Electrical Power and Energy Systems 83 (2016) 525–540

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

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

# Dynamic modeling and control of the tidal current turbine using DFIG and DDPMSG for power system stability analysis

Hamed H.H. Aly *

*Ivan Curry School of Engineering, Acadia University, Canada*
*Faculty of Engineering, Zagazig University, Egypt*

ARTICLE INFO

*Article history:*
Received 14 September 2015
Received in revised form 26 March 2016
Accepted 29 March 2016
Available online 30 April 2016

*Keywords:*
Tidal current power
Direct drive permanent magnet synchronous generator (DDPMSG)
Doubly fed induction generator (DFIG)
Power system stability

ABSTRACT

This paper describes the overall dynamic models of tidal current turbine driving either a doubly fed induction generator (DFIG) or a direct drive permanent magnet synchronous generator (DDPMSG) connected to a single machine infinite bus system including controllers to improve system stability. Testing with ranges of controller gains is carried out to establish zones of stability. The overall results show the advantages of using the DDPMSG over the DFIG. In this paper we used two different models for each machine; the full model and the reduced order model. Also IEEE-9 bus system is used in this work for multi-machine system and tested for a small signal stability analysis.


## Introduction

Tidal current turbines extract electric energy from the water. Tidal currents are fluctuating, intermittent but easier to predict source of energy. Its use is very effective as it relies on the same technologies used in wind turbines but it is still under development and requires more research to respond to the challenges of the sea. The electrical-side layout and modeling approaches used in tidal in-stream systems are similar to those used for wind and offshore wind systems. The speed of water currents is lower than wind speed, while water density is higher than the air density and as a result wind turbines operate at higher rotational speeds and lower torque than tidal in-stream turbines which operate at lower rotational speed and high torque [2,3].

The easier predictability of the tidal in-stream energy resource makes it easier to integrate in an electric power grid. Recognizing that future ocean energy resources are available far from load centers and in areas with limited grid capacity will result in challenges and technical limitations. With the growing penetration of tidal currents energy into the electric power grid, it is very important to study the impact of tidal current turbines on the stability of the grid and to do that we should model the overall system [6].

DFIG and DDPMSG are the most commonly used generators with tidal current turbines. Different controllers are used for stabilization of DFIG and DDPMSG for both the grid side converter and the generator side converter for offshore wind turbines. Some control approaches use the generator side converter controller to maintain the rotational speed of the generator at an optimal value, and minimize core losses; and use the grid side converter controller to maintain the voltage of the DC-link, and control the output reactive power to a certain level. Other control approaches use the generator side converter controller to control the output active power and reactive power, while using the grid side converter controller for controlling the DC-link voltage and the terminal voltage of the turbine system [1]. The following sections describe the dynamic model of the whole system including the proposed controllers and the state space representation of the whole system.

## Tidal current model using DFIG

### *The speed signal resource model*

Eddine et al. [4] have proposed a formula for the tidal current speed as a function of the spring tide speed, neap tide speed and tides coefficient ($C_s$)

$$V_{tide} = V_{nt} + \frac{(C_s - 45) + (V_{st} - V_{nt})}{95 - 45}$$

* Address: Ivan Curry School of Engineering, Acadia University, Canada.
*E-mail addresses:* hamed.aly@dal.ca, hamed.aly@acadiau.ca

http://dx.doi.org/10.1016/j.ijepes.2016.03.055
0142-0615/

**Nomenclature**

| | |
|---|---|
| $V_{tide}$ | tidal current speeds |
| $V_{nt}$ | neap tide speed |
| $V_{st}$ | spring tide speed |
| $C_s$ | constant and equals 95 for spring, 45 for neap tide |
| $P_{ts}$ | tidal in-stream power |
| $\rho$ | density of the water (1025 kg/m$^3$) |
| $A$ | cross-sectional area perpendicular to the flow direction |
| $T_m$ | mechanical torque applied to the turbine |
| $A$ | cross-sectional area perpendicular to the flow direction |
| $C_p$ | marine turbine blade design constant in the range of 0.35–0.5 |
| $\omega_s$, $\omega_r$, $\omega_t$ | stator, rotor electrical angular velocities, and turbine speed at hub height upstream the rotor |
| $T_e$ | electrical torque of the generator |
| $D_s$ | shaft stiffness damping |
| $H_t$, $H_g$ | turbine and generator inertia constants |
| $K_s$ | shaft stiffness coefficient |
| $\theta_t$, $\theta_r$ | turbine and generator rotor angles |
| $B$ | tidal turbine pitch angle |
| $S$ | rotor slip |
| $d$, $q$ | indices for the direct and quadrature axis components |
| $s$, $r$ | indices of the stator and the rotor |
| $v$, $R$, $i$, $\psi$ | voltage, resistance, current, and flux linkage of the generator |
| $K_{pt}$, $K_{it}$ | coefficients for the proportional-integral controller of the pitch controller |
| $P_g$, $P_{DC}$ | active power of the AC terminal at the grid side converter and DC link power respectively |
| $v_{Dg}$, $v_{Qg}$ | $D$ and $Q$ axis voltages of the grid side converter |
| $i_{Dg}$, $i_{Qg}$ | $D$ and $Q$ axis currents of the grid side converter |
| $C$ | capacitance of the capacitor |
| $v_{DC}$, $i_{DC}$ | voltage and current of the capacitor |
| $K_{p1}$, $K_{p2}$, $K_{p3}$ | proportional controller constants for the generator side converter controller |
| $K_{i1}$, $K_i$, $K_{i3}$ | integral controller constants for the generator side converter controller |
| $i_{Dg}$, $i_{Qg}$ | $D$ and $Q$ axis grid currents |
| $v_{Dg}$, $v_{Qg}$ | $D$ and $Q$ axis grid voltages |
| $K_{p4}$, $K_{p5}$, $K_{p6}$ | proportional controller constants for the grid side converter |
| $K_{i4}$, $K_{i5}$, $K_{i6}$ | integral controller constants for the grid side converter |
| $X_c$ | grid side smoothing reactance |
| $\dot{x}$ | state variable |

*The rotor model*

The power ($P_{ts}$) may be found using: $P_{ts} = 1/2\rho A(V_{tide})^3$. The turbine harnesses a fraction of this power, hence $P_t = 1/2\rho C_p A(V_{tide})^3$. The mechanical torque applied to the turbine ($T_m$) can be expressed as:

$$T_m = \frac{0.5\rho\pi R^2 C_p V_{tide}^3}{\omega_t} \tag{1}$$

Nunes et al. [10], and Mihet-Popa et al. [9], used two mass systems for describing the shaft system, one for the turbine and the other for the generator as shown:

$$2H_t\frac{d\omega_t}{dt} = T_t - K_s(\theta_r - \theta_t) - D_s(\omega_r - \omega_t) \tag{2}$$

$$2H_g\frac{d\omega_r}{dt} = T_e - K_s(\theta_r - \theta_t) - D_s(\omega_r - \omega_t) \tag{3}$$

$$\theta_{tr} = (\theta_r - \theta_t) \tag{4}$$

$$\frac{d\theta_{tr}}{dt} = (\omega_r - \omega_t) \tag{5}$$

The same model used for the offshore wind is used for tidal in-stream turbines; however, there is a number of differences in the design and operation of marine turbines due to the changes in force loadings, immersion depth, and different stall characteristics.

*Dynamic model of DFIG*

The DFIG model is developed using a synchronously rotating $d$–$q$ reference frame with the direct-axis oriented along the stator flux position. The reference frame rotates at the same speed as the stator voltage. The stator and rotor active and reactive power are given by [1]:

$$P_s = 3/2(v_{ds}\ i_{ds} + v_{qs}\ i_{qs}), \quad P_r = 3/2(v_{dr}\ i_{dr} + v_{qr}\ i_{qr}) \tag{6}$$

$$P_g = P_s + P_r \tag{7}$$

$$Q_s = 3/2(v_{qs}\ i_{ds} - v_{ds}\ i_{qs}), \quad Q_r = 3/2(v_{qr}\ i_{dr} - v_{dr}\ i_{qr}) \tag{8}$$

Slootweg et al. [11], Janaka et al. [5], and Yazhou et al. [8] used the fourth order model for describing the DFIG as follows:

$$v_{ds} = -R_s i_{ds} - \omega_s\psi_{qs} + \frac{d}{dt}\psi_{ds} \tag{9}$$

$$v_{qs} = -R_s i_{qs} - \omega_s\psi_{ds} + \frac{d}{dt}\psi_{qs} \tag{10}$$

$$v_{dr} = -R_r i_{dr} - s\omega_s\psi_{qr} + \frac{d}{dt}\psi_{dr} \tag{11}$$

$$v_{qr} = -R_r i_{qr} - s\omega_s\psi_{dr} + \frac{d}{dt}\psi_{qr} \tag{12}$$

$$\psi_{ds} = -L_{ss}i_{ds} - L_m i_{dr,}\psi_{qs} = -L_{ss}i_{qs} - L_m i_{qr} \tag{13}$$

$$\psi_{dr} = -L_{rr}i_{dr} - L_m i_{ds,}\psi_{qr} = -L_{rr}i_{qr} - L_m i_{qs} \tag{14}$$

$$s = (\omega_s - \omega_r)/\omega_s \tag{15}$$

$$\frac{d\omega_r}{dt} = -\omega_s\frac{ds}{dt} - \omega_s\frac{ds}{dt} \tag{16}$$

where $L_{ss} = L_s + L_m$, $L_{rr} = L_r + L_m$, $L_s$, $L_r$ and $L_m$ are the stator leakage, rotor leakage and mutual inductances, respectively. The previous model may be reduced by neglecting stator transients and is described as follows:

$$v_{ds} = -R_s i_{ds} + X' i_{qs} + e_d \tag{17}$$

$$v_{qs} = -R_s i_{qs} - X' i_{ds} + e_q \tag{18}$$

$$\frac{de_d}{dt} = -\frac{1}{T_0}(e_d + (X - X')i_{qs}) + s\omega_s e_q - \omega_s\frac{L_m}{L_{rr}}v_{qr} \tag{19}$$