Energy Conversion and Management 78 (2014) 173–183

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Considering linear generator copper losses on model predictive control for a point absorber wave energy converter

Dan-El Montoya Andrade [a,*], Antonio de la Villa Jaén [b], Agustín García Santana [c]

[a] School of Electrical Engineering, Central University of Venezuela, Caracas, Los Chaguaramos 1041, Venezuela
[b] Department of Electrical Engineering, University of Seville, Camino de los Descubrimientos s/n, 41012 Seville, Spain
[c] Department of Electrical Engineering, AG Ingeniería, Palmas Altas, 41012 Seville, Spain

ARTICLE INFO

Article history:
Received 14 July 2013
Accepted 14 October 2013
Available online 18 November 2013

Keywords:
Wave energy conversion
Model predictive control
Point absorber
Wave power
Linear generator

ABSTRACT

The amount of energy that a wave energy converter can extract depends strongly on the control strategy applied to the power take-off system. It is well known that, ideally, the reactive control allows for maximum energy extraction from waves. However, the reactive control is intrinsically noncausal in practice and requires some kind of causal approach to be applied. Moreover, this strategy does not consider physical constraints and this could be a problem because the system could achieve unacceptable dynamic values. These, and other control techniques have focused on the wave energy extraction problem in order to maximize the energy absorbed by the power take-off device without considering the possible losses in intermediate devices. In this sense, a reactive control that considers the linear generator copper losses has been recently proposed to increase the useful power injected into the grid. Among the control techniques that have emerged recently, the model predictive control represents a promising strategy. This approach performs an optimization process on a time prediction horizon incorporating dynamic constraints associated with the physical features of the power take-off system.

This paper proposes a model predictive control technique that considers the copper losses in the control optimization process of point absorbers with direct drive linear generators. This proposal makes the most of reactive control as it considers the copper losses, and it makes the most of the model predictive control, as it considers the system constraints. This means that the useful power transferred from the linear generator to the power converters increases. In this sense, the average power delivered to the grid increases and the implementation viability improves. In this paper, the results of the simulations are compared with those obtained from other control strategies in irregular waves.
© 2013 Elsevier Ltd. All rights reserved.

1. Introduction

In recent years, researchers in wave energy conversion have focused on point absorbers, and especially on the control of energy extraction [1,2]. In general, the wave energy converter (WEC) system consists of three stages. The first stage is the oscillating system or point absorber which intercepts the energy of the waves. This system is composed of the buoy, the moving part of the linear generator and the spring that is attached to the translator in order to act as a restoring force in wave troughs. The second stage is represented by the power take-off (PTO) system (in this case, the linear generator) that captures and converts the wave energy into electrical energy. The last stage involves the connection interface to the grid by means of a power electronic converter.

It is well known that the reactive control developed by Budal and Falnes [3] states that the maximum energy absorption for point absorbers occurs when the impedance of the PTO system is coupled to the oscillating system in such a way that the imaginary component of the net impedance is zero and the real component is twice the radiation damping. Thus, the maximum amount of energy absorbed by the oscillating system is achieved at the expense of bi-directional flow of large amounts of energy between the PTO system and the oscillating system. This bi-directional flow condition causes large amplitude oscillations and energy losses in the PTO system and high peak-to-average power ratios, which requires the use of large devices with oversized power ratings.

On the other hand, the reactive control applied in irregular waves is noncausal because it is necessary to predict the future waves behavior. In order to apply the reactive control in practice, suboptimal causal approaches such as approximate complex-conjugate control have been proposed [1].

A reactive control that considers the linear generator copper losses has been proposed recently [4]. This reactive control approach significantly reduces the generator losses, increases the useful power and reduces the maximum excursion and maximum

* Corresponding author. Tel.: +58 2126053105; fax: +58 2126053300.
E-mail address: danel.montoya@ucv.ve (D.-E. Montoya Andrade).

0196-8904/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.enconman.2013.10.037

speed reached by the system. However, this control strategy does not allow for consideration of the system constraints.

When compared with other control techniques which have emerged recently, Model Predictive Control (MPC) yields higher performance and thus represents a promising development in the field of wave energy extraction control techniques [1]. Reactive control is a linear strategy in the frequency domain, whereas MPC is a nonlinear control technique in the time domain that takes into account the hydrodynamics constraints. This technique requires an oscillating system model and an excitation force prediction within a time interval in order to predict the next control action on the PTO force. This action is obtained by optimizing a proposed objective function over the prediction interval [5].

MPC was first applied to point absorbers by Gieske in the AWS converter [6]. Hals et al. proposed two alternatives in the formulation of the MPC objective function [7]. The first optimizes the velocity by means of a balance between the excitation power and the radiated power. On the other hand, the second alternative optimizes the power absorbed directly by the PTO system. Brekken applied MPC strategy in order to track the optimum velocity obtained by a reactive control approximation considering the radiation resistance as a constant value [8]. Cretel et al. incorporated the triangular discretization in order to obtain the discrete state system equations and proposed different alternatives to model the objective function based on penalty terms, which are added to the objective function and depend on the PTO force [9]. This way, Cretel et al. suggested that losses can be taken into account by a term that considers the instantaneous weighted value of the PTO force.

This paper proposes a predictive control based on a model that includes the copper losses in the control optimization process of point absorbers which incorporate linear generators. This proposed MPC maximizes the power transferred from the linear generator to the power electronic converter (power converter), instead of maximizing the power captured by the PTO system. In addition, the system constraints located at the maximum translator excursion and the maximum PTO force can be considered when the MPC is applied.

The simulation results show that by using the proposed MPC, the average power delivered to the power converter is higher than using the reactive control when the linear generator copper losses are considered. In order to show the proposed MPC performance, the simulation results are compared with those obtained through approximate complex-conjugate, passive and conventional MPC controls.

2. Hydrodynamic system model of the point absorber

In this work the linear wave theory has been considered. The dynamic equation which describes the body motion with a single degree of freedom, oscillating in heave is [10]:

$$f_e(t) + f_{pto}(t) + f_r(t) + f_s(t) = m\ddot{x}(t) \tag{1}$$

where m is the mass of the buoy, x is the heave excursion, $f_e(t)$ is the wave excitation force (which is the sum of pressure forces on the body surface due to incident and diffracted waves), $f_{pto}(t)$ is the force provided by the linear generator, $f_r(t)$ is the wave radiation force due to the radiated wave when the body moves and $f_s(t)$ is the net restoring stiffness force, which is the difference between the gravitational and buoyancy forces plus the spring force:

$$f_s(t) = -(\rho g S + k_s)x(t) \tag{2}$$

where ρ is the water density, g is the acceleration of gravity, S is the water plane area and k_s is the spring stiffness force constant.

The radiation force can be obtained by [11]

$$f_r(t) = -m_\infty\ddot{x}(t) - \int_{-\infty}^{t} k(t-\tau)\dot{x}(\tau)d\tau \tag{3}$$

where m_∞ is the added mass at infinity (representing the inertia of the surrounding fluid) and $k(t)$ is the impulse response function of the radiation. The integral term of Eq. (3) can be approximated by a state space model of order n [11]:

$$\dot{\mathbf{Y}}_r(t) = \mathbf{A}_r\mathbf{Y}_r(t) + \mathbf{B}_r\dot{x}(t) \tag{4}$$

$$\int_{-\infty}^{t} k(t-\tau)\dot{x}(\tau)d\tau \approx \mathbf{C}_r\mathbf{Y}_r(t) \tag{5}$$

where $\mathbf{Y}_r(t)$ is the state vector of the subsystem. The companion form applied by Yu and Falnes [11] is used to determine the matrices $\mathbf{A}_r, \mathbf{B}_r$ and $\mathbf{C}_r$ [11]. Taking into account Falnes' suggestion that the model can be represented satisfactorily by a model of third or fourth order in radiation problems [11], a fifth-order representation has been chosen in this work.

The excitation force is obtained by processing the wave elevation by means of the method proposed by McCabe et al. [12].

In order to obtain the state space model of the buoy hydrodynamics, Yu and Falnes [11] defined the model state vector $\mathbf{Z}(t) = [\mathbf{Y}_r(t)^T\, x(t)\, \dot{x}(t)]^T$ and considered Eqs. (4), (5) and (2) in (1) to obtain:

$$\dot{\mathbf{Z}}(t) = \mathbf{A}\mathbf{Z}(t) + \mathbf{B}f_e(t) + \mathbf{B}f_{pto}(t) \tag{6}$$

where the matrices $\mathbf{A}$ and $\mathbf{B}$ are:

$$\mathbf{A} = \begin{bmatrix} \mathbf{A}_r & 0_{n,1} & \mathbf{B}_r \\ 0_{1,n} & 0 & 1 \\ -\mathbf{C}_r/(m+m_\infty) & -(\rho g S + k_s)/(m+m_\infty) & 0 \end{bmatrix} \tag{7}$$

$$\mathbf{B} = [0_{1,n} \quad 0 \quad 1/(m+m_\infty)]^T \tag{8}$$

and $0_{a,b}$ is a null matrix with a rows and b columns.

3. Electrical system model

The electrical system is formed by a linear generator, a generator side power converter, a DC link and a grid side power converter as shown in Fig. 1.

It is usual to use decoupled control to the generator side and the grid side power converter. In this sense, the generator side power converter control is responsible for reducing copper losses and keeping generator reaction force in the value set by the control strategy. On the other hand, the grid side power converter control has to keep the DC link voltage and the grid side signals in the range of desirable values.

3.1. Linear generator

In this paper, a generic direct-drive three-phase synchronous permanent magnet linear generator (PMLG) is used. Thus, conversion is necessary through a power converter before delivering the energy into the grid.

A coordinate transformation for the PMLG between the *abc* frame of reference and the *dq* frame of reference without homopolar component is considered [13], so that the model of the PMLG in *dq* reference frame is used. The *dq* reference frame is fixed in the translator. This way, the electrical angular speed is related with the translator speed by $\omega_e(t) = \pi\dot{x}(t)/\tau_p$ where τ_p is the pole width of the linear generator.

Based on the *dq*-transformation, the PTO force may be written as [14]

$$f_{pto}(t) = -1.5\pi\psi\, i_q(t)/\tau_p \tag{9}$$

where $i_q(t)$ is the q stator current component in the *dq*-transformation and ψ is the flux due to the permanent magnets. Note that parameters τ_p and ψ only depend on the generator features. Thus, the PTO force can be directly controlled by $i_q(t)$.

Download English Version:

https://daneshyari.com/en/article/764070

Download Persian Version:

https://daneshyari.com/article/764070

Daneshyari.com