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Simple bottom-up hierarchical control strategy for heaving wave energy converters

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ABSTRACT

The objective of this study was to improve the power captured in heaving wave energy converters using a simple robust hierarchical control strategy (HCS). A HCS comprises a higher level controller (HLC) and a lower level controller (LLC). The HLC provides a reference velocity for the buoy, which is in-phase with the wave's excitation force. The LLC follows the reference despite the uncertainties in the model. We propose a new HCS called bottom-up HCS (BU-HCS), where the LLC is designed before the HLC. The LLC is implemented using a feedback controlled system with a simple lead-lag compensator as its controller. The lead-lag compensator is designed using $\mathcal{H}_\infty$ theory with the objectives of maximizing the robustness and tracking properties of the LLC while minimizing the control force of the power take-off (PTO) device. A set of optimization problem is obtained for designing the parameters of the lead-lag compensator, which are solved using a genetic algorithm. The HLC in the BU-HCS provides the velocity reference, which satisfies a constraint on the control force and the PTO's utilization index. The HLC is implemented by designing the value of an intrinsic resistance constant, which can be found using the Bode magnitude plot of a transfer function. Based on the plot, a look-up table for the intrinsic resistance constant is generated as a function of the significant height and the peak period of the wave. We tested the proposed method in various scenarios and its performance was compared with existing control techniques.

1. Introduction

One of the most promising renewable energy resources is marine energy and it has been estimated that the global marine energy potential is around 32 TW. The current marine energy market comprises tidal energy, wave energy, and energy generated from ocean salinity and temperature differences [1]. Wave energy has an estimated global potential of 2 TW, which is almost equivalent to the world's electricity consumption. However, due to the irregularity of wave resources as well as the physical constraints to construct a power take-off (PTO) in wave energy converters (WECs), only 25% of the available potential can be harnessed (i.e., 0.5 TW) [2].

Various control strategies have been proposed to enhance the power-to-cost ratio of WECs. An appropriately designed control strategy can improve the WEC capture width, impose system limitations, make the system less susceptible to model imperfections and external disturbances, and provide adequate support to the power take-off (PTO) mechanism [3]. The simplest forms of control for heaving WECs are passive control strategies (e.g., resistive and reactive loading), which lack reference signal tracking (i.e., open loop control) [4]. Although they are simple and cost-effective, these passive control strategies are usually designed based on a single frequency per sea state. Therefore, the performance of the controlled system is lower at other frequencies. In addition, methods based on heuristic control strategies have been reported previously, e.g., fuzzy-based controllers [5,6]. Many predictive control strategies have also been proposed (e.g., see [7,8]). Predictive controllers can produce the optimum control effort and introduce system constraints into the control problem, but greater computational capacities are required since a constrained optimization problem is solved at each sampling instance. Furthermore, predictive controllers are model-based techniques and thus extra measures are required to prevent modelling mismatches. The other category of controllers comprises reference-based control techniques, where a desired signal is tracked in a feedback controlled system. The reference signal is often selected as the heave velocity of the WEC's floater, which is determined

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based on the principle of maximum power transfer [9]. This is usually formulated as a hierarchical control strategy (HCS), which comprises a higher level controller (HLC) responsible for generating the reference signal and a lower level controller (LLC) that performs reference tracking. In [10], a simple HCS was proposed, where the LLC utilizes a lead compensator, whereas an ultra-local model principle is used to compensate for the model uncertainties and un-modelled dynamics. In [11,12], internal mode control was employed in the LLC as a measure to improve the controllers robustness. In [13], the reference-based method was combined with predictive control, where the velocity reference to be followed was generated using model predictive control (MPC).

In this study, we propose a new form of hierarchical control for WECs called bottom-up HCS (BU-HCS), which improves the existing HCS methods. The generation of the reference velocity for the HLC proposed by [11,13,12] is based on the radiation resistance value of the floater/buoy. However, this approach has a major drawback because the HCS is tuned only over a single wave's frequency. This is impractical because irregular sea states contain a mix of incoming frequencies that can be represented in a spectrum. Recently, this drawback was addressed by [10,14], who used the intrinsic resistance to construct the velocity reference, which could be varied based on the significant height and peak frequency of the wave within an interval of time. However, the algorithm required to design the intrinsic resistance is complex. The proposed BU-HCS provides a much simpler method for finding the intrinsic resistance as a function of the wave's significant height and peak frequency. Moreover, the HLC in the BU-HCS incorporates a constraint on the maximum value of the control force from the PTO device and thus PTO utilization. The PTO utilization is defined as the ratio of the maximum converted power relative to the average converted power. In order to limit the control force in BU-HCS, the intrinsic resistance is not designed using the topology of the buoy alone. The design process also involves a dynamic model of the LLC. Thus, in the BU-HCS, there is an interconnection process during the designing of the LLC and the HLC, where the LLC is designed before the HLC in the BU-HCS. Robust tracking controllers (i.e., internal mode control, sliding mode control, and model-free control) are used in the LLC, as proposed by [10–12]. However, there is no physical constraint consideration during the LLC design process. The constraints on the control force, buoy position, and velocity were considered using a MPC by [13], but the MPC incurs high computational costs and it is prone to model uncertainty. In the proposed BU-HCS, a simple lead-lag compensator is used as the main controller in the LLC to provide a good tracking controller and robustness against the model uncertainties and disturbance, as well as minimizing the control force in the system. Therefore, many new features are provided by the BU-HCS compared with the existing HCS.

The remainder of this paper is organized as follows. The mathematical model of the WEC is described in Section 2. The proposed control strategy is given in Section 3. The simulation setup and results are given in Section 4. Finally, we give our conclusions in Section 5.

2. Mathematical modelling

In this study, we consider the Upsalla single-body sea-based heaving WECs, as depicted in Fig. 1. The WEC comprises a buoy, a tether, and a PTO. The PTO comprises a permanent magnet linear generator (PMLG) and a power converter module. The power converter is set up in a back-to-back scheme, where the machine-side converter (MSC) is responsible for controlling the heave velocity of the PMLG by regulating the machine stator current. The grid-side converter is employed to smooth the power before sending it to the grid. The DC-link maintains the instantaneous power balance between the two sides of the converter. The PTO has two roles, i.e., generating electricity and providing the control force to maximize energy absorption from the wave. The PTO can maximize the energy absorption by applying a damping force on the buoy so the buoy's velocity moves in phase with the excitation force. The damping force can be generated by controlling the current in the stator of the PMLG. The current can be regulated using the switches in the power converter module.

The mathematical model of the WEC comprises mechanical and electrical models. The details of these models are described in the following sections.

2.1. Mechanical model

The mechanical model describes the forces acting on the WEC buoy. In this study, a linear approximation is used in the mechanical model, where the buoy's elevation $z(t)$ is around an equilibrium point. In the linear approximation, the dynamics of the buoy are described using the following equation

$$f_e(t) - f_r(t) - f_b(t) - f_l(t) - f_s(t) + f_u(t) = m\ddot{z}(t), \tag{1}$$

where $f_e(t)$, $f_r(t)$, $f_b(t)$, $f_l(t)$, $f_s(t)$, and $f_u(t)$ are the excitation force, radiation force, buoyancy force, the losses force, the spring force, and the control force, respectively [15]. The constant m is the total mass of the PTO, which comprises the buoy, the rod, and the translator of the PMLG. The acceleration of the buoy is denoted as $\ddot{z}(t)$.

The excitation force, $f_e(t)$, is the major force that moves buoy, which is caused by the incident waves on the floating body. The excitation force is formulated using the following causal equation

$$f_e(t) = k_e(t) * \eta(t) = \int_{-\infty}^{t} k_e(\tau - t)\eta(\tau)d\tau, \tag{2}$$

where $\eta(t)$ and $k_e(t)$ are the wave elevation and excitation convolution kernel, respectively. The excitation convolution kernel in (2) can be linearly approximated using a transfer function $K_e(s)$ [16]. Therefore, Eq. (2) is written as

$$F_e(s) = K_e(s)H(s), \tag{3}$$

where $F_e(s)$ and $H(s)$ are the Laplace transforms of $f_e(t)$ and $\eta(t)$, respectively. The transfer function $K_e(s)$ is obtained using the following procedure. Numerical data are generated based on the parameters of the buoy and the sea. In this study, a hydrodynamic software system called WAMIT was used to generate the data [17]. The transfer function is formed by fitting the data using an identification method in the frequency domain.

The radiation force, $f_r(t)$, is the force applied by surrounding waves onto the submerged portion of the buoy. As proposed by [16], the time domain radiation force can be modelled as

$$f_r(t) = m_\infty \ddot{z}(t) + \int_0^t k_r(t - \tau)\dot{z}(t)d\tau, \tag{4}$$

where m_∞ and k_r represent the body added mass at the infinite frequency and the radiation convolution kernel, respectively. Similar to the excitation force, the convolution term in (4) can be approximated by a transfer function using the same procedure. In this study, the convolution term is modelled by a fourth order transfer function. Using this transfer function, the convolution term can be written in the state-space model as

$$\int_0^t k_r(\tau)\eta(t-\tau)d\tau \approx \mathbf{C_r}\mathbf{q_r}(t)$$
$$\dot{\mathbf{q}}_\mathbf{r}(t) = \mathbf{A_r}\mathbf{q_r}(t) + \mathbf{B_r}\dot{z}(t),$$