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Modeling and Simulation of Marine Current Energy Conversion System with Six-Phase Permanent Magnet Synchronous Generator

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Abstract: This paper presents the analysis and simulation for a marine tidal current turbine system with a six-phase permanent magnet synchronous generator. The aim is to demonstrate the possibility of harnessing electricity generation for small towns along continental shorelines from strong marine tidal currents in the coastal region of the Gulf of Guinea along the Southwest region of Nigeria. Due to its advantages of being a clean form of renewable energy and much more predictable than wind and solar, marine current energy has received much attention in recent years. One of the most popular technologies for producing wind and tidal energy is the permanent magnet synchronous generator (PMSG), which is suitable for low speed tidal current and offers better power control choices for marine current turbines with a horizontal axis. However, multiphase PMSG is a machine for reaching this goal for low maintenance, high reliability systems in the tough underwater circumstances. Due to the turbine power coefficient's ability to effectively follow the ideal curve with any change in water current speed, the maximum electrical power extraction of 198 kW is made possible within the permitted range of tidal currents. The effectiveness of the proposed model was extensively investigated with MATLAB/Simulink software

Keywords: PMSG, Marine tidal current, Multi-phase, Power coefficient, Gulf of Guinea

Introduction

Discourse on global energy discussion is currently centered on the implications of energy source depletion and price variations. As a result, it is now urgently necessary to support possible abilities of generating energy through the development of low-carbon technologies, particularly those based on renewable resources. Marine tidal current energy is available on some remote islands and is a potential renewable energy source for Nigeria's coastal regions because of its great predictability (Okoli et al., 2017).

The kinetic energy in tidal currents can be transform into electricity utilizing rather advanced turbine tools, despite there being many different types of energy that may be collected from the ocean, including wave energy, thermal energy, ocean osmosis (salinity gradients), and biomass energy. With current technology, it is projected

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that there is 75 GW of marine current power that can be used globally and 11 GW in Europe. Among the European nations, the UK and France have the biggest tidal current capabilities (6 GW and 3.4 GW, respectively) (Zeyringer et al., 2018). It ought to be highlighted that the distinct benefit of energy from tidal is tied to the resource's great certainty. Gravitational interplay of the Earth, Moon, and Sun system determines the astronomical nature of tides, which makes the tidal currents greatly predictable with 98 percent accuracy for some years (Zhou et al., 2017).

The two essentially methods for utilizing marine tidal resources are: creating a tidal barrage over a bay or an estuary, or by directly capturing kinetic energy from moving tidal currents. The only disadvantage of the barrage approach is the a sizable barrage configuration might alter the hydrology and take a detrimental effect on the surrounding ecology(Zhou et al., 2017). Technologies have been created for some years that directly harness the kinetic energy of tidally-driven marine currents. The variable system scalability of tidal current turbines over tidal barrages is one benefit. Tidal barrages are more expensive and typically designed based on high GW competencies, which may be more than tiny coastal communities or isolated islands require.

The current consensus among energy stakeholders is that non-conversional energy expertise may be effectively used to close the growing breach amid energy demand, its sustainable supply, affordable, and abundant as well as to assure a less contaminated atmosphere. The best options among the renewable energies appear to be wind and hydropower (Amarante Mesquita et al., 2014; Güney & Kaygusuz, 2010; Zhou et al., 2019). The potential energy contained in reservoirs is harnessed by conventional hydropower through the use of dams and impoundments to create a hydraulic head difference, which is then turned into electrical energy by proper turbo machinery. Marine and hydrokinetic energy conversion technology, on the other hand, is a new class of hydro-to-electrical power systems that is rapidly becoming acknowledged as a distinctive and non-conventional energy solution (Ibrahim et al., 2021).

A marine current turbine (MCT) is a device that transforms the kinetic energy from the tidal fluctuation into electrical energy. Its process looks like that of wind turbines, with the exception that fluid density is substantially higher since energy is generated by the flow of water rather than air. Utilizing the kinetic energy of rivers, streams, tidal, or other artificial waterways for the purpose of producing energy is known as hydrokinetic energy conversion. It is a type of hydropower known as "zero head" that harnesses the energy of flowing water's velocity to drive a generator. It can alternatively be described as a low pressure, run-of-the-river turbine with an extremely low head requirement of less than 0.2 meters (Ladokun et al., 2013). Although they obtain energy via the hydrodynamic process as opposed to the aerodynamic lift or drag, their operating principle is identical to that of wind turbines. This innovative technique is viewed as a unique and unconventional approach to power generation that falls under the area of marine energy and in-land water resources (Güney & Kaygusuz, 2010).

Utilizing and converting ocean energy resources—derived from wind, waves, tidal currents, or marine currents— to reliable, abundant electrical power. Transformation systems can be simply incorporated into the existing utility power supply infrastructure and networks and are easily customizable. However, many nations have adopted policies in the development of renewable energy technology that are heavily dependent on the conversion of huge amounts of offshore wind energy into electrical power, with little focus being paid to other forms of renewable energy. It is important to avoid marginalizing the use of other non-conversional resources, such as marine energy sources, by focusing work and rerouting the available funds to offshore wind alone, despite the fact that this imbalance is understandable given how much more advanced wind technologies are.

However, low maintenance, high-reliability systems are strongly advised to support the progress in this area because the harsh underwater conditions hold down technological advancements. Therefore, a high-power density generation system is needed to efficiently harness marine current power and use tidal current, and a permanent magnet synchronous machine is needed to drive the rotor that has a high power-density and high efficiency. From the perspectives of efficiency, greater power factor, and higher torque density, is typically favoured over induction machines(Tola et al., 2022; Tola et al., 2021; Tola & Umoh, 2017). The high magnetic loading provided by the high residual flux density allows for a comparatively small active region of the air gap and thus a relatively compact overall machine (Tola et al., 2022).

Utilizing multiphase machines is another technique for achieving this goal, and it is made possible by the advent of power electronics converters. Less torque pulsation and little zero sequence harmonics are among its features, as well as high fault tolerance, or the capacity to continue operating even if one or two phases are defective (Wei et al., 2022) (Levi et al., 2016). Strong tidal current is necessary for tidal power, and a tidal current generator can be constructed in a region where a flow rate of at least 1.0 m/s occurs. The majority of tidal power plants that employ permanent magnet synchronous generators (PMSG) are capable of producing electricity at different speeds (Abo-Khalil & Alghamdi, 2021). Additionally, it is recommended that low speed tidal current generators use direct drive permanent magnet synchronous generators (PMSGs), which have superior power management options for horizontal axis marine current turbines than doubly fed induction generators (DFIG) (Zhou et al., 2019).

Nigeria's hydrological setting is consecrated with a setup of waterways, tributaries, tidal, and marine currents along with non-natural water passages and other water physiques, displays substantial hydro potential both at the greater measure (megawatts) and the lesser measure (Kilowatts), which is based on the necessity to embrace and upturn renewable energy skills in Nigeria's energy network (Ladokun et al., 2013).

In order to generate electricity for remote or off-grid areas and to increase the output of already-existing non-conventional power plants, marine current energy conversion technology is being deployed in this study along with detailed modeling and analysis of six-phase PMSG. And it also emphasizes and gives a brief overview of the chances for using marine current resources in the Gulf of Guinea, which is in the southwest of Nigeria and along the Atlantic Ocean. This area is a possible site for the construction of tidal energy plants.

Methodology

A Marine Current Turbine

As with wind turbines for systems that convert wind energy, the stream turbine is utilized to capture the kinetic energy of the tidal current. In contrast to the vertical axis turbine's aerodynamic drag, marine current and wind energy systems frequently employ horizontal axis turbines, which have superior efficiency. The turbine's kinetic power output and the accompanying speed are given as (Abo-Khalil & Alghamdi, 2021).

$$P_t = \frac{1}{2}\rho C_p(\lambda,\beta)Av^3 \tag{1}$$

$$C_p(\lambda,\beta) = 0.5176\left[\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{-\left(\frac{21}{\lambda_i}\right)} + 0.0068\lambda\right] \tag{2}$$

$$\lambda_i^{-1} = \left(\lambda - 0.08\beta\right)^{-1} - 0.035\left(1+\beta^3\right)^{-1} \tag{3}$$

Where $C_p(\lambda,\beta)$ is how efficient the turbine is, and depends on how efficiently the turbine operates and how the turbine blades move in relation to the fluid flow, ρ is sea water density and β is the pitch angle and the term λ is the "tip speed ratio" refers to the relative speed between the water and the turbine blades and is defined as:

$$\lambda = \frac{\omega r}{v} \tag{4}$$

Where v is the velocity of the fluid, ω the angular velocity of the turbine and r is the turbine blade radius and ρ is sea water density. For a certain tip speed ratio λ_{opt}, the power coefficient will achieve its maximum value for a precise tip speed ratio, and the turbine will afterwards provide the most power capture.

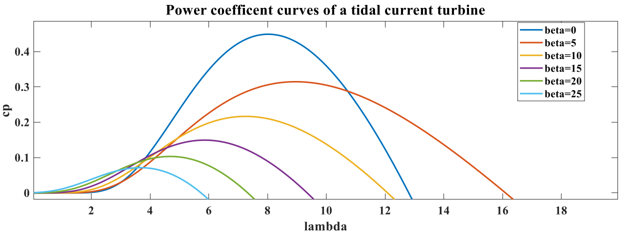


Figure 1. Power coefficient curves verse speed trip ratio

The main speed ratio at its optimum value, as shown in Figure 1, determines the output coefficient of the tidal current turbine, with varying pitch angles acting as a dependent variable. Additionally, the ideal speed ratio determines the tidal current turbine's output coefficient. It is essential to run at peak performance in order to generate the most power possible based on the flow rate.

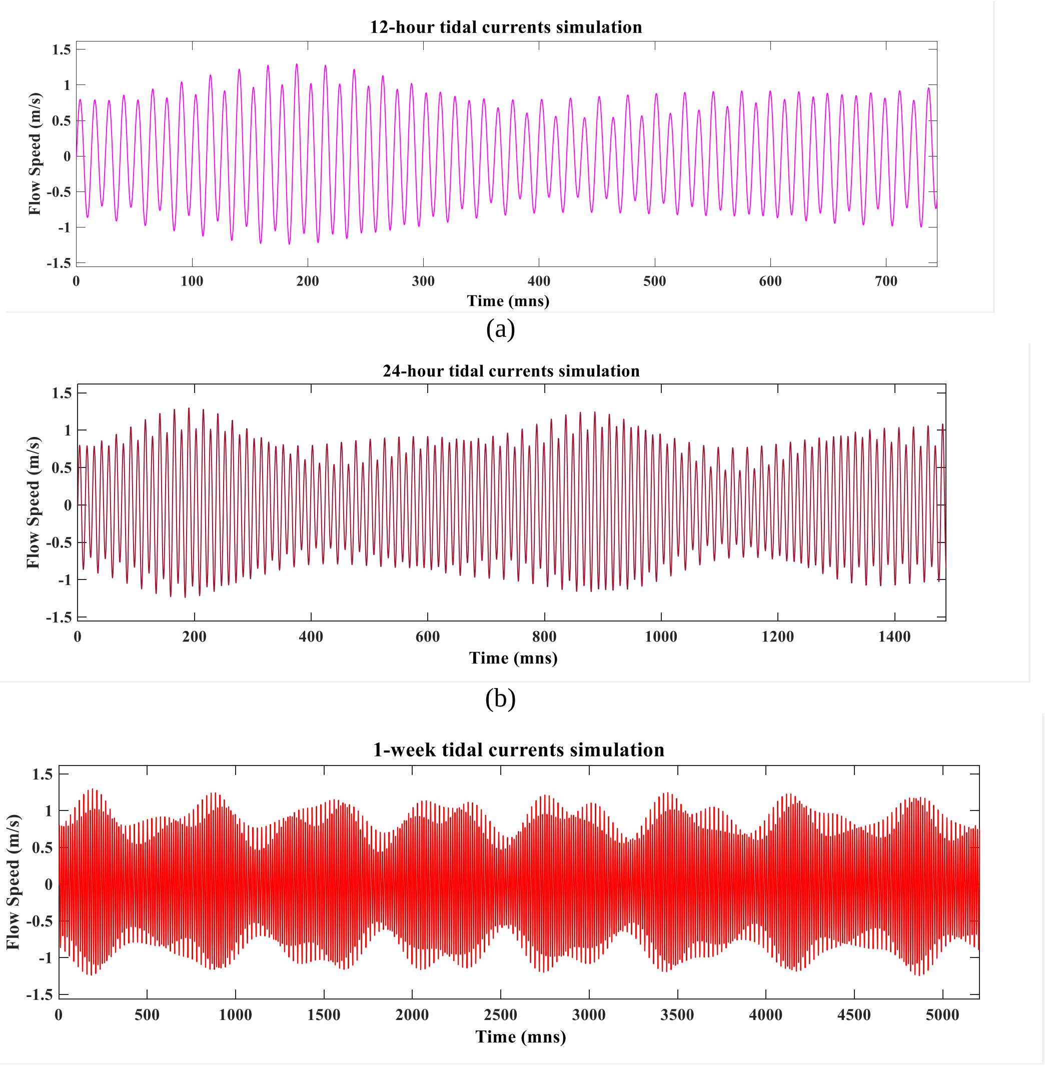
This shows how the power coefficient of performance and tip speed ratio λ for different blade pitch angles β for a common maritime turbine relate to one another. Cp typically ranges from 0.25 to 0.5 for wind turbines. The maximum is for extremely effective machinery with minimal mechanical losses. According to Figure 1, Cp for marine turbines is thought to be between 0.35 and 0.5.

According to (Okoli et al., 2017), the tidal velocity of the Nigerian coastline region is examined using the harmonic analysis method. Tidal currents can be described as a stream of harmonics using equation (5) because they are a regular horizontal water flow that accompanies the rise and fall of the tide.

$$v(t) = \sum v_i . \sin\left(2\pi f_i t + p_i\right) \tag{5}$$

where the sinusoidal relationship between the tidal current magnitude and speed vi, tidal period f_i, and harmonic phase p_i.

The data supplied in (Okoli et al., 2017) the constituent of the tidal current in the coastal region of Nigeria are model and the tidal current simulation model are shown as illustrated in Figure 2.



(a)

(b)

(c)

Figure 2. Tidal current simulation (a) 12-hour hour (b) 24-hour (c) 1-week

Modelling of a Six-Phase PMSG

The machine has two sets of three-phase stator windings: (abc) and (xyz). According to Figure 3, the two windings abc and xyz, whose magnetic axes are offset by 30^0, share a common magnetic structure and are located in the same stator slots (Kim et al., 2013; Karttunen et al., 2014; Tola et al., 2022). The following is the expression for the voltage equations that explain the electrical behavior of the machine in the machine variable (Tola et al., 2017):

$$\begin{cases} V_{abcs} = -R_s i_{abcs} + p\lambda_{abcs} \\ V_{xyzs} = -R_s i_{xyzs} + p\lambda_{xyzs} \end{cases} \tag{6}$$

where

$$\begin{cases} \lambda_{abcs} = L_{abc} i_{abcs} + L_{abcxyz} i_{xyzs} + \psi_{PM} \\ \lambda_{xyzs} = L_{abcxyz}^{T} i_{abcs} + L_{xyz} i_{xyzs} + \psi_{PM} \end{cases} \tag{7}$$

The flux linkages are functions of inductances and currents. And the flux linkage can be expressed as

$$L_{abc} = \begin{bmatrix} L_{la} + L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{lb} + L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{lc} + L_{\mathrm{cc}} \end{bmatrix} \tag{8}$$

$$L_{xyz} = \begin{bmatrix} L_{lx} + L_{xx} & L_{xy} & L_{xz} \\ L_{yx} & L_{ly} + L_{yy} & L_{yz} \\ L_{zx} & L_{zy} & L_{lz} + L_{zz} \end{bmatrix} \tag{9}$$

$$L_{abcxyz} = L_{12} + L_{l12} \tag{10}$$

$$\begin{cases} L_{12} = \begin{bmatrix} L_{ax} & L_{ay} & L_{az} \\ L_{bx} & L_{by} & L_{bz} \\ L_{cx} & L_{cy} & L_{cz} \end{bmatrix} \\ L_{l12} = \begin{bmatrix} L_{lax} & L_{lay} & L_{laz} \\ L_{lbx} & L_{lby} & L_{lbz} \\ L_{lcx} & L_{lcy} & L_{lcz} \end{bmatrix} \end{cases} \tag{11}$$

where L_{lax}, L_{lby}, L_{lcx} are inductances (mutual leakage) between the winding sets, L_{aa}, $L_{bb}, L_{cc}, L_{xx}, L_{yy}, L_{zz}$ are self –inductances, L_{ax}, L_{by}, L_{cz} are inductances (mutual) between the winding sets, ψ_{PM} is the PM flux linking the stator and considering sinusoidal distribution with ε as the displacement angle between the sets winding and λ_m is the permanent magnet amplitude is expressed as:

$$\psi_{PM}=\lambda_m\begin{bmatrix}\sin\theta\\ \sin\left(\theta-\frac{2\pi}{3}\right)\\ \sin\left(\theta+\frac{2\pi}{3}\right)\\ \sin\left(\theta-\varepsilon\right)\\ \sin\left(\theta-\frac{2\pi}{3}-\varepsilon\right)\\ \sin\left(\theta+\frac{2\pi}{3}-\varepsilon\right)\end{bmatrix} \tag{12}$$

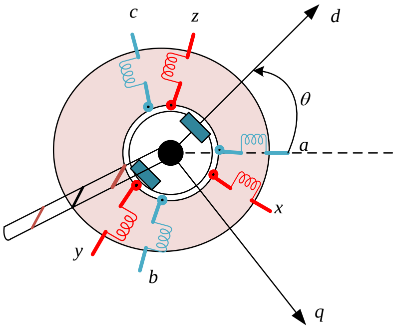


Figure 3. abc phase and xyz phase model of PMSM

The generator model's voltage and flux linkage equations in the d-q reference frame are expressed as:

$$\begin{cases}\frac{di_{d1}}{dt}=-\frac{1}{L_d}v_{d1}-\frac{R_s}{L_d}i_{d1}+\frac{L_q}{L_d}\omega_r i_{q1}\\ \frac{di_{q1}}{dt}=-\frac{1}{L_q}v_{q1}-\frac{R_s}{L_q}i_{q1}-\frac{L_d}{L_q}\omega_r i_{d1}-\frac{\lambda_m}{L_q}\omega_r\\ \frac{di_{d2}}{dt}=-\frac{1}{L_d}v_{d2}-\frac{R_s}{L_d}i_{d2}+\frac{L_q}{L_d}\omega_r i_{q2}\\ \frac{di_{q2}}{dt}=-\frac{1}{L_q}v_{q2}-\frac{R_s}{L_q}i_{q2}-\frac{L_d}{L_q}\omega_r i_{d2}-\frac{\lambda_m}{L_q}\omega_r\end{cases} \tag{13}$$

The six-phase PMSG electromagnetic torque and its dynamic are given by:

$$T_e=\frac{3n_p}{2}\left[-\lambda_m\left(i_{q1}+i_{q2}\right)+\left(L_d-L_q\right)\left(i_{d1}i_{q1}+i_{d2}i_{q2}\right)\right] \tag{14}$$

$$T_e=J\frac{d\omega_m}{dt}+f\omega_m \tag{15}$$

where n_p is the number of pole pair, J is moment of inertia, f is the viscous friction coefficient and ω_m is the generator speed.

The total electricalpower expressed in the abc variables is expressed as

$$P_{out} = v_{abc}^{T} i_{abc} + v_{xyz}^{T} i_{xyz} \tag{16}$$

$$P_{dq} = v_{dq}^{T} (k^{-1})^{T} (k^{-1}) i_{dq} \tag{17}$$

where k is the transformation constant. Therefore, the active and reactive power are expressed as:

$$\begin{cases} P = \left(v_{d1} i_{d1} + v_{q1} i_{q1}\right) + \left(v_{d2} i_{d2} + v_{q2} i_{q2}\right) \\ Q = \left(v_{d1} i_{q1} + v_{d2} i_{q2}\right) - \left(v_{q1} i_{d1} + v_{q2} i_{d2}\right) \end{cases} \tag{18}$$

And the KVA rating of the generator is given as:

$$S = \sqrt{P^{2} + Q^{2}} \tag{19}$$

Results and Discussion

The following figures show the results of a dynamic simulation used to illustrate how well the generator performs when the region's tidal current speed fluctuations are used. When the tidal flow is at zero pitch angle and the turbine in Figure 1 is operating at tip speed ratio of 8, the power performance parameters of the turbine are within the operational range of 0.48. At a given zero, pitch angle, the stator currents are shown in Figure 4. The output power of the proposed generator, which is 198 kW and about equal to the machine's rated power, is shown in Figure 7 along with its active, reactive, and apparent power. The stator winding current is shown in Figure 4 with a clear indication of the displacement of the two-winding set. Figure 5 shows the electromagnetic torque, which is 6500 N-m and stable after 4 seconds. Figure 6 depicts the generator's rotational speed, which is 1500 rpm and synchronized after 4 seconds.

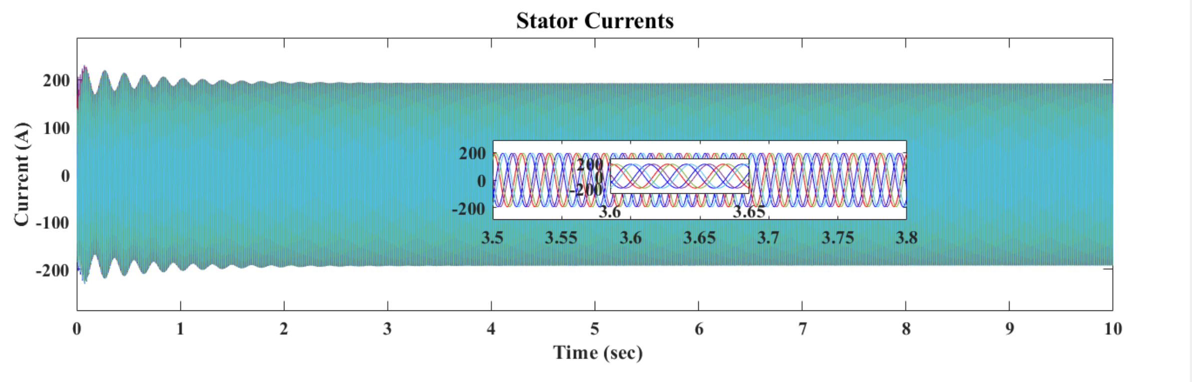


Figure 4. Stator currents

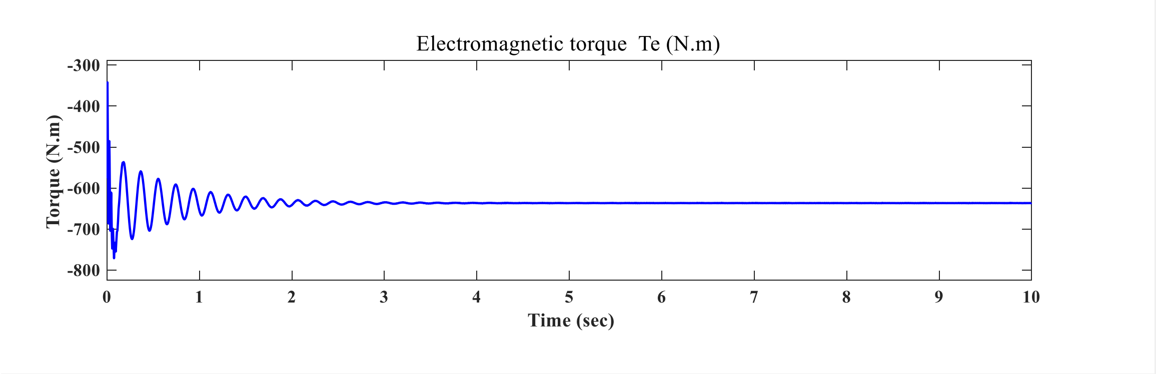


Figure 5. Electromagnetic torque

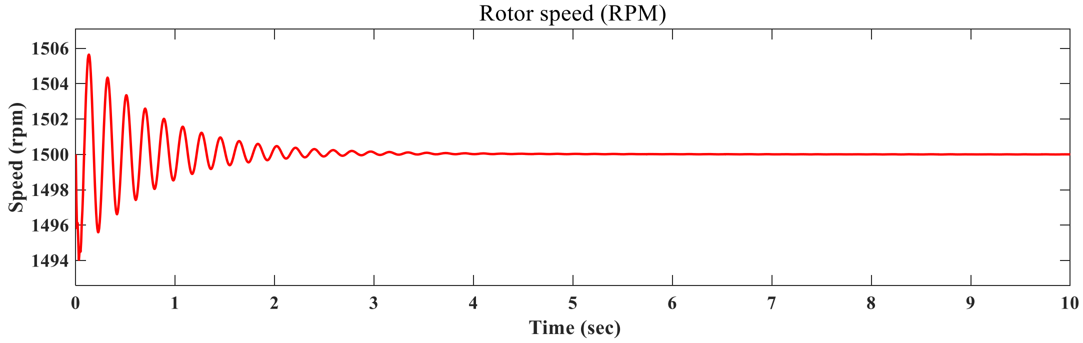


Figure 6. Rotor speed

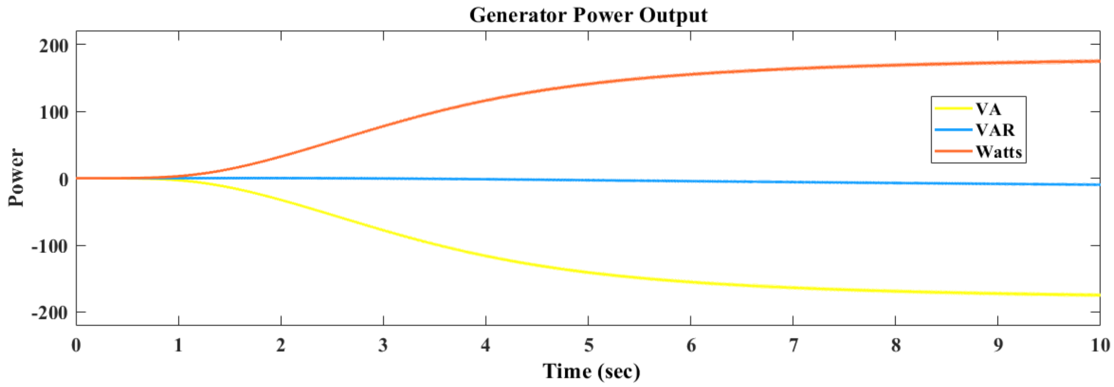


Figure 7. Generator Power

Conclusion

The fundamental need for human life is energy. Currently, oil and fossil fuels are used to meet the majority of the world's energy needs. However, these are finite resources. Therefore, harnessing renewable energy sources is urgently needed on a global scale. Since tidal energy is independent of the seasons and weather, it has some advantages over other renewable energy sources like wind and solar energy because it is more predictable over a longer time scale. Tides are a substantial potential source of clean renewable energy for generation of electricity in the coastal region of the Gulf of Guinea along the South-West region of Nigeria and small communities located near continental shorelines, or on remote islands with strong marine tidal currents. An overview of the power extraction from a marine tidal current turbine's speed profile is given. Moreover, d-q rotor reference frame has been used to model a detail PMSG model due to its advantages. Based on the speed of the tidal current in the Nigerian coastline region with a zero-pitch angle, the generator current, output power, electromagnetic torque, and rotor angular speed in a transient state are also shown. The outcomes suggest that the six-phase PMSG can be used successfully in the coastal region.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Acknowledgements or Notes

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