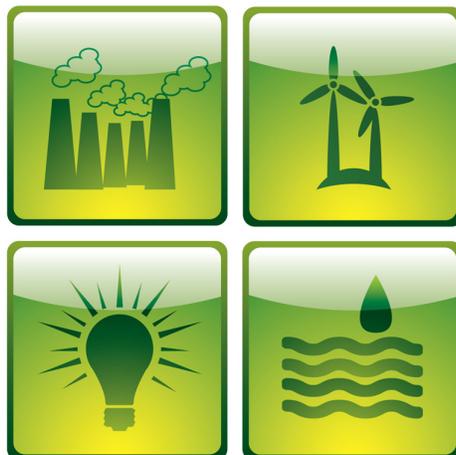




The  
University  
Of  
Sheffield.



# E-Futures

## Mini-project report

**Modelling and control of a variable-speed subsea tidal turbine equipped with permanent magnet synchronous generator.**

**Shoan Mbabazi – [dtp09sm@sheffield.ac.uk](mailto:dtp09sm@sheffield.ac.uk)**

**August 2010**

# Modelling and control of a variable-speed subsea tidal turbine equipped with permanent magnet synchronous generator

S. Mbabazi

**Abstract** – This paper focuses on the modelling and control of a variable-speed tidal turbine equipped with permanent magnet synchronous generator (PMSG). Emphasis will be placed on the analysis of the electrical part of the system i.e. the generator, power electronics convertors and control. The operation and characteristics of the machine is investigated through a series of computer simulations. To limit the scope of investigation, the generator is assumed to be connected to a battery bank via an IGBT PWM inverter.

**Keywords** – Permanent magnet machines, Battery charging, Tidal energy, Power generation, synchronous generators, renewable energy.

## 1 Introduction

THE soaring use of fossil fuels and their depletion over the last two decades combined with a growing concern over the increase of greenhouse gases in the atmosphere, have lead to the exploiting clean energy resources. There are several renewable energy sources; this includes tidal, wind, solar, geothermal etc. This article focuses on Tidal energy; tides occur as a result of gravitational forces between the moon, the sun and the earth causing the rhythmic rising and lowering of ocean waters[1]. Unlike most of the other known clean energy sources, the time and magnitude of tidal energy can be predicted for decades ahead.

## 2 Aim

The key objective is to model, control and analyse the performance of a variable-speed

tidal turbine equipped with a PMSG. By understanding the characteristics of the system, a control system will be implemented to better match the input to the output power, thus maximising tidal power harnessed at any tidal speed. Emphasis will be placed on the analysis of the electrical part of the system i.e. the PMSG, power electronic inverter and control.

## 3 Tidal Power

Tidal power contains two components; potential  $E_p$  and kinetic  $E_k$ . Potential power is created as a result of the difference in height between high and low tides[1]. This implies that this type of power can only be exploited using equipment that can capture energy from the vertical rise and fall of water.  $E_p$  can be defined as:

$$E_p = \frac{1}{2} C_p(\lambda) \rho \omega_r^2 A h^2 \dots \dots \dots (1)$$

Where  $C_p$  is the power coefficient as a function of the tip speed ratio  $\lambda$

$$\lambda = \frac{R\omega_r}{V_t} = \frac{4\pi}{n}$$

,  $\rho$  is the density of seawater in mass per unit volume,  $A$  is the area under consideration,  $g$  is acceleration due to gravity,  $R$  is the radius of the tidal turbine rotor,  $n$  is the number of rotor blades,  $\omega_r$  is the tidal turbine rotor speed and  $h$  is the tide amplitude.

$E_k$  is produced as a result of moving water with respect to its velocity  $V_t$ , [1]for which is similar to the principle behind wind turbines. Thus, it can only be exploited by using equipment that can harness power from tidal currents or

horizontal water sows induced by tides. It is defined by:

$$E_k = \frac{1}{2} C_p(A) \rho A V_t^3 \dots \dots \dots (2)$$

The total tidal power  $E_t$  for a given area of the sea/ocean is the sum of its potential and kinetic power components.

$$E_t = E_p + E_k \dots \dots \dots (3)$$

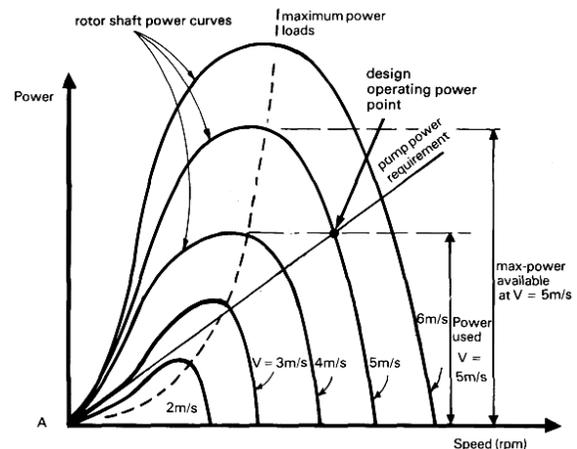
Dynamic tidal power systems can harness both potential and kinetic power; this could be done by constructing long dams from the coast into the sea/ocean, without enclosing an area[1]. Hence both the obstruction of the tidal flow by the dam, as well as the tidal phase differences introduced by the presence of the dam, leads to the differences in height between high and low tides along the dam.

The power generating system under consideration is a subsea tidal turbine which uses tidal currents to produce energy. For this reason, only the kinetic power component shall be investigated.

From equation (2) above is it apparent that running the turbine at optimum  $C_p$ , maximum tidal power can be extracted from the tide.

As  $V_t$  changes,  $\omega_r$  changes, therefore it is necessary to maintain optimum  $\lambda$ .

**Fig 1** illustrates the mechanical power generated by the tidal turbine as a function of rpm for the different tidal speeds. The maximum power available at a given tidal speed is shown as a dashed line on the same graph.



**Fig 1.** Output power Vs Rotor Speed( $\omega_r$ )

#### 4 Permanent Magnet Synchronous Generator (PMSG)

The generator under consideration is a three phase alternator equipped with high resistivity permanent magnets (PM), thus induced rotor currents are negligible. To limit the scope of investigation, the generator is assumed to be connected to a battery bank via a PWM inverter.

The terminal voltage  $V_s$  of the generator is determined by the DC bus voltage  $V_{dc}$ , which is the voltage across the battery bank. The relationship between  $V_s$  and  $V_{dc}$  can be derived from the balance of power equation below [2]:

$$3V_s \cdot I_s = V_{dc} \cdot I_{dc} \dots \dots \dots (5)$$

Where  $I_s$  is the AC stator current, and  $I_{dc}$  is the DC current.

The PMSG is modelled with dc voltages and currents in the rotor d, q axes; with the d-axis being the direction of the flux from the PM. The mathematical model equations of a PMSG are presented below [2-7]:

$$v_d^s = -r_s \cdot i_d^s + \frac{d\phi_d^s}{dt} - \omega_s \cdot \phi_q^s \dots \dots \dots (6)$$

$$v_q^s = -r_s \cdot i_q^s + \frac{d\varphi_q^s}{dt} + \omega_s \cdot \varphi_d^s \dots \dots \dots (7)$$

$$v_0^s = -r_s \cdot i_0^s + \frac{d\varphi_0^s}{dt} \dots \dots \dots (8)$$

$$\varphi_d^s = -L_d^s \cdot i_d^s + \varphi_{af}^m \dots \dots \dots (9)$$

$$\varphi_q^s = -L_q^s \cdot i_q^s \dots \dots \dots (10)$$

Where  $v_{d,q}^s, i_{d,q}^s, \varphi_{d,q}^s$  are d, q axes voltages, currents and flux linkages respectively,  $\varphi_{af}^m$  is the flux linkage due to the rotor magnets linking the stator,  $r_s$  is the stator winding resistance,  $L_d^s$  is the stator linkage inductance, and  $\omega_s$  is the electrical angular velocity or inverter frequency and relates to  $\omega_r$  as follows:  $\omega_s = P\omega_r$ , with  $P$  being the number of pole pairs.

The electrical angular velocity  $\omega_s$  can also be defined as:

$$\frac{d\omega_s}{dt} = T_m - T_e \cdot \frac{P}{J} \dots \dots \dots (11)$$

Where  $J$  is the moment of inertia,  $T_m$  is the mechanical/turbine torque on the shaft and  $T_e$  is the electrical/generator torque.

$$T_e = -\left(\frac{3P}{2}\right) \cdot \varphi_{af}^m \cdot i_q^s + (L_d^s - L_q^s) \cdot i_d^s \cdot i_q^s \dots (12)$$

$$T_e = -\left(\frac{3P}{2}\right) \cdot \varphi_{af}^m \cdot i_q^s \text{ when } i_d^s \text{ is set to } 0$$

Equations (7),(8),(9) are inserted into(4),(5), (6) to obtain the following;

$$\frac{di_d^s}{dt} = -\frac{1}{L_d^s} (v_d^s + r_s \cdot i_d^s - \omega_s \cdot L_q^s \cdot i_q^s \dots (13)$$

$$\frac{di_q^s}{dt} = -\frac{1}{L_q^s} (v_q^s + r_s \cdot i_q^s + \omega_s \cdot L_d^s \cdot i_d^s - \omega_s \cdot \varphi_{af}^m) \dots (14)$$

$$\frac{d\omega_r}{dt} = -\frac{1}{J} (T_e - T_m - \beta \omega_r) \dots \dots \dots (15)$$

$\beta$  being the viscous friction coefficient factor constant

The  $a, b, c$  variables are obtained from the  $d, q, 0$  variables through the park transform defined below:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) & 1 \\ \cos(\theta - \frac{2\pi}{3}) & \sin(\theta - \frac{2\pi}{3}) & 1 \\ \cos(\theta + \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) & 1 \end{bmatrix} \cdot \begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} \dots (16)$$

The  $d, q, 0$  variables are obtained from the  $a, b, c$  variables through the park transform defined below:

$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = \frac{2}{3} \cdot \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin(\theta) & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \cdot \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \dots (17)$$

These transforms apply equally to currents, and flux linkages. The total output power ( $P_e$ ) for a balanced PMSG is;

$$P_e = \frac{3}{2} (v_d i_d + v_q i_q + v_0 i_0) \dots \dots \dots (18)$$

$$P_e = v_a i_a + v_b i_b + v_c i_c \dots \dots \dots (19)$$

## 5 Control strategy

In a conventional system no active control is used, therefore the power flow from the turbine into the system is dedicated solely to the velocity of the tide and any losses from the interactions with various system components.

A control system is required to ensure that the generator is run at optimum speed so that

maximum power is harnessed at any tidal/rotor speed, as shown in Fig 1.

It is shown in Fig 1 that for any tidal speed, there is always a matching rotor speed that produces maximum power. Therefore if the controller could successfully follow the changes in tidal speed, maximum power can be harnessed at any speed. The control system should also be able to protect the system from over power [6] i.e. In the low tidal region, the control system should enable the turbine/generator to generate maximum available power, however at higher tidal speeds the turbine/generator should be protected from over load and over torque conditions caused by sudden tidal raises.

The tidal power generation system circuit shown in Fig 4, is controlled as follows:

The actual *a, b, c* stator currents are measured, converted to *d, q* axis currents using the park transform equation (17). The converted *d, q* currents are then compared to the reference current values. *I<sub>d</sub>* does not contribute to the torque production [8], and therefore in order to obtain unity power factor [9], *I<sub>d</sub>* is maintained at zero maximising the torque per Ampere capability. The *q* axis reference current *i<sub>iq</sub><sup>\*</sup>* is calculated as follows;

The turbine rotor speed *ω<sub>r</sub>* is measured or obtained by using a position speed sensor, to calculate reference torque *T<sup>\*</sup>* using equation (20).

$$T^* = \frac{P_{opt}}{\omega_r} \dots \dots \dots (20)$$

$$P_{opt} = \frac{1}{2} \cdot \rho \cdot A \cdot C_{p_{opt}} \left[ \frac{R}{\lambda_{opt}} \right]^3$$

*P<sub>opt</sub>* is the optimum power at a given tidal/rotor speed in Watts.

*C<sub>p<sub>opt</sub></sub>*

 is the optimum power coefficient.

*λ<sub>opt</sub>* is the optimum tip speed ratio.

*T<sup>\*</sup>* is then used to obtain reference current *i<sub>iq</sub><sup>\*</sup>*.

$$i_{iq}^* = \frac{T^*}{K_t} \dots \dots \dots (21)$$

The torque constant  $K_t = \frac{3 \cdot P \cdot \varphi_{af}^m}{2}$

When the tidal velocity changes the rotor speed should adjust to follow this change, thus providing the system with a new reference torque and current.

The difference between reference and actual current signals *e<sub>id</sub>* and *e<sub>iq</sub>* are transmitted to the current controller in order to track current changes and also convert *d, q* current signals to *d, q* voltage signals, using the following equations:

$$v_d = K_F \cdot e_{id} + K_i \int \frac{de_{id}}{dt} - \omega_s \cdot L_q \cdot i_q \dots \dots \dots (22)$$

$$v_q = K_F \cdot e_{iq} + K_i \int \frac{de_{iq}}{dt} - \omega_s \cdot (L_d \cdot i_d + K_e) \dots (23)$$

Back emf constant *K<sub>e</sub>* = *P · φ<sub>af</sub><sup>m</sup>*, proportional

gain  $K_F = \frac{L_{sT} \cdot \omega_c}{2 \cdot V_{dc}}$ , integral gain *K<sub>i</sub>* = *ω<sub>c</sub> · K<sub>F</sub>*.

Where *L<sub>sT</sub>* is the total system inductance, *ω<sub>c</sub>* is the triangular carrier frequency

The output signals of the current controller *v<sub>d</sub>*, *v<sub>q</sub>* are converted back to *v<sub>a</sub>*, *v<sub>b</sub>*, *v<sub>c</sub>* signals. These act as modulating signals with the desired frequency and amplitude that compared with a triangular carrier wave as shown in Fig 2. The intersections define the PWM inverter switching instants as shown in Fig 3.

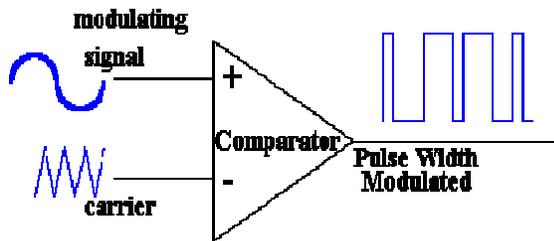


Fig 2. Pulse Generator

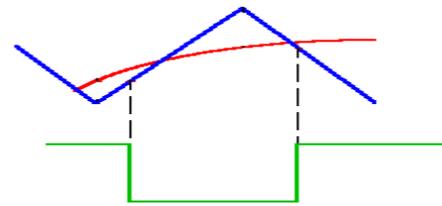


Fig 3. Sampled PWM

The pulses created generate logic signals that control the inverter, in turn control the output current and power.

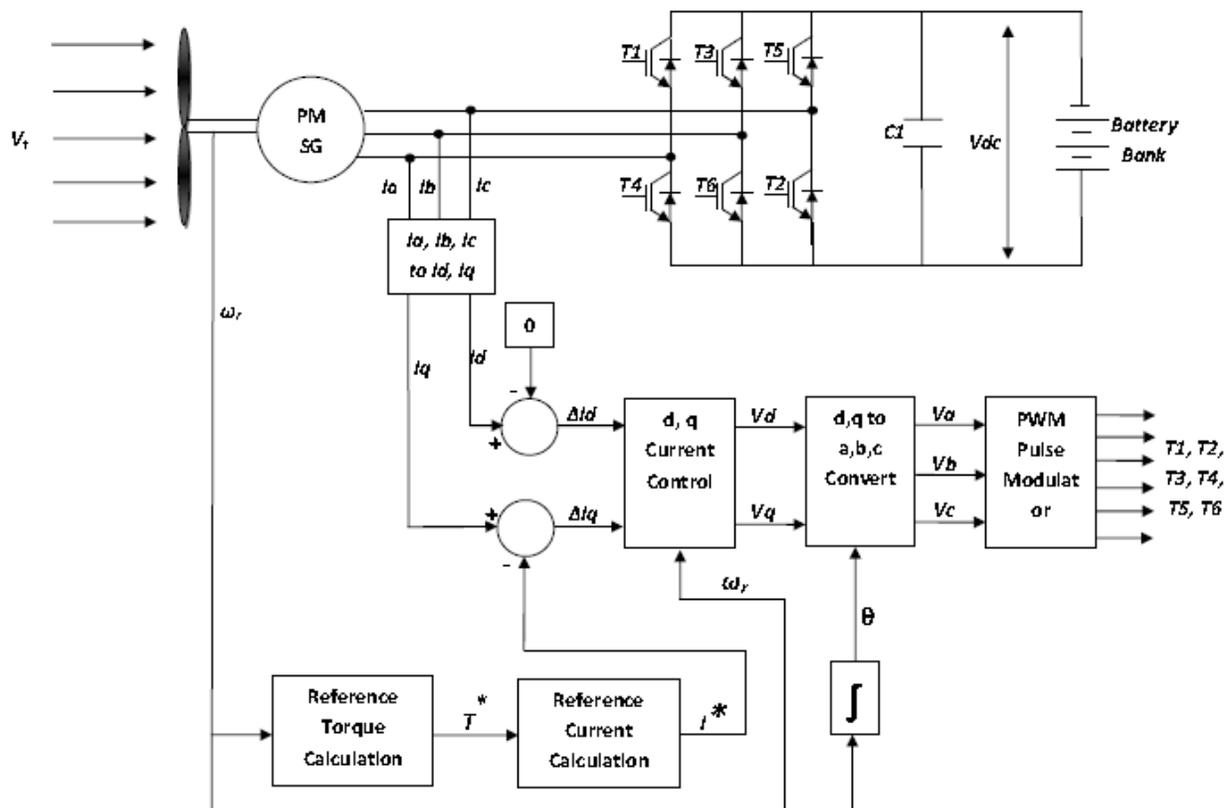


Fig 4. Electrical configuration of a tidal power generation system

### 5.1 Current Control

The torque capabilities of both the generator and the turbine are limited by the characteristics of the connected load/dc side. Therefore to optimise the operation of the tidal

turbine and PMSG, control of the applied load characteristics is required in order to utilise the maximum power available from the tidal currents.

Although there are many ways to implement the concept described above, one possible way is to control dc current flowing to the load/ link capacitor  $i_{dc}$ . When the rotor speed changes, the  $i_{dc}$  wave form is consequently modified by the current controller through PWM to track this change in power. By controlling the instant at which **T1-T6** gate pulses are applied with respect to the ac current waveform,  $i_{dc}$  can be controlled in magnitude. Thus, regulating  $I_s$  and leading to maximum tidal power utilisation.

The output of each rectifier leg depends on  $\omega_r$  and the switching status. If **T1-T6** are assumed to be ideal switches, and trigger angle  $\sigma$  is equal to Zero,  $i_{dc}$  will be equal to the sum of the output currents from each rectifier leg. During the interval between  $0$  and  $\pi/3$ , the average  $i_{dc}$  at  $\sigma = 0$  is calculated as follows [10]:

$$i_{dc0} = \frac{3\sqrt{2}}{\pi} \cdot I_L = 1.35 \cdot I_L \dots \dots \dots (24)$$

Where  $I_L$  is the line current

Since the  $i_{dc}$  waveform repeats every  $\pi/3$  radians, triggering at any angle other than  $0$  results in a drop in average  $i_{dc}$ . Therefore, for a given  $\sigma$  average  $i_{dc}$  is calculated as follows [10]:

$$i_{dc\sigma} = \frac{3\sqrt{2}}{\pi} \cdot I_L \cdot \cos \sigma = 1.35 \cdot I_L \cdot \cos \sigma \dots \dots (25)$$

Therefore, equation (25) shows that average  $i_{dc}$  is independent of the  $V_{dc}$  and the load as long, as  $I_{dc} > 0$ . Using PWM controlled rectifier allows  $i_{dc}$  to be controlled continuously by means of  $\sigma$ . whereby when  $\sigma$  is in the range of  $0^\circ - 90^\circ$ ,  $i_{dc}$  is positive representing a rectifier mode of operation and  $90^\circ - 180^\circ$  represents inverter operation.

## 6 Simulation

The performance of the above mentioned system is demonstrated using Matlab/Simulink.

A tidal power generation system model is constructed using properly selected sub blocks.

The simulations are based on a 0.5 seconds running time. Longer simulation times were desirable but, impractical due to the memory of the pc used.

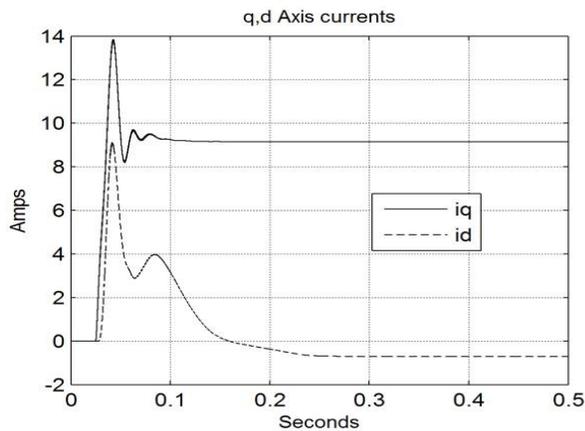
The modelled system parameters are as follows;

Battery bank reference Voltage	300 V
d,q inductance	0.00153 H ( $L_d, L_q$ )
Stator resistance	0.129 Ohms
Magnetic flux inductance	0.1821 H
Moment of inertia (J)	0.003334
Friction factor ( $\beta$ )	0.000425
Number of pole pairs	4
DC link capacitance	6800 $\mu$ F
Switching frequency	10 kHz
Sampling time	0.025 s

**Table 1.** system parameters

### 6.1 Simulation results

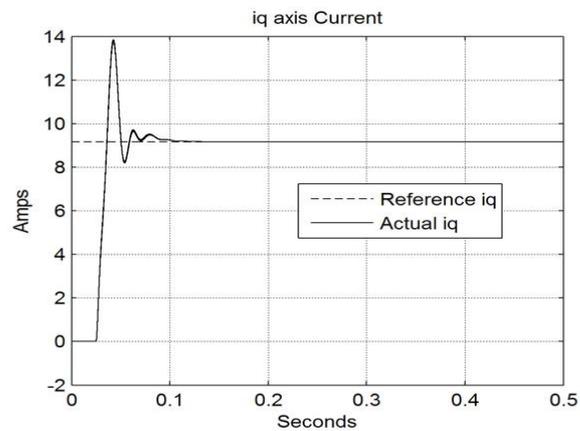
The simulation results for the stator currents  $i_q$  and  $i_d$  are shown in **Fig. 5**. The results are influenced by the mechanical torque generated by the turbine.



**Fig 5.**

As illustrated in **Fig. 5**,  $i_d$  settles approximately at Zero, this shows that the current controller performs as required, even though  $i_d$  is required to be exact zero.

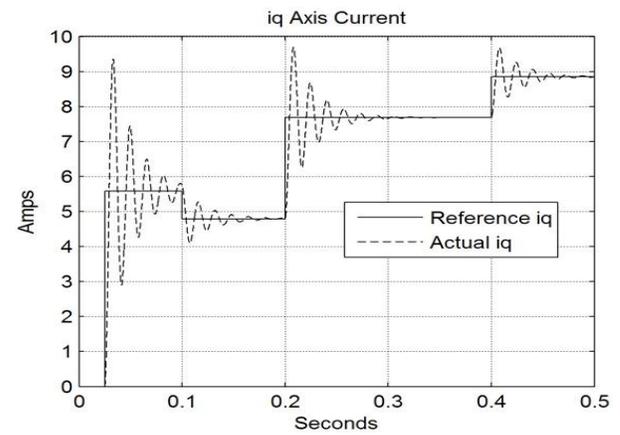
**Fig.6** represents the output current  $i_q$  adjusted by the current controller to equal the reference current.



**Fig.6**

When tidal velocity changes, the mechanical power and torque produced by turbine also varies, thenceforth changing the reference current as a result. To utilise the optimum power available at any given tidal velocity, the current generated by the PMSG has to follow the variations in reference current.

**Fig.7** exemplifies the control outcome of the reference current and output q\_axis currents, as tidal velocity varies.



**Fig.7**

**Fig 8, Fig 9, Fig 10, Fig 11 and Fig 12** in the appendix section are the simulink models for the tidal turbine, PMSG, Control circuit and current controller respectively

## 7 Conclusion

Just like wind and solar power, tidal power generation needs to be distributed over large areas thereby making tidal power capture a challenge. Also it struggles to compete economically with conventional power plants which use cheap oil or coal, presently available in abundance.

One of the main advantages of tidal energy is clean and cannot be exhausted, which is in contrast to oil and coal whose reserves are rapidly diminishing.

For tidal power to be potentially considered as a substantial source of energy for the future, efficient, low cost and environmentally friendly apparatus for power extraction are required.

For example: current prototype marine turbines contain enough power electronics to ensure that the electricity produced by each individual

turbine is of grid standard, this is ideal if one turbine is to be installed. However if an entire farm of tidal turbines was to be installed, it would be uneconomical.

## 8 Future work

To expand further on the findings, an investigation on ways of reducing the amount of power electronics required when two or more turbines are connected. This needs to be

- [1] A. M. Gorlov, "TIDAL ENERGY," *Academic Press*, pp. 2955-2960, 2001.
- [2] S. D. Eduard Muljadi, Richard Holz, "Title," unpublished].
- [3] T. P. Fuglseth, "Modelling a 2.5 MW direct driven wind turbine with permanent magnet generator," Norwegian University of science and technology 2005.
- [4] M. F. M. M.N. Mansouri, B. Benghanem, M. Annabi, "Simulation model for wind turbine with asynchronous generator interconnected to the electric network," *ELSEVIER Science Direct*, pp. 422-428, 2003.
- [5] S. E. Paul Deglaire, Andreas Solum, "Simulation and control of direct driven permanent magnet synchronous generator (PMSG)," Uppsala University 2009.
- [6] S. A. P. D.C. Aliprantis, M.P. Papadopoulos, A.G. Kladas, "Modeling and control of a variable-speed wind

done while ensuring the electricity at the point of connection on the grid is of the required standard.

In addition, different ways of connecting the turbines to the grid on shore including potential gains from running the collection network at different voltages and frequencies (including DC).

## 9 References

- turbine equipped with permanent magnet synchronous generator," Purdue University and National Technical University GREECE 2009.
- [7] R. K. Pragasen Pillay, "Modeling, Simulation, and Analysis of Permanent-Magnet Motor Drives, Part 1: The Permanent-Magnet Synchronous Motor Drive," *IEEE*, vol. 25, pp. 265-273, 1989.
- [8] LectureNotes, "Motion Control and Servo Drive Systems," ed: University of Sheffield, Electronic and Electrical Engineering 2009.
- [9] S.-K. S. Jong-Woo Choi, "Fast Current Controller in 3-Phase AC/DC Boost Converter Using d-q Axis Cross Coupling," *IEEE Xplore*, pp. 177-182, 1996.
- [10] K. G. K. B. M. BIRD, D. A. G. PEDDER, *An introduction to Power Electronics*, Second ed.: WILEY, 1983.



Fig 11. Control circuit model

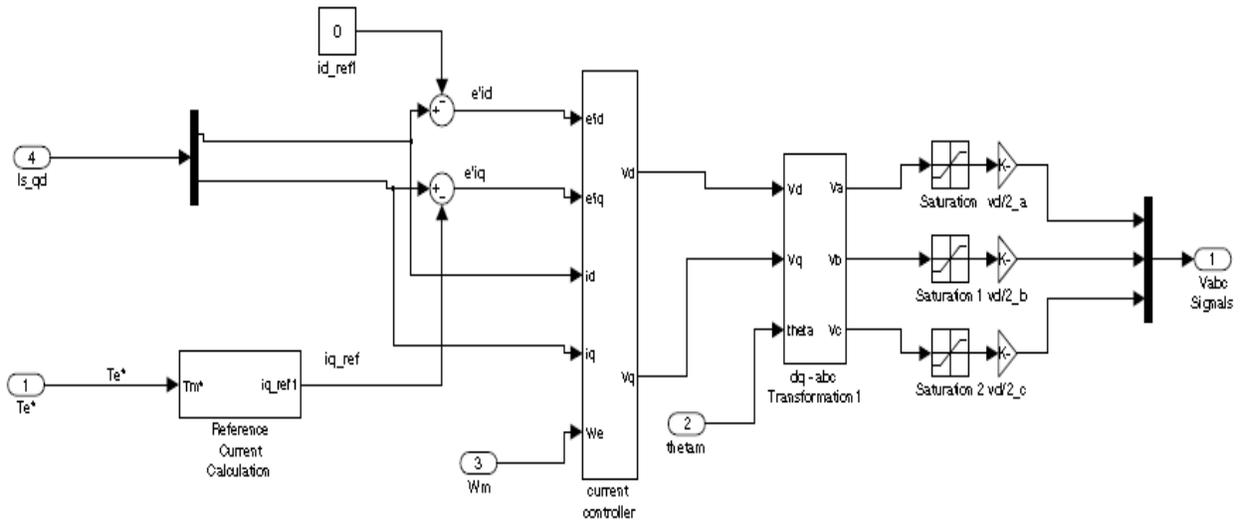


Fig 12. Current controller

