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Modeling and power optimization control of tidal energy systems

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ABSTRACT

As interest in emergency power has increased, and the research on engine generators has been actively conducted. Permanent magnet synchronous generators (PMSGs) are suitable for small-capacity engine generators, because they have higher efficiency and faster response than other motors. In this paper, the static and dynamic characteristics of the tidal turbine have been modeled and implemented experimentally. The rotational speed of the PMSG is regulated to extract the generator maximum power at a variable tidal velocity using the conventional optimum tip-speed ratio method. It has been implemented to the proposed tidal power system since it is a simple method. The performance of the PMSG in the tidal power system has been investigated at different tidal speeds. The experimental results have validated the efficiency of the proposed controller to extract the maximum power point.

Keywords: Tidal power generation; Tip-speed ratio; Permanent magnet synchronous generator.

INTRODUCTION

Recently, the need for new and renewable energy development is increasing due to the economic and policy factors caused by rising oil prices, the depletion of fossil energy, and the changing consciousness of people who value the environment. In addition, advanced countries such as the EU have already implemented the carbon dioxide emission trading system (ETS) in 2005 in relation to the climate change agreement and the Kyoto Protocol. Therefore, the government is planning to expand to 3% of total energy by 2010 and 5% by 2015 [1]–[3]. Therefore, it is necessary to accelerate the development of cheap and safe new and renewable energy sources.

Marine energy, one of the renewable energy sources, has been spotlighted as a clean and infinite energy resource. The energy being developed in the oceans around the world is tidal power generation, wave power generation, ocean temperature difference power generation, tidal power generation, etc. The only commercial tidal power generation has a global capacity of 3000 GW [4].

Tidal power is a technology that generates power by converting kinetic energy generated at this time into electric energy by driving a turbine or a rotor through the flow of seawater and is applied to areas with high flow rates. In general, the flow rate of seawater for tidal current generation is at least 1 m / s. However, when considering economics, it should be installed at a location of 2 m / s or more. Accordingly, tidal power has the advantage of predicting the amount of power generation compared to solar or wind power, which is, sometimes, difficult to predict. Tidal power generation has numerous advantages; some of these advantages will be explained below [5]:

- It is a predictable resource as it depends on the tides;
- It has a slight environmental impact, but much less than other electricity generation systems, both renewable and conventional;
- A tidal turbine with a current speed between 2 and 3 m/s can obtain about four times more annual power than an equivalent wind turbine. So, the increase in the cost of both installation and maintenance of the tidal power system is more than offset by the increase in production;
- Among the positive effects attributed to wave power generating farms are breaking the waves and reducing erosion on the coasts, and some manufacturers attribute these devices the ability to harbor marine life, since that acts as artificial reefs.

There is only one point that the tidal turbine produces the optimum power according to the change of each flow velocity, and it is essential to understand the dynamic characteristics of the blade in order to control the MPPT to operate at this optimum point. In literature, a tidal power generation system with the PMSG is presented in [4]; this generator is connected to the grid by means of a variable frequency converter, which consists of two pulse width modulation (PWM) converters connected in back-to-back configuration with a DC link in the middle and with field-oriented vector control. The generator-side converter is responsible for controlling the speed of the generator to maximize power extraction, and the network-side converter is responsible for keeping the DC link voltage constant and controlling the supply of active and reactive power to the grid. The choice of PMSG in the tidal system is a good decision, as it does not need external excitation current, which simplifies the project and eliminates the need for slip rings and brushes. The choice of two six-switch converters in back-to-back configuration has the advantage of allowing vector control of the network-side converter and the machine-side converter, but it is more expensive compared to the diode rectifier configuration. On the generator side, the control consists of an internal current loop and an external speed loop. The reference signal is obtained from the speed loop, i_q, where i_d is zero to guarantee maximum torque obtained from the current ratio. On the network side, the control has an internal loop to control the grid current and an external loop to control the DC link voltage, reference i_q is zero for a unit power factor, and reference i_d is obtained from the external control loop of the DC link voltage. The synchronization is done through a phase loop locked (PLL).

The use of Direct Drive Permanent Magnet Synchronous Generator (DDPMSG) to generate energy from tidal currents is presented in [5], in which the configuration of the full-scale power converter is used. The generator is Direct Drive due to the low speed of the marine current and the high energy stored in the density of the water. This means that it does not need a gearbox and continuous maintenance. Small signal stability analyses are performed using PMSG with and without a controller. In this configuration, the generator side converter (MSC) is used to maintain the rotation speed at the optimum value of the DDPMSG and thus minimize losses in the air gap. The grid-side converter (GSC) is responsible for controlling the voltage of the DC link and for controlling the reactive output power in a certain reference. It is also commented that other controllers use the generator-side converter to control the active and reactive power of the DDPMSG output, while using the network-side converter to control the voltage in the DC link and the terminal voltage of the turbine system.

A tidal power generation system composed of three synchronous generators connected in a single common DC link by means of diode rectifiers is proposed in [7]. This configuration has as main objective the reduction of costs due to the lower use of converters. The power output of each generator is regulated by controlling the excitation of each generator's field and thus achieving maximum power extraction. The voltage of each generator is rectified and connected in parallel to a common DC link, and then, it is transmitted to an on-shore station, where it is supplied to the network by means of a DC-AC converter. To control power variations due to changing currents, the control system consists of two loops, an internal loop that controls the excitation current of the field and an external loop that controls the generator power.

A hybrid wind-tidal system composed of an induction machine that works as a tidal generator and a permanent magnet wind generator is proposed in [8]. The connection to the grid is made through the DC side. The tidal generator provides smooth power output, while the output of the wind turbine depends on the wind speed. The power generated by the wind and tidal generator is converted into DC power, and this is again converted to AC power by means of an inverter to be connected to the grid. The tidal turbine is used as a flywheel, where this type of system has the purpose of the bidirectional flow of power, so that the power is injected into the network by the wind turbine located at sea or stored as kinetic energy output/input from the marine system.

A hybrid system composed of a tidal farm (PMSG) and a wind farm (DFIG) with a flywheel storage system is proposed in [10], and the connection to the grid is through power converters. This system is more expensive but allows independent control of each system. The response to a wind speed disturbance allows us to observe that the flywheel reduces the reactive power but has no significant effect on reducing the amplitude of the active power of the wind farm since the active power generated from the wind farm is directly related to the disturbance of the wind farm, wind speed. In relation to the marine farm, the flywheel reduces the amplitudes of active and reactive power.

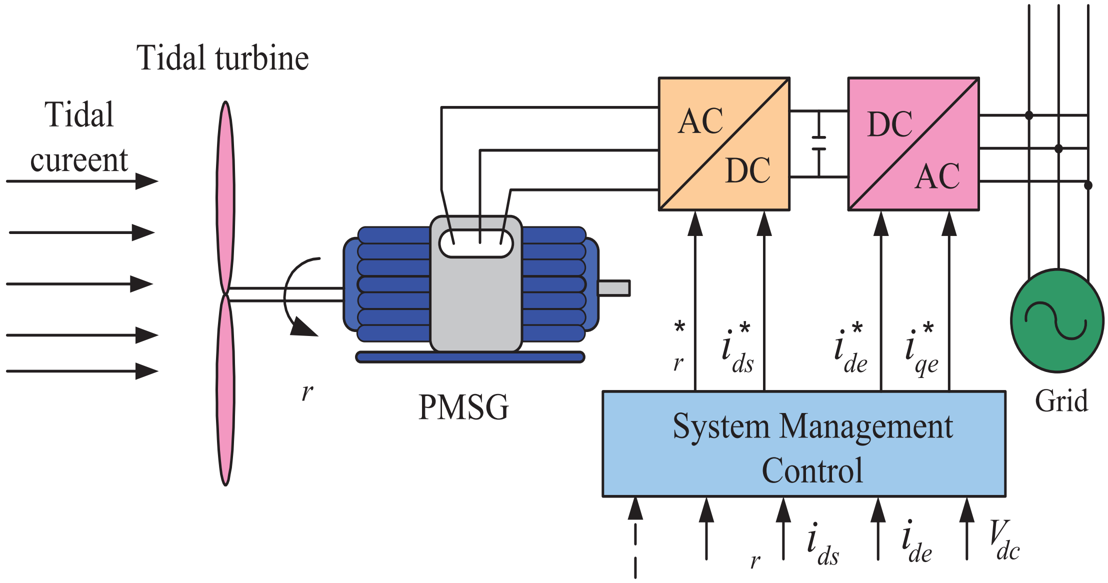

Figure 1. Tidal generation system block diagram.

To implement the tidal power generation system shown in Figure 1, the system is constructed using a back-to-back converter using a squirrel cage induction machine turbine model [11]. In particular, the proposed system is a place where MPPT can be obtained at a specific tidal velocity for each flow rate. By controlling the rotation speed of the generator, a system with higher efficiency than a fixed-speed power generation system can be implemented. It has the advantage of being. In the existing MPPT method, tide velocity was measured and used as a control variable. However, this method requires additional measuring equipment, thus brings a cost burden, and has a lot of difficulties in measuring the flow velocity due to vortex. Therefore, by improving the above disadvantages, this paper proposes a system to find the maximum power point without flow rate information [12]–[14].

Since the proposed system is controlled by reflecting the characteristics of the turbine, it can be said to be a very good way to understand MPPT control characteristics of tidal currents and tidal power generation systems that do not use flow velocity information in a limited laboratory environment. The effectiveness of the proposed system was verified through simulation and experimental results.

MATHEMATICAL MODEL OF TIDAL POWER GENERATION SYSTEM

2.1 The Mathematical Model of Tidal Turbine

The horizontal axis tidal turbine is similar to the wind turbine, and the mechanical output is expressed as follows [15]–[17]:

$$P_{blade} = \frac{1}{2}\rho\pi R_{blade}^2 v_{tide}^3 C_p(\beta,\lambda) \quad (1)$$

where ρ is the water density, R_{blade} is the radius of the blade, β is the pitch angle, and λ is the tip speed ratio (TSR), v_{tide} is the tidal current speed, which is the ratio of the tidal speed of the blade tip to the rotation speed of the turbine, and C_p is the power coefficient.

The general C_p function is the same as equations (2), (3) [18]:

$$C_p(\beta,\lambda) = C_1\left(\frac{C_2}{\lambda_1} - C_3\beta - C_4\right)e^{\frac{-C_5}{\lambda_1}} + C_6\lambda \quad (2)$$

$$\frac{1}{\lambda_1} = \frac{1}{\lambda - 0.08\beta} - \frac{0.035}{\beta^3+1} \quad (3)$$

$C_1 = 0.5176$, $C_2 = 116$, $C_3 = 0.4$, $C_4 = 5$, $C_5 = 21$, $C_6 = 0.0068$.

The TSR(λ) is defined as equation (4) as the ratio of the blade end velocity to the flow velocity [19]:

$$TSR = \frac{\omega_r\ R_{blade}}{v_{tide}} \quad (4)$$

where ω_r is the blade rotational speed in [rad/s]. Since the control of the pitch angle is not taken into account in this study, it is set to zero (β =0). Figure 2 represents the change of the output coefficient according to the main speed ratio. The output coefficient of the tidal current turbine is determined by the main speed ratio of the optimum value as illustrated in Fig. 2. Using this characteristic, it can be expressed as Equation (5) to generate the maximum output of the tidal current turbine [20]–[22]:

$$P_{max} = \frac{1}{2}\rho\pi R_{blade}^2 v_{tide}^3 C_{pmax} \quad (5)$$

As mentioned earlier, the output coefficient of the tidal current turbine is defined by the optimal speed ratio. In order to produce the maximum power depending on the flow rate, it is necessary to operate at the optimum circumferential speed. Figure 3 shows the tidal turbine characteristics at different tidal speed. In high tidal speed, the turbine power increases and becomes maximum at certain operating rotational speed.

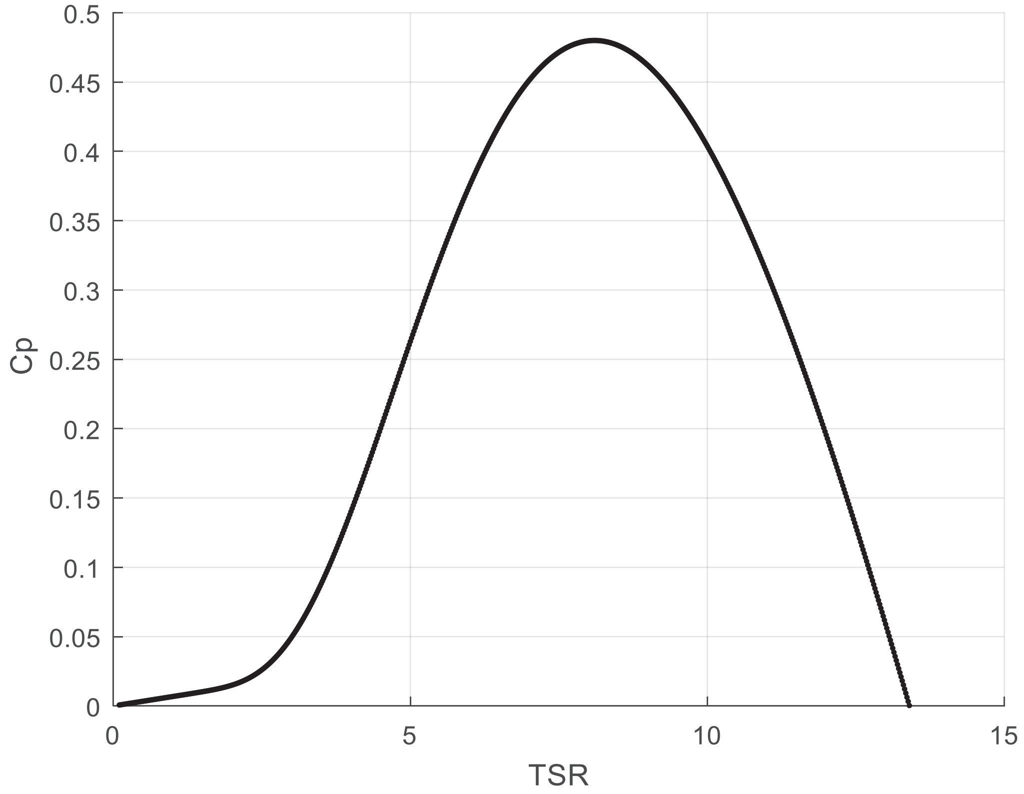

Figure 2. C_P versus TSR characteristic curve.

For varying tidal current velocities, Figure 4 depicts the power harnessed by the turbine. The power difference between the cut in speed V_c and the rated speed V_n is determined by the optimum operating points characteristic. Since the tidal current speed is predictable, there is no cut-off limit for tidal current turbines.

Second, even the most intense storm surge currents levied on the peak spring tides are usually not much stronger than the monthly mean spring tidal currents. The tidal turbine, on the other hand, must be built to withstand peak tidal speeds that are many times higher than the average monthly daily tidal speed.

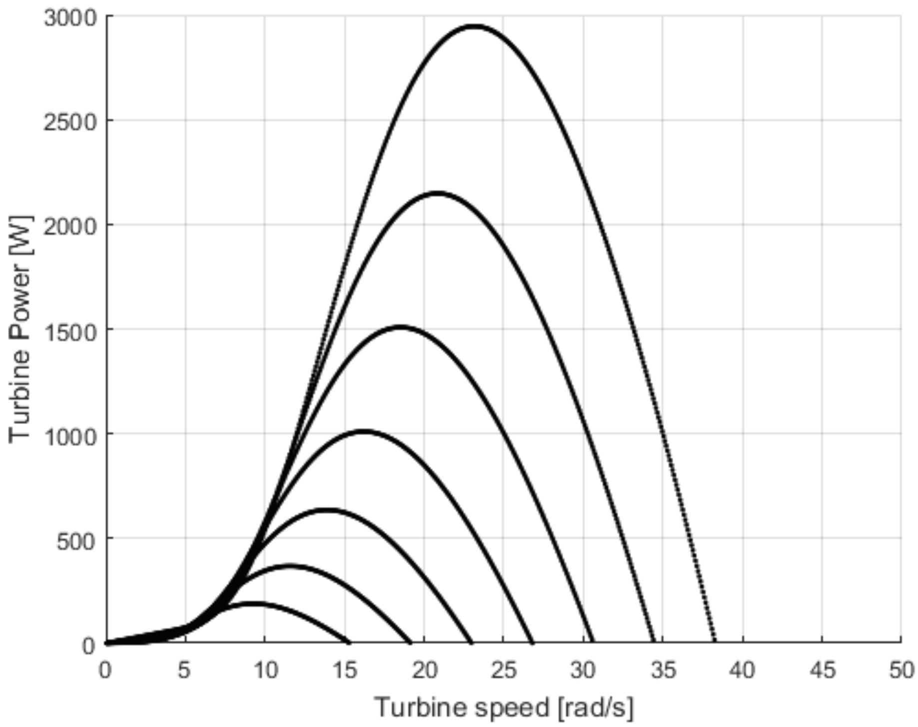

Figure 3. Power curve as a function of generator speed.

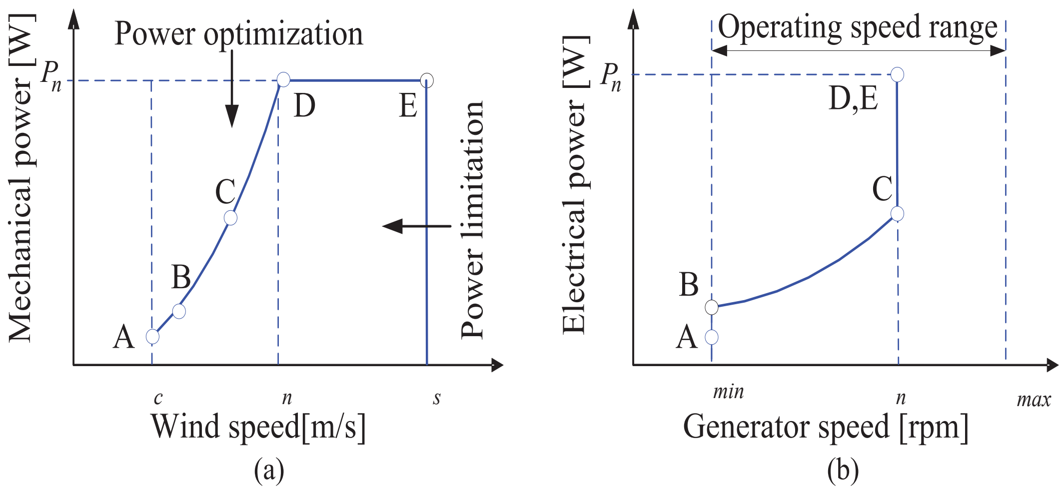

Figure 4. Power curve in different modes.

2.2 PMSG Modeling

The characteristics of permanent magnet type synchronous motor are high efficiency since there is no need for an excitation winding for generating the magnetic flux of the rotor, and a high output density compared to the volume of the motor has a high output density. The electric modeling of the permanent magnet type synchronous motor in the synchronous coordinate system is expressed by equation (6) [23]:

$$\begin{bmatrix} v_{ds}^r \\ v_{qs}^r \end{bmatrix} = \begin{bmatrix} R_s + pL_s & -\omega_r L_s \\ \omega_r L_s & R_s + pL_s \end{bmatrix} \begin{bmatrix} i_{ds}^r \\ i_{qs}^r \end{bmatrix} + \begin{bmatrix} \Psi_f \\ 0 \end{bmatrix} \tag{6}$$

where Rs, Ls, ω_r and Ψ_f mean stator winding resistance, stator: inductance, electric angular velocity, and rotor magnetic flux, $p = d / dt$, respectively.

The electric torque of the permanent magnet synchronous generator is expressed as Eq. (7) [24]:

$$\mathrm{T_e} = \frac{3}{2}\mathrm{np}\Psi_f i_{qs}^r \tag{7}$$

where n_p is the number of poles, and Ψ_f is the magnetic flux that binds the stator windings in magnitude.

MPPT control using the optimal circumferential speed ratio creates a speed command value that gives the maximum output, and to control the torque of the generator, the speed controller outputs a command value of the q-axis current. In addition, the d-axis current is set to zero to maintain the generator flux constant. Therefore, the torque depends only on the q-axis component of the stator current amplitude. Figure 5 is a control block diagram of a permanent magnet synchronous generator.

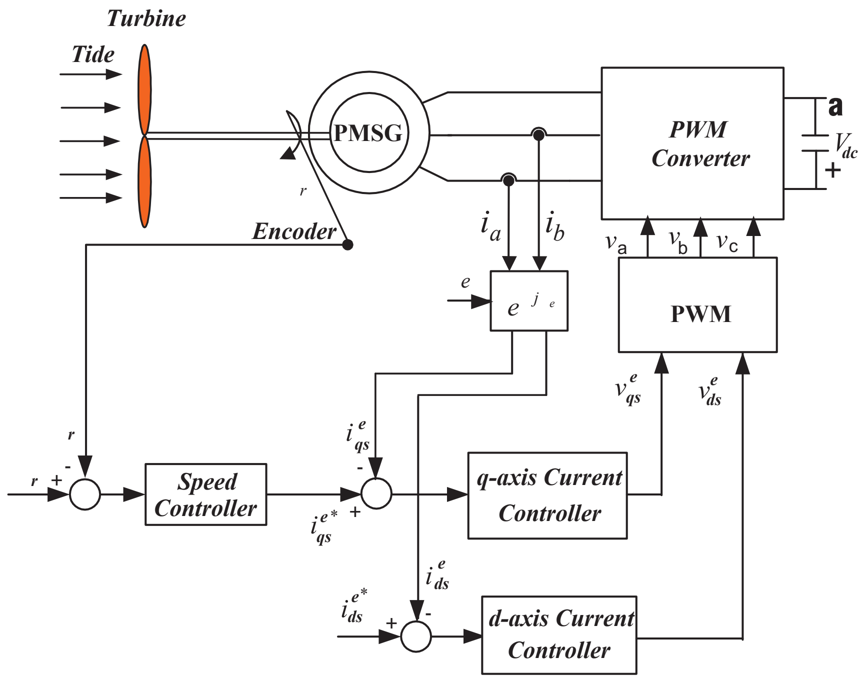

Figure 5. Block diagram of overall control structure of generator-side converter.

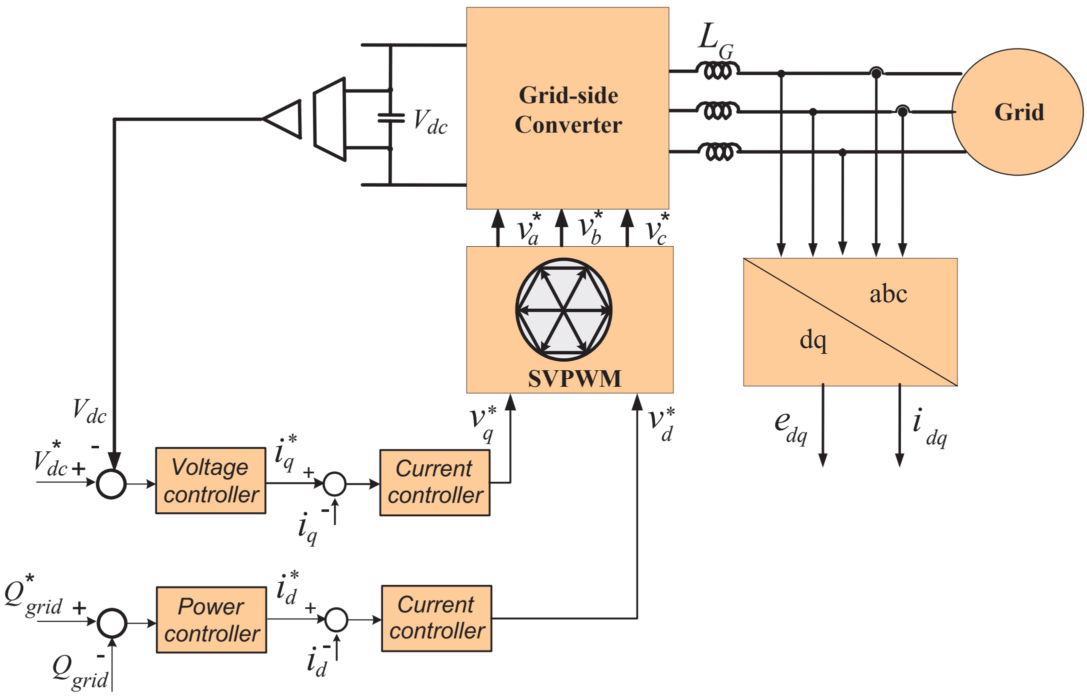

Figure 6. Block diagram of overall control structure of grid-side PMSG.

The voltage equation on the system side is expressed in Equation (83) when expressed on the synchronous coordinate system using the three-phase voltage and the control voltage of the converter [25], [26]:

$$\begin{bmatrix} V_{dg}^e \\ V_{qg}^e \end{bmatrix} = \begin{bmatrix} R_g + pL_g & -\omega_e L_g \\ \omega_e L_g & R_g + pL_g \end{bmatrix} \begin{bmatrix} i_{dg} \\ i_{qg} \end{bmatrix} + \begin{bmatrix} v_{dg} \\ v_{qg} \end{bmatrix} \tag{8}$$

where R_g and L_g are the resistance and inductance between the grid-side converter (GSC) and the utility grid, respectively, ω_e is the angular frequency of the grid, and $V_{dg},\ I_{dg},\ V_{qg}, and\ I_{qg}$ are the dq components of the stator voltage and current at GSC, respectively. v_{dg}^e and v_{qg}^e are the dq components of grid voltage, respectively. Figure 4 presents the current control loop of the GSC in dq axis.

From the above equation, it can be seen that the q- axis is related to the active power, and the d-axis is independent of the active power and only to the reactive power [27], [28]:

$$P_{grid} = \frac{3}{2}\left(v_{dg}^e i_{dg}^e + v_{qg}^e i_{qg}^e\right) \tag{9}$$

$$Q_{grid} = \frac{3}{2}\left(-v_{dg}^e i_{dg}^e + v_{qg}^e i_{qg}^e\right) \tag{10}$$

From Eqs. (9) and (10), the active and reactive power outputs are calculated by dq-axis current m control, according to GSC. Consequently, q-axis current control can control DC-link voltage, while d-axis current control can control the reactive power output to the system. Figure 6 depicts the GSC's d-q axis current control loop.

EXPERIMENTAL RESULTS

Figure 7 illustrates the full control scheme for the permanent magnet synchronous motor used in the experiment. The main system configuration comprises of PMSG with rating of 2.7 kW, a DC motor with capacity of 3 kW, which is employed as a load, tidal simulator, inverter to convert the Dc to AC electric power, and controller. The PWM inverter's switching frequency was 10kHz.

The utilized processor is TMS320VC33-120MHz. The characteristics of the PMSG are introduced in the appendix section.

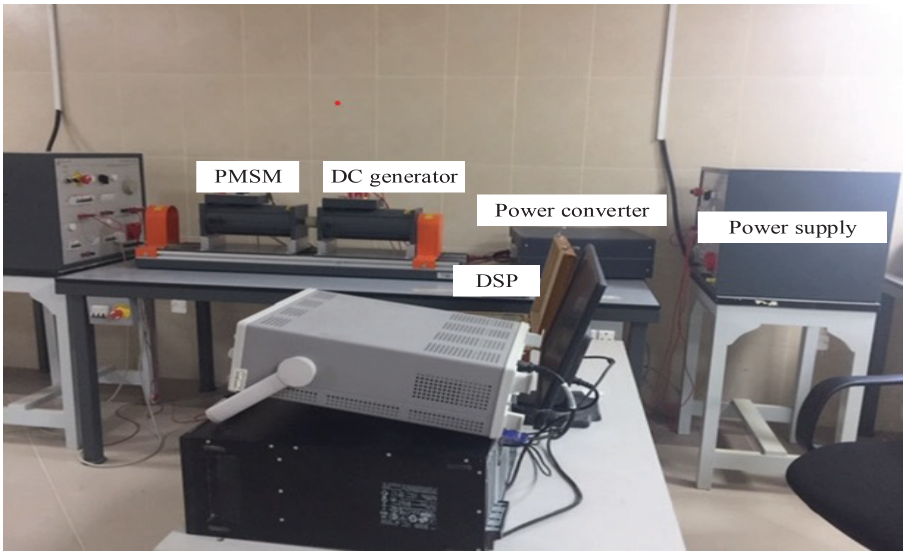

Figure 7. PMSG experimental setup.

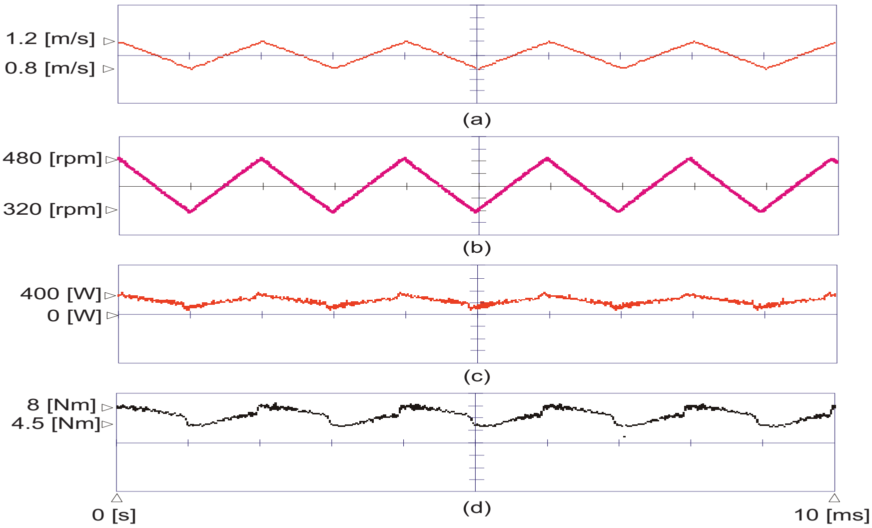

Figure 8. Maximum power point tracking for variable water speed: (a) tidal speed, (b) generator speed, (c) generator power, (d) generator torque.

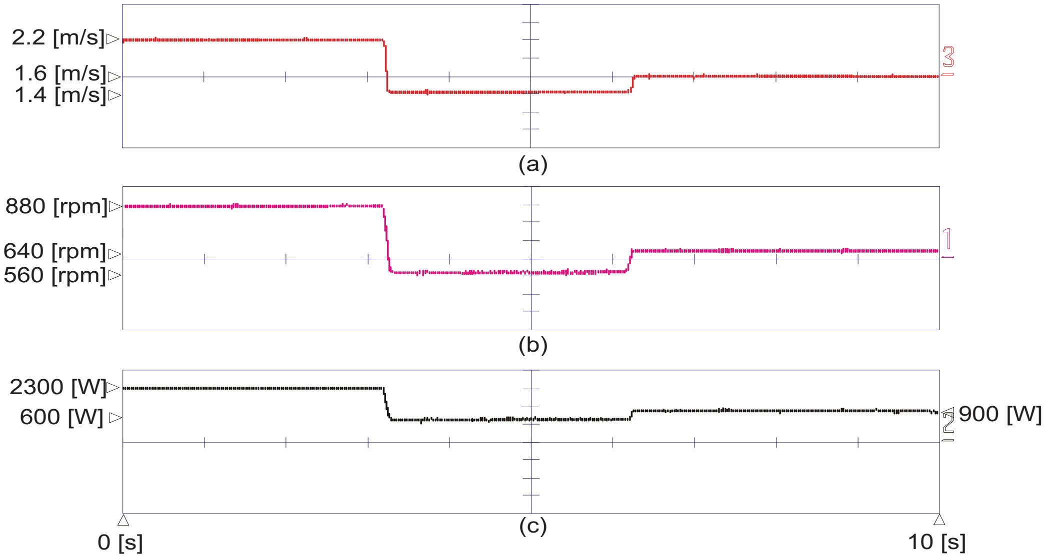

Figure 9. Maximum power point tracking for variable water speed:
(a) tidal speed, (b) generator speed, (c) generator power.

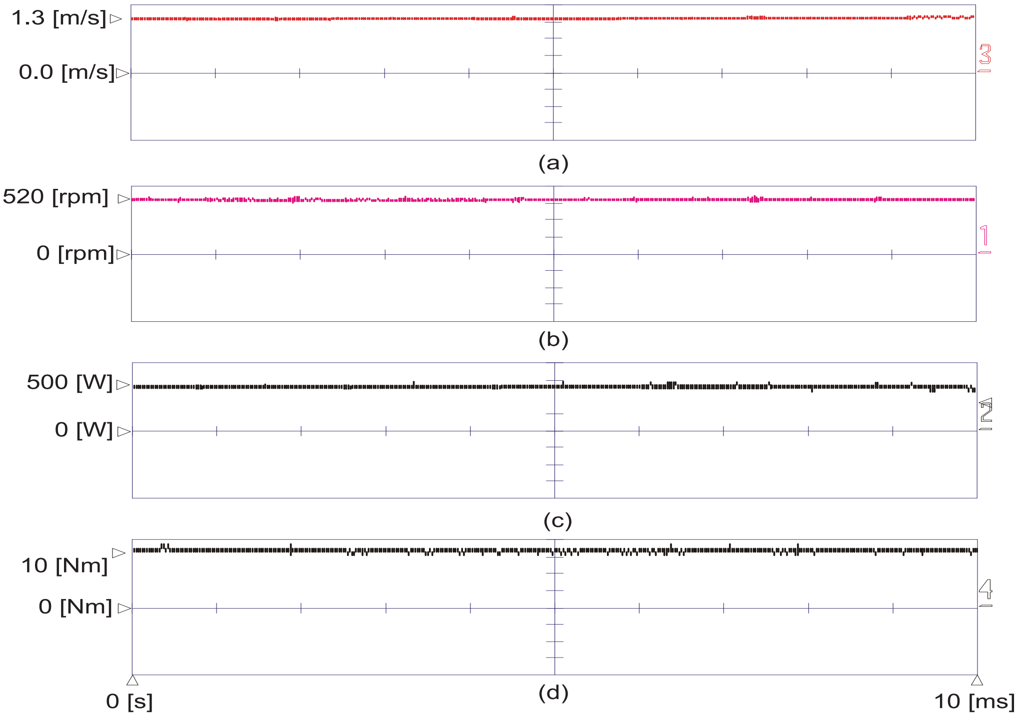

Figure 10. Maximum power point tracking for constant water speed: (a) tidal speed, (b) generator speed, (c) generator power, (d) generator torque.

.The water speed pattern was changed to be sawtooth from 0.8 m/s to 1.2 m/s as shown in Fig. 8(a). The rotational speed follows the tidal speed pattern as shown in Fig. 8(b). The TSR algorithm adjusts the rotational speed to extract the generator maximum power, which is shown in Fig. 8(c). The maximum electromagnetic torque is also shown in Fig. 8(d).

Figure 10 shows that the controller performance is investigated during the tidal speed increasing in steps. The tidal speed is stepped up from 1.4 [m/s] to a short step of 1.6 [m/s] and then long step of 2.2 [m/s] as shown in Fig. 9(a). In the speed optimization strategy, the MPPT algorithm adjusts the generator speed continuously to the optimum rotational speed reference signal provided by the maximum power out of the tide as shown in Fig. 9 (b) and (c).

The performance of the PMSG in a constant tidal current is shown in Fig. 10. When the tidal speed is 1.3 [m/s], the optimum generator rotational speed is adjusted to about 520 [rpm]. This speed is related to the peak power, which is 500 [W]

CONCLUSION

Through this paper, an MPPT control of a permanent magnet synchronous tidal current generation system and a tidal turbine emulator using a squirrel cage induction turbine model was implemented, and its effectiveness was verified. Experimental results show that the used controller has a satisfactory control of the PMSG rotor speed. Through TSR MPPT method, the system can control MPPT in an efficient way, in which the performance was as satisfactory as the conventional strategy, based on PI controllers. As with the conventional vector control, there are one outer loop to control the generator speed and two inner current controllers' loop to control the d and q axis currents. The generator speed is adjusted to extract the maximum power by calculating the optimum rotational speed from the optimum tip-speed ratio at each tidal current speed. It was found that the presented controller improved the system efficiency by extracting the maximum power in different tidal speed.

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APPENDICES

The characteristics of the PMSM which is used for experiment are illustrated in Table 1.

R= 1.5, TSR =4, w rated =100 rpm

Table 1. Parameters of the PM synchronous machine.

Parameters	Value
Rated Power	2.7 [kW]
Rated speed	1200 [rpm]
Number of poles	6
Rated current	9.5 [A]
Stator resistance	0.5 [Ω]

d-axis inductance	3 [mH]
q-axis inductance	7 [mH]
Flux Linkage	0.175 [Wb]
Moment of inertia	$1.8X10^{-3}$ [$kg.m^2$]

Table 2. Parameters of Tidal Turbine Blades.

Parameters	Value
Blade radius	0.65 [m]
Max. power conv. coeff.	0.45
Optimal tip-speed ratio	4
Cut-in speed	0.7 [m/s]

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