A Predictive power control of Doubly Fed Induction Generator for Wave Energy Converter in Irregular Waves

Mouna Lagoun, Atallah Benalia, Mohamed Benbouzid

To cite this version:


HAL Id: hal-01023509
https://hal.archives-ouvertes.fr/hal-01023509
Submitted on 13 Jul 2014

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L’archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.
A Predictive power control of Doubly Fed Induction Generator for Wave Energy Converter in Irregular Waves

M.S. Lagoun 1, A.Benalia1
1Laboratoire d’Analyse et de Commande des Systèmes d’Energie et Réseaux Electriques LACoSERE, Laghouat, Algeria
mouna.lagoun@gmail.com

M.E.H Benbouzid2
2Laboratoire Brestois de Mécanique et des Systèmes, EA 4325 LBMS Brest, France
Mohamed.Benbouzid@univ-brest.fr

Abstract— In last decades, renewable energy resources are considered as an alternative energy resource to the World’s excessive energy demand. An extremely abundant and promising source of energy exists in oceans. Currently, there are several wave energy converters to harness this energy. Some of them, as in tidal applications, use the Doubly-fed induction generator. This paper deals then with a predictive power control of this generator based Wave Energy Converter under irregular wave climate which is modeled as time series elevation from using Bretschneider spectra. In the proposed control approach, the predicted output power was calculated using a linearized state-space model. The DFIG-based WEC power tracking performances further illustrates the dynamic features of the proposed predictive power control approach.

Keywords— Wave energy converter (WEC), irregular wave, doubly-fed induction generator (DFIG), predictive power control,

I. INTRODUCTION

The world energy demand is increasing at an alarming rate, and producing electricity from alternative or renewable energy sources is becoming a necessity. Among renewable energy harvesting technologies which are still being investigated through various industrial and academic group, wave energy harvesting technology has already shown to be practical, since oceans cover almost 70% of the earth’s surface [1-2].

Numerous techniques for extracting energy from the sea have been suggested, most of which can be included in one of the following categories: wave energy, marine and tidal current energy, ocean thermal energy, energy from salinity gradients (osmosis), and cultivation of marine biomass. The global theoretical energy from waves corresponds to 1500 TWh/year, which is about 100 times the total hydroelectricity generation of the whole planet [3].

To harness the power energy in waves present a different set of technical challenges and a wide variety of designs have been suggested. There are many devices which are generally categorized by the installation location and the power take-off. Therefore, most devices can be characterized as belonging to six types. These are attenuator, point absorber, oscillating wave surge converter, oscillating water column, overtopping device, and submerged pressure differential [4-5].

In all WECs, a mechanical interface is used to convert the slow rotational speed or reciprocating motion into high speed rotational motion for connection to a conventional rotating electrical generator as a DFIG (Fig. 1).

![Fig.1. An illustrative example of DFIG-based WEC.](image)
The control of the active and reactive power is achieved with a rotor current controller. Several investigations have been carried-out for that reason like the classical PI controllers. However, the problem in the use of PI controllers is gains tuning and DFIG terms cross-coupling in the whole operating range. There are many interesting methods to solve these problems have been presented in [6–15].

In the last reference, we have applied a Model-Based Predictive Control (MBPC) strategy for DFIG-based wave energy converters with the main objective to solve the above-cited control problems. In this paper, we applied the same algorithm in case that our converter is under irregular wave.

II. IRREGULAR WAVE MODEL

A. Nomenclature

\[ \rho \] Water density
\[ g \] Gravity
\[ T_s \] Peak period of wave
\[ \omega_0 \] Peak Frequency of wave
\[ H_s \] Significant height of the wave
\[ \eta \] Wave surface elevation
\[ \varphi \] Wave phase

Wave motion and wave energy absorption are composed of time-varying oscillatory phenomena. For the study of regular waves, it is necessary to take into account wave climate spectrum that indicates the amount of wave energy at different wave frequencies. Then, the regular wave is modeled and is typically described in terms of power per meter of wave front (wave crest length) [5],[16-18].

\[ P_{wf} = \rho g^2 H_s^2 T_s / 32\pi \] (1)

There are different mathematical models that are used for defining such specters[18]. The analytical form is given by the following equation:

\[ S(\omega) = \frac{5}{16} H_s^2 \frac{\omega_0}{\omega} e^{-\frac{5}{4} \left( \frac{\omega_0}{\omega} \right)^4} \] (2)

The spectrum used for the simulations is illustrate in (Fig. 2.) where \(T_s = 11s\) and \(H_s = 7s\).

Once the spectrum has been defined, the wave surface elevation of the \(i^{th}\) component wave can be found and created by randomly phase shifting and summing several sinusoids of different heights and periods by this equation:

\[ \eta(x, t) = \sum_{i=1}^{n} H_i \cos(\omega_i t + \varphi_i) \]

III. DFIG MODEL AND ROTOR CURRENT CONTROL

A. Nomenclature

\( s, (r) \) Stator (rotor) index;
\( d, q \) Synchronous reference frame index;
\( V (I) \) Voltage (Current);
\( \Psi \) Flux;
\( R \) Resistance;
\( L \) Inductance;
\( L_m \) Magnetizing inductance;
\( \sigma \) Leakage coefficient, \( \sigma = 1 - \frac{L_m^2}{L_s L_T} \);
\( \omega_s (\omega_{mec}) \) Synchronous speed (rotor speed)
\( (\omega_{el} = \omega_s - P \omega_{mec}) \);
\( P \) Pole-pair number;
For decoupled control, dynamic model is required. The DFIG model in the synchronous reference frame is given by [19]-[20]:

\[
\begin{align*}
\dot{\psi}_{dq} &= R_s I_{dq} + \frac{d\psi_{dq}}{dt} + j \omega_s \psi_{dq} \\
\dot{\psi}_{r} &= R_r I_{r} + \frac{d\psi_{r}}{dt} + j(\omega_s - \omega_m) \psi_r
\end{align*}
\]  

where the relationship between fluxes and currents is:

\[
\begin{align*}
\psi_{dq} &= L_s I_{dq} + L_m I_{r} \\
\psi_{r} &= L_m I_{dq} + L_r I_{r}
\end{align*}
\]

And generator active and reactive power are:

\[
\begin{align*}
P &= \frac{3}{2} (V_{ds} I_{ds} + V_{qs} I_{qs}) \\
Q &= \frac{3}{2} (V_{ds} I_{ds} - V_{qs} I_{qs})
\end{align*}
\]  

The DFIG power control aims independent stator active and reactive power control by means a rotor current regulation. For this principle, and are represented as functions of each individual rotor current. We use stator flux oriented control that decouples the dq axis, which means \(\psi_{ds} = \psi_s\):

\[
\begin{align*}
I_{ds} &= \frac{\psi_s}{L_s} - \frac{L_m}{L_s} I_{dq} \\
I_{qs} &= -\frac{L_m}{L_s} I_{dq}
\end{align*}
\]

By using stator flux oriented the stator voltage becomes \(V_{ds} = 0\) and “(5)” can be written:

\[
\begin{align*}
P &= \frac{3}{2} V_s I_{dq} + V_{qs} I_{qs} \\
Q &= \frac{3}{2} \left( \frac{\psi_s}{L_s} - \frac{L_m}{L_s} I_{dq} \right)
\end{align*}
\]  

The rotor currents control, using “(7)”, allows the DFIG power control. The rotor voltage “(3)”, in the synchronous referential frame using the stator flux position, and by using “(6)”, becomes:

\[
\begin{align*}
\dot{\psi}_{dq} &= (R_s + j \omega_m \omega_s) I_{dq} + \frac{dI_{dq}}{dt} \\
&+ j \frac{L_d}{L_s} \omega_s \psi_r
\end{align*}
\]  

The last equation can be writing in space state form:

\[
\begin{align*}
\dot{x} &= Ax + Bu + Gw \\
y &= Cu
\end{align*}
\]

\[
\begin{bmatrix}
P \\
Q
\end{bmatrix} = \begin{bmatrix}
-R_r & -g \omega_s \\
g \omega_s & -R_r
\end{bmatrix} \begin{bmatrix}
P \\
Q
\end{bmatrix} + \begin{bmatrix}
3 V_M \\
-3 V_M
\end{bmatrix} \begin{bmatrix}
\frac{1}{2 L_s} & \frac{1}{2} \\
\frac{1}{2} & \frac{1}{2 L_r}
\end{bmatrix} \begin{bmatrix}
V_{qr} \\
V_{dr}
\end{bmatrix}
\]

C is the identity matrix. For a simple time, \(\omega_{meq}\) is constant [21] and the rotor applied voltage is constant during a control period of the PWM voltage source inverter. This equation can be discretized as:

\[
\begin{align*}
x(k+1) &= A_d x(k) + B_d u(k) + G_d w(k) \\
y(k+1) &= C_d u(k)
\end{align*}
\]  

Where

\[
\begin{align*}
A_d &= e^{A \tau} \equiv I + A \tau \\
B_d &= \int_0^\tau e^{A \tau} B \, dt \equiv B \tau \\
G_d &= \int_0^\tau e^{A \tau} G \, dt \equiv G \tau \\
C_d &= C
\end{align*}
\]

This linear discrete space state model of DFIG will be used in our scheme algorithm to calculate output power.

IV. MODEL BASED PREDICTIVE CONTROL

A. Nomenclature

\[
\begin{align*}
N_p &= \text{Prediction horizon output;} \\
N_v &= \text{Control horizon;} \\
Y &= \text{Predicted output;} \\
U &= \text{Input.}
\end{align*}
\]

B. MBPC

Model-based predictive control involves a class of control techniques that consists of two main elements: the model of the system being controlled and the optimizer that determines the optimal future control actions. The system model is used to predict the future behavior of the system with control law obtained by optimizing a cost-function [14].

The cost-function considers the effort needed to control the deviation between the expected and the real values.

\[
Y = N_x(k) + HU + DW \quad (11)
\]

Where

\[
\begin{align*}
Y &= \begin{bmatrix} y(k+1) & y(k+2) & \cdots & y(k+n_y) \end{bmatrix}^T \\
U &= \begin{bmatrix} u(k+1) & u(k+2) & \cdots & u(k+n_u) \end{bmatrix}^T
\end{align*}
\]  

\[
\begin{align*}
\mathbf{f} &= \mathbf{A} \mathbf{x} + \mathbf{B} \mathbf{u} + \mathbf{G} \mathbf{w} \\
\mathbf{y} &= \mathbf{C} \mathbf{u}
\end{align*}
\]
The power extract from the wave is adopted like an active voltage. an also voltage of semiconductor used in AC/AC converter are controlled.

In the next two figures, we present the zoom of rotor currents ans we take as an example one phase to show that the current and the voltage are in phase that means the reactive power is zero.
This paper deals with a model-based predictive power control of a doubly-fed induction generator based wave energy converter under irregular waves. These waves are modeled by using Bretschneider energy spectrum. From this spectrum we have generated times series of 90 seconds.

In this context, the control law was derived from an objective function optimization (quadratic error between the predicted powers and the specific references that are control-dependent. The predicted active/reactive powers were calculated using a linearized state-space model.

The obtained results clearly show the MBPC approach effectiveness in terms of DFIG powers tracking performances. Further investigations are required to further assess the effectiveness of the proposed MBPC under constraints (input, output and space state) for this type generator and different WECs.

**REFERENCES**


