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Modeling and Implementation of a Wave Energy Converter Emulator for Testing Multi-port Power Converters in a Marine DC Microgrid

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Abstract

A DC Microgrid system has tremendous potential for extracting ocean energy and providing power to coastal communities in remote locations. However, experimentation with Wave Energy Converters (WEC), power electronic converters, storage, and load during the microgrid development stages poses challenges due to the limited accessibility to physical WECs. This paper presents the modeling, design and hardware implementation of a WEC emulator with real WEC characteristics and a physical testbed using a power-hardware-in-the-loop (PHIL) set-up that can provide a reliable testbed to facilitate the design, optimization, and development of a DC microgrid system for marine renewable energy resources. The WEC emulator is precisely modeled to replicate the paddle dimensions, gearbox, and generator, accurately reflecting the system found in real WECs when driven by ocean waves with real ocean wave data. A Multiport Power Converter (MPC) is used in the testbed to integrate generation, storage, and load in the DC microgrid.

Keywords: WEC; emulator; modeling; testbed; microgrid.

1. Introduction

Marine and hydrokinetic (MHK) technologies have the high potential to provide clean energy to meet the ever-growing societal demand for energy. A WEC emulator configured with real wave data can serve as the renewable power generation source and connect to the power converter stage for the development and hardware evaluation of a DC marine microgrid. A motor-generator based WEC emulator aids controller development with maximum power extraction from the renewable generation source. The testbed built with the WEC emulator, and the power converter also helps evaluate the energy storage unit supporting the generation and load profiles. The actual data from NREL (National Renewable Energy Laboratory) HERO (the Hydraulic and Electric Reverse Osmosis) WEC is used to model this WEC. For the power converter stage, a multiport converter (MPC) is used to integrate the renewable generation,

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storage and load. The design and development of the MPC, shown in Fig. 1, is reported in [1]. There are different types of WECs used for wave energy extraction such as the paddle-type [2] or the buoy-type [3, 4]. This paper focuses on creating a physical testbed by modeling a particular WEC-type and emulating the characteristics in a hardware based WEC emulator for a wave energy-based DC marine microgrid. The WEC output will have the speed-torque profile of the power-take-off (PTO) device with real-world wave input data. The WEC emulator and PTO output is the generated three-phase AC output voltage that feeds into the MPC for integrating with the storage and load. In the laboratory testbed, a 5kW MPC processes the generator power input and manages the charge/discharge of the energy storage unit to meet the load demand continuously. This MPC includes a renewable energy generation port (WEC), a storage port for power stabilization, and a split-phase AC load/grid connection port. It manages power flow from the WEC to storage or loads, regulating a 400V DC bus. The split-phase AC port can power two 120V loads or one 240V load and connect to the grid.

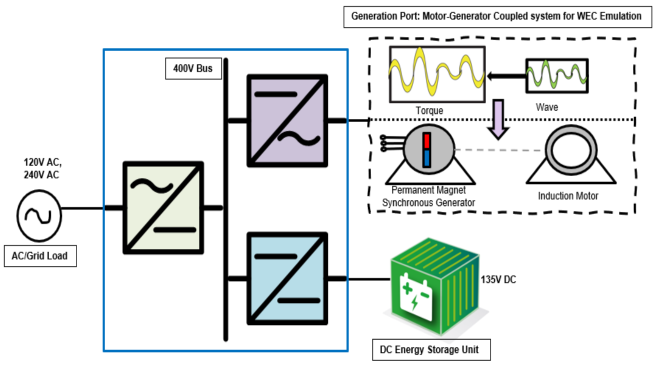

Fig. 1. WEC emulator and MPC for a marine microgrid.

2. Wave Energy Converter Modeling

The paddle-type WEC has either a gearbox or a wench-pulley system to transform the linear movement of the paddle into the rotational speed for the generator. Fig. 2 shows the system architecture of a paddle-type WEC using a gearbox for creating that rotational speed for the generator to start moving. The paddle type of WEC moves back and forth by the oscillating sea water. The shaft torque developed due to the water movement drives the generator. The actual WEC's paddle dynamics, gear and generator dynamics are emulated through a power amplifier. This grid simulator and its controller will emulate the dynamics of a WEC, accurately replicating actual WEC data. This emulation is useful for processing and integration of this renewable energy into the microgrid. This emulation process will help to use any kind of WEC's data (a paddle type or a buoy type) and make it useful for validating a microgrid which can harness ocean waves. The WEC systems dynamic behavior is emulated within the microcontroller of the power amplifier to generate the appropriate torque demand for generating the variable voltage and variable frequency of the WEC's output. Any WEC's dynamics mostly include the physical and mechanical structure of its device. The paddle's mechanical structure is crucial for maximizing power extraction from waves to the PTO.

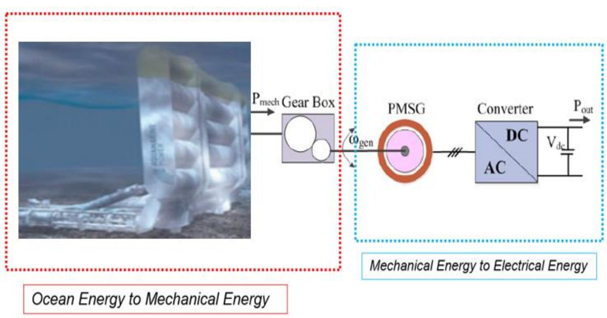

Fig. 2. Actual paddle-type WEC system architecture.

The paddle type of WEC as shown in Fig. 3, is installed near the seashore and is driven by the kinetic energy of the sea wave. It is also considered that the paddle is always completely submerged. *R*, *D* and *W* are the radius, uniform depth and width of the paddle, respectively. Due to rotary motion of the paddle, the linear velocity of the paddle along its radius is not the same. Consequently, the force developed on the paddle also varies along the radius. Therefore, the total force and torque on the paddle are calculated by integrating the elementary deferential force over the radius. The total force (F_T) on a moving body submersed in an oscillatory flow can be computed by the Morison Equation [2]:

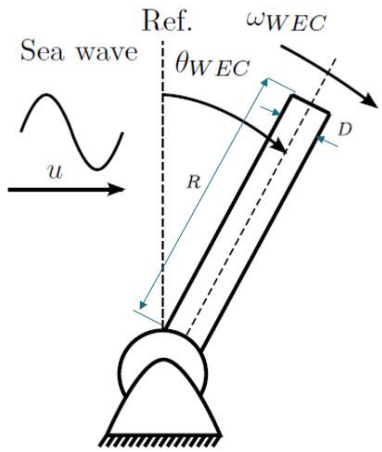

Fig. 3. WEC position under oscillating water flow.

$$F_T = F_{fk} + F_h + F_d \quad (1)$$

where the constituent forces are Froude-Krylov force, $F_{fk} = \rho V\dot{u}$; hydrodynamic mass force, $F_h = \rho V C_a(\dot{u} - \dot{v})$ and the drag force, $F_d = 0.5\rho V C_d A(u - v)|u - v|$. C_d is the drag coefficient, C_a is the added mass coefficient, ρ is the density of the fluid, A is the area of the body facing to the flow, V is the volume of the body, u and v are the velocity of the fluid and the body in the same direction. The direction of the total force is also in the direction of the velocity u. The surface velocity of the sea water is considered as $u = u_m \ sin(\omega_{wave}t)$. Since the paddle rotates around a fixed point, the velocity of the water and the paddle in the tangential direction are considered for computing force and torque. The tangential velocity and acceleration of the water and paddle at an angular position of θ_{wec} are $u_t = u \ cos(\theta_{wec})$; $\dot{u}_t = \dot{u}\, cos(\theta_{wec})$;

$$v_t = \dot{\theta}_{wec}; \quad \dot{v}_t = r\, \ddot{\theta}_{wec} \quad (2)$$

where u_t and v_t are the tangential linear velocity of the water and the paddle and $\dot{u}_t$ and $\dot{v}_t$ are the tangential acceleration of the water and the paddle. $\dot{\theta}_{wec}$ and $\ddot{\theta}_{wec}$ are the angular speed and acceleration of the paddle.

The total Froude-Krylov torque and the hydrodynamic torque on the paddle can be found by integrating all the torque elements along the radius of the paddle as

$$T_{fk} = \rho V\dot{u}\, cos(\theta_{wec})\frac{R}{2}; \qquad T_h = \rho\, C_a\, V\{\frac{R}{2}\dot{u}\, cos(\theta_{wec}) - \frac{R^2}{3}\ddot{\theta}_{wec}\} \quad (3)$$

Except for the forces due to oscillatory water, buoyancy force is also applied on the paddle. Assuming the thickness of the paddle, D to be uniform for the entire paddle, the center of mass is located at $R/2$. Considering the mass of the paddle as M and with g as the gravitational constant of the earth, the buoyancy torque applied on the paddle towards the reference vertical position can be computed as

$$T_b = (\rho V - M)g\frac{R}{2}sin(\theta_{wec}) \quad (4)$$

To compute the total drag force on the paddle by integration over radius r, the sign of the term (u_t- v_t) needs to be evaluated. Although u_t is constant over the entire paddle, v_t varies along the radius. Therefore, the sign of the term (u_t- v_t) depends on the operating conditions. Based on the sign of (u_t- v_t) the limits of the integral changes dynamically. For simplification, considering (u_t- v_t) > 0 over the entire radius of the paddle, the total drag torque can be computed as

$$T_d = \frac{1}{2}\rho\, C_d W\, \{\frac{R^2}{2}u^2\, cos^2(\theta_{wec}) + \frac{R^4}{4}\dot{\theta}_{wec}^{\,2} - \frac{2R^3}{3}u\dot{\theta}_{wec}\, cos(\theta_{wec})\} \quad (5)$$

The total mechanical torque T_{wec} on the paddle can be given as, $T_{wec} = T_{fk} + T_h + T_d - \mathrm{T_b}$ (6)

The electrical generator is coupled to the shaft of the WEC paddle through step-up gear. With the gear ratio N_g, the shaft torques at the low speed (T_{g_high}) and high speed (T_{g_low}) sides are related as

$$T_{g\_low} = N_g\, T_{g\_high} \quad (7)$$

Now, the generator mechanical dynamics can be given as, $T_{g\_high} - T_e = J_g\frac{d\omega_g}{dt}$ (8)

where T_e is the electro-mechanical torque, J_g is the inertia and ω_g is the rotational speed of the generator. With k_b as the voltage constant, the speed of the generator is given as, $\omega_g = \frac{T_{wec}\, N_g}{k_b + s\, J_{gen}}$ (9)

Thus, with the pole pair number P, we get the terminal voltage of the generator as

$$V_\varphi = k_b\omega_g\, sin(P\omega_g t) \quad (10)$$

3. Simulation Results

The developed model of the paddle is verified through simulation with sinusoidal wave excitation. Using the modeling equations and the actual wave data [5], the simulation of the modeling of the paddle-type WEC was validated using MATLAB. The parameters for simulation chosen are given in Table 1. Simulation is carried out to verify the dynamics of the WEC. For paddle type of WEC device, the wave data are the oscillating speed of the sea water. Fig. 4 demonstrates such practical waves. The torque profiles are shown in Fig. 5. The oscillatory voltage is generated at the terminal of the generator (Fig. 6).

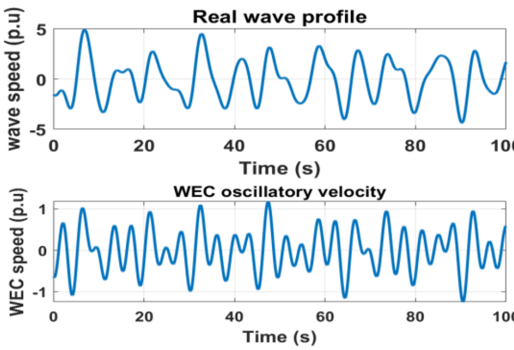

Fig. 4. Practical wave profile.

Table 1. Parameters for the simulation of the system.

Parameter	Value
Height of the paddle (R)	5 m
Width of the paddle (W)	10 m
Depth of the paddle (D)	0.5 m
Added mass co. (C_a)	1030 kg.m^{-3}
Density of sea water (ρ)	0.1
Drag co. (C_d)	1.0
Mass of the paddle (M)	21995 kg
Inertia of the generator (J_g)	183289 kg.m^2
Generator Stator Voltage	220 V
Generator Power Rating	3 hp
Generator Speed	1200 rpm
Gear ratio (Ng)	125
Inertia of the WEC (J_{wec})	8579 kg.m^2

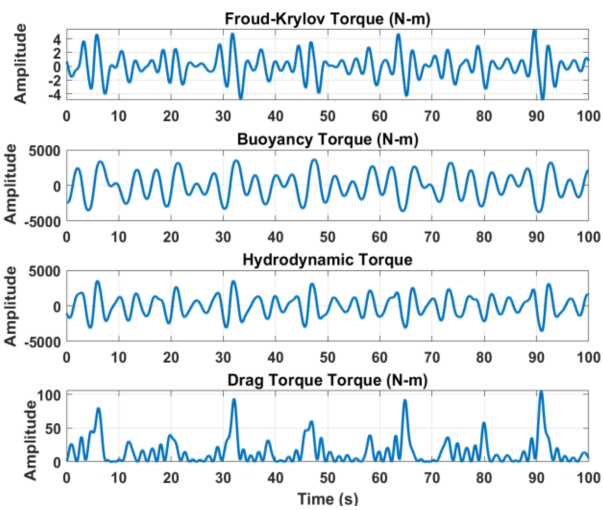

Fig. 5. Torque profile of the WEC modeling.

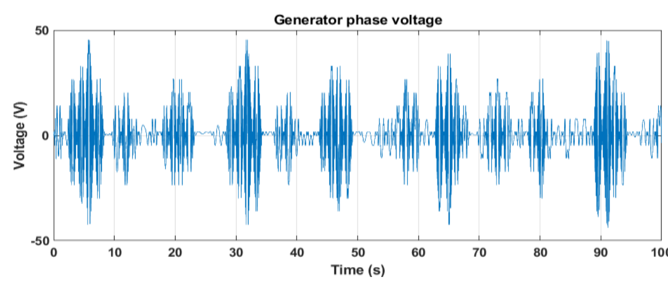

Fig. 6. Generated oscillatory voltage.

4. Experimental Validation of the Microgrid

To validate the Multi-port Power Converter, an experimental test was done by generating a variable voltage and frequency using a programmable power supply. Fig. 7 shows an example of emulated WEC three-phase generation for a voltage range of 0-27V and a frequency range of 16-40Hz. The WEC emulator output has been used to test a modular 5-kW power electronic MPC designed that harnesses the WEC output. The physical testbed that incorporates the WEC Emulator, MPC, storage and load are shown in Fig. 8. Hardware tests to evaluate the MPC controller performance has been completed which shows the usefulness of a WEC emulator to conduct laboratory experiments (Fig. 9).

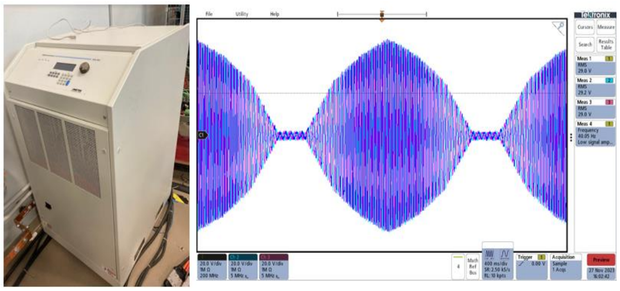

Fig. 7. Scope output of the emulation of the WEC from the programmable power supply.

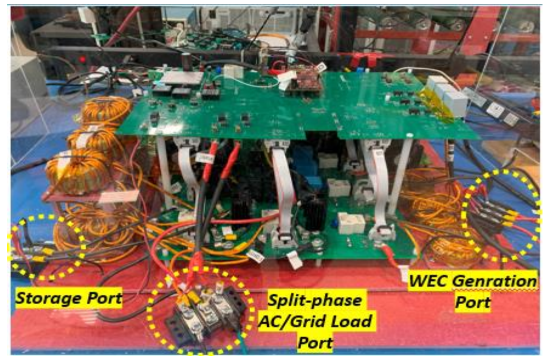

Fig. 8. Experimental setup of Multi-port Power Converter.

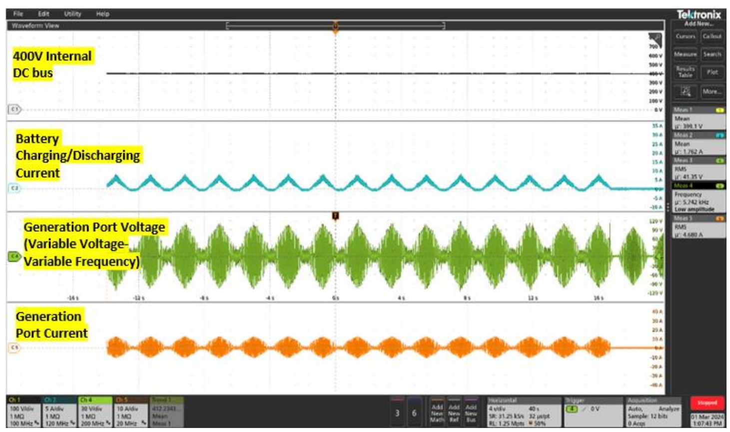

Fig. 9. Scope output of the validation of the MPC harnessing WEC power.

5. Conclusions

This paper presents the modeling, design, and implementation of the WEC emulator for experimental evaluation of an MPC-based DC marine microgrid. The established model and emulation scheme can be readily extended for high-power Wave Energy Converters (WECs), although this study presents a low-power evaluation. As such, the designed WECs, generators, and power converters for real commercial installations can benefit greatly from the derived models and the suggested WEC emulation method.

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