Modeling of Offshore Wind and Tidal Current Turbines for Stability Analysis

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ABSTRACT

Offshore wind and tidal current are of the most common energy resources for generating electricity in the near future because of the oil problems (crises and pollution). The dynamic model of the offshore wind and tidal current are very important topic for dealing with these renewable energies. This paper describes the overall dynamic models of tidal current turbine using three different types of generators (doubly fed induction generator (DFIG), squirrel cage induction generator (SCIG)) and direct drive permanent magnet synchronous generator (DDPMSG)). The state space for all types of the generators of these two types of turbines are concluded. All models are validated using a common property of the generator for the validation.

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Introduction

Wind energy is the energy produced from the simple air in motion and this motion is caused by the uneven heating of the earth’s surface by the sun. The air over the sea absorbs the heat faster than the land and so the air moves from the sea to the land causing the wind but in the night the air motion is changed from the land to the sea because the air over the sea cools faster than the air over the land. This wind is hardly predictable source of energy. Tidal current turbines extract electric energy from the water. Tidal currents are fluctuating, intermittent but a predictable 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. There are two tide types; spring tide which happens when the moon and the sun are on the same line and neap tide which happens when the moon and the sun are at right angles and so they pull water at the sea in different directions. 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 the 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 [1-5].

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 current energy into the electric power grid system, it is very important to study the impact of tidal current turbines on the stability of the power system grid and to do that we should model the overall system. The model of the ocean energy system consists of three stages. The first stage contains the fluid mechanical process. The second stage consists of the mechanical conversion and depends on the relative motion between bodies. This motion may be mechanical transmission and then using mechanical gears or may be depending on the hydraulic pumps and hydraulic motors. The third stage consists of the electromechanical conversion to the electrical grid [4-9].

Offshore wind and tidal current turbine system, DFIG, SCIG, the converter and the controllers.

The speed signal resource model for the tidal current and offshore wind

The tidal current speed may be expressed as a function of the spring tide speed, neap tide speed and tides coefficient. Paper (10) proposed different algorithm models for the tidal current speed.

The Wind Speed Signals Model $v_\text{wind}$ consists of four components related to the mean wind speed ($v_{\text{mean}}$), the wind speed ramp ($v_{\text{run}}$) (which is considered as the steady increase in the mean wind speed), the wind speed gust ($v_{\text{gust}}$), and the turbulence ($v_{\text{turb}}$).

$$v_\text{wind} = v_{\text{mean}} + v_{\text{run}} + v_{\text{gust}} + v_{\text{turb}}$$

The mean wind speed is a constant; a simple ramp function will be used for ramp component (characterized by the amplitude of the wind speed ramp ($A_\text{r}$ (m/s)), the starting time ($T_\text{r}$)), and the ending time ($T_\text{e}$)). The wind speed gust component is characterized by the amplitude of the wind speed gust ($A_\text{g}$ (m/s)), the starting time ($T_\text{g}$), and the ending time ($T_\text{e}$)). The wind speed gust may be expressed as a sinusoidal function.

The most used models are given by:

$$v_\text{run} = A_\text{r}(1 - \cos(2\pi(t/D_\text{r} - T_\text{g}/D_\text{r}))$$

$$v_\text{turb} = 0 \quad T_\text{rg} \leq t \leq T_\text{e}$$

$$D_\text{r} = T_\text{e} - T_\text{rg}$$

A triangular wave is used to represent the turbulence function which has adjustable frequency and amplitude [11].
The rotor model

For the offshore wind the rotor model represents the conversion of kinetic energy to mechanical energy. The wind turbine is characterized by \( C_p \) (wind power coefficient), \( \lambda \) (tip speed ratio), and \( \beta \) (pitch angle). \( \lambda = \omega_R/R \omega_w \), where \( R \) is the blade length in m, \( \omega_w \) is the wind speed in m/s, and \( \omega_R \) is the wind turbine rotational speed in rad/sec. \( C_p \beta \) curves are manufacturer-dependent but there is an approximate relation expressed as

\[
C_p = \frac{1}{2\left[\left(\frac{\kappa}{\beta_0} - 0.026\beta - 2\right) + 0.5\frac{\kappa}{\beta_0}\right]^{1.088} \beta^{0.073}}.
\]

\( C_p \) is the wind turbine blade design constant.

The rotor model may be represented by using the equation of the power extracted from the wind (\( P_w = \frac{1}{2} \rho \omega^2 V_{wind}^3 \)), or the mechanical torque applied to the turbine (\( \tau_m \)). \( \omega_w \) is the turbine speed at hub height upstream the rotor, \( \rho \) is the density of the air [11].

For the tidal current turbines the rotor model may be represented by using the equation of the power extracted from the wind (\( P_w = \frac{1}{2} \rho \omega^2 V_{tidal}^3 \)).

The power \( (P_w) \) may be found using: \( P_w = \frac{1}{2} \rho \omega^2 (V_{tidal})^3 \). The turbine harnesses a fraction of this power, hence the power output may be expressed as: \( P_t = \frac{1}{2} \rho C_p\omega^2 (V_{tidal})^3 \).

The power output is proportional to the cube of the velocity. The velocity at the bottom of the channel is lower than at the water column above seabed. The mechanical torque applied to the turbine \( (T_m) \) can be expressed as [4-9]:

\[
T_m = \frac{1}{2} \rho C_p\omega^2 (V_{tidal})^3.
\]

The shaft system for tidal current and offshore turbines may be represented by a two mass system one for the turbine and the other for the generator as shown in:

\[
2H_{\text{rot}} = T_1 - K_1(\Theta_1 - \Theta_0) - D_1(\omega_0 - \omega_1).
\]

\[
2H_{\text{rot}} = T_2 - K_2(\Theta_2 - \Theta_0) - D_2(\omega_0 - \omega_2).
\]

\[
\Theta_0 = \Theta_1 - \Theta_2.
\]

(5)

There is a ratio for the torsion angles, damping and stiffness that need to be considered when one adds a gear box as all above calculations must be referred to the generator side and calculated as: \( a = \frac{L_{stg}}{L_{stg}^p} \), \( \Theta_{\text{rot}}^p = \Theta_{\text{rot}} \), \( \Theta_{\text{stg}}^p = \Theta_{\text{stg}} \). 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. Since the extracted power from the tidal currents is proportional to the area and the cube of the velocity, hence narrow channels is preferred for tidal turbines to extract higher power as the velocity is higher.

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 [4-10]:

\[
P_d = \frac{3}{2}(v_{ds} i_{ds} + v_{qs} i_{qs}) \quad P_q = \frac{3}{2}(v_{dq} i_{dq} + v_{qf} i_{qf})
\]

\[
Q_d = \frac{3}{2}(v_{qs} i_{ds} - v_{ds} i_{qs}) \quad Q_q = \frac{3}{2}(v_{qf} i_{dq} - v_{dq} i_{qf})
\]

(7)

(8)

The model of the DFIG can be described as:

\[
v_{ds} = -R_s i_{ds} - \omega_0 \psi_{qs} + \frac{d}{dt}\psi_{ds}
\]

(9)

\[
v_{dq} = -R_s i_{dq} - \omega_0 \psi_{qs} + \frac{d}{dt}\psi_{dq}
\]

(10)

\[
v_{ds} = -R_s i_{ds} - \omega_0 \psi_{qs} + \frac{d}{dt}\psi_{ds}
\]

(11)

\[
v_{dq} = -R_s i_{dq} - \omega_0 \psi_{qs} + \frac{d}{dt}\psi_{dq}
\]

(12)

\[
\frac{d}{dt}\psi_{ds} = -L_{ms} i_{ds} - L_{m} i_{ds} \quad \frac{d}{dt}\psi_{dq} = -L_{ms} i_{dq} - L_{m} i_{dq}
\]

\[
\frac{d}{dt} i_{ds} = -\frac{1}{L_m} (\psi_{ds} + (X - X_m) i_{ds}) + s\omega_0 i_{qs} - \omega_0 L_{ms} i_{qs}
\]

\[
\frac{d}{dt} i_{dq} = -\frac{1}{L_m} (\psi_{dq} - (X - X_m) i_{dq}) - s\omega_0 i_{qs} + \omega_0 L_{ms} i_{qs}
\]

(13)

(14)

(15)

(16)

Where, \( L_m = L_1 + L_{ms} \), \( L_{ms} = L_r + L_{ms} \), \( L_r \) 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:

\[
v_{ds} = -R_s i_{ds} + X^p i_{qs} + e_d
\]

\[
v_{dq} = -R_s i_{dq} + X^p i_{qs} + e_q
\]

\[
\frac{d}{dt} \psi_{ds} = \frac{1}{T_p} (e_d + (X - X_m) i_{ds}) + s\omega_0 e_q - \omega_0 L_{ms} e_q
\]

\[
\frac{d}{dt} \psi_{dq} = \frac{1}{T_p} (e_q - (X - X_m) i_{dq}) - s\omega_0 e_q + \omega_0 L_{ms} e_q
\]

(17)

(18)

(19)

(20)

The components of the voltage behind the transient (the internal voltage components of the induction generator) are:

\[
e_d = -\frac{L_{ms} e_q}{L_m} \quad \text{and} \quad e_q = \frac{L_{ms} e_d}{L_m}
\]

The stator reactance \( X = \omega_0 L_{ms} = X_s + X_m \), and the stator transient reactance \( X^p = \omega_0 (L_m - L_{ms}/L_m) = X_s + (X_s X_m)/(X_s + X_m) \). The transient open circuit time constant is \( T_p = L_m / R_s = (L_s + L_{ms}) / R_s \), and the electrical torque is \( \tau_e = (i_{ds} d_{ds} - i_{dq} d_{dq}) X_s / \omega_2 \). Figure (1) shows d and q – axis equivalent circuit of DFIG.
\[ 0 = -R_e \frac{d}{dt} i_{dr} + s \omega_b \psi_{dr} \]
\[ 0 = -R_e \frac{d}{dt} i_{qr} - s \omega_b \psi_{qr} \]

\[ d \text{ - axis equivalent circuit of SCIG} \]

\[ q \text{ - axis equivalent circuit of SCIG} \]

Figure (2) d and q - axis equivalent circuit of FSIG

\[ P_r = 0; \quad Q_r = 0 \]

In the SCIG there are capacitors to provide the induction generator magnetizing current and for compensation. Figure (2) d and q - axis equivalent circuit of FSIG.

The pitch controller model

The pitch controller is used to adjust the tidal current turbine to achieve a high speed magnitude. This may be represented by a PI controller with a transfer function \( K_{p\theta} + \frac{I}{s} \) shown in Figure (3).

\[ \beta = (K_{p\theta} + \frac{I}{s}) \omega_b \]

Figure (3) Pitch angle control block

\[ \frac{\beta}{s} = \frac{K_{p\theta}}{s} \frac{\beta}{s} + \frac{I}{s} \]

The converter model

A converter feeds or takes power from the rotor circuit and gives a variable speed (a partial scale power converter used). The rotor side of the DFIG is connected to the grid via a back to back converter. The converter at the side connected to the grid is called the supply side converter (SSC) or grid side converter (GSC) while the converter connected to the rotor is the rotor side converter (RSC). The RSC operates in the stator flux reference frame. The direct axis component of the rotor current acts in the same way as the field current as in the synchronous generator and thus controls the reactive power change. The quadrature component of the rotor current is used to control the speed by controlling the torque and the active power change. Thus the RSC governs both the stator-side active and reactive powers independently. The GSC operates in the stator voltage reference frame. The d-axis current of the GSC controls the DC link voltage to a constant level, and the q-axis current is used for reactive power control. The GSC is used to supply or draw power from the grid according to the speed of the machine. If the speed is higher than synchronous speed it supplies power otherwise it draws power from the grid but its main objective is to keep the dc-link voltage constant regardless of the magnitude and direction of the rotor power.

The back to back converter using a DC link is shown in Figure (4). The balanced power equation is given by [13, 14]:

\[ P_r = P_g + P_{DC} \]

\[ P_{DC} = v_{DC} i_{DC} = -v_{DC} i_{DC} \]

\[ v_{DC} \frac{d}{dt} = v_{DC} i_{DC} + v_{DC} i_{Q} \]

\[ v_{DC} \frac{d}{dt} = v_{DC} i_{DC} + v_{DC} i_{Q} \]

\[ v_{DC} \frac{d}{dt} = v_{DC} i_{DC} + v_{DC} i_{Q} \]

Figure (4) Back to back converter

Rotor side converter controller model

The rotor side controller used here is represented by four states \( \delta_1, \delta_2, \delta_3, \delta_4 \). \( \delta_1 \) is related to the difference between the generated power of the stator and the reference power that is required at a certain time, \( \delta_2 \) is related to the difference between the quadrature axis generator rotor current and the reference current that is required at a certain time, \( \delta_3 \) is related to the difference between the stator terminal voltage and the reference voltage that is required at a certain time, and \( \delta_4 \) is related to the difference between the direct axis generator rotor current and the reference current that is required at a certain time [13, 14]. Figure (5) shows the rotor side converter controller. This is described by equations (26-34).

\[ \delta_1 = P_{ref} - P_s \]

\[ \delta_2 = -K_{q1}/K_{p1}\delta_2_1 + 1/K_{p1} i_{q,ref} \]

\[ \delta_3 = i_{q,ref} - i_{q} \]

\[ \delta_4 = K_{p2}/K_{b1} \delta_3_1 + K_{d1} \delta_3_2 - i_{q} \]

\[ \delta_5 = -K_{p2}/K_{b1} \delta_3_1 + K_{d1} \delta_3_2 - i_{q} \]

\[ \delta_6 = v_{s,ref} - v_{s} \]

\[ \delta_7 = -K_{p2}/K_{p2}\delta_4_1 + 1/K_{p2} i_{d,ref} \]

\[ \delta_8 = i_{d,ref} - i_{d} \]
\[
\dot{\delta} = \frac{K_{p}\delta - K_{d}\delta}{L_s i_{ds}} + L_s i_{ds} - \omega_s L_m / K_{p}\delta - \omega_0 L_m / K_{p}\delta + \omega_s \dot{\delta} + (L_m / K_{p}\delta) i_{qs}(\omega_0 - \omega_s)
\]

(34)

Grid side converter controller model

The grid side converter controller used here is represented by four states \( (\delta, \theta, \theta_p, \theta_q) \), \( x_3 \) is related to the difference between the DC voltage and the reference DC voltage required at a certain time, \( x_4 \) is related to the difference between the grid terminal voltage and the reference terminal voltage required at a certain time, \( x_5 \) is a combination of \( x_3 \) and direct axis grid current and \( x_6 \) is a combination of \( x_4 \) and quadrature axis grid current as shown in equations (35-40). Figure (6) shows the grid side converter controller.

![Figure (6) Grid side converter controller](image)

TIDAL current turbine MODEL using DDPMSG

In this section we review the dynamic model of the direct drive permanent magnet synchronous generator, the converter and the proposed controllers.

The dynamic modeling of the DDPMSG

The DDPMSG can be modeled as the following [3, 13]:

\[
v_{ds} = -R_s i_{ds} - \omega_s \psi_{ds} + \frac{d}{dt} \psi_{ds}
\]

(41)

\[
v_{qs} = -R_s i_{qs} - \omega_s \psi_{qs} + \frac{d}{dt} \psi_{qs}
\]

(42)

where:

- \( R_s \) is the stator resistance
- \( \omega_s \) is the rotor angular speed
- \( \psi_{ds} \) and \( \psi_{qs} \) are the d- and q-axis flux linkages

The flux linkages and the torque can be expressed as:

\[
\psi_{ds} = \frac{L_d}{L_s} \times i_{ds} + \psi_f
\]

(43)

\[
\psi_{ds} = \frac{L_q}{L_s} \times i_{qs} + \psi_f
\]

(44)

\[
T_r = \frac{(3/2) p}{L_s} i_{qs} \times ((L_s - L_q) i_{ds} + \psi_f)
\]

(45)

Figure (7) d-q axis component of PMSG

The generator side converter controller model for DDPMSG

The generator side converter controller used here is represented by two states only \( (x_1, \theta) \), \( x_1 \) related to the difference between the generated power and the reference power that required at a certain time, \( x_2 \) related to the difference between the direct axis generator current and the reference current required at a certain time [13-15]. Figure (8) shows the generator side converter controller described by:

\[
\dot{K}_1 = P_r \times P_{ref}
\]

(48)

\[
\dot{K}_2 = i_{ds} - \theta_{ref}
\]

(49)

\[
v_{ds} = K_{p1} x_1 + K_{i1}(L_s - L_q) \times i_{ds}
\]

(50)

\[
v_{ds} = K_{p2} x_1 + K_{i2}(L_s - L_q) \times i_{ds}
\]

(51)

where: \( K_{p1}, K_{p2} \) represent the proportional controller constants and \( K_{i1}, K_{i2} \) represent the integral controller constants for the generator side converter controller.

![Figure (8) Generator side converter controller for DDPMSG](image)

Grid side converter controller model for DDPMSG

The grid side converter controller used here is represented by four states \( (x_3, x_4, x_5, x_6) \), \( x_3 \) related to the difference between the DC voltage and the reference DC voltage that required at a certain time, \( x_4 \) related to the difference between the terminal voltage and the reference terminal voltage that required at a certain time, \( x_5 \) is a combination of \( x_3 \) and direct axis grid current and \( x_6 \) is a combination of \( x_4 \) and quadrature axis grid current. Figure (9) shows the grid side converter controller.

![Figure (9) Grid side converter controller for DDPMSG](image)
\[ V_{DC,ref} - V_{DC} \]
\[ = K_{pd} i_d + K_{ps} x_d i_d \]
\[ = V_{ref} - v_i \]
\[ = K_{pd} i_d + K_{ps} x_d i_d \]
\[ = V_{DC} - v_{Dg} \]
\[ = K_{p3} i_d + K_{p4} x_d i_d \]
\[ = K_{p3} i_d + K_{p4} x_d i_d \]
\[ = K_{p3} i_d + K_{p4} x_d i_d \]
\[ = K_{p3} i_d + K_{p4} x_d i_d \]
\[ = K_{p3} i_d + K_{p4} x_d i_d \]
\[ = K_{p3} i_d + K_{p4} x_d i_d \]
\[ = K_{p3} i_d + K_{p4} x_d i_d \]
\[ = K_{p3} i_d + K_{p4} x_d i_d \]

Where: \( V_{DC} \) is the DC link voltage, \( i_{Dg}, i_{Qg} \) are the D and Q axis grid currents, \( v_{Dg}, v_{Qg} \) are the D and Q axis grid voltages, \( K_{p3}, K_{p4}, K_{p5} \) represent the proportional controller constants, \( X_c \) is the grid side smoothing reactance, and \( K_{id}, K_{iq}, K_{id} \) represent the integral controller constants for the grid side converter.

Validation of the models

As the value of the resistance or inductance changes the stability degree will change. In this section we will try to find the relation between the increasing or decreasing of these values and the stability degree as a way of validation for the models. Figure (10) shows the relation between different values of the rotor resistance and the eigenvalues of the changed mode in case of DFIG. Figure (11) shows the relation between different values of the stator resistance and the eigenvalues of the changed mode in case of DDPMSG. From Figures (11, 12) we conclude that as the resistance value of the rotor increase, the stability degree will increase. Figure (12) shows the relation between different values of the rotor inductance and the eigenvalues of the changed mode in case of DFIG. Figure (13) shows the relation between different values of the stator inductance and the eigenvalues of the changed mode in case of DDPMSG. From Figures (12, 13) we conclude that as the inductance value increase as the stability will decrease because of increasing the delay time.

Conclusion

The use of offshore wind and tidal current as a renewable source of energy is very effective as it relies on similar technologies. The overall dynamic system of the offshore and tidal current turbine based on three different types of generators for a single machine infinite bus system has been modeled. The converter used has been modelled. Different controllers are also models for different machines. The state space representation of the overall system is concluded. All models are validated using a common property of the machine for the validation (changing the degree of the system stability by changing the value of the resistance and the inductance). If the resistance value of different generators increases, the stability degree will increase and if the inductance value of the machine increases, the stability degree will decrease.

References


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