Proceedings of the ASME 2021
International Mechanical Engineering Congress and Exposition
IMECE2021
November 1-5, 2021, Virtual, Online

IMECE2021- 71754

A SMALL-SCALE EXPERIMENTAL OCEAN CURRENT TURBINE APPARATUS FOR POWER MEASUREMENT

S. Rouhi
University of New Orleans
New Orleans, LA

N. Xiros
University of New Orleans
New Orleans, LA

E. Aktosun
University of New Orleans
New Orleans, LA

C. Sultan
Virginia Tech.
Blacksburg, VA

J. VanZwieten
Florida Atlantic University
Boca Raton, FL

J. Ioup
University of New Orleans
New Orleans, LA

S. Sadeqi
University of New Orleans
New Orleans, LA

ABSTRACT

The objective of this work is to propose an experimental apparatus setup for a small-scale three-bladed, horizontal-axis Ocean Current Turbine (OCT). This OCT model is under investigation using the University of New Orleans (UNO) towing tank to establish an electromechanical power takeoff system to produce sustainable renewable energy. The system is currently in the design phase. This paper describes the experimental apparatus design by considering sizing elements, bill of materials, schematics, and performance simulation for the expected system. The implementation of an actual experimental small-scale turbine complements the analytical and numerical investigations on turbine design characteristics achieved by ongoing research at UNO based on conformal mapping methods along with Blade Element Momentum Theory (BEM) for generated power prediction. The towing tank experimental approach is used to verify performance of the turbine.

Keywords: Ocean Current Turbine (OCT), Experimental Design, Power measurement, PMDC motor, DC generator, Dynamic simulation, Matlab Simulink.

NOMENCLATURE

V_{ind}	generated voltage
ω	motor shaft speed
K_s	speed constant
V_t	generated voltage
R_m	motor resistance
I_l	load current
$I_{l_{Max}}$	maximum load current
τ	driving torque
I_0	no-load current
K_t	motor torque constant
K_e	motor voltage constant
P_e	electrical power
$P_{e_{Max}}$	maximum electrical power
$\frac{\Delta\omega}{\Delta\tau}$	motor speed-torque gradient
P_m	mechanical power
η_g	generator efficiency
P_{out}	output power
V_{out}	output voltage
I_{out}	output current
P_{in}	input power
$effic$	estimated efficiency
L	required inductor
D	duty cycle
f_s	switching frequency
ΔI	current ripple
C	required capacitor
ΔV	voltage ripple

1. INTRODUCTION

An increase in world energy demand is undeniable. This growth in energy consumption is in addition to the fact that expendable resources such as fossil fuels are both limited in amount and often harmful to our planet lead us to replace them with renewable energy resources that are naturally replenished. Ocean currents are a potentially vast renewable hydrokinetic energy resource. Indeed, they have the ability of high energy production rates due to the immense amount of marine hydrokinetic energy involved in the movement of water [1, 2]. Much research has been done so far to demonstrate the hydrokinetic energy conversion principle. Minh N. Doan et al. proposed a power measurement system for a cross-flow hydrokinetic turbine operated in an experimental water tunnel [3]. E. Muljadi et al. described a simplified power conversion system by taking advantage of photovoltaic inverters for a river and tidal turbine generator [4]. N. K. Sarma et al. evaluated a simple three bladed Savonius turbine performance in a water channel. The hydrokinetic turbine power measurements showed enhanced performance when compared to an identically designed wind turbine [5]. J. Riglin et al. developed a hydrokinetic turbine prototype for river applications. This turbine loading was manually adjusted to produce a performance curve for each given flow speed [6].

This paper is based on the work done on blade element momentum (BEM) theory code which was written in Matlab [7]. BEM theory is a well-known technique to analyze the performance of turbines. This technique considers the specific conditions of the fluid and rotors. Many parameters, e.g. differential torque, thrust and power estimation, were obtained by using our in-house BEM Matlab code. Using predictions from our BEM code, a small-scale three-bladed horizontal underwater turbine is developed. This small-scale turbine is used for proof-of-concept testing and numerical model verification since it is more cost-effective than full-scale testing [8]. The test turbine is under construction at the University of New Orleans. In order to perform the experiment, an electrical system is needed to cope with all the requirements and to measure the generated power [8,9]. V. Tzelepis developed a PID controller to achieve specified speed set-points in the ocean current energy conversion system and to implement a simulation to estimate the average electric power generation. Also, a control system of induction motor/generator was proposed [10]. C. McConnell et al. designed a small-scale prototype hydrokinetic turbine by using BEM theory to obtain optimal blade twist [11].

OCTs generate power due to local forces, especially the lift force applied to the rotor blades. In addition, there are some undesirable forces on the carriage which are considered in order to avoid any structural damage in a full-scale prototype. The method is used to estimate the nominal generated power at different carriage speed and rotor blade rotational speed. The carriage speed mimics the motion of the water current that contains akinetic energy. The tip speed ratio is varied in order to achieve optimal power production at a constant carriage speed to measure the power obtained from the OCT. This can be done by adjusting the rotational speed of the rotor blades. The apparatus system design has been divided into two subsystems: motor power supplier and generator power production. The motor drive power supply should be capable of creating a DC bus voltage from the AC line voltage by utilizing a switch-mode power supply. Adjusting the rotational speed can be done by regulating the duty cycle to make the output voltage variable in order to control the DC motor speed. Once the reference rotational steady state speed is obtained, the AC line voltage must be removed to allow electrical brake circuitry to connect to the DC motor while the carriage moves the turbine. The DC motor generates electrical current that flows through electrical brake and can be measured to compute the power generated, along with the rotor rotational speed. The results of the experiment described in the current research as well as the analytical data acquired will be the basis for evaluating the efficiency of the generator and calculating the optimum terminal power.

This paper is arranged as follows. Section 2 discusses the design process and sizing of the apparatus components. Section 3 shows simulation results for the proposed drive. Finally, section 4 presents conclusions, followed by acknowledgment and references.

2. MATERIALS AND METHODS

In order to develop an appropriate design, many considerations must be made prior to the beginning of this process. First and foremost, what is the expectation for the whole system and what is the best way to build the system with the required components. Due to the fact that we have very limited carriage speed in the UNO towing tank, our DC machine must reach the steady-state reference rotational speeds before being used as a generator. Therefore, electricity will be supplied to the motor by a means of power supplier in order to obtain the desired speed. By obtaining the assigned rotational speed, the power provider is then disconnected and the braking resistor load is switched on in order to measure the generated power. Each circuit element within the system must then be selected and sized.

2.1 DC motor as a generator

Any direct current (DC) motor can be run as a generator based on the fundamental principle of induction with induced voltage proportional to the motor shaft speed for the unloaded generator [12]

$$V_{ind} = \omega / K_s \quad (1)$$

where V_{ind} is the generated voltage (V), ω is the motor shaft speed (rpm), K_s is the speed constant of the motor, aka, speed equation constant (rpm/V). The speed constant is the inverse of the motor voltage constant (K_e).

$$K_s = 1/K_e \quad (2)$$

It is important to note that these relationships are valid for the ideal case without any losses. Once the generator is loaded with current, the induced DC voltage at the terminals will be reduced because of the motor resistance. Hence, we can rewrite equation (1) as follows

$$V_t = \frac{\omega}{K_s} - R_m * I_l \quad (3)$$

where V_t is the generated voltage (V), ω is the motor shaft speed (rpm), K_s is the speed constant of the motor (rpm/V), R_m is the motor resistance (Ω), I_l is the current that goes through the wire (A).

We can graph the voltage-current line of the generator by using equation (3). The maximum possible generated voltage is at no-load current (open circuit), and the maximum load current corresponds to the no-voltage induction (short circuit). Therefore, the maximum load current is

$$I_{l_{Max}} = \omega / K_s * R_m \quad (4)$$

The torque to drive the generator in order to overcome the generator internal losses and produce the load current is given by equation (5).

$$\tau = K_t * (I_l + I_0) \quad (5)$$

where τ is the required driving torque (Nm), I_l is the current through the wire (A), I_0 is the motor no-load current (A) corresponding to the internal torque losses, K_t is the motor torque constant or motor constant (Nm/A). The torque constant is equal to the motor voltage constant (K_e).

$$K_t = K_e \quad (6)$$

The generator power consists of two different parts, electrical output power and mechanical input power. The electrical output power can be calculated using equation (7).

$$P_e = V_t * I_l \quad (7)$$

where P_e is the electrical power (W), V_t is the generated voltage (V), I_l is the load current (A).

The maximum electrical output power at a given speed can be found from

$$P_{e_{Max}} = \frac{\pi}{30000} * \frac{\omega^2}{4} * \left(\frac{\Delta\omega}{\Delta\tau}\right)^{-1} \quad (8)$$

where $P_{e_{Max}}$ is the largest electrical output power (W), ω is the motor shaft speed (rpm), $(\frac{\Delta\omega}{\Delta\tau})$ is the motor speed-torque gradient (rpm/Nm).

Similarly, the mechanical input power can be calculated using equation (8).

$$P_m = \frac{\pi}{30} * \omega * \tau \quad (9)$$

where P_m is the mechanical power (W), ω is the motor shaft speed (rpm), τ is the driving torque (Nm).

In general, efficiency is described as the ratio of useful output to total input. Hence, the generator efficiency is measured as the ratio of electrical output power to mechanical input power.

$$\eta_g = P_e / P_m \quad (10)$$

where η_g is the generator efficiency (1), P_e is the electrical power (W), P_m is the mechanical power (W).

Essentially, for a machine that runs as a generator, the generator efficiency behaves similarly to its motor efficiency. We can obtain the higher efficiency at the higher circular speed, and the maximum efficiency occurs at a lower load current with a given rotational speed.

2.2 Modelling of PMDC motor/generator

In this study, a permanent magnet direct current (PMDC) motor is selected to use as a small scale experimental hydrokinetic turbine. Based on the required tasks and the fact that PMDCs are quite slow to react to high frequency switching, q pulse width modulated (PWM) regulator is chosen to control the motor speed. PWM is a technique that is used to reduce the average power delivered be an electrical supply [13]. The average value of the voltage fed to the load is controlled by turning a switch located between power supply and load on and off at a very high frequency. The PWM signal can emulate the effect of a variable DC power supply through appropriate manipulation of its duty cycle. By varying the duty cycle, the average DC voltage delivered to the output can be controlled. The required DC output voltage consists of rectangular voltage width which could be eliminated to form an averaged duty cycle modulated DC voltage by a mean of appropriate LC filter [14]. It is essential to predetermine some of the parameters for the PWM power supply. First, we have to specify the power output by using equation (11).

$$P_{out} = V_{out} * I_{out} \quad (11)$$

where P_{out} is the output power (W), V_{out} is the output voltage (V), I_{out} is the output current (A).

Equation (12) gives the input power with the estimated efficiency.

$$P_{in} = P_{out} / effic \quad (12)$$

where P_{in} is the input power (W), P_{out} is the output power (W), $effic$ is the estimated efficiency (1).

Equation (13) is used to find the average input current.

$$I_{in} = P_{in} / V_{in} \quad (13)$$

The purpose of using an inductor is to store energy for the load during the switch off period to integrate (smooth) the rectangular switching pulses into DC [15]. In addition, the current in the output inductor dictates the mode of operation. The minimum inductance needed for the output to maintain operation in continuous conduction mode where the current does not reach zero is given by equation (14).

$$L = \frac{V_{out} * (1 - D)}{f_s * \Delta I} \quad (14)$$

where L is the minimum required inductance (H), V_{out} is the output voltage (V), D is the duty cycle (1), f_s is the switching frequency (Hz), ΔI is the current ripple, equal to 10-40% of I_{out} based on the standard rule of thumb (A).

The most basic line filter is a filter capacitor. It is used to suppress electrical noise coming from the power supply line. The role of the filter capacitor is to attenuate some of the electrical noise by shorting out high frequencies while passing through low frequencies (a low-pass filter). Equation (15) gives the minimum capacitance to filter the switching pulses.

$$C = \frac{\Delta I}{8 * f_s * \Delta V} \quad (15)$$

where C is the minimum required capacitor (F), f_s is the switching frequency (Hz), ΔV is the voltage ripple that is equal to 1% of V_{out} based on the standard rule of thumb (V).

From a power switch perspective, the most common choice is MOSFET. First, it is more economic in comparison to a bipolar transistor. Its saturation loss is another positive point, along with its straightforward design. In addition, it switches five to ten times faster. From motor to generator switching and vice versa, speed can be measured by using an encoder sensor. Once the motor reaches the given speed, the power provider is disconnected and the turbine carriage starts moving to simulate water current. This water current contains torque and thrust that can then be utilized with our turbine to generate power.

Essentially, whenever a motor reaches the given speed, it must be reduced or eliminated by using the electrical brake. Electrical braking can be divided in to three main techniques: plugging type braking, dynamic braking, and regenerative braking. Since the power generated is because of water current forces on the turbine induced from carriage movement, the most practical braking strategy should be dynamic. In this method of braking, when the motor is running at the adjusted speed, it will be disconnected from the power supply and connected across a resistor. When the motor is disconnected from the power source, the rotor keeps turning due to inertia and the water current forces and works as a self-excited generator. The switching can be done with the help of solid-state relay switches. Note that when the PMDC motor works as a generator, the direction of the current reverses. Lastly, in order to calculate the generated power, voltage and current across the resistor are measured.

2.3 Simulation of PMDC motor/generator

Simulations have been performed for the PMDC motor generator using the parameters shown in Table 1. The models were developed in Matlab and Simulink environments.

Motor Data		
Nominal Voltage	V	12
No Load Speed	rpm	8130
No Load Current	A	0.32
Speed Constant	rpm/V	699
Torque Constant	Nm/A	0.0137
Motor Resistance	Ω	0.079
Rotor Inertia	gcm^2	99.5
Braking Load Resistance	Ω	1
Load Torque	Nm	0.12

TABLE 1: PARAMETERS OF PMDC MACHINE

This paper evaluates the power generated by the maximum water current load torque obtained by using the results of BEM theory [5]. This approach calculates the length, density, and corresponding two-dimensional force coefficients.

3. RESULTS AND DISCUSSION

Figure 1 shows the voltage current line of the generator. The lower right end of the plot is the point with no terminal voltage and maximum possible load current.

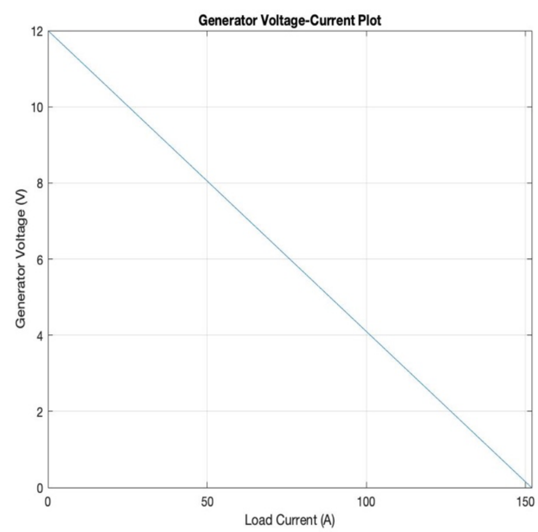


FIGURE 1: GENERATOR VOLTAGE VS CURRENT

Figure 2 is the graphical representation of the generator efficiency. This efficiency is depending on the generated current at different rotational speed. In order to get the assigned power of 40 watts, a generator speed of 4065 rpm is needed at a load current of 4.562 amperes. This current is slightly less than the continuous current of 6 amperes. Similarly, for 30 watts output power, the optimum load current is 3.739 amperes at a generator speed of 3049 rpm. Also, for 20 watts output power, the optimum load current is 3.234 amperes at a generator speed of 2033 rpm. Noting that, those numbers are based on ideal performance with absence of any noise.

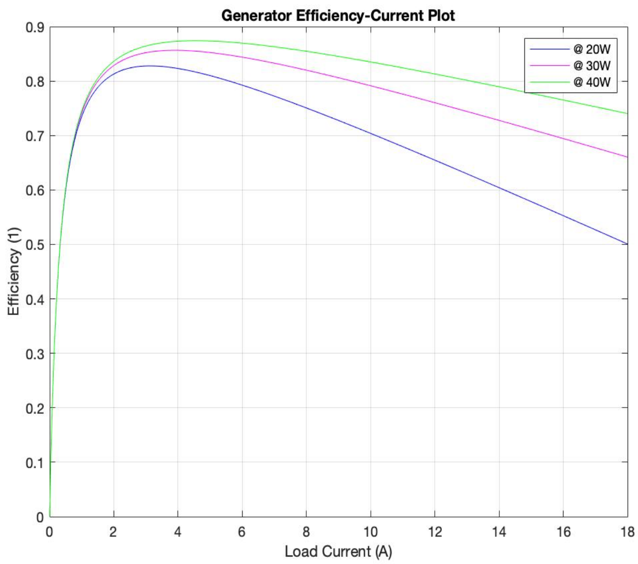
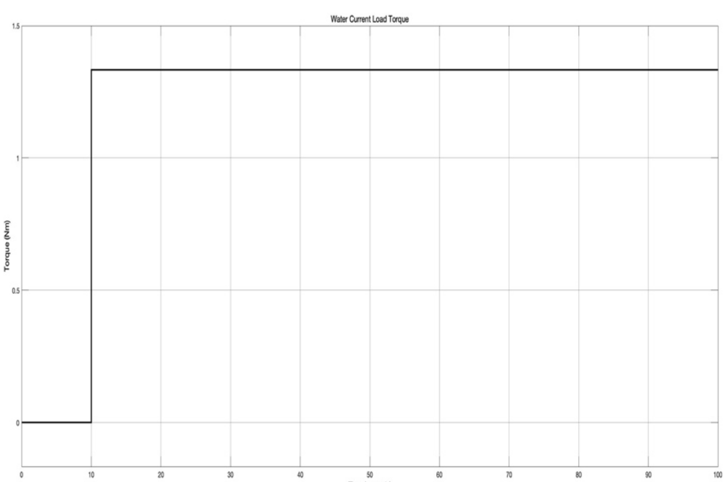
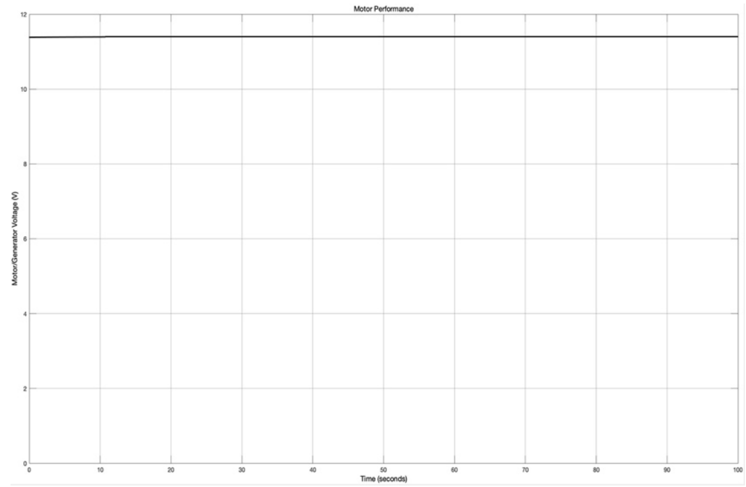


FIGURE 2: GENERATOR EFFICIENCY VS LOAD CURRENT FOR 3 POWER VALES

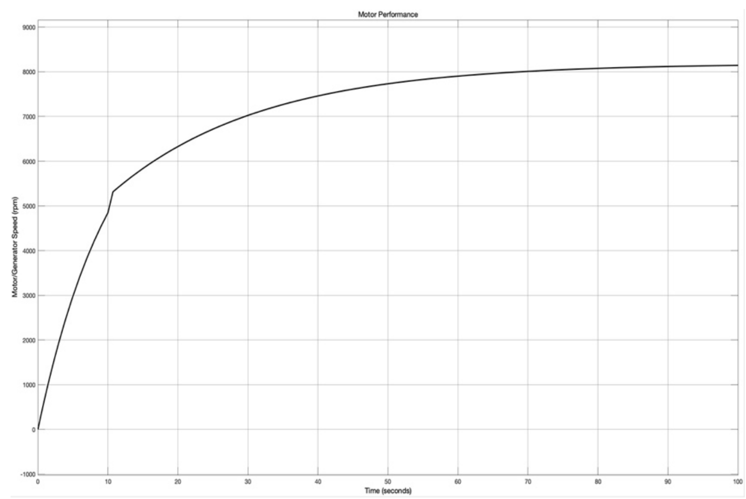
Figure 3 shows simulation results for the dynamic behavior of the drive under load disturbance. We applied a step load torque of 0.12 Nm to the system at time t = 10 (s) to simulate the water current load to switch the performance of the PMDC machine from motor to generator role.



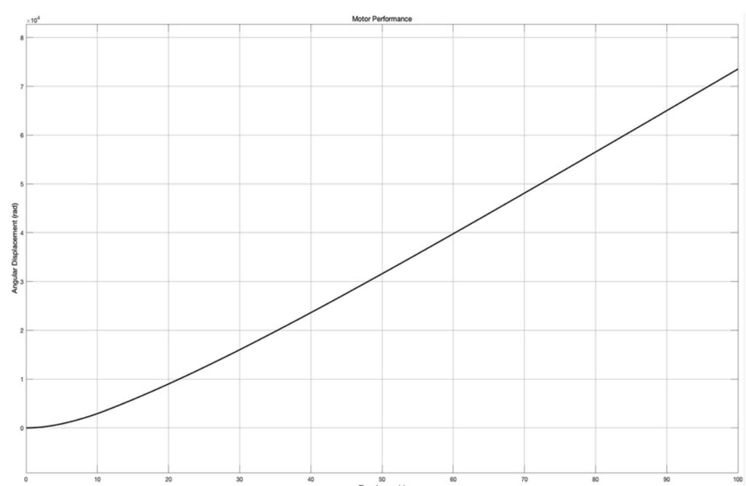
(a) Load Torque vs Time



(b) Motor/Generator Voltage vs Time



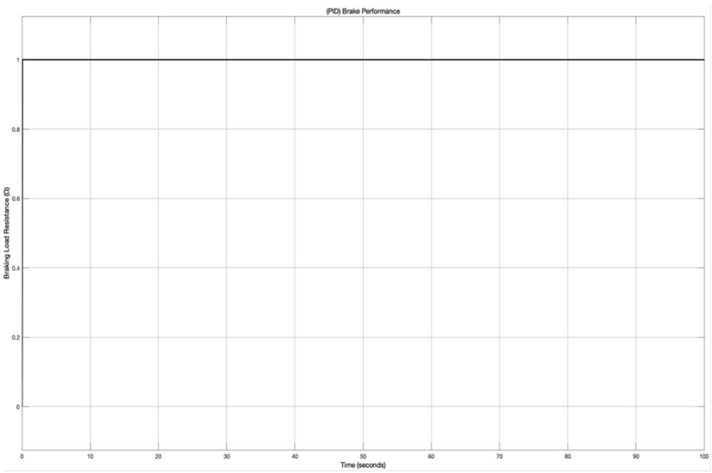
(c) Motor/Generator Speed vs Time



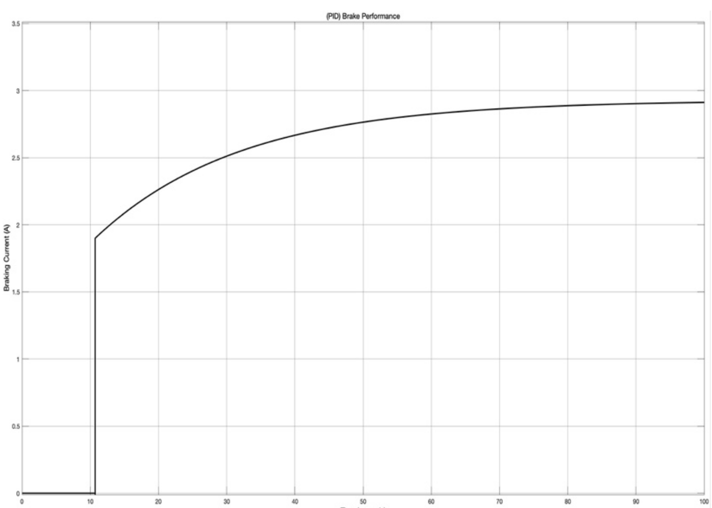
(d) Motor/Generator Angular Displacement vs Time

FIGURE 3: RESPONSE WAVEFORMS OF PMDC MACHINE UNDER STEP CHANGE OF WATER CURRENT LOAD TORQUE

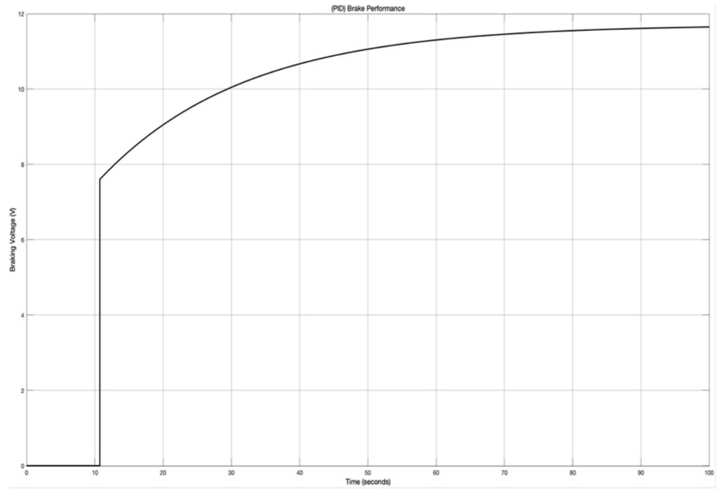
Figure 4 gives simulation results of the dynamic behavior of the braking provided by a 1 Ω resistor in order to measure the generated current, voltage, and power. By applying a load torque at t = 10 (s), we can see a jump from zero to almost 15 watts of generated power. As time passes, the generator reaches steady state performance.



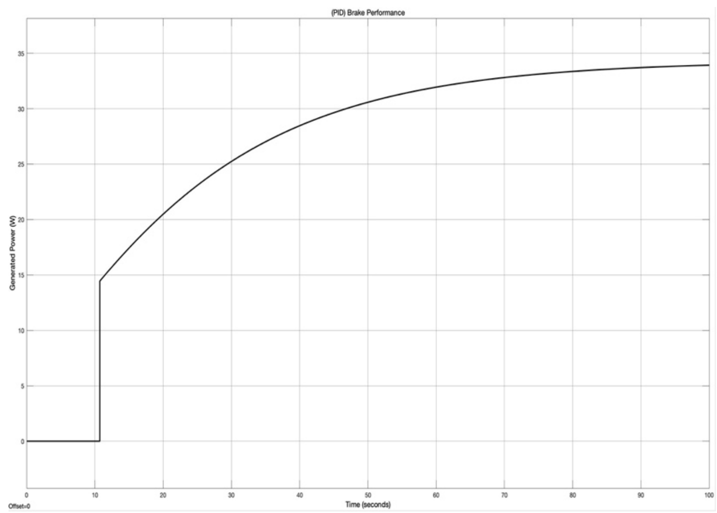
(a) Braking Resistance vs Time



(b) Braking Current vs Time



(c) Braking Voltage vs Time



(d) Power Generated vs Time

FIGURE 4: RESPONSE WAVEFORMS OF DYNAMIC BRAKING UNDER STEP CHANGE OF WATER CURRENT LOAD TORQUE

The efficiency under the operating conditions of Fig. 4 is usually slightly below 50%. The maximum output mechanical power for this type of PMDC machine is 80 watts when it runs as a motor. Hence, for the 33.9 watts of generated power here, our PMDC machine works as a generator with 42.4% efficiency at the highest assigned torque calculated using BEM analysis.

4. CONCLUSION

This paper presented a proposed experimental apparatus for a small-scale ocean current turbine. The design described how to size each element as well as predicting the performance of the drive. The simulation results confirmed the validity of the drive to control the speed of the PMDC machine at the time that it runs as a motor in addition to the process of switching it to a generator in order to measure the power produced.

ACKNOWLEDGEMENTS

The authors would like to thank the National Science Foundation (NSF) and specifically the Energy, Power, Control and Networks (EPCN) program for their valuable ongoing support in this research within the framework of grant ECCS-1809182 'Collaborative Research: Design and Control of Networked Offshore Hydrokinetic Power-Plants with Energy Storage'.

REFERENCES

[1] S. Rouhi, S. Sadeqi, N. Xiros, J. Ioup, *CFD analysis of filling process for a hydrogen energy storage, 5th Thermal and Fluids Engineering Conference, TFEC-2020- 32066, 2020*

[2] Manhar R. Dhanak, Nikolaos I. Xiros, *Springer Handbook of Ocean Engineering, 2016.*

[3] Minh N. Doan, Yuriko Kai, and Shinnosuke Obi, *Twin Marine Hydrokinetic Cross-Flow Turbines in Counter Rotating Configurations: A Laboratory-Scaled Apparatus for Power Measurement, Journal of Marine Science and Engineering 2020.*

[4] E. Muljadi, V. Gevorgian, A. Wright, J. Donegan, C. Marnagh, J. McEntee, *Electrical Power Conversion of a River and Tidal Power Generator, www.nrel.gov/publications, NREL/CP-5D00-66866 September 2016.*

[5] N.K. Sarma, A. Biswas, R.D. Misra*, Experimental and computational evaluation of Savonius hydrokinetic turbine for low velocity condition with comparison to Savonius wind turbine at the same input power, Energy Conversion and Management, 83, 2014.*

[6] Jacob Riglin, Fred Carter III, Nick Oblas, W. Chris Schleicher, Cosan Daskiran, Alparslan Oztekin, *Experimental and numerical characterization of a full-scale portable hydrokinetic turbine prototype for river applications, Renewable Energy 99 2016.*

[7] S. Sadeqi, N. Xiros, S. Rouhi, J.Ioup, J. VanZwieten, C. Sultan, Numeri Numerical Investigation of an Experimental Ocean Current Turbine Based on Conformal Mapping Techniques and Blade Element Momentum Theory, OMAE2021-63010

[8] S. Rouhi, N. Xiros, S. Sadeqi, J. Ioup, C. Sultan, J. Vanzwieten, *CFD validation of the thermodynamic model of a compressed gaseous hydrogen storage tank, 6th Thermal and Fluids Engineering Conference, TFEC-2021-36525*

[9] S. Sadeqi, N. Xiros, S. Rouhi, J.Ioup, J. VanZwieten, C. Sultan, Wavelet transformation Analysis Applied to Incompressible Flow Field About a Solid Cylinder, ASTFE, TFEC-2021-36526

[10] Vasileios Tzelepis, *Electromechanics of an Ocean Current Turbine, University of New Orleans Theses and Dissertations, 2015.*

[11] Christopher McConnell, Jedediah Perron, Tess Royds, *Compound hydrokinetic submersible turbine, Worchester Polytechnic Institute, 2015.*

[12] mmag, Urs Kafader, *Maxon motors as generators, Maxon Academy, Revision 2019.*

[13] Nikolaos I. Xiros, et al. *Theoretical and experimental investigation of unmanned boat electric propulsion system with PMDC motor and water jet.*

[14] Marty Brown, *Series for design engineers, Power Supply, Second edition.*

[15] Abraham Pressman*, Switching power supply, Second edition.*

[16] Stephen J. Chapman, *Electric Machinery Fundamentals, Fifth Edition.*

[17] Alexander Gray, *Electrical Machine Design, The Design and Specification of Direct and Alternating Current Machinery, McGraw Hill Book Company.*

[18] M G Say, *Alternating Current Machinery, Fourth Edition, Pitman Publishing.*

[19] S. K. Sahdev, *Electrical Machines, Cambridge University Press.*

[20] Robert W. Erickson, et al. *Fundamentals of Power Electronics, Kluwer Academic/Plenum Publishers.*

[21] Paul C. Krause, et al. *Analysis of Electric Machinery and Drive systems, Second Edition, Wiley Interscience.*

[22] Chee-Mun Ong, *Dynamic Simulation of Electric Machinery using MATLAB/SIMULINK, Prentice Hall PTR.*

