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Assessment of Damping Control Using Maximum Power Point Tracking Methods for Heaving Wave Energy Converters

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ABSTRACT There are not many studies conducted in the implementation of maximum power point tracking (MPPT) methods for heaving wave energy converters (WECs). An assessment of damping control using various MPPT methods for heaving WEC was conducted in this study. Damping control was implemented using a DC–DC boost converter. The duty cycle for MPPT was determined using a perturb and observe algorithm. This assessment study determines the following for applying MPPT for heaving WECs: best location for the observing parameters; best performance index for the MPPT; and effect of averaging the performance index. Three locations for the observing parameters (mechanical parameters near the source, electrical parameters at the load, and electrical parameters between the source and load) and three performance indices (maximising power, minimising impedance, and maximising admittance) were assessed and evaluated. Finally, the effects of applying the running mean and conventional instantaneous value on the performance index were compared. Various scenarios using nine MPPT methods were tested using simulated regular and irregular sea states. The test results were validated experimentally using a simple and low-cost hardware-in-the-loop (HIL) scheme. The HIL scheme was developed using off-the-shelf devices that can be used for any topology of WECs. The results showed that the MPPT method has an optimum performance by using the performance index for maximising power, using observing parameters between the source and the load, and deploying conventional instantaneous values for the observing parameters.

INDEX TERMS Damping control, hardware-in-the-loop, hill-climbing method, maximum power point tracking, perturb and observe algorithm, wave energy converters.

I. INTRODUCTION

Ocean wave energy has a tremendous potential to become the primary renewable energy source in the future with its global capacity reaching up to 3.7 TW [1]. The IEA Ocean Energy Systems Committee has identified that ocean energy could generate up to 750 GW by 2050, which will help

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create 160,000 direct jobs by 2030 [2]. Wave energy converters (WECs) are devices that convert wave power into electrical power, and there are many WEC designs. One example is a heaving WEC that uses a permanent magnet linear generator (PMLG) [3]. However, the control of WECs remains a problem that limits the widespread use of this renewable energy [2].

The application of a control strategy for WECs can considerably improve power generation. To this end, damping

control and maximum power point tracking (MPPT) are considered for WECs. Unlike a reactive control strategy [4]–[8], damping control ensures unidirectional power flow from the source to the load [9], [10]. Conventional damping control requires modelling the power take-off impedance as a pure frequency-dependent resistance [11]. MPPT, especially using a perturb and observe (P&O) algorithm, offers a viable alternative to control renewable sources because it does not require a model of the controlled systems. A combination of damping control using the MPPT technique provides a practical method for generating unidirectional power flow for WEC systems. Few studies have been conducted on damping control using MPPT for WECs [12], [13], where DC–DC converters were used to implement the control strategies. One study used MPPT for direct-drive WECs [14]. However, a reactive control strategy was used, wherein the PTO served as a motor for some time because of the bidirectional power flow.

The current study assesses various issues related to the application of damping control using the MPPT strategy for heaving WECs. The first discussion is related to identifying the best observation parameters for MPPT because WECs experience variations in their source (caused by the change in the sea state) and load. Further, the performances indices of the MPPT methods are compared under three scenarios: MPPT using the observing parameters close to the source, at the load, and between the source and the load. The second discussion is related to the formulation of the performance index of MPPT for WECs. Recent MPPT applications for WECs consider maximising power as the performance index [13], [15]–[17]. However, minimising impedance or maximising admittance can be used as an alternative performance index for some MPPT methods [18], [19]. Therefore, the effects of using power, impedance, and admittance as the performance indices of MPPT for WECs are compared. Finally, the effect of averaging the performance index is studied because MPPT using the P&O algorithm for WECs is different from that employed for solar or wind energy converters. In solar or wind energy converters, the increase or decrease in the performance index (such as power, impedance, or admittance) within a certain amount of time is dependent on only the searching direction in the MPPT algorithms. For example, solar irradiance changes slowly throughout the day, which is not the case in a WEC where it has a source from an irregular wave. Thus, the increase or decrease in the performance index of MPPT for the WECs can be attributed to the decreasing or increasing power content in the wave and not only to the result of the direction policy in the MPPT methods. Averaging the performance index parameters can stabilise the fluctuation of the power from the sea wave and provide time for the MPPT algorithm to reach its peak. A simulated assessment study was conducted and validated via an experiment using the concept of the hardware-in-the-loop (HIL) scheme. The HIL setup used off-the-shelf devices, which helps avoid the need to build a customised WEC setup [20]–[25]. This study showed the viable

construction of the HIL setup for testing damping control strategies for WECs.

The remainder of this paper is organised as follows: Section II discusses the modelling of the WEC systems. Section III describes the objective of the assessment and the proposed MPPT methods. Section IV presents the simulation results and experimental verification. Finally, conclusions are presented in Section V.

II. HEAVING WAVE ENERGY CONVERTER MODEL

The heaving WEC topology from Upsalla University was adopted in this study [26]. Figure 1 shows a schematic of the heaving WEC; it comprises a buoy, a permanent magnet linear generator (PMLG), a connecting tether, and two springs. The main components of the PMLG include the winding stator and translator composed of a stack of permanent magnets. The end-spring mechanism is used to stop extreme buoy excursions.

The mathematical model of the WEC comprises mechanical and electrical models. The mechanical model describes the interaction between the hydrodynamic forces and floating buoy, and the electrical model represents the mathematical models of the PMLG and the power converter. The mathematical model is used only for the simulation, wherein the proposed MPPT does not require the model to implement its control strategies.

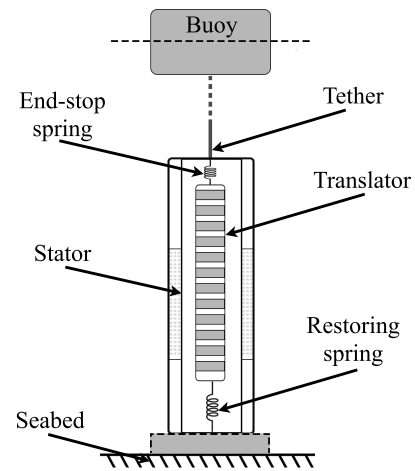


FIGURE 1. Schematic of the heaving WEC system.

A. MECHANICAL MODEL

The mechanical model can be described using

$$f_{ex}(t) - f_{rd}(t) - f_{bc}(t) - f_{rs}(t) - f_{dr}(t) - f_{fr}(t) - f_{es}(t) + f_u(t) = m\ddot{z}(t) \quad (1)$$

where $f_{ex}(t)$, $f_{rd}(t)$, $f_{bc}(t)$, $f_{rs}(t)$, $f_{dr}(t)$, $f_{fr}(t)$, $f_{es}(t)$, $f_u(t)$, m , and $\ddot{z}(t)$ denote the wave excitation force, radiation force, buoyancy force, restoring spring force, drag force, friction force, force produced by the end-stop spring, control force generated by the PTO mechanism, total mass of the moving

parts (mass of the buoy, tether, springs, and translator), and acceleration of the buoy, respectively.

The excitation and radiation forces were estimated using a similar procedure. The excitation force was modelled as

$$f_{ex}(t) \approx \int_0^t k_{ex}(t - \tau)\eta(t)d\tau \quad (2)$$

where $k_{ex}(t)$ and $\eta(t)$ represent the excitation convolution kernel and wave elevation, respectively. For the given characteristics of a buoy and seabed, (2) can be approximated in the frequency domain with a finite-order transfer function using WAMIT or other available hydrodynamic software as

$$\frac{F_{ex}(s)}{E(s)} = \frac{N_{ex}(s)}{D_{ex}(s)} \quad (3)$$

where $F_{ex}(s)$ and $E(s)$ represent the Laplace transforms of $f_{ex}(t)$ and $\eta(t)$, respectively [27]. The numerator and denominator of the transfer function between the excitation force and wave elevation are denoted by $N_{ex}(s)$ and $D_{ex}(s)$, respectively. The radiation force is linearly modelled as

$$\dot{x}_{rd}(t) = \mathbf{A}_{rd}x_{rd}(t) + \mathbf{B}_{rd}\dot{z}(t) \quad (4)$$

$$f_{rd}(t) \approx \int_0^t k_{rd}(t - \tau)\dot{z}(t)d\tau = \mathbf{C}_{rd}x_{rd} + m_\infty\ddot{z}(t) \quad (5)$$

where $k_{rd}(t)$, m_∞ , and $\mathbf{x}_{rd}$ represent the radiation convolution kernel, added mass at infinite frequency, and state vector of the radiation force, respectively. Matrices $\mathbf{A}_{rd}$, $\mathbf{B}_{rd}$, and $\mathbf{C}_{rd}$ represent the system, input, and output matrices for modelling the radiation force, respectively. These matrices are obtained using a procedure similar to $f_{ex}(t)$ by employing WAMIT, where $f_{rd}(t)$ is estimated by the n -order equation in the frequency domain.

The buoyancy and restoring spring forces were modelled using linear equations. These forces were modelled as stiffness forces using

$$f_{bc}(t) = C_{bc}z(t) = (\rho g A_w)z(t) \quad (6)$$

$$f_{rs}(t) = C_{rs}z(t) \quad (7)$$

where C_{bc} , C_{rs} , ρ , g , and A_w denote the stiffness coefficient of buoyancy force, stiffness coefficient of restoring spring, sea water density, gravity of Earth, and submerged surface area of the buoy, respectively.

The drag force, friction force, and end-stop spring force were modelled using nonlinear equations. The drag force is calculated using

$$f_{dr}(t) = 0.5\rho A_w C_{dr}|\dot{z}(t)|\dot{z}(t) \quad (8)$$

where C_{dr} denotes the damping coefficient of the drag force. The friction force is modelled as a function of the velocity of the translator as

$$f_{fr}(t) = \alpha_c \text{sgn}(\dot{z}(t)) + \alpha_v \dot{z}(t) + (\alpha_s - \alpha_c)e^{(\dot{z}(t)/\dot{z}_s)} \text{sgn}(\dot{z}(t)) \quad (9)$$

where α_c , α_v , and α_s denote the Coulomb, viscous, and stiction coefficients, respectively. Further, $\dot{z}_s$ represents the

Stribeck velocity threshold. The end-stop spring is active when the translator reaches its maximum allowable stroke. It is modelled as

$$f_{es}(t) = C_{es}(z(t) + \text{sgn}(z(t))z_l)\mathbb{H}(|z(t)| - z_l) \quad (10)$$

where C_{es} , z_l , and $\mathbb{H}$ denote the spring coefficient of the end stop, maximum allowable stroke, and Heaviside function, respectively.

Equations (1)–(10) can be collectively written in a single state-space equation with separation between the linear and nonlinear terms as follows:

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}(f_{ex}(t) + f_{fr}(t)) + \mathbf{\Theta} \quad (11)$$

$$\mathbf{y} = \mathbf{C}\mathbf{x} \quad (12)$$

where $\mathbf{x} = [z(t) \dot{z}(t) \mathbf{x}_{rd}(t)]^T \in \mathbb{R}^{(n+2) \times 1}$ denotes the state vector, and the state-space matrices $\mathbf{A} \in \mathbb{R}^{(n+2) \times (n+2)}$, $\mathbf{\Theta} \in \mathbb{R}^{(n+2) \times 1}$, $\mathbf{B} \in \mathbb{R}^{(n+2) \times 2}$, $\mathbf{C} \in \mathbb{R}^{1 \times (n+2)}$ are

$$\mathbf{A} = \begin{bmatrix} 0 & 1 & \mathbf{0}_{1 \times 4} \\ \frac{-(C_{bc} + C_{rs})}{m + m_\infty} & \frac{-\alpha_v}{m + m_\infty} & \frac{-\mathbf{C}_{rd}}{m + m_\infty} \\ \mathbf{0}_{(n+2) \times 1} & \mathbf{B}_{rd} & \mathbf{A}_{rd} \end{bmatrix}$$

$$\mathbf{\Theta} = \begin{bmatrix} \frac{-0.5\rho A_w C_{dr}|x_2|x_2 - C_{es}(x_1 + \text{sgn}(x_1)z_l)\mathbb{H}(|x_1| - z_l)}{m + m_\infty} \\ \frac{-\alpha_c \text{sgn}(x_2) - (\alpha_s - \alpha_c)e^{(x_2(t)/\dot{z}_s)} \text{sgn}(x_2)}{m + m_\infty} \\ \mathbf{0}_{(n+2) \times 1} \end{bmatrix}$$

$$\mathbf{B} = \begin{bmatrix} 0 & 0 \\ \frac{1}{m + m_\infty} & \frac{1}{m + m_\infty} \\ \mathbf{0}_{(n+2) \times 1} & \mathbf{0}_{(n+2) \times 1} \end{bmatrix}$$

$$\mathbf{C} = [0 \quad 1 \quad \mathbf{0}_{1 \times (n+2)}]$$

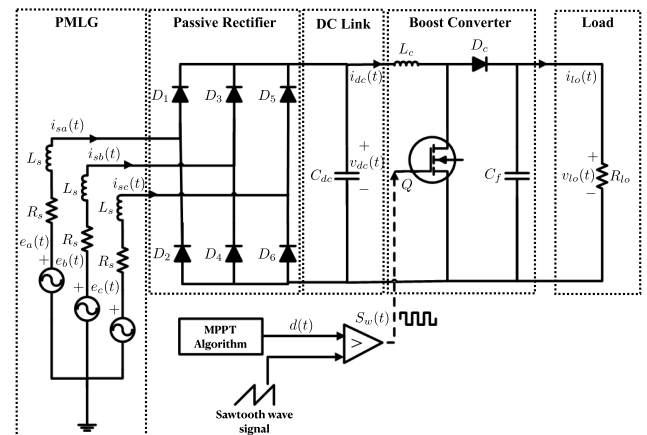


FIGURE 2. Schematic of the electrical model of the WEC system.

B. ELECTRICAL MODEL

A schematic of the electric model used to assess the performance of MPPT for the WECs is shown in Fig. 2. It comprises a PMLG, three-phase diode bridge rectifier, DC–DC boost converter, and load.

The electrical model of the PMLG is described as follows: The net flux $\psi(t)$ in the PMLG coils caused by vertical

movements is expressed as

$$\psi(t) = \hat{\psi} \sin\left(\frac{\pi z(t)}{\tau}\right) \quad (13)$$

where $\hat{\psi}$ and τ represent the maximum flux and width of the magnet pole, respectively [28]. The machine-induced electromotive force (EMF) is expressed as

$$e(t) = -N \frac{d\psi(t)}{dt} = -\frac{N\pi\hat{\psi}}{\tau} \dot{z}(t) \cos\left(\frac{\pi z(t)}{\tau}\right) \quad (14)$$

where N represents the number of turns per phase. For a three-phase machine, the EMF voltages can be expressed in the abc frame, $e(t) = [e_a(t) \ e_b(t) \ e_c(t)]^T$, as

$$e_a(t) = -\frac{N\pi\hat{\psi}}{\tau} \dot{z}(t) \cos\left(\frac{\pi z(t)}{\tau}\right), \quad (15)$$

$$e_b(t) = -\frac{N\pi\hat{\psi}}{\tau} \dot{z}(t) \cos\left(\frac{\pi z(t)}{\tau} - \frac{2\pi}{3}\right) \quad (16)$$

$$e_c(t) = -\frac{N\pi\hat{\psi}}{\tau} \dot{z}(t) \cos\left(\frac{\pi z(t)}{\tau} + \frac{2\pi}{3}\right). \quad (17)$$

The stator phase currents $i_s(t) = [i_{sa}(t) \ i_{sb}(t) \ i_{sc}(t)]^T$ can be found as

$$i_s(t) = \frac{[e(t) - v_s(t)]}{R_s + j\omega_e(t)L_s} \quad (18)$$

where $v_s(t) = [v_{sa}(t) \ v_{sb}(t) \ v_{sc}(t)]$, R_s , L_s , and $\omega_e(t)$ denote the PMLG terminal voltages, stator resistance, stator inductance, and electrical angular velocity, respectively. Furthermore, the electrical angular frequency can be expressed as

$$\omega_e(t) = \frac{\pi}{\tau} \dot{z}(t). \quad (19)$$

The relationship between the mechanical and electrical models is expressed as

$$f_u(t) = \frac{3\pi\phi_{pm}}{2\tau} i_{sq}(t) \quad (20)$$

where ϕ_{pm} and $i_{sq}(t)$ denote the total flux generated by the permanent magnets and quadratic component of $i_s(t)$ obtained using the dq transformation, respectively. The last equation shows that the dynamics of the buoy can be altered using the stator current. The stator current can be changed by changing the value of $v_s(t)$, which can be achieved by controlling the power converter switches.

The PMLG is connected to a passive three-phase full-bridge rectifier as shown in Fig. 2. The phase-to-ground voltages at the terminal input of the rectifier are equal to

$$v_{sa}(t) = \tilde{v}_{dc}(t) \text{sgn}(i_{sa}(t)) - \frac{1}{3} \tilde{v}_{dc}(t) \Upsilon \quad (21)$$

$$v_{sb}(t) = \tilde{v}_{dc}(t) \text{sgn}(i_{sb}(t)) - \frac{1}{3} \tilde{v}_{dc}(t) \Upsilon \quad (22)$$

$$v_{sc}(t) = \tilde{v}_{dc}(t) \text{sgn}(i_{sc}(t)) - \frac{1}{3} \tilde{v}_{dc}(t) \Upsilon, \quad (23)$$

where

$$\Upsilon = \text{sgn}(i_{sa}(t)) + \text{sgn}(i_{sb}(t)) + \text{sgn}(i_{sc}(t)) \quad (24)$$

$$\tilde{v}_{dc}(t) = v_{dd} + \frac{v_{dc}(t)}{2}. \quad (25)$$

In the last equation, v_{dd} and $v_{dc}(t)$ represent the voltage drop across the diode and voltage across the DC-link capacitor (C_{dc}), respectively.

The passive rectifier is connected to the DC-DC boost converter, and its mathematical model can be found in many references [29], [30]. The converter comprises a switch Q (IGBT or CMOS), an inductor L_c , and a diode D_c . The relationship between the input and output voltages in the converter can be written as

$$v_{lo}(t) = \frac{v_{dc}(t)}{1 - d(t)} \quad (26)$$

where $v_{lo}(t)$ and $d(t)$ represent the output voltage of the converter (voltage in the load) and the duty cycle, respectively. Furthermore,

$$v_{dc}(t) = i_{dc}(t) R_{dc}(t) \quad (27)$$

where $i_{dc}(t)$ and $R_{dc}(t)$ denote the input current at L_c and the input resistance of the converter, respectively. The relationship between $R_{dc}(t)$ with the duty cycle and load resistance R_{lo} is written as

$$R_{dc}(t) = R_{lo}(1 - d(t))^2. \quad (28)$$

The last equation shows that by controlling the duty cycle, we can change the input resistance; that is, the stator current can be altered. The gating signal $S_w(t)$ is generated as the input signal for the switch by comparing $d(t)$ with the sawtooth waveform.

Finally, the DC-DC boost converter is connected to a shunt capacitor C_f and load resistance; the capacitor is utilised for smoothing. The load resistance R_{lo} can be replaced by a voltage-source converter for integrating the WEC system into an electrical grid.

III. ASSESSMENT OBJECTIVES AND PROPOSED MPPT METHODS

A. ASSESSMENT OBJECTIVES

This assessment study considers the following objectives:

- 1) Determine the best observation parameters (i.e. parameters near the source, at the load, or between the source and the load).
- 2) Determine the best performance index for the MPPT method.
- 3) Determine the effect of averaging the selected performance index.

For the first objective, three MPPT methods were proposed: the first method that observes the parameters of the mechanical model of the WECs (MPPT-M), the second method that observes parameters at the input of the boost converter (MPPT-I), and finally, the third MPPT method that observes parameters at the load or the output of the boost converter (MPPT-O). The three MPPT methods use the observing parameters near the source, at the load, and between the source and load. MPPT-M utilises the observing parameters

in terms of $f_u(t)$ and $\dot{z}(t)$, as described in Section II-A. MPPT-I uses $v_{dc}(t)$ and $i_{dc}(t)$, whereas MPPT-O uses $v_{lo}(t)$ and $i_{lo}(t)$, as shown in Fig. 2. In terms of applicability, $v_{dc}(t)$, $i_{dc}(t)$, $v_{lo}(t)$, and $i_{lo}(t)$ can be easily measured using current and voltage sensors. The mechanical parameters of $\dot{z}(t)$ require a mechanical sensor, which is more expensive than the current and voltage sensors. The parameter $f_u(t)$ can be determined by measuring the stator current and applying Eq. (20). Therefore, MPPT-I and MPPT-O are easier to implement than MPPT-M.

For the second objective, three performance indices were used for the MPPT method: maximising power, minimising impedance, and maximising admittance. The three performance indices were combined with the three MPPT methods, as stated in the first objective. This resulted in the following MPPT methods:

- MPPT-MP, MPPT-MZ, and MPPT-MY, which are MPPT methods that use the mechanical parameters of $f_u(t)$ and $\dot{z}(t)$ for maximising mechanical power, minimising mechanical impedance, and maximising mechanical admittance, respectively.
- MPPT-IP, MPPT-IZ, and MPPT-IY, which are MPPT methods that use electrical parameters of $v_{dc}(t)$ and $i_{dc}(t)$ for maximising electrical power, minimising electrical impedance, and maximising electrical admittance, respectively.
- MPPT-OP, MPPT-OZ, and MPPT-OY, which are MPPT methods that use electrical parameters of $v_{lo}(t)$ and $i_{lo}(t)$ for maximising electrical power at the load, minimising electrical impedance at the load, and maximising electrical admittance at the load, respectively.

For the third objective, the performance indices of the MPPT method were tested using two methods: conventional instantaneous measurement and averaging of the performance index using the running mean method. The running mean was calculated using

$$\text{Running mean} = \frac{1}{k} \sum_{k=1}^j u_k \quad (29)$$

where k denotes the sampling instant, and u_k represent the performance indices such as power, impedance, and admittance. In MATLAB, the running mean is available in the Simulink block.

The details of the nine MPPT methods are discussed in Sections III-B–III-D. The discussion is divided into three groups based on the location of the observing parameters: MPPT methods that use mechanical parameters (MPPT-MP, MPPT-MZ, and MPPT-MY); parameters at the input of the boost converter (MPPT-IP, MPPT-IZ, and MPPT-IY); and parameters at the load (MPPT-OP, MPPT-OZ, and MPPT-OY). The complete derivation of the MPPT algorithm is described for MPPT-PM; the derivations are omitted for the rest of the MPPT methods to avoid repetition.

B. PROPOSED MPPT METHODS USING MECHANICAL PARAMETERS (MPPT-M)

1) MPPT-M FOR MAXIMISING MECHANICAL POWER (MPPT-MP)

The relationship between the mechanical power $P_m(t)$ and $d(t)$ is determined using the following procedure. Mechanical power is defined as

$$P_m(t) = f_u(t)\dot{z}(t). \quad (30)$$

On substituting the last equation into Eq. (20)

$$P_m(t) = \frac{3\pi\phi_{pm}}{2\tau} i_{sq}(t)\dot{z}(t). \quad (31)$$

The relationship between the input and outputs currents of the converter is

$$i_{dc}(t) = \frac{i_{lo}(t)}{1 - d(t)}. \quad (32)$$

The performance index for MPPT-MP is maximising $P_m(t)$. Using Eqs. (30) and (31), $P_m(t)$ is proportional to $i_{sq}(t)$. Moreover, $i_{sq}(t)$ is proportional to $i_{dc}(t)$. From Eq. (32), $i_{dc}(t)$ is proportional to $d(t)$. Therefore, $P_m(t)$ is proportional to $d(t)$.

MPPT-MP can be implemented using the following procedure. First, the initial value of $d(t)$ is set. At each sampling time, the values of $f_u(t)$ and $\dot{z}(t)$ are obtained, and $P_m(t)$ is calculated using Eq. (30). If the value of $P_m(t)$ increases compared to the previous value, the controller is heading in the right direction. Therefore, the duty cycle in the next sampling time increases; otherwise, the next duty cycle decreases if the present value of $P_m(t)$ decreases. The new duty cycle in the next sampling instance $d(t+1)$ is calculated using

$$d(t+1) = d(t) \pm d_s \quad (33)$$

where d_s denotes the fixed-step size. The value of d_s is carefully selected. An excessively large value of d_s produces higher ripples in voltage or current in the load despite the rapid rate of reaching the maximum power transfer. In contrast, an excessively low value of d_s generates a smoother voltage or current in the load; however, it requires a slower rate to reach the maximum power transfer. Figure 3 shows a flowchart of MPPT-MP. The flowchart for the other MPPT methods is not shown because it is similar to the flowchart in Fig. 3.

2) MPPT-M FOR MINIMISING MECHANICAL IMPEDANCE (MPPT-MZ)

Mechanical impedance is formulated using

$$Z_m(t) = \frac{f_u(t)}{\dot{z}(t)}. \quad (34)$$

The objective of MPPT-MZ is to minimise $Z_m(t)$. Using the procedure described in Section III-B1, $Z_m(t)$ is proportional to $d(t)$. If the value of $Z_m(t)$ decreases compared to the previous value, the controller is heading in the right direction.

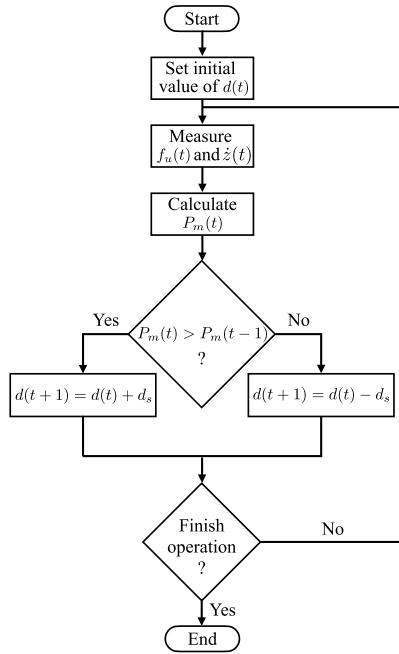


FIGURE 3. Flowchart for the control algorithm in MPPT-MP.

Therefore, the duty cycle in the next sampling time decreases. Otherwise, the next duty cycle will increase if the value of $Z_m(t)$ increases.

3) MPPT-M FOR MAXIMISING MECHANICAL ADMITTANCE (MPPT-MY)

The mechanical admittance is formulated using

$$Y_m(t) = \frac{\dot{z}(t)}{f_u(t)}. \quad (35)$$

The objective of MPPT-MY is to maximise $Y_m(t)$. Using the same procedure as in Section III-B1, $Y_m(t)$ is inversely proportional to $d(t)$. If the value of $Y_m(t)$ increases compared to the previous value, the controller is heading in the right direction. Therefore, the duty cycle in the next sampling time decreases. Otherwise, the next duty cycle will increase if the value of $Y_m(t)$ increases.

C. PROPOSED MPPT METHODS USING PARAMETERS AT THE INPUTS OF THE BOOST CONVERTER (MPPT-I)

1) MPPT-I FOR MAXIMISING ELECTRICAL POWER AT THE INPUT OF BOOST CONVERTER (MPPT-IP)

The relationship between the electrical power at the input of the converter $P_e(t)$ and $d(t)$ is determined using the following procedure. The electrical power at the input of the converter is defined as

$$P_i(t) = v_{dc}(t)i_{dc}(t). \quad (36)$$

Substituting the last equation into Eq. 26,

$$P_i(t) = v_{lo}(t)i_{dc}(t)[1 - d(t)]. \quad (37)$$

From Eq. (37), it is clear that $P_i(t)$ is inversely proportional to $d(t)$.

2) MPPT-I FOR MINIMISING ELECTRICAL IMPEDANCE AT THE INPUT OF BOOST CONVERTER (MPPT-IZ)

The relationship between the electrical impedance at the input of the converter $Z_e(t)$ and $d(t)$ is determined using the following procedure. The electrical impedance at the input of the converter is defined as

$$Z_i(t) = \frac{v_{dc}(t)}{i_{dc}(t)}. \quad (38)$$

Substituting the last equation into Eq. (26),

$$Z_i(t) = \frac{v_{lo}(t)[1 - d(t)]}{i_{dc}(t)}. \quad (39)$$

From Eq. (39), $Z_i(t)$ is inversely proportional to $d(t)$.

3) MPPT-I FOR MAXIMISING ELECTRICAL ADMITTANCE AT THE INPUT OF BOOST CONVERTER (MPPT-IY)

The relationship between the electrical admittance at the input of the converter $Y_i(t)$ and $d(t)$ is determined using the following procedure. The electrical admittance at the input of the converter is defined as

$$Y_i(t) = \frac{i_{dc}(t)}{v_{dc}(t)}. \quad (40)$$

Substituting the last equation into Eq. (26),

$$Y_i(t) = \frac{i_{dc}(t)}{v_{lo}(t)[1 - d(t)]}. \quad (41)$$

From Eq. (41), $Y_i(t)$ is proportional to $d(t)$.

D. PROPOSED MPPT METHODS USING PARAMETERS AT THE LOAD (MPPT-O)

1) MPPT-O FOR MAXIMISING ELECTRICAL POWER AT THE LOAD (MPPT-OP)

The relationship between the electrical power at the load $P_o(t)$ and $d(t)$ is determined using the following procedure. The electrical power is defined as

$$P_o(t) = v_{lo}(t)i_{lo}(t). \quad (42)$$

Substituting the last equation into Eq. (26)

$$P_o(t) = \frac{v_{dc}(t)i_{lo}(t)}{[1 - d(t)]}. \quad (43)$$

Therefore, $P_o(t)$ is proportional to $d(t)$.

2) MPPT-O FOR MINIMISING ELECTRICAL IMPEDANCE AT THE LOAD (MPPT-OZ)

The relationship between the electrical impedance at the load $Z_o(t)$ and $d(t)$ is determined using the following procedure. The electrical power is defined as

$$Z_o(t) = \frac{v_{lo}(t)}{i_{lo}(t)}. \quad (44)$$

Substituting the last equation into Eq. (26),

$$Z_o(t) = \frac{v_{dc}(t)}{i_{lo}(t)[1 - d(t)]}. \quad (45)$$

Therefore, $Z_o(t)$ is proportional to $d(t)$.

3) MPPT-O FOR MAXIMISING ELECTRICAL ADMITTANCE AT THE LOAD (MPPT-OY)

The relationship between the electrical admittance at the load $Y_o(t)$ and $d(t)$ is determined using the following procedure. The electrical power is defined as

$$Y_o(t) = \frac{i_{lo}(t)}{v_{lo}(t)}. \quad (46)$$

Substituting the last equation into Eq. (26),

$$Y_o(t) = \frac{i_{lo}(t)[1 - d(t)]}{v_{dc}(t)}. \quad (47)$$

From Eq. (47), $Y_o(t)$ is inversely proportional to $d(t)$.

TABLE 1. Setting parameters for the simulation and the experiment.

Parameter (symbol)	Value [Unit]
Buoy shape	Cylindrical
Buoy radius (r)	2.5 m
Total mass (m)	31,000 kg
Buoy infinite added mass (m_∞)	28,518 kg
Water plane area (A_w)	19.6 m ²
Buoyancy stiffness coefficient (C_{bc})	197,370 N/m
Restoring spring coefficient (C_{rs})	1 $\times$ 10 ⁵ N/m
Sea water density (ρ)	1,025 kg/m ³
Gravity of Earth (g)	9.8 m/s ²
Submerged surface area (A_w)	19.6 m ²
Drag force damping coefficient (C_{dr})	6 $\times$ 10 ³ Ns/m
Coulomb friction coef. (α_c)	1 $\times$ 10 ⁴ N
Viscous friction coef. (α_v)	0.7 $\times$ 10 ⁴ Ns/m
Stiction friction coef. [α_s]	2 $\times$ 10 ⁴ N
Stribeck velocity threshold [$\dot{z}_s$]	1 m/s
End-stop spring coef. (C_{es})	5 $\times$ 10 ⁵ N/m
Maximum stroke (z_l)	2 m
Number of turns of the stator coils (N)	300
Magnet pole pitch (τ)	0.1 m
PMLG peak flux (ϕ)	0.1 Wb
PMLG stator resistance (R_s)	5 Ω
PMLG stator inductance (L_s)	32 mH
DC link capacitance for the sim. (C_{dc})	0.5 F
Induc. in the boost conv. for the sim. (L_c)	0.1 H
Cap. in the boost conv. for the sim. (C_f)	5 mF
DC link capacitance for the exp. (C_{dc})	40 mF
Induc. in the boost conv. for the exp. (L_c)	1 mH
Cap. in the boost conv. for the exp. (C_f)	68 μ F
Scaling factor for the exp.	18

IV. RESULTS AND DISCUSSIONS

A. SIMULATION AND EXPERIMENTAL SETUPS

Table 1 summarises the parameters of the mechanical model, electrical model, and calculated boost converter for the simulation and the experiment. The assessment was conducted using regular and irregular sea states. The irregular sea states used the JONSWAP spectrum frequency with the significant

height (H_s) and peak period (T_p) are varied from 1–3 m and from 7.4 s (or 0.85 rad/s) to 11.4 s (or 0.55 rad/s), respectively [31]. The resistive load (R_{lo}) was varied from 20 Ω to 100 Ω . The step size for the MPPT methods was fixed to 0.001. The value of duty cycle was limited within the range of 0.1 to 0.9, and the initial value of the duty cycle was set to 0.1. The simulation was performed using MATLAB with a sampling time of 0.0001 s. Figure 4 summarises the simulation setup using the various MPPT algorithms.

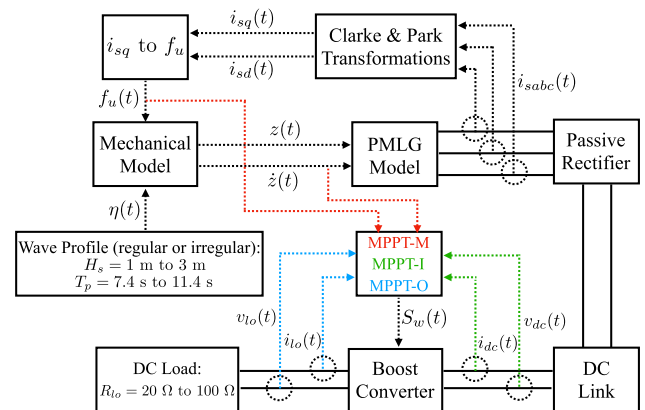


FIGURE 4. Schematic of the simulation setup for the MPPT algorithms where the red, green, and blue coloured signals are the measuring signals for the MPPT-M, the MPPT-I, and the MPPT-O, respectively. The solid and dotted lines are representing the physical connections and the signals or measurements, respectively.

The experimental setup was implemented using the HIL concept. A schematic of the physical configuration of the HIL is shown in Fig. 5 and Fig. 6, respectively. The HIL comprises two parts: the simulation environment inside the dSPACE MicroAutoBox and the external hardware setup. A sampling time of 0.001 s was used by MATLAB for the HIL.

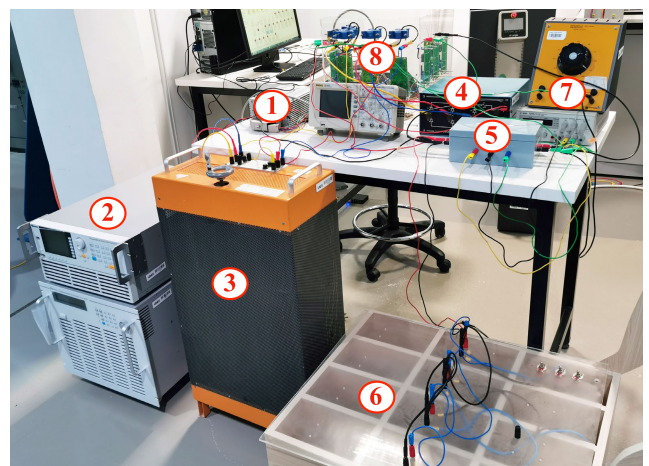


FIGURE 5. Physical configuration of HIL: dSPACE board (1), programmable AC source (2), PMLG's intrinsic resistance (3), passive rectifier (4), boost converter (5), DC link capacitor (6), DC load (7), and V-I sensors (8).

The simulation environment in the HIL contains mechanical and electrical models of the system, as described in

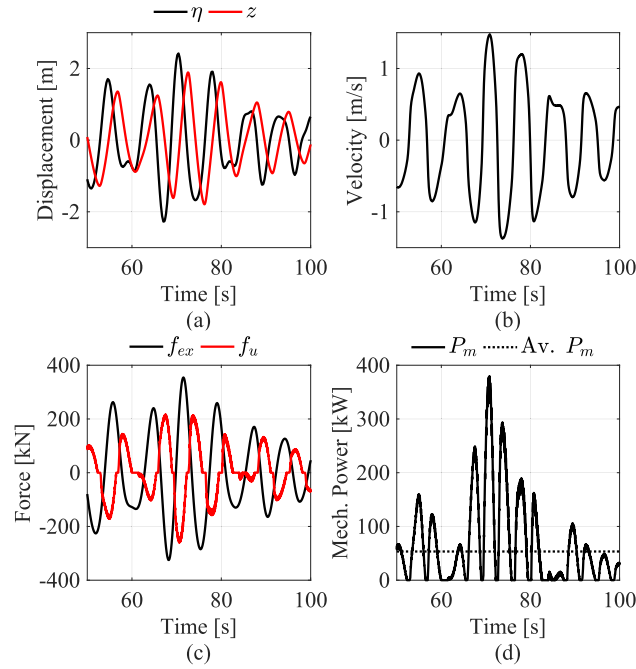


FIGURE 9. Simulation results in term of the mechanical parameters using MPPT-PI for an irregular sea state with $H_s = 3$ m, $T_p = 8.4$ s, and a DC load of 60Ω : the wave elevation and position of the buoy (a), velocity of the buoy (b), the excitation and control forces (c), and the mechanical force and its average value (d).

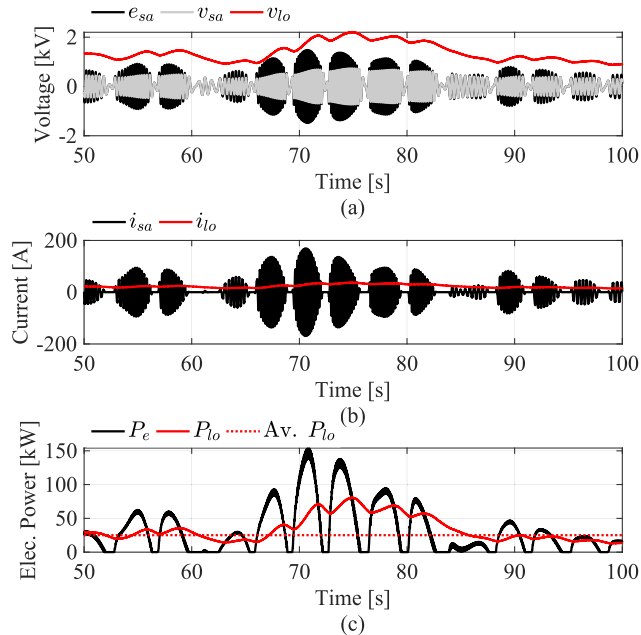


FIGURE 10. Simulation results in term of the electrical parameters using MPPT-PI for an irregular sea state with $H_s = 3$ m, $T_p = 8.4$ s, and a DC load of 60Ω : voltages at the stator and the load (a), currents at the stator and the load (b), converted electrical power and electrical power at the load (c).

various scenarios. MPPT-IP uses the instantaneous value for the performance index.

The results of the simulation in terms of electrical parameters are shown in Figs. 9. Figure 9a shows plots of the wave

elevation $\eta(t)$ and the buoy's elevation $z(t)$. The velocity of the buoy is shown in Fig. 9b. Figures 9a–b indicates that the MPPT method does not cause any extreme excursion of the buoy. Furthermore, the control force $f_u(t)$ does not exceed the excitation force $f_e(t)$ as depicted in Fig. 9 (c). This ensures a unidirectional power flow from the source to the load, as shown in Fig. 9d. Mechanical power $P_m(t)$ with an average of 52 kW was obtained using the controlled system.

The results of the simulation in terms of electrical parameters are shown in Fig. 10. Figure 10a shows the EMF voltage for phase a ($e_{sa}(t)$), terminal voltage for phase a ($v_{sa}(t)$), and voltage at the load ($v_{lo}(t)$). The EMF and terminal voltages have amplitude-and frequency-modulated signals because of the irregularity of the sea wave. Figure 10b shows the stator current for phase a ($i_{sa}(t)$) and the current at the load ($i_{lo}(t)$). The stator current has a shape similar to that of $e_{sa}(t)$ or $v_{sa}(t)$. Figure 10c shows the instantaneous electrical power $P_e(t)$ and the power at the load $P_{lo}(t)$. The instantaneous electrical power was calculated using

$$P_e(t) = v_{sa}(t)i_{sa}(t) + v_{sb}(t)i_{sb}(t) + v_{sc}(t)i_{sc}(t). \quad (48)$$

Figure 10c shows $P_{lo}(t)$ with an average of 25 kW.

The assessment for the various MPPT techniques was conducted using the following procedure.

- 1) Decide the best method within the groups of MPPT-M, MPPT-I, and MPPT-O. The three best candidates were selected from this process. The best performance index formulation was determined based on this assessment.
- 2) The three best candidates were assessed to decide the best method. The best observation parameters were determined from this assessment.
- 3) The effect of the running mean on the performance index was assessed using the selected MPPT method against the conventional instantaneous value.

1) DECIDING THE BEST MPPT METHODS WITHIN THE GROUP OF MPPT-M, MPPT-I, AND MPPT-O

The assessment was conducted using two regular sea states and various DC loads to test the MPPT methods against variations in the wave and the load. The two regular sea states were a sea state with $H_s = 2$ m and $T_p = 9.7$ s and a sea state with $H_s = 2$ m and $T_p = 7.4$ s, which represent less and more energetic sea states, respectively. Sea states with different H_s values were not used for the assessment because the results had the same trends. The DC load was varied from 20Ω to 100Ω . In this section, all figures a–b are generated using the less energetic regular sea state, while all figures c–d are generated using the more energetic regular sea state. All results are evaluated based on the obtained average mechanical power $\bar{P}_m(t)$ and the average electrical power at the load $\bar{P}_{lo}(t)$.

The results of the assessment within the MPPT-M group are shown in Fig. 11. From the figure, MPPT-MP exhibits superior performance for all simulation scenarios in terms of the average mechanical power and average electrical power at the load. The performances of MPPT-MZ and MPPT-MY are

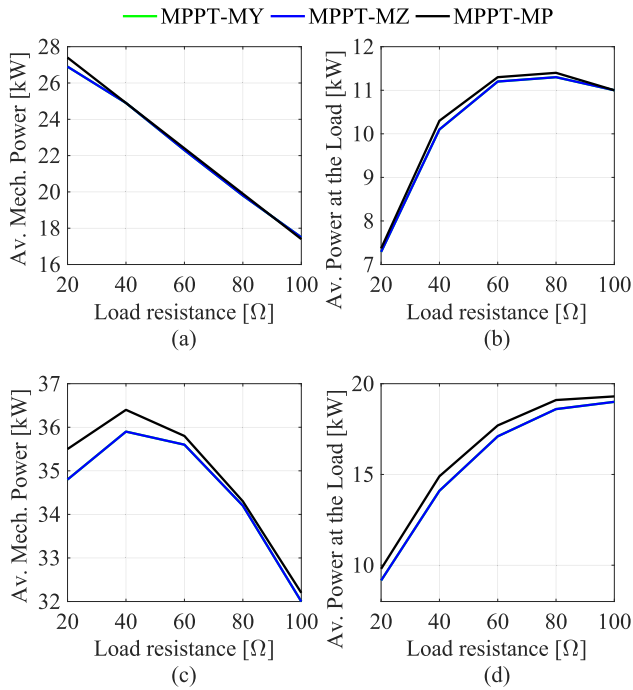


FIGURE 11. Comparison results for all MPPT methods within the group of MPPT-M using a less energetic sea state (a–b) and a more energetic sea state (c–d). MPPT-MZ and MPPT-MY overlap.

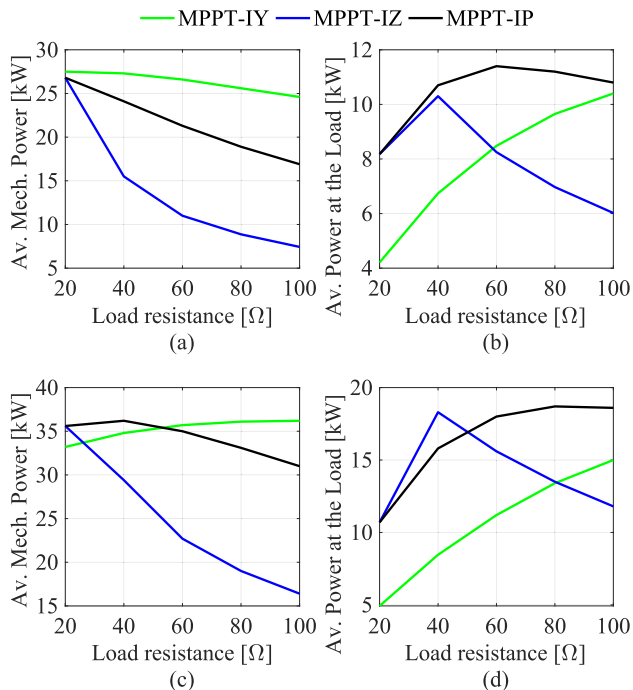


FIGURE 12. Comparison results for all MPPT methods within the group of MPPT-I using a less energetic sea state (a–b) and a more energetic sea state (c–d).

equal. Therefore, MPPT-MP is selected as the best method in the MPPT-M group.

The results of the assessment within the MPPT-I group are shown in Fig. 12. MPPT-IY shows a superior performance

in terms of $\bar{P}_m$ in the majority of cases. However, MPPT-IP obtains the highest $\bar{P}_{lo}$ in the majority of scenario cases. MPPT-IP is selected as the best method within the MPPT-I group because the electrical power at the load is the final useful product from the system.

The results of the assessment within the MPPT-O group are shown in Fig. 13. MPPT-OP and MPPT-OZ achieved similar results, and they obtained the highest $\bar{P}_m$ in all simulation scenarios. Further, they obtained the highest power in the majority of the scenario cases in terms of $\bar{P}_{lo}$. Following trends shown in Figs. 11 and 12, MPPT-OP is selected as the best method within the MPPT-O group where the performance index for maximising the power exhibits better performance.

Figs. 11–13 conclude that the performance index for maximising the power is the best for MPPT compared to minimising impedance or maximising admittance.

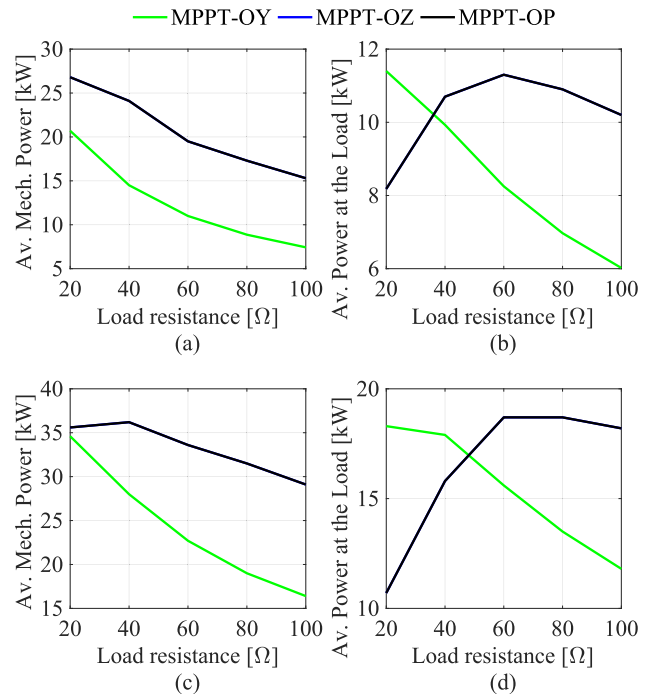


FIGURE 13. Comparison results for all MPPT methods within the group of MPPT-O using a less energetic sea state (a–b) and a more energetic sea state (c–d). MPPT-OP and MPPT-OZ overlap.

2) DECIDING THE BEST MPPT METHODS AMONG MPPT-MP, MPPT-OP, AND MPPT-IP

The three MPPT methods were tested against various scenarios in the sea states and DC load. MPPT-MP, MPPT-OP, and MPPT-IP represent the MPPT method with the observation parameters near the source, at the load, and at the middle, respectively. In this section, irregular sea states are used for all simulation scenarios.

First, the assessment results on the effect of changing the sea states for the MPPT methods are shown in Fig. 14. In this simulation, the DC load is fixed at 100 Ω and irregular

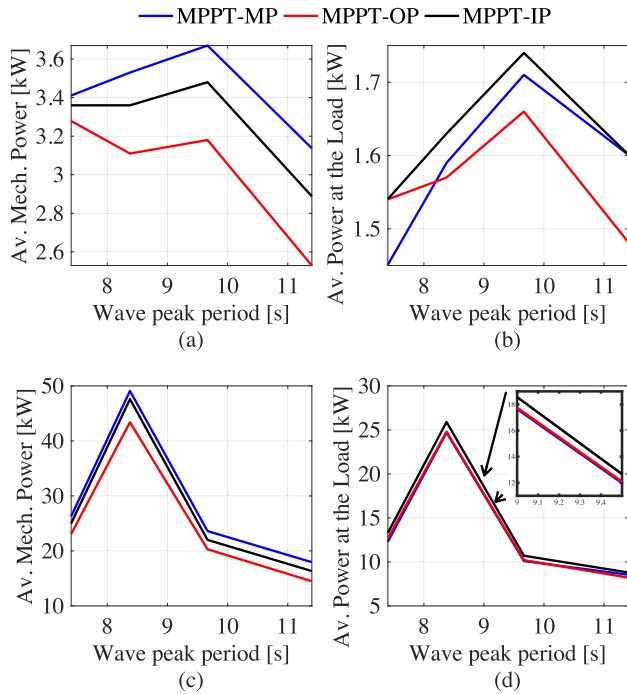


FIGURE 14. Comparison results using MPPT-MP, MPPT-IP, and MPPT-OP with a fixed $R_{lo} = 100 \Omega$ and regular sea states with $H_s = 1$ m (a–b), $H_s = 3$ m (c–d), and various T_p .

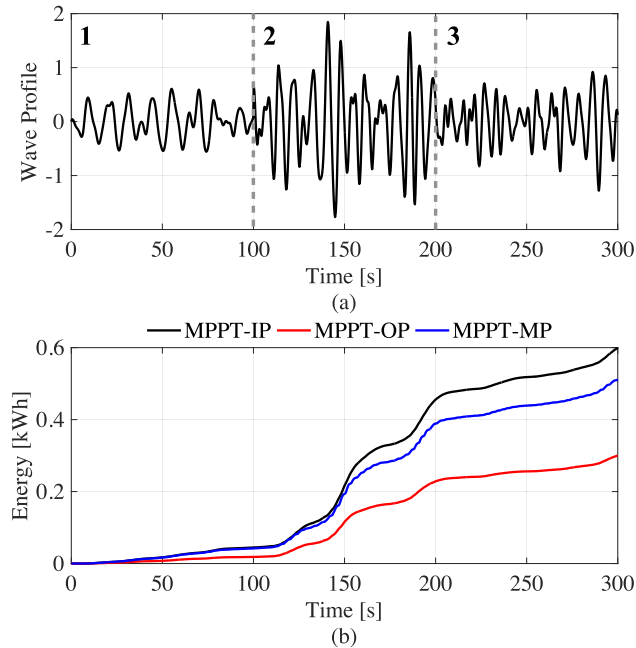


FIGURE 15. Comparison results using MPPT-MP, MPPT-IP, and MPPT-OP with a fixed $R_{lo} = 60 \Omega$ and three different irregular sea states (a), and its resulting electrical energy at the load (b).

sea states with $H_s = 1$ m (Fig. 14a–b) and $H_s = 3$ m (Fig. 14c–d) are used. Fig. 14a and c shows that MPPT-MP exhibits the best performance in terms of the obtained $\bar{P}_m$, followed by MPPT-IP and MPPT-OP. This is understandable

because the MPPT-MP has observing parameters based on the mechanical side, which can detect changes in sea states better than that with MPPT-IP and MPPT-OP. However, after power conversion, MPPT-IP has the highest obtained $\bar{P}_{lo}$ at the load, as shown in Fig 14b and d.

Further study was conducted using three successive irregular sea states with a fixed R_{lo} to assess the effect of changes in sea states. The results are presented in Fig. 15. As depicted in Fig. 15a, irregular sea states of $H_s = 1$ m and $T_p = 11.4$ s, $H_s = 3$ m and $T_p = 8.4$ s, and $H_s = 2$ m and $T_p = 7.4$ s are used for time durations of 1, 2, and 3, respectively. The electrical energy at load is shown in Fig. 15b. Again, the performance of MPPT-PI is better than those of MPPT-MP and MPPT-OP.

The assessment results of the three MPPT methods against changes in the sea states in Figs. 14 and 15 indicate that the MPPT-IP, which has observing parameters at the location between the source and the load, achieves a better performance. MPPT-MP obtains a higher mechanical power; however, it experiences a significant reduction after conversion to its electrical power at the load. MPPT-PO cannot anticipate the change in the sea states because its performance index is designed to maximise the power at the load. MPPT-IP provides the best optimum solution where the observing parameters are close to the mechanical parameters, thereby recognising the change in the sea states with the performance index maximising the electrical power close to the load.

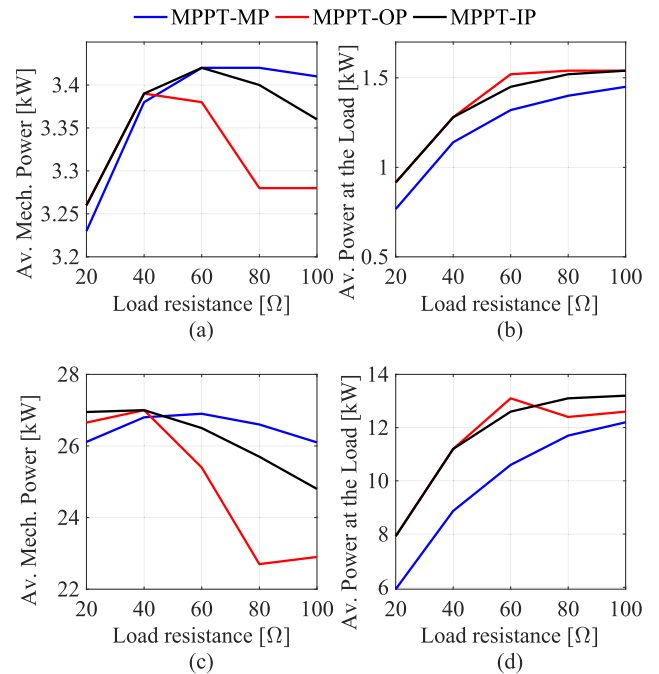


FIGURE 16. Comparison results using MPPT-MP, MPPT-IP, and MPPT-OP using lower (a–b) and higher (c–d) energetic sea states with variations at the load.

Next, the three MPPT methods are further assessed against variations in the load. The methods are tested using two irregular sea states: $H_s = 1$ m, $T_p = 7.4$ s and $H_s = 3$ m,

$T_p = 7.4$ s, which represent a lower and higher energetic sea states, respectively. The load is varied from 20Ω to 100Ω . The results are presented in Fig. 16. In terms of mechanical power, as shown in Fig. 16a and c, MPPT-MP performs better than the other MPPT methods in the majority of the scenario cases. In terms of the power obtained at the load shown in Fig. 16b and d, MPPT-PO has the best performance in the majority of cases because it acknowledges the variation in the load. However, its performance did not differ significantly from that of MPPT-IP. In fact, there are many cases where MPPT-IP has similar performances (or even had better performance in a few cases) compared to that of MPPT-OP.

MPPT-PI is the best candidate that provides an optimal performance against the variation in the sea states and at the load as indicated by combining the assessment results from Figs. 14–16.

3) ASSESSMENT RELATED TO THE EFFECT OF THE RUNNING MEAN ON THE PERFORMANCE INDEX

Further assessments were conducted to determine the effect of the running mean on the performance index. MPPT-MP and MPPT-IP were selected to test the effect of the running mean on the mechanical power and power at the load, respectively. The running mean was applied to $P_m(t)$ in MPPT-MP and $P_i(t)$ in MPPT-IP.

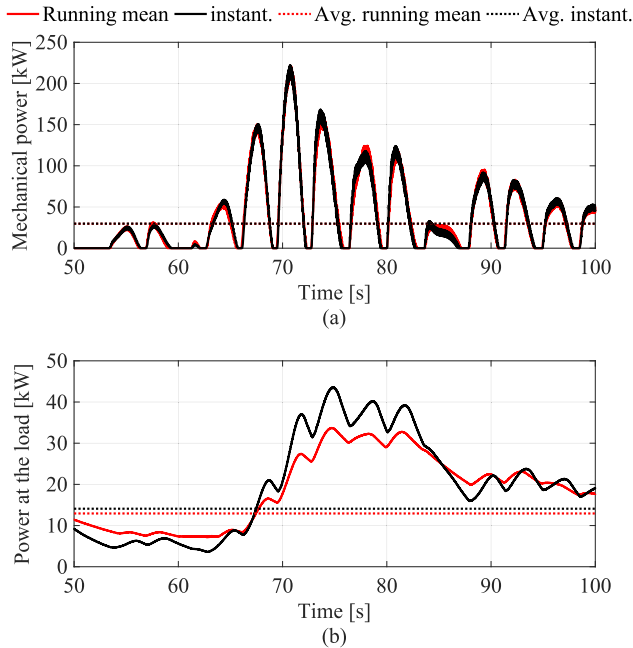


FIGURE 17. Resulted mechanical power using MPPT-MP (a) and electrical power at the load using MPPT-IP (b).

The results were compared with the conventional instantaneous values of the performance index; the irregular sea state of $H_s = 2$ m and $T_p = 7.4$ s was used. The simulation results are presented in Fig. 17. Only the mechanical power for MPPT-MP and the electrical power at the load for MPPT-IP

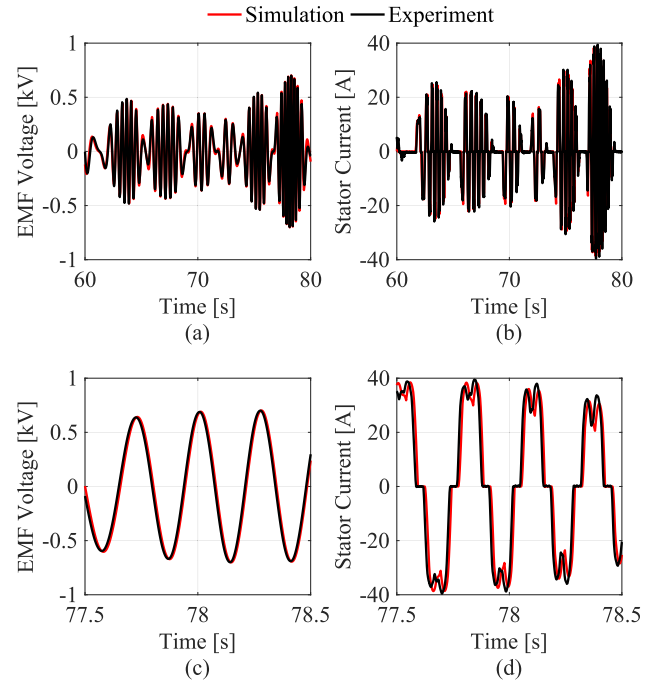


FIGURE 18. Comparison between the experimental and simulation results using MPPT-IP with $H_s = 2$ m, $T_p = 11.4$ s, and $R_{lo} = 150 \Omega$ for: the EMF voltage (a), stator current (b), zoomed section of EMF voltage (c), and zoomed section of stator current (d).

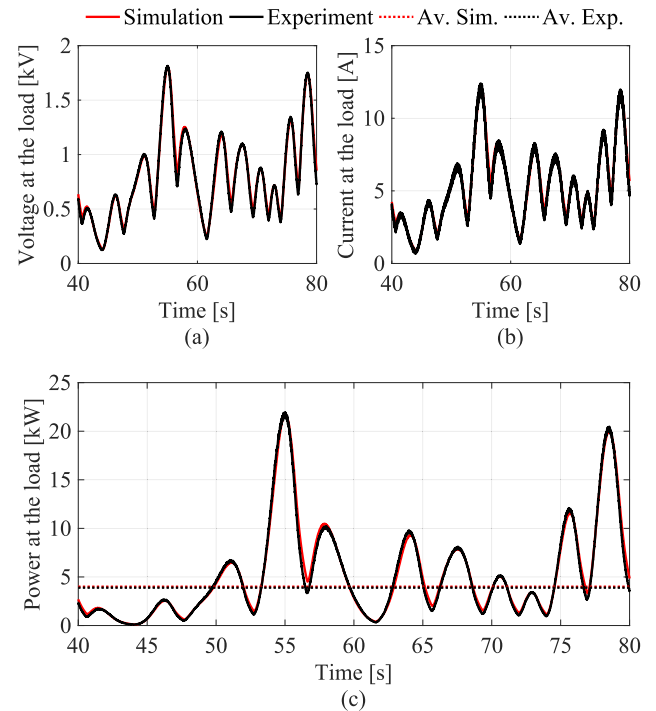


FIGURE 19. Comparison between the experiment and simulation results using MPPT-IP with $H_s = 2$ m, $T_p = 11.4$ s, and $R_{lo} = 150 \Omega$ for: voltage at load (a), currents at load (b), and power at load (c).

are plotted in the figure. Fig. 17a shows that there is no difference between deploying the running mean and using the conventional instantaneous value in the maximising $P_m(t)$ in

TABLE 2. Average power at the load using different methods of MPPT and different values of DC load.

Scenario	$R_L = 90 \Omega$			$R_L = 120 \Omega$			$R_L = 150 \Omega$		
	MPPT-MP	MPPT-IP	MPPT-OP	MPPT-MP	MPPT-IP	MPPT-OP	MPPT-MP	MPPT-IP	MPPT-OP
Average power (exp.)	1.4 kW	1.4 kW	1.3 kW	1.2 kW	1.4 kW	1.2 kW	1.1 kW	1.3 kW	1.1 kW
Average power (sim.)	1.3 kW	1.7 kW	1.4 kW	1.2 kW	1.5 kW	1.2 kW	1.1 kW	1.4 kW	1.1 kW

TABLE 3. Average powers at the load using the different methods of MPPT and different values of the significant height.

Scenario	$H_s = 1 \text{ m}$			$H_s = 2 \text{ m}$			$H_s = 3 \text{ m}$		
	MPPT-MP	MPPT-IP	MPPT-OP	MPPT-MP	MPPT-IP	MPPT-OP	MPPT-MP	MPPT-IP	MPPT-OP
Average power (exp.)	1.1 kW	1.3 kW	1.1 kW	3.2 kW	3.9 kW	2.8 kW	7.3 kW	7.8 kW	6.4 kW
Average power (sim.)	1.1 kW	1.4 kW	1.1 kW	2.7 kW	4.0 kW	2.7 kW	6.2 kW	9.0 kW	6.2 kW

MPPT-MP. Both scenarios generated 30 kW of mechanical power. Therefore, there is no effect of using the running mean that can ‘flatten’ the source to provide time for MPPT to find its true direction. In fact, the deployment of the running mean reduces the power obtained at the load, as shown in Fig. 17b. The conventional instantaneous value for the performance index using MPPT-IP generates 14 kW of electrical power, compared to the 13 kW of electrical power generated when the method uses the running mean.

C. EXPERIMENTAL VERIFICATION RESULT AND DISCUSSION

This section shows the similarity in the results between the experiment using the HIL and the simulation. Therefore, only selected scenarios are shown; the main findings of this study are found using the simulation results discussed in Section IV-B.

Figure 18 shows the comparison between the experimental and simulation results using MPPT-IP with $H_s = 2 \text{ m}$, $T_p = 11.4 \text{ s}$, and $R_{lo} = 150 \Omega$. Very similar results are obtained from the experiment and the simulation in term of the EMF voltage and stator current. Furthermore, the comparison between the experiment and simulation in term of the voltage and current at the load is depicted in Fig. 19. There are very minor discrepancies between the simulation and the experiment results. Therefore, the resulting powers at the load are very similar. In Fig. 19, the average powers of 4 kW and 3.9 kW result from the simulation and experiment, respectively. This result yields a small percentage of error (2.5 %) between the two results. All experimental results are multiplied by the scaling factor.

Further tests are conducted using MPPT-MP, MPPT-IP, and MPPT-OP to show the similarity between the experimental and simulation results. Table 2 summarises the average power at the load using an irregular sea state ($H_s = 1 \text{ m}$, $T_p = 11.4 \text{ s}$) and various DC load resistances. Table 3 lists the average power at the load using the three different sea states in terms of its significant heights, while fixing the values of the peak period of the wave ($T_p = 11.4 \text{ s}$) and the DC load resistance ($R_{lo} = 150 \Omega$). Similar results were obtained from experiments and simulations in a majority of the scenarios.

V. CONCLUSION

This study assessed nine MPPT methods for the heaving WEC to determine the best performance index and the effect of averaging the performance index. The results indicated that it is best to observe parameters between the mechanical parameters and the load. This was implemented by setting parameters before the boost converter, which yielded an optimum performance against the variation at the source, in terms of sea states, and at the load. The best performance index was found to be maximising power. The study also showed that there was an advantage in averaging the performance index. Using the resulting conclusion for the nine MPPT methods, MPPT-PI that used an instantaneous value for the performance index had an optimum performance compared with the other MPPT methods.

Further, the study showed the development of an HIL scheme using off-the-shelf devices for implementing the damping control for WECs. There was no need to build customised PTO devices. All types of PTO devices can be implemented by programming a programmable AC source. The verification results showed very similar results. Therefore, it can be used as a low cost, effective method for testing other damping control strategies.

Future work for this study will be an assessment study of the MPPT for WEC involving reactive control in MPPT. This will require modifications of the HIL, which allows bidirectional power flow.

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