rotor friction is ignored, the mechanical characteristics of a marine current turbine can be described as (Tafticht *et al*., 2006):

$$P_m - P_e = \omega_m J \cdot \frac{d\omega_m}{dt} \quad (3)$$

$$\omega_e = n_p \omega_m \quad (4)$$

where,

- T_m = Mechanical torque at the marine current turbine side
- ω_m = The rotor mechanical angular frequency
- ω_e = The electrical angular frequency
- J = The turbine's moment of inertia
- P_m, P_e = Mechanical and electromagnetic power respectively

Model of diode rectifier and boost circuit: The dynamic behavior of the whole system needs to be analyzed so as to improve the efficiency of the small power marine current turbine. Diode rectifier which is used to convert the AC output waveforms of the PMSG to a DC voltage. Figure 2 gives the schematic diagram of the small power marine current energy system.

Assuming that the generator consists of only the synchronous reactance (the stator resistance is neglected), the generated electromotive force E of the PMSG is shown as (Hussein *et al*., 2010):

$$E = k\phi_f \omega_m \quad (5)$$

where, k is the constant of the generator. And the phase voltage for a PMSG may be written as:

$$E^2 = V_g^{\ 2} + \left(L\omega_e I_g \right)^2 \quad (6)$$

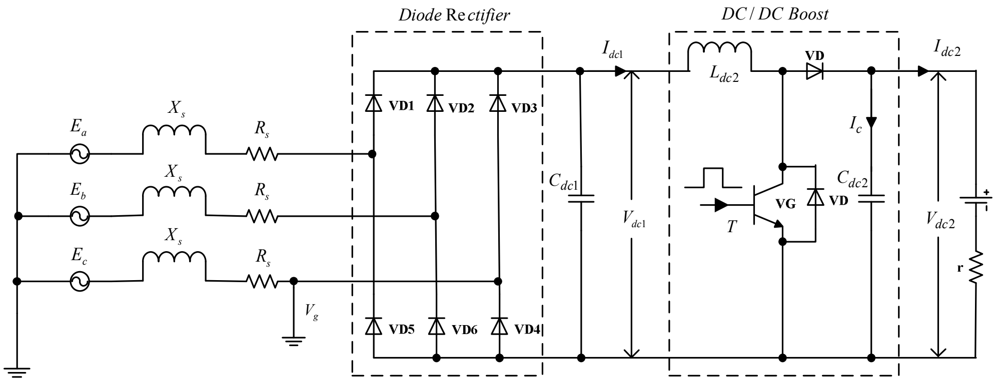

Fig. 2: Connection generator to the diode rectifier circuits

where,
V_g & I_g : The terminal phase voltage and current
L : The synchronous generator inductance

Replacing (4), (5) in (6), the following equation is obtained:

$$I_g = \frac{\sqrt{(k\phi\omega_m)^2 - V_g^2}}{Ln_p\omega_m} \tag{7}$$

The generator is connected with rectifier circuits as shown in Fig. 2. It is assumed that the power generated from the generator is converted into DC power through the H-bridge diode rectifier circuits with a unity power factor and that the load current is continuous, that is to say it meets the law of conservation of power:

$$P = 3V_g I_g = V_{dc1} I_{dc1} \tag{8}$$

where,
V_{dc1} & I_{dc1} : The voltage and current of DC side
V_{dc2} & I_{dc2} : The voltage and current of boost side

The mean value of DC voltage can be described by:

$$\begin{aligned} V_{dc1} &= \frac{3}{\pi}\cdot\int_{-\frac{\pi}{6}}^{\frac{\pi}{6}} V_{LLpeak}\cos\theta\cdot d\theta = \frac{3}{\pi}\cdot V_{LLpeak} \\ &= \frac{3\sqrt{2}}{\pi}\cdot V_{LL} = \frac{3\sqrt{6}}{\pi}\cdot V_g \end{aligned} \tag{9}$$

where,
V_{LLpeak} = The maximum value of line voltage
V_{LL}, V_g = The line voltage and phase voltage

From (8) and (9), the following equation is derived:

$$I_{dc1} = \frac{3V_g I_g \pi}{3\sqrt{6}V_g} = \frac{\pi}{\sqrt{6}}\cdot I_g \tag{10}$$

Replacing (5), (8) in (9), the following equation is derived:

$$P = \frac{\pi}{\sqrt{6}}\cdot V_{dc1}\cdot\frac{\sqrt{(k\phi\omega_m)^2 - \left(\frac{\pi}{3\sqrt{6}}\cdot V_{dc1}\right)^2}}{Ln_p\omega_m} \tag{11}$$

According to the Eq. (11), the dc bus voltage determines the rotor speed at which the PMSG begins to generate energy. That is to say, the higher the dc bus voltage, the higher is the rotor speed of the PMSG before it starts to produce energy. Thus it is necessary to impose a low dc bus voltage or used a boost converter circuit so as to recover the small power marine current energy for the low current velocity. It is assumed that the load current is continuous in boost circuit, that is to say it meets the law of conservation of power. It is assumed that in a battery charging application the output voltage is constant and defined by the battery ($V_{dc2} = V_{bat}$):

$$V_{dc1}\cdot I_{dc1} = V_{dc2}\cdot I_{dc2} \tag{12}$$

$$V_{dc2} = \frac{1}{1-D}\cdot V_{dc1} \tag{13}$$

From (11), (12) and (13), the following equation between power and duty cycle is obtained:

$$P = \frac{\pi\cdot(1-D)\cdot V_{dc2}}{\sqrt{6}}\cdot\frac{\sqrt{(k\phi\omega_m)^2 - \left[\frac{\pi}{3\sqrt{6}}\cdot(1-D)\cdot V_{dc2}\right]^2}}{Ln_p\omega_m} \tag{14}$$

Model of the single-phase inverter: Shown in Fig. 1, the single-phase inverter includes an LC output filter in order to attenuate the high frequency harmonics injected by the inverter.

In the Laplace domain, transfer functions of the open-loop inverter system are given as:

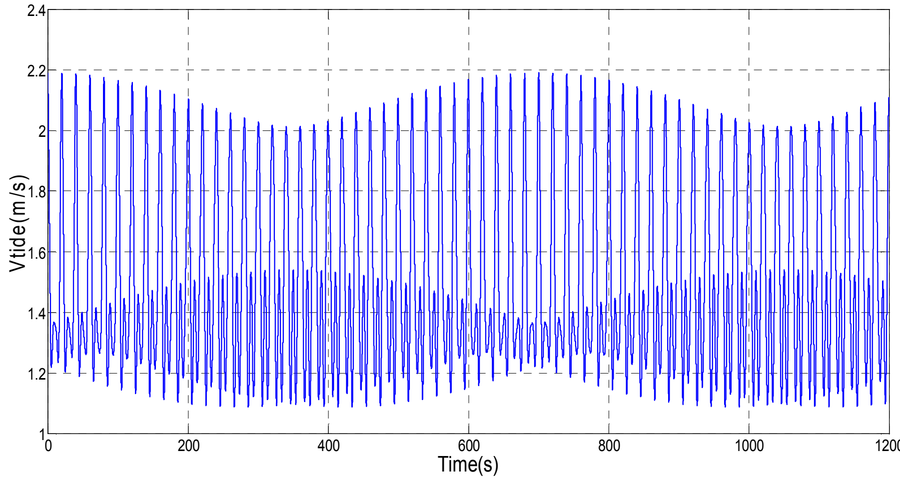

Fig. 3: Waveform of current velocity

$$G_{io}(s) = \frac{V_o(s)}{V_m(s)} = \frac{K_{pwm}}{L_o C_o s^2 + L_o s / R_0 + 1} \quad (15)$$

$$I_o(s) = \frac{V_o(s)}{R_0} \quad (16)$$

where,

$V_m(s)$, $V_o(s)$ & $I_o(s)$: Small signal ac perturbations on the input voltage, the output voltage and the current, respectively
L_o & C_o : The inductance and capacitance of the filter,
R_o : The load resistor
K_{PWM} : Simplified model of the inverter

Model of marine current and turbine: In order to simulate the current velocity, the comprehensive considerations such as wind, sea wave, seabed boundaries need to be taken. This study uses multiple cosine functions to simulate the influence of current velocity and adds average current velocity or adds noise signals such as white noise in order to simplify the analysis (Ben Elghali *et al*., 2009):

$$v(t) = a + A_1 \cdot \cos(\omega_1 t) + A_2 \cdot \cos(\omega_2 t) + \cdots + b(t) \quad (17)$$

where,

a : The constant value representing average current velocity
b (t) : Noise signal
A_x & ω_x (x = 1, 2, …) : Amplitude and angular frequency respectively

The details about the data need to be obtained by monitoring current velocities. The waveform of current velocity is shown in Fig. 3.

Model of marine current turbine: The design of marine current turbine blade is similar to the wind turbine blade, thus it also has a maximum limit referred to as the Betz limit, or more accurately the Lanchester-Betz limit (Ben Elghali *et al*., 2009).

The amount of mechanical power that can be extracted from the marine current turbine and fed to the PMSG is governed by the following well know equation:

$$P_m = \frac{1}{2} \rho \pi R^2 v^3 \cdot C_p(\lambda, \beta) \quad (18)$$

where,

ρ = The seawater density
R = The turbine radius
v = The current velocity
C_p (λ, β) = The power coefficient
β = The pitch angle
λ = Tip speed ratio

The tip speed ratio is defined by:

$$\lambda = \frac{\omega_m R}{v} \quad (19)$$

where, ω_m is the rotor rotational speed. Then the mechanical torque T_m of the marine current turbine is described as:

$$T_m = \frac{P_m}{\omega_m} = \frac{\rho \pi R^5 \omega_m^2 \cdot C_p(\lambda, \beta)}{2\lambda^3} \quad (20)$$

Figure 4 shows the simulation of power coefficient versus tip speed ration, where the experimental data are from available literature (Myers and Bahaj, 2006; Bahaj *et al*., 2007). The simulation is under the conditions: current turbine with a radius of 0.8 m, current velocity with 1.5 m/s and pitch angle with 25°.

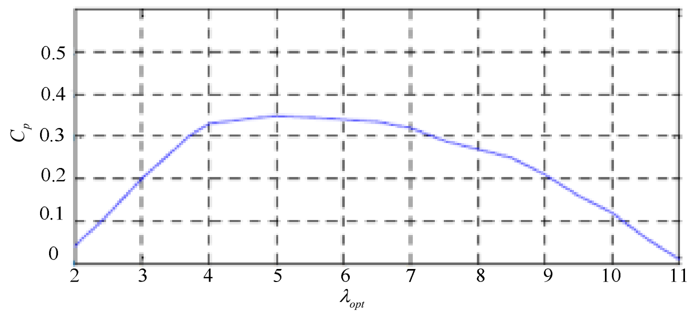

Fig. 4: Power coefficient fitting curve

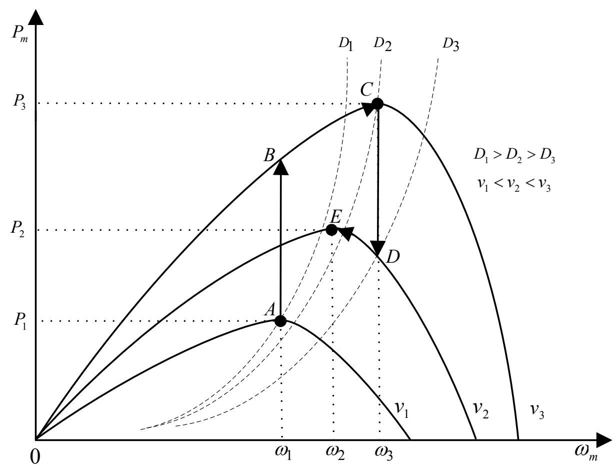

Fig. 5: Marine current power versus duty cycle curves for different current velocities

MPPT CONTROL METHOD

Because the low power stand alone marine current system cannot always work in the maximum power point, it is necessary to add the MPPT device between the generator and the load in order to capture the maximum power of the marine current energy all the time (Li *et al*., 2008; Pena *et al*., 2011), battery as energy storage is needed for stable operation due to the variable current velocities characteristics.

Figure 5 gives the power-rotor speed-duty cycle characteristics of a marine current turbine for varying values of current velocities.

For each current velocity, the maximum power point corresponds to only one value of the turbine speed (Ben Elghali *et al*., 2009), where the equation is written as:

$$\frac{dP}{d\omega_m} = 0 \tag{21}$$

From (4), (5), (13) and (21), the following equations are obtained:

$$\begin{cases} \dfrac{d\omega_e}{d\omega_m} = n_p > 0 \\ \dfrac{dV_{dc1}}{d\omega_e} > 0 \\ \dfrac{dD}{dV_{dc1}} = -\dfrac{1}{V_{dc2}} \neq 0 \\ \dfrac{dP}{d\omega_m} = \dfrac{dP}{dD}\cdot\dfrac{dD}{dV_{dc1}}\cdot\dfrac{dV_{dc1}}{d\omega_e}\cdot\dfrac{d\omega_e}{d\omega_m} = 0 \end{cases} \tag{22}$$

Then from (22) the following equation can be derived:

$$\frac{dP}{dD} = -\frac{\left[\left(k\varphi\omega_m\right)^2 - 2\cdot\left(\dfrac{\pi}{3\sqrt{6}}\cdot(1-D)\cdot V_{dc2}\right)^2\right]\cdot\pi\cdot V_{dc2}}{\sqrt{6}Ln_p\omega_m\sqrt{\left(k\varphi\omega_m\right)^2 - \left[\dfrac{\pi}{3\sqrt{6}}\cdot(1-D)\cdot V_{dc2}\right]^2}} \tag{23}$$

From (23), the equation between duty cycle and rotor speed is described by:

$$D_{opt} = 1 - \frac{3\sqrt{3}k\phi\omega_m}{\pi V_{dc2}} \tag{24}$$

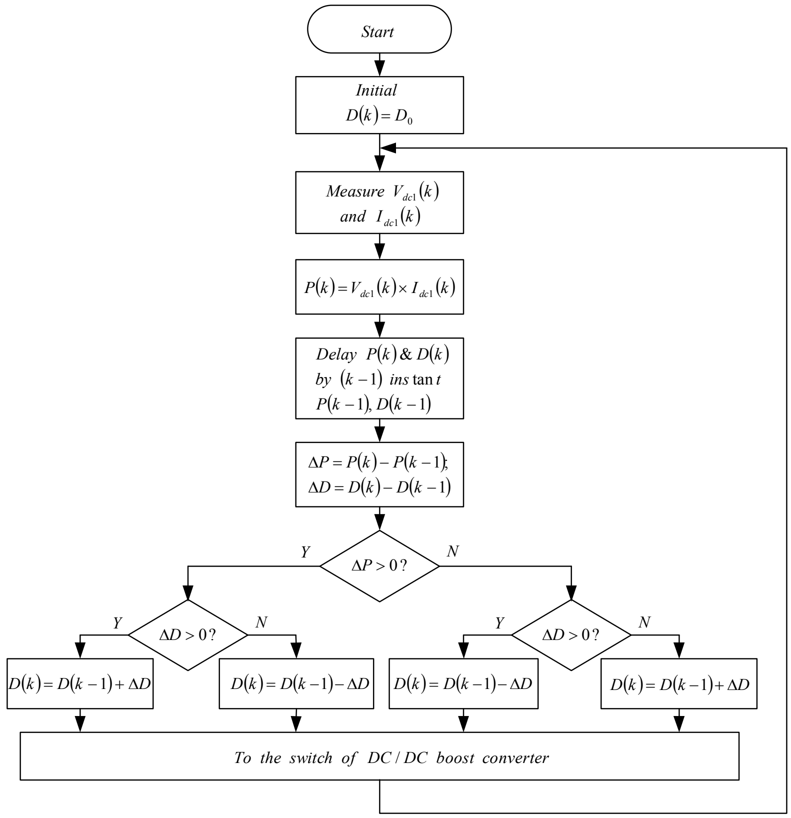

Fig. 6: Flow chart of the MPPT control

The MPPT algorithm proposed in this study includes several steps, which can be summarized as follows:

Step 1: Measure the value of DC voltage and DC current at the diode rectifier terminals.
Step 2: Calculate the value of the power from DC voltage and DC current values.
Step 3: Increase or decrease the value of duty cycle (*D*) by a certain perturbation value (ΔD).
Step 4: Calculate the sign of (*D*) and the sign of (ΔD). The duty cycle of DC/DC boost converter can be changed according to the following Eq. (23).
Step 5: Repeat steps 4-5 to obtain the maximum operating point.

Figure 6 indicates the steps of MPPT technique algorithm to get the optimum value of duty cycle.

Design and control of single phase inverter: Double closed loops control algorithm of single phase inverter has three typical types: external voltage RMS loop and internal instantaneous voltage loop, the external voltage loop and internal capacitance current loop, external voltage loop and internal inductive current loop (Wei *et al*., 2008). In this study, the control algorithm of external voltage RMS loop and internal instantaneous voltage loop is used. Outer and inner voltage controllers are regulated by the PI controller a. In this case, the proportional element adopted by inner regulator used to add damping coefficient of the single phase inverter in order to improve stability and reliability. Outer regulator used to make output voltage waveform follow the setting value precisely. The control system chart of single phase inverter is shown in Fig. 1.

Inner controller: Considering the PI controller, then the open-loop transform function can be derived as:

$$G_{io}(s)G_i(s) = (K_{ip} + \frac{K_{ii}}{s})\frac{K_{pwm}}{LCs^2 + Ls/R_0 + 1} \quad (25)$$

The Bode plot of inner loop with or without compensator is shown in Fig. 7, where corner frequency of the *LC* filter is designed as 1 kHz. Therefore, the crossover frequency of the current loop should be not exceed or even be close to the corner frequency, since it will create a 180º phase lag, whose resulting an insufficient phase margin. Here, the crossover frequency is set as 0.1 times the corner frequency, not considering delays caused by sampling and modulation. Then the PI controller parameter can be determined by

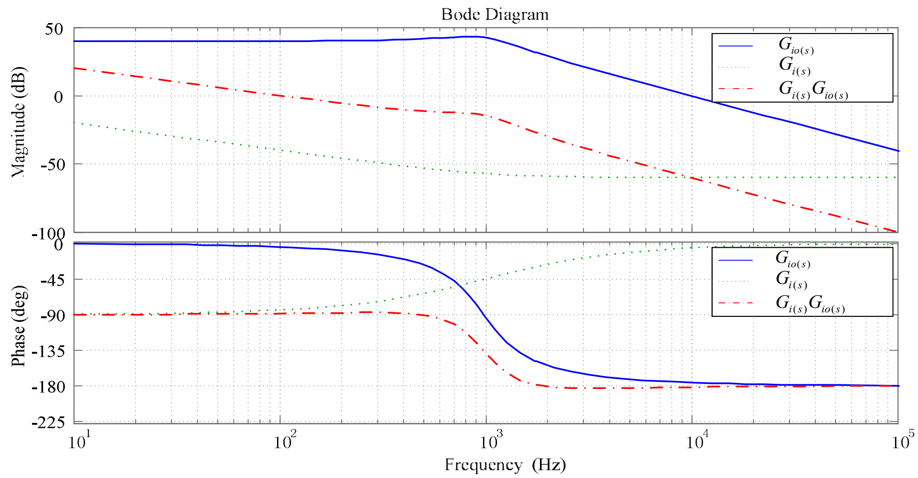

Fig. 7: Bode plot of the inner loop

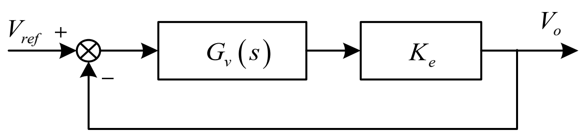

Fig. 8: Simplified model for outer loop

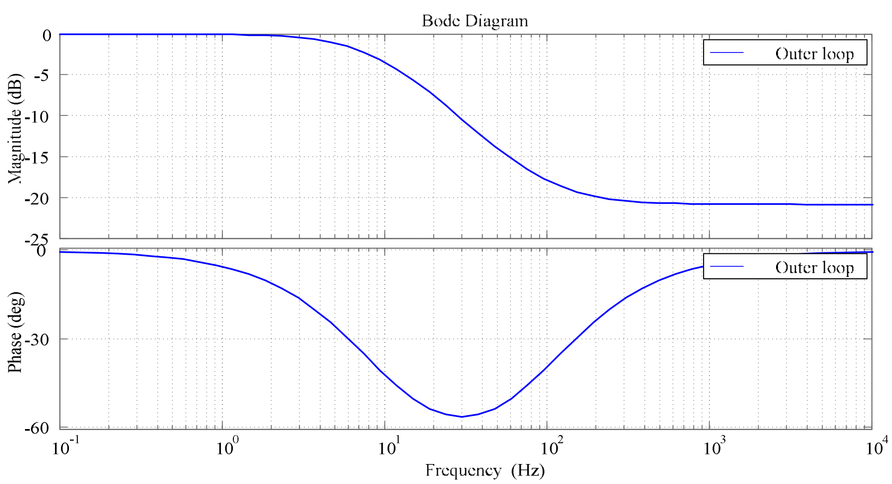

Fig. 9: Bode plot of the inner loop

setting the gain of G_{io} (s) G_i (s) to zero. The red curve shown in Fig. 8 proposes the Bode diagram of the inner loop with PI compensator. The G_i (s) is set to 0.001 + 6.28/s.

Outer controller: The outer loop ensures RMS of the output voltage. Then the outer loop time response should to be ten times slower than the inner loop time response. Therefore the inner loop of the inverter can be simplified as a constant K_e shown in Fig. 8, which is the gain of G_{io} (s) G_i (s) at the crossover frequency of outer loop. Based on the analysis, the G_v (s) is set to 0.112 + 70.4/s. Then Fig. 9 shows the Bode diagram of the inverter with inner and outer loop.

SIMULATION RESULTS

In order to check the proposed algorithm of MPPT control strategy and double closed loops control strategy, the whole small power marine current system is shown in Fig. 10 which has been simulated using

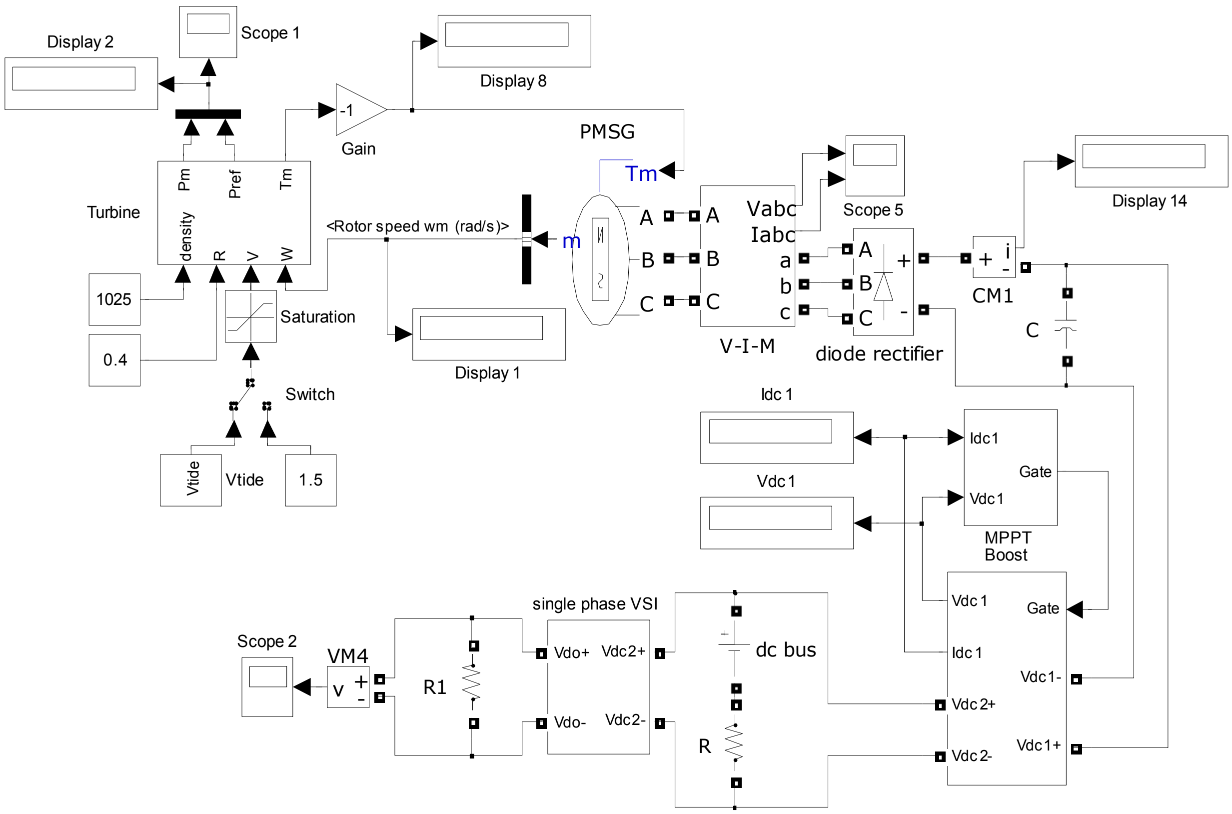

Fig. 10: Model of the proposed system in MATLAB/Simulink

Table 1: Parameters of the proposed system

Parameters		Value
MCT		
P_N	Nominal power of MCT	500 W
V_{udc}	Nominal current velocity	1.5 m/s
n_N	Optimal rotor seed at nominal current velocity	179 rpm
R	Radius of the blade	0.4 m
Generator		
P_r	Rated output power of generator	300 W
n_o	Number of pole pairs	12
R_z	Stator resistance	0.02 Ω
L_z	Synchronous inductance	0.85 mH
J	Rotor inertia	0.12 kg.m^2
Boost converter		
C_{bc1}	Input capacitor	4700 μF
L_{bc}	Boost inductor	1.2 mH
C_{bc2}	Output capacitor	100 μF
V_{dc2}	Rated output voltage	100 V
f_z	Switching frequency	10 kHz
Battery		
V_{bat}	Rated voltage	100 V
C_b	Capacity	100 Ah
SOC%	State of charging	75
Inverter		
V_c	DC voltage	100 V
V_o	Output voltage (RMS)	45 V
f_o	Frequency	50 Hz
P_o	Rated power	250 W
L_o	Inductor	1.2 mH
C_o	Capacitor	22 μF
f_{oo}	Switching frequency	10 kHz

MATLAB/Simulink software. The parameters of the system are shown in Table 1.

Figure 11 and 12 present the maximum output power that can be obtained from turbine and the output voltage waveform of single phase inverter in constant current velocity condition respectively. The red curve is the expected power curve and the blue curve is the real captured power curve. Voltage total harmonic distortion of single phase inverter is 0.52%.

Figure 13 shows the maximum output power that can be obtained from turbine in fluctuation current velocity condition respectively. The red curve is the expected power curve and the blue curve is the real captured power curve. Voltage total harmonic distortion of single phase inverter is 0.65%.

Figure 14 shows the maximum output power that can be obtained from turbine in transient current velocity condition. The red curve is the expected power curve and the blue curve is the real captured power curve. Voltage total harmonic distortion of single phase inverter is 0.68%.

EXPRIMENTAL RESULTS

To validate the proposed system, a prototype has been built in the laboratory, based on the same parameter values listed in Table 1 for DC/DC and DC/AC converter. And a programmable DC voltage source is used to simulate the generator and diode

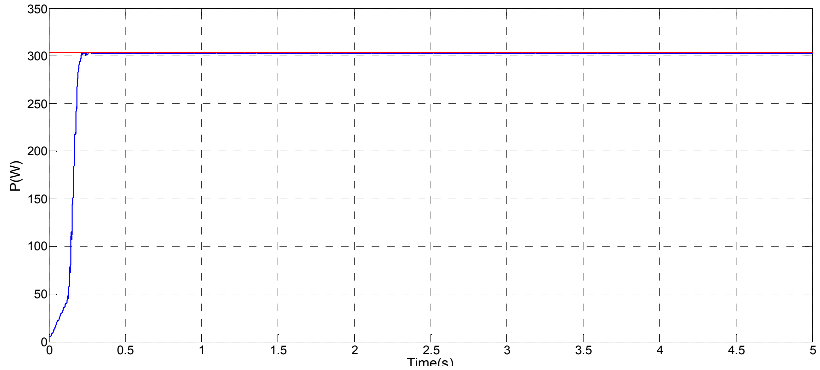

Fig. 11: Expected and real power curves

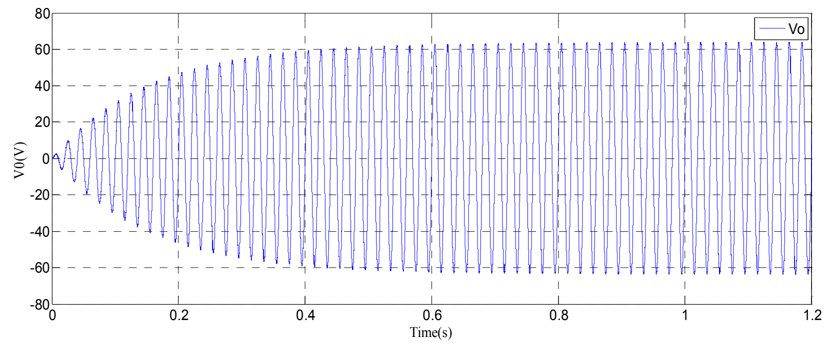

Fig. 12: Output voltage in the case of constant current velocity

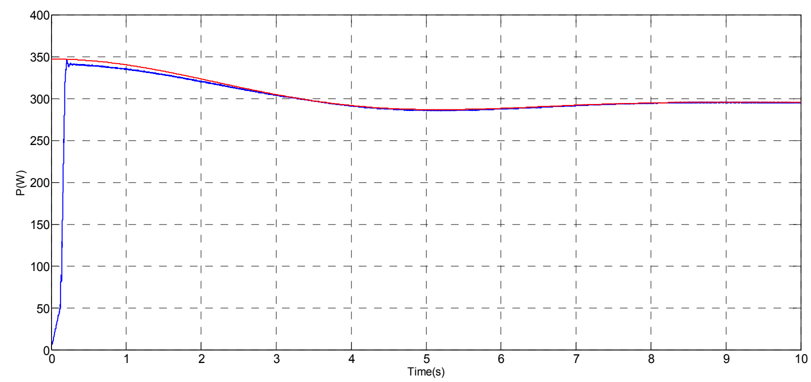

Fig. 13: Output power in the case of fluctuation current velocity

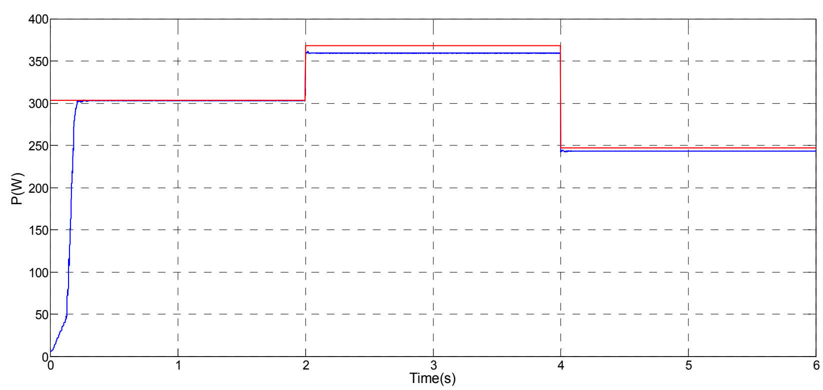

Fig. 14: Output power for step response

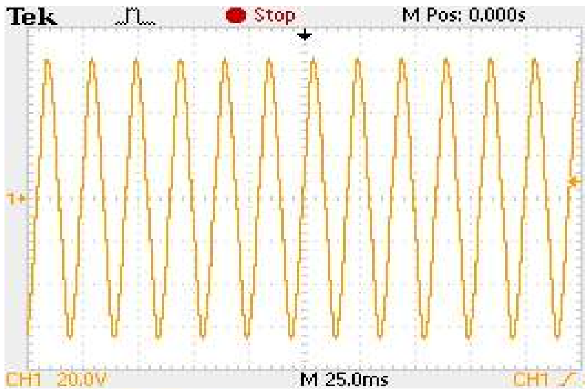

Fig. 15: Output voltage of the inverter

rectifier circuit. The developed control algorithm is executed in a dSPACE1104 real-time platform.

The MPPT method can track the maximum power point at 299 W, when the ideal output power is 300.5 W. And the Fig. 15 shows the output voltage of the inverter with a THD of 0.94%.

CONCLUSION

Through above research, a steady state modeling and a simple topological structure is suited for the small scale stand alone marine current system. The proposed DC/DC boost converter duty cycle control method is simple and easy to track the maximum power point of the current generator with hill-climbing searching algorithm. The double closed loops control can improve the dynamic and static performance of single phase inverter. The proposed system has been modeled and simulated using MATLAB/Simulink software. A prototype has been developed on dSPACE1104 real-time platform in order to demonstrate the feasibility and validity of the proposed control strategies.

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