TELKOMNIKA Indonesian Journal of Electrical Engineering
Vol. 13, No. 1, January 2015, pp. 57 ~ 64
DOI: 10.11591/telkomnika.v13i1.7017

Modelling and Simulation of Tidal Current Turbine with Permanent Magnet Synchronous Generator

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Abstract

This paper explain the creation of a Matlab-Simulink model for a tidal current turbine system through the modeling of the source, the rotor, drive train and the generator. The aim of the simulation model is to illustrate how the tidal current energy system works and how to make use of it in power generation. Harnessing tidal currents power done through various types of water current turbines. Owing to its advantages in producing power from tidal currents, OpenHydro tidal current turbine will be used in this work. With its Permanent magnet synchronous generator (PMSG) that is suitable for low tidal current speeds and no need for gearbox. The rotational motion of the turbine rotor is transferred to the electrical generator by means of a mechanical transmission system called drive train. MATLAB/SIMULINK interface has been examined and the maximum electrical power extraction within the allowable range of tidal currents can be achieved if the controller can properly follow the optimum curve with any water current speed change.

Keywords: *Renewable energy, Tidal currents, Tidal energy conversion, OpenHydro turbine, PMSG.*

1. Introduction

Renewable energies, that are naturally replenished, are that generated from natural resources such as wind, sunlight, tide, hydro, biomass , geothermal and ocean. Energy crisis, climate changes such as atmosphere temperature rise due to the increase of greenhouse gases emission, high oil prices, limitation and depletion of fossil fuels reserves increased demand in these green energies [1]. Away from conventional hydro and tidal barrage systems drawbacks (intermittent source of energy, high initial costs, limited locations and bad effect on marine lives) tidal current turbines can generate power from free flowing water with almost zero environmental effects.

The energy is stored in oceans in several forms as chemical and biological products, thermal energy and kinetic energy (waves and currents). The main advantage of tidal energy over other renewable energy technologies is its predictability away from effects due to changing in weather patterns [2].Tidal currents are the flow of water as a tide ebbs and floods, Despite the fact that ocean currents move slowly relative to typical wind speeds, water is 800 times denser than air. Therefore, for the same surface area, water moving 12 knots exert the same amount of force as a constant 110 knots wind. Because of this physical property, tidal currents contain an enormous amount of energy that can be captured and converted to a usable form [3].

This paper presents the mathematical modelling and simulation for tidal current energy system i.e. tidal current speed profile, tidal current turbine, drive train and the generator. Applying these models in Matlab/Simulink and output results are analyzed.

2. Location of case study

The Suez gulf, Egypt, is chosen to be the site under consideration, the location has 28°45′ North 33°00′ East. Tidal current speed ranges between 0.5 m/s and 1.2 m/s [4].this location was chosen as it have the highest tidal current speed in egypt with suitable water depth.

Received August 2, 2014; Revised September 18, 2014; Accepted October 16, 2014

3. Tidal Currents Power System

Tidal current devices seek to extract energy from the kinetic movement of water much as wind turbines extract energy from movement of air; these tidal currents are often enlarged where water is forced to flow through narrow channels or around beaches.

The following figure shows the general scheme of tidal currents power system.

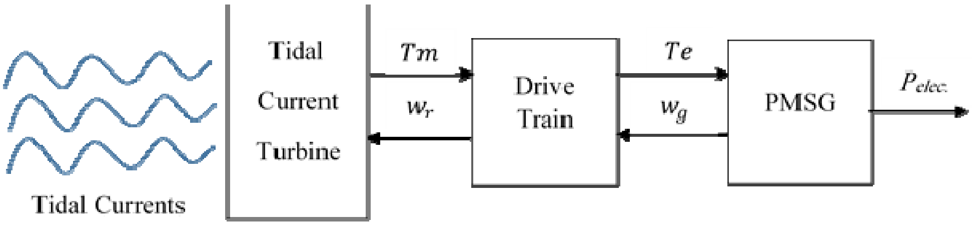

Figure 1. Tidal current energy system

The main components of this system are the tidal currents, tidal currents turbine (i.e. OpenHydro), the mechanical drive train and the generator. Turbine converts the kinetic energy of the tidal currents into mechanical energy represented in form of mechanical torque Tm that controls the drive train with the generator angular speed w_g producing electrical torque Te that drive the generator and rotor angular speed w_r controlling the tip speed ratio of the turbine.

4. Mathematical Modelling

4.1. Tidal Current Speed Profile

As tidal currents are a periodic horizontal flow of water accompanying the rise and fall of the tide they can be modeled as a stream of harmonics according the following equation.

$$v(t) = \sum v_i \,.\sin(2\pi f_i \mathrm{t} + P_i) \tag{1}$$

Where, v_i is the amplitude, T is the period and P_i is the phase for i-th harmonic constituents. Each constituent is defined by its angular frequency in solar hours. The phase of each component has to be specified [5].A simulink model for five harmonic constituents below in figure 2 gives the tidal turbine speed profile as in figure 3.

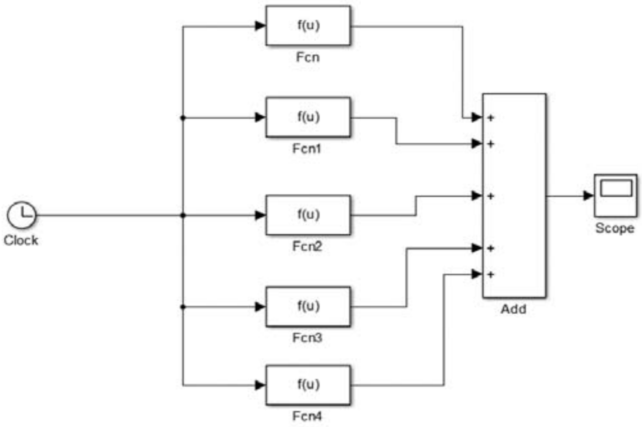

Figure 2. Water speed profile implementation in Simulink

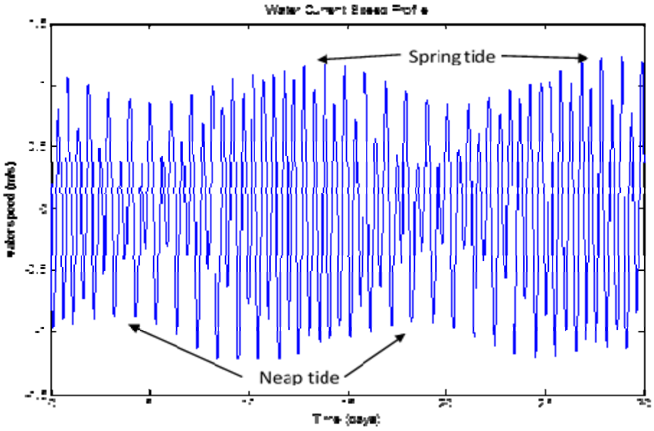

Figure 3. Tidal current speed profile for 30 days.

It is clear from figure 3 that during one lunar month there are two spring tides (at times of new and full moon) and two neap tides (at times of first and last quarter of the moon). This speed profile repeats for all year months.

4.2. Tidal Current Turbine

Generating electricity from flowing water can be done either by building a tidal barrage across a bay in high tide areas (tidal potential energy), or by extracting energy from free flowing water (tidal kinetic energy). The amount of power that a tidal current turbine can extract from flowing water depends on the turbine design. Factors such as rotor diameter and tidal current speed affect this amount of power. Power available in tidal currents is given by [3]:

$$P_{avl} = 0.5\rho A V^3 \qquad (1)$$

Where, ρ is the seawater density =1025, A is the rotor blade area and V is the water current speed. Actual power can be harnessed as follows by P_{act}

$$P_{act} = 0.5\rho C_P(\lambda,\beta) A V^3 \qquad (2)$$

Where, $C_P$is the power coefficient that is a function in tip speed ratio TSR (λ) and turbine blade pitch angle (β) and it is the percentage of power that the turbine can extract from the water flowing through the turbine. Tip speed ratio can be given by the following equation:

$$\lambda = \frac{\mathrm{R}\omega_{\mathrm{r}}}{\mathrm{V}} \qquad (3)$$

Where, R are the rotor blade radius and ω_{r} is the rotor angular speed. The power coefficient C_P can be determined from the following equation

$$C_P(\lambda,\beta) = c1\left(\frac{c2}{\lambda i} - c3\beta - c4\right)e^{-c5/\lambda i} + c6\lambda \qquad (5)$$

$$\lambda i = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \qquad (6)$$

Where, λi is the next value of λ, C_P can't excess 0.593 that means that the power extracted from the water is always less than 59.3% (Betz 's limit) [6] that is reflect to various aerodynamic losses depend on the rotor construction (number and shape of blades, weight, stiffness, etc.).

In this work, OpenHydro turbine, having specifications in table 1 and power curve in figure 4, is used as it possesses many gains make it preferable than other tidal current turbines. Such simple construction with only one moving section, scalability (10 m diameter generate 1

MW rated power) and It is a self-contained rotor with a solid-state permanent magnet generator encapsulated within the outer rim meaning there are no seals and no gearbox needed. No seals means there is no minimum or maximum depth. This concept permits in fact the minimization of maintenance requirements. The main advantage distinguish OpenHydro turbine is its ability to operate in bidirectional tidal flow and saving marine life [7].

Table 1. OpenHydro specifications.

ROTOR DIAMETER	15m	RATED POWER	1.5 MW at v=2.57 m/s
CUT IN SPEED	0.7m/s	OUTPUT POWER	11 kV AC,50- 60 HZ-3φ

When the tidal current speed exceeds the 2.57 m/s speed range the extracted power will be limited to 1.5 MW by power control strategy.

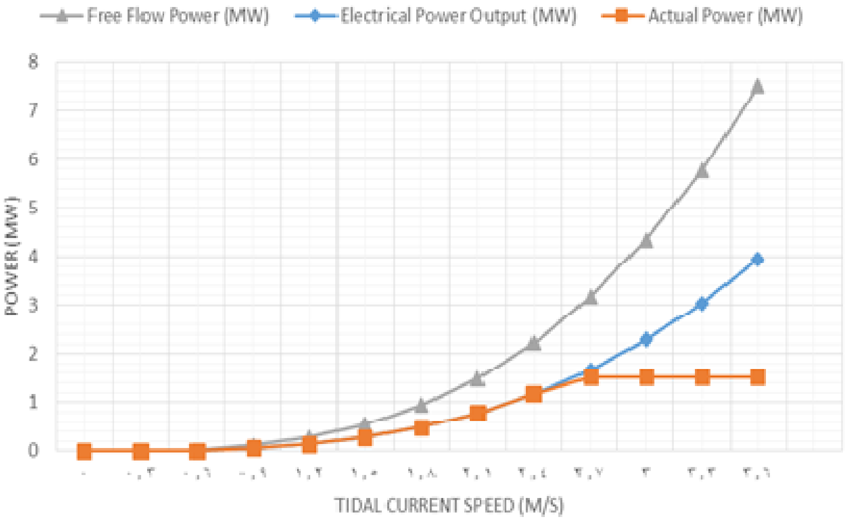

Figure 4.OpenHydro power curves with tidal current speed.

The generator is rated electrically to 1.520 MW as a maximum value and at any other higher water speeds; the output is limited to this value as shown in the bottom curve.

For c1=0.5176, c2=116, c3=0.4, c4=5, c5=21, c6=0.0068 in equation (5), changing β shows that C_P has its maximum value at one particular value of λ for specific blade pitch. Hence, by being able to maintain the λ at this optimum value, the maximum value of C_P can be maintained dependably , and thereby extract the maximum power from the turbine.

Figure 5 shows that the maximum value of C_P ($C_P$max≈0.48) is achieved for β =0 degree and for λ=6.5. This particular value of λ defined as the nominal value (λ nom). For maximum power point tracking of water currents power with currents variation, it is necessary to adjust the rotor speed with the optimum value of λ (λ nom). Equation (1)-(5) describing tidal current turbine implemented in Matlab/ Simulink as given in Figure 6.

4.3. Drive Train

Drive train is the connector that delivers the turbine rotor mechanical motion to the generator. It generally consists of low-speed shaft, connected to the turbine hub, speed multiplier and high-speed shaft, motivating the electrical generator. Direct drive transmission (i.e. the generator and the rotor are coupled on the same shaft without gearbox and speed multiplier) is used in case of multi pole synchronous generator.

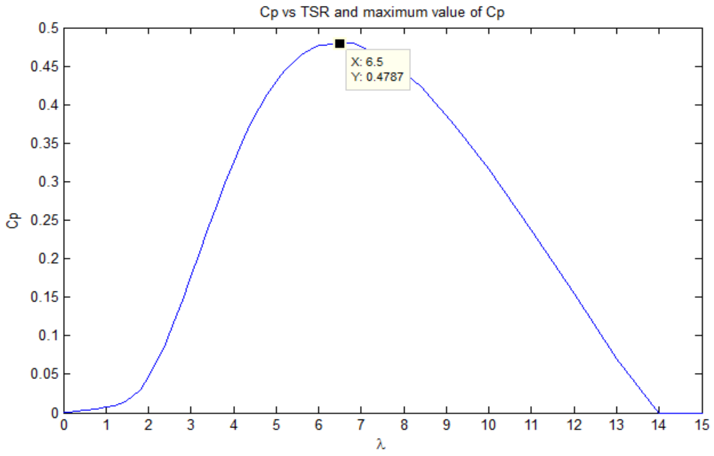

Figure 5. Power coefficient relation with tip speed ratio with β =0.

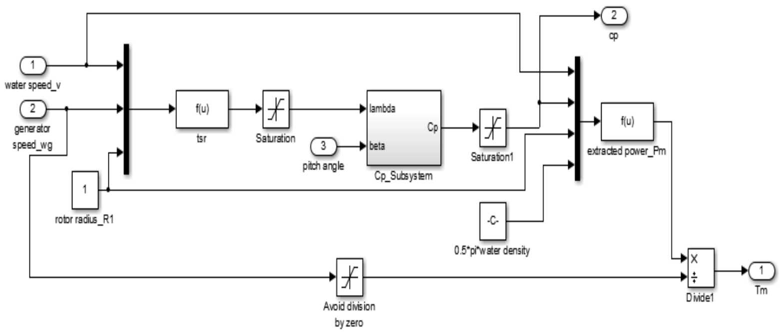

Figure 6. SIMULINK model of tidal current turbine

Modelling is done under the assumption that the mechanical transmission has a constant efficiency for the entire speed range; the effect of the construction features (e.g., vibrations, gear type, gear reaction, etc.) on its performance is considered very small and will be neglected.

The drive train can be modeled as follows whitch consider the system as a number of discrete masses.

$$j\frac{dw_g}{dt} = Tm - Te - V_f w_g \tag{7}$$

$$Tm = \frac{Pact}{w_r} = \frac{0.5\rho CP\ (\lambda,\beta) AV^3}{w_r} \tag{8}$$

Where, j is the summation of rotor and generator inertia, Tm is the turbine mechanical torque, Te is the generator electromagnetic torque , V_f is the viscous friction coefficient or damping ratio, w_g is the generator angular speed and w_r is the rotor angular speed. Mathematical model of the drive traine is represented in Matlab/Simulink as indicated in Figure 7.

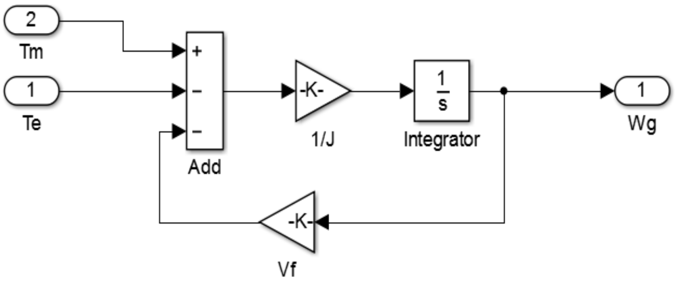

Figure 7. SIMULINK drive train and shaft model

4.4. Permanent Magnet Synchronous Generator (PMSG)

As the output is 3-ϕ Ac system, Clarke/Park transformation is used for two reasons: many of electric machines properties can applied without complexities in voltage equations and to avoid any conflict as rotor according to stator angle can't be known [8].

PMSG has several advantages over other types of generators, which used in water and wind energy systems these advantages such as its simple structure, ability of operation at slow speed, self-excitation capability leading to high power factor and high efficiency operation. With low speed of PMSG operation, there is no need for a gearbox that often suffers from faults and requires regular maintenance making the system unreliable, so in this work PMSG was preferred over other types of generators [9].

The mathematical model of the PMSG according to the synchronous d-q reference frame is given by [10]:

$$Vd = -LqIqWe + Ld\frac{dId}{dt} + RId \quad (9)$$

$$Vq = LdIdWe + Lq\frac{dIq}{dt} + RIq + \varphi_{pm}We \quad (10)$$

$$\varphi d = LdId + \varphi_{pm} \quad (11)$$

$$\varphi q = LqIq \quad (12)$$

$$We = PWg \quad (13)$$

Where, Vd, Vq are the direct and quadrature stator voltages, respectively, Ld, Lq are the direct and quadrature stator inductances, respectively, Id, Iq are the direct and quadrature stator currents, respectively, φd, φq are the direct and quadrature stator fluxes, respectively, φ_{pm} is the permanent magnet flux, We, Wg are the electrical(rotor) and generator(stator) angular velocity, respectively and P is the number of poles[10].

The electromagnetic torque can be expressed in the same frame as follows:

$$Te = \frac{3}{2}P[(Lq - Ld)IdIq + \varphi_{pm}Iq \quad (14)$$

PMSG Equation (9)-(14) execution on Matlab/Simulink shown in Figure 8.

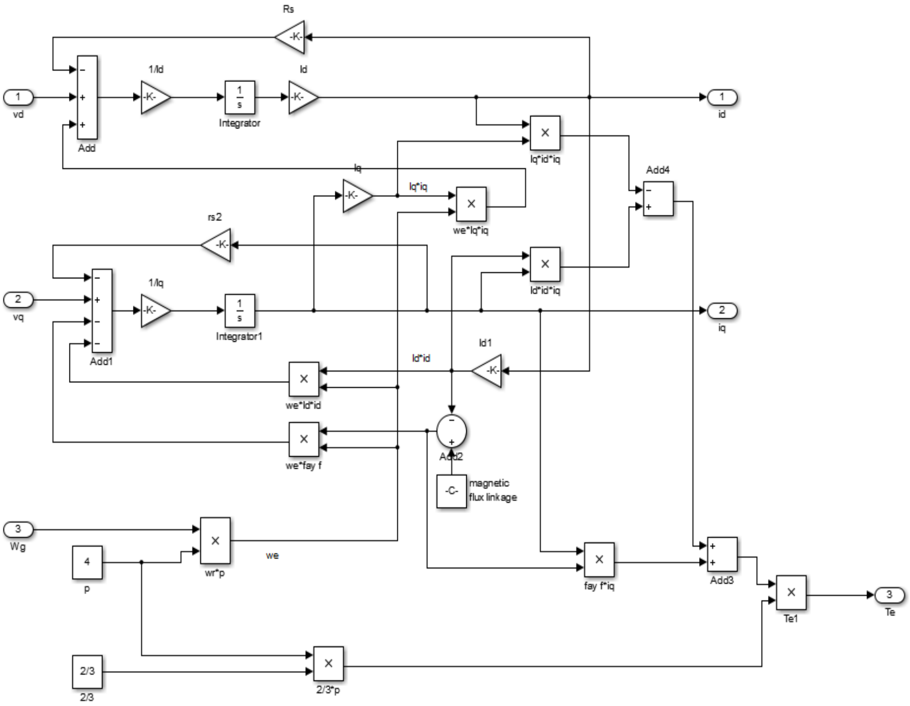

Figure 8. Matlab/Simulink model for PMSG.

5. *S*imulation Results

Output stator voltage, current, power and angular rated speed in transient state at 1 m/s tidal current speed and fixed zero pitch angle is cleared as shown in Figure 9.

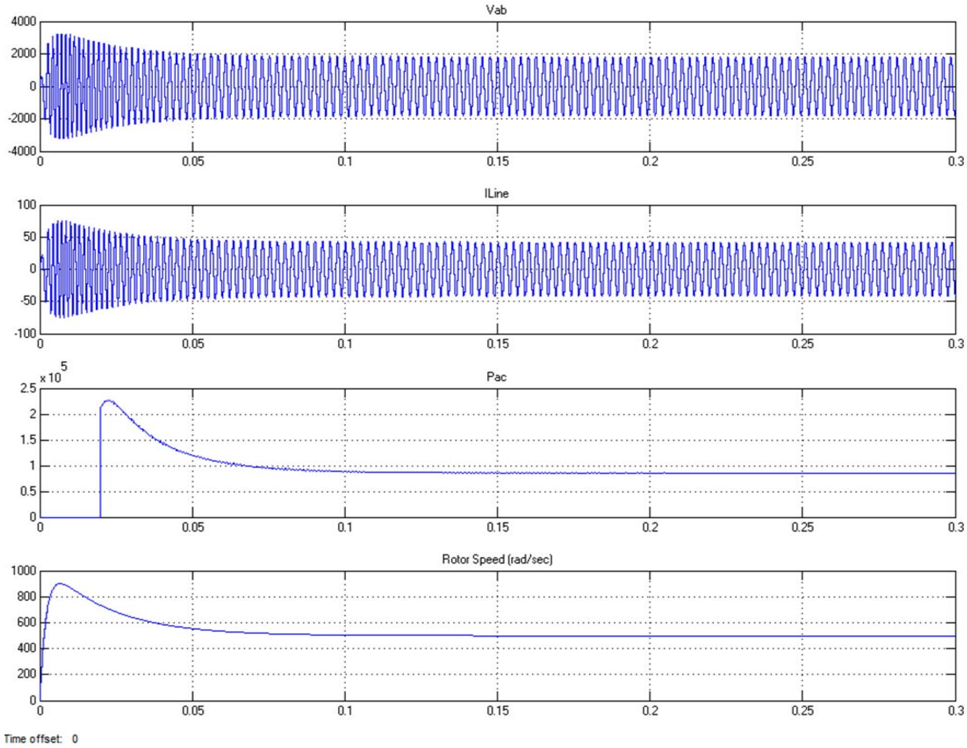

Figure 9. Transient state load voltage, current, power and rotor angular speed at tidal current speed v=1 m/s.

It is clear that the output reaches steady state within a very short time approximately 0.075 second resulting power =84.55 kW which is approximately equal to that from equation 1 and according to turbine parameter and power curve verifying the validity of the generated Simulink model. Voltage and current also has the same frequency, which is 50Hz.

Figure 9 shows that the active power stability at steady state value is delayed compared to the speed signal, due to the MPPT characteristics. The MPPT is designed in such a way that the active power production is remained constant at its rated value even in small range below rated generator speed in order to avoid unwanted power fluctuations with tidal current speed change.

6. Conclusion

The basic theory of mechanical power extraction from tidal currents is described briefly. A detailed electrical model for tidal current speed profile, turbine, drive train and PMSG has been introduced. The model has been implemented in Matlab/ Simulink in order to validate it. Current speed profile and maximum power curves are presented.power coefficient and tip speed ratio curve indicated that increase in C_P value with the icrease in λ value until reaching its maximum value, further increase in λ over its nominal value decreasesC_P. From power characteristics of tidal current turbine it can be concluded that tidal current turbines are monotonic system in which for each tidal current speed there is one optimal rotor speed that will yield maximum power. Generator model has been modelled in d-q synchronous rotating reference frame due to its advantages cleared. Finally, voltage, current, power and rotor angular speed in transient state also presented tidal current speed =1 m/s and zero pitch angle.

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