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Hierarchical Control Strategy for Maximising Power Conversion in Heaving Wave Energy Converters ⋆

Addy Wahyudie * **Omsalama Saeed** * **Mohammed Jama** *

* *Electrical Engineering Department, United Arab Emirates University, F1 Building, PO Box 15551 UAE (e-mail: addy.w@ uaeu.ac.ae)*

Abstract: This paper considers hierarchical control strategy (HCS) for maximising power conversion between mechanical and electrical powers in heaving wave energy converters. The maximisation conversion were obtained by designing the optimum reference for the buoy. This reference were found by relating the mechanical and electrical models of the power-takeoff (PTO) device. A simple look-up table of the intrinsic resistance constant was obtained as function of wave's significant height and peak frequency. A Robust PID controller was used to track this reference. The PID controller was tuned using complex polynomial stabilisation method to convert the robust performance specification into a set of linear programming problem. The interesting feature of the method is all (not only one) set of PID parameters, which satisfies the robust performance, were found. Finally, the simulation results were presented to verify the control objectives.

Keywords: Robust Control, Linear Control Systems, PID Controller, Control and Modeling for Wave Energy Converters, Ocean Energy.

1. INTRODUCTION

This paper considers a procedure to maximise the conversion between mechanical and electrical powers in the heaving wave energy converters (HWECs) using hierarchical control strategy (HCS). The HCS comprise of a higher hierarchical control (HHC) and a lower hierarchical control (LHC). The HCS provides the velocity reference for maximising the powers conversion, while the LHC follows this reference despite modeling uncertainties. The novelty of the proposed control strategy lies in the design of HHC and LHC. Unlike the existing HCS (e.g. Fusco et al (2014) and A. Wahyudie et al (2017)) where only used the mechanical model of designing the velocity reference, we used electrical and mechanical models for generating the velocity reference for the buoy. Furthermore, we utilised a simple robust PID controller in the LHC. The utilisation of PID have not discussed as the main controller in any existing HCS.

The paper is composed using the following order. The mechanical and electrical models of HWECs are provided in Section 2. Section 3 describes the proposed control strategy. A simulation results is discussed in Section 4.2. Finally, conclusion is given in Section 5.

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2. MODELING

The mathematical model of the HWEC comprise of the mechanical and electrical models. The detail of these model are given in the following sections.

2.1 Mechanical Model

The mechanical model describes the forces acting in the buoy. In the linear region, the buoy's movement is described using the following equation

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

where $\ddot{z}(t)$ is the heave acceleration of the buoy, and $f_e(t)$, $f_r(t)$, $f_b(t)$, $f_l(t)$, $f_s(t)$, and $f_u(t)$ are the excitation, radiation, buoyancy, losses, spring, and control forces, respectively. Constant m is the total mass of the PTO, which comprises the buoy, rod, and translator of the PMLG. The detail of the mechanical model can be found in A. Wahyudie et al. (2015).

2.2 Electrical Model

As mentioned above, the calculated $f_u(t)$ is implemented by controlling the current in the PMLG. To calculate the controlling current, the PMLG is modelled using its $d-q$ equivalent circuit, which represents the synchronous frame direct and quadrature components, as shown in Fig. 1. The Park transformation is used to transform the three-phase voltages and currents into the synchronous frame components. The d-q components of the stator voltage $v_s(t)$ at the terminal are formulated by the following equations.

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$$v_{sd}(t) = R_s i_{sd}(t) - \omega_e(t)\lambda_{sq}(t) + \frac{d}{dt}(L_{sd} i_{sd}(t) + \lambda_{PM}),$$
$$v_{sq}(t) = R_s i_{sq}(t) - \omega_e(t)\lambda_{sd} + \frac{d}{dt}(L_{sq} i_{sq}(t)),$$
$$\lambda_{sd}(t) = L_{sd} i_{sd}(t) + \lambda_{PM},$$
$$\lambda_{sq}(t) = L_{sq} i_{sq}(t),$$

where $i_s(t)$, λ_{PM}, λ_s, R_s, and L_s are the stator current, permanent magnet flux, stator flux linkage, machine synchronous resistance, and inductor, respectively. Variable $\omega_e(t)$ is the electrical angular frequency, which is given by the following equation

$$\omega_e(t) = \frac{2\pi \dot{z}(t)}{p_\omega},$$

where p_ω is the pole width of the PMLG. In this study, a surface-mounted PMLG is used where the stator inductance quantities in the d- and q-axes are almost identical, or $L_{sd} \approx L_{sq}$.

Converted (electrical) power $P_e(t)$ is given by

$$P_e(t) = \frac{3}{2} p \lambda_{PM} \omega_e(t) i_{sq}(t), \quad (2)$$

where p is the number of magnetic pole pairs. Mechanical power $P_m(t)$ is expressed by

$$P_m(t) = f_u(t)\dot{z}(t). \quad (3)$$

Using (2) and (3) and the assumption that there is no loss in the conversion between $P_m(t)$ and $P_e(t)$, we have

$$f_u(t)\dot{z}(t) = \frac{3p\lambda_{PM}\omega_e(t) i_{sq}(t)}{2}.$$

Therefore, controlling current $i_{sq}(t)$ is obtained as

$$i_{sq}(t) = \frac{2 f_u(t)\dot{z}(t)}{3p\lambda_{PM}\omega_e(t)}. \quad (4)$$

3. PROPOSED CONTROL STRATEGY

The proposed reference-based control strategy for the WEC comprises the reference generation and servo feedback control system, as depicted in Fig. 2. The reference generation provides the reference velocity. The servo feedback control system follows the reference despite the existence of model uncertainties. In the process of designing the reference velocity, the controller in the servo feedback control system is involved. Therefore, the PID controller was designed before the reference was generated.

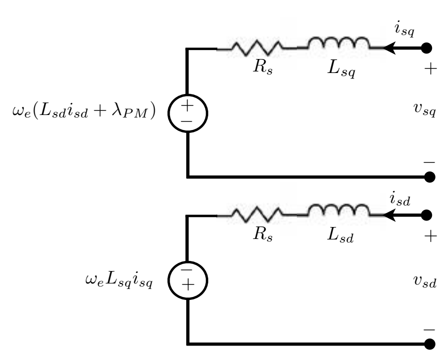

Fig. 1. Equivalent circuit of the PMLG.

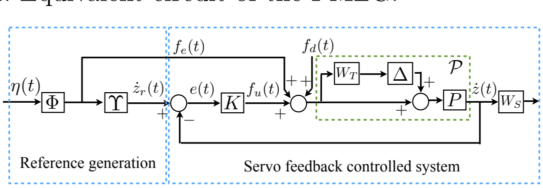

Fig. 2. Proposed control system configuration for WEC systems.

3.1 Servo feedback control system

The servo feedback control system comprises two transfer functions, the mechanical models of the WEC and PID controller, denoted as $\mathcal{P}(s)$ and $K(s)$, respectively. In this study, $\mathcal{P}(s)$ comprises a nominal model of plant $P(s)$ with an input multiplicative uncertainty and receives three input forces. Force $f_u(t)$ is a manipulable force, whereas $f_e(t)$ and the disturbance force $f_d(t)$ are two non-manipulable forces. We formulated transfer function $P(s) = V(s)/F_e(s) = N_P(s)/D_P(s)$ where $V(s)$ is the Laplace transform of $\dot{z}(t)$, and $N_P(s)$ and $D_P(s)$ are the numerator, and denominator of $P(s)$, respectively. $P(s)$ can be found using the mechanical model of HWECs. Moreover, $\Delta(s)$ is a stable and proper transfer function with $\|\Delta\|_\infty \leq 1$. The transfer functions $W_T(s) = N_T(s)/D_T(s)$ and $W_S(s) = N_S(s)/D_S(s)$ are the weighting functions that represent the model uncertainty and nominal performance specification, respectively. The transfer function of the PID controller is formulated as

$$K(s) = k_p + \frac{1}{k_i s} + k_d s = \frac{k_i + k_p s + k_d s^2}{s}. \quad (5)$$

The objectives of the PID controller in the servo feedback control system are

1) to stabilise the nominal feedback control system;
2) to follow the reference velocity despite the existence of uncertainties in the model.

The first objective can be satisfied by placing the closed-loop poles of the nominal feedback control system in the left-half-plane of the complex plane or equivalently

$$\alpha(s, k_p, k_i, k_d) \triangleq s D_P(s) + (k_d s^2 + k_p s + k_i) N_P(s), \quad (6)$$

is Hurwitz. The second objective is solved using the $\mathcal{H}_\infty$ design technique framework, described in Ho et al. (2003). We define the complementary sensitivity function as

$$T(s) = \frac{K(s)P(s)}{1 + K(s)P(s)}.$$

The system has robustness stability if the following equation is satisfied:

$$\|W_T(s)T(s)\|_\infty < 1. \quad (7)$$

The tracking performance can be measured by defining the sensitivity function as the following transfer function, which relates the reference with the error,

$$S(s) = \frac{1}{1 + K(s)P(s)}.$$

Using $\mathcal{H}_\infty$ theory, the nominal tracking performance for minimising the tracking error can be formulated as

$$\|W_S(s)S(s)\|_\infty < 1. \quad (8)$$

The following robust performance for solving the second objective is obtained by combining (7) and (8) as

$$\| |W_S(s)S(s)| + |W_T(s)T(s)| \|_\infty < 1. \quad (9)$$