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Dynamic Performance Simulation of Hydraulic Transmission for Low Speed Vertical Axis Marine Current Turbine Using MATLAB Simulink

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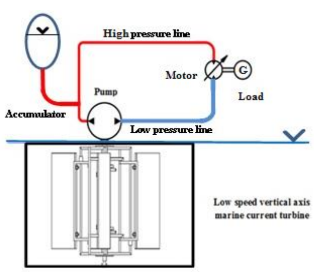
Graphical abstract



Low Speed Vertical Axis Marine Current Turbines with Hydraulic Transmissions System

Abstract

For Malaysia, ocean energy can be the best resource of green marine renewable energy. This is for the reason, the generation of the electricity by burning of fossil fuels produces undesired greenhouse gases and moreover the reserves of fossil fuels are being depleted and there is no accurate way to determine how much still remains. Turbines using hydraulic drive are being used for generating electricity by some manufacturers in the wind industry as an alternative to gearbox drive-trains because of reliability issues. Likewise, in the marine renewable sector, hydraulic-drive is an attractive option in terms of improved system efficiency, reliability and robustness. This paper presents a time domain simulation of hydraulic transmissions for Low Speed Vertical Axis Marine Current Turbines (VACT) using MATLAB Simulink software. These turbines are applied to harness marine current energy because of their relative simplicity and represent a promising technology to exploit low speed currents due to their small plants with reduced installation and maintenance costs.

Keywords: Renewable energy; low speed vertical axis marine current turbine; hydraulic transmissions; MATLAB simulink; time domain simulation

■1.0 INTRODUCTION

Ocean energy can be the best resource of green marine renewable energy because the generation of the electricity by burning of fossil fuels produces undesired greenhouse gases. As known, the resources of marine energy, especially the ocean energy can be categorized into tidal, wave, current, thermal gradient and salinity gradient,[1-2] to harness energy from marine current, there are two kinds of hydro-turbines; vertical-axis and horizontal-axis turbines that can be used as power generation devices.[3] Many studies and researches were carried out to demonstrate the feasibility and advantages of power generation plants. Horizontal-axis turbines are complex system and they are suitable only for large size plants where high installation and maintenance costs are balanced by large energy produced. On the other hand, the vertical-axis current turbines (VACT) are relatively simple and represent a promising technology to exploit marine currents due to their small plants with reduced installation and maintenance costs and they are suitable for deployment in remote areas. One type of VACT is the conventional Savonius turbine, which has good potentials and suitable for the Malaysia's water requirement; low speed current and shallow water depth.[4-5] But this turbine has a main drawback which is the low tip speed ratio(TSR) (λ) and difficult to integrate with the generator.

Recently, large wind turbines are using speed-increasing gearboxes to connect the high speed, RPM of generators to the slow motion rotors. However, these gearboxes are heavy and have numerous mechanical problems. Also, their maintenance work and replacement process are costly and very expensive. Other, wind/marine turbines use direct drive low-speed generators which are connected directly to the generator. Even though these machines are efficient and reliable, they are expensive and very heavy. Also, they need full-power electronic frequency and voltage converters to condition their power to supply the grid to avoid the network instability.

Conventional hydraulic transmission systems have long been considered for wind turbines and to make them attractive some companies and researchers have developed new, highly efficient hydraulic pumps and drive motors such as variable displacement and digital displacement machines. So, a continuously variable transmission ratio allows the rotor to be operated at the appropriate speed for optimal power capture, while the synchronous generator is driven at a much higher constant speed. Besides, short-term storage in hydraulic reservoirs (accumulators) can smooth out wind/current turbulence. So this is a good motivation to use these new solutions and developed technologies for marine current turbines due to the important features of the hydraulic system which are:

- Continuously variable transmission ratio
- Save and reliable operation
- Good damping characteristics

For Malaysian sea, which has low current speed and shallow depth, the researchers had proposed a Savonius vertical-axis turbine to harness current energy.[4-5] But this type of turbine has a main drawback which is the low tip speed ratio (λ) and difficult to integrate it with a generator. To solve this problem, this paper presents a dynamic performance simulation of a Low Speed VACT and matching it with a synchronous generator using a hydraulic transmission system (HTS).

■2.0 HYDRAULICTRANSMISSIONSSYSTEM

Currently, power transmission systems being used are heavy with high cost of components. Energy transfer systems may experience high dynamic loads and requires high maintenance. Hydraulic power transmission can be used as a solution to the problem. Hydraulic transmission has a steeples gear ratio, which enables the rotor to change speed independent of the generator. To illustrate this, a functional principal sketch of the hydraulic drive train system for the current turbine is shown in (Figure 1).

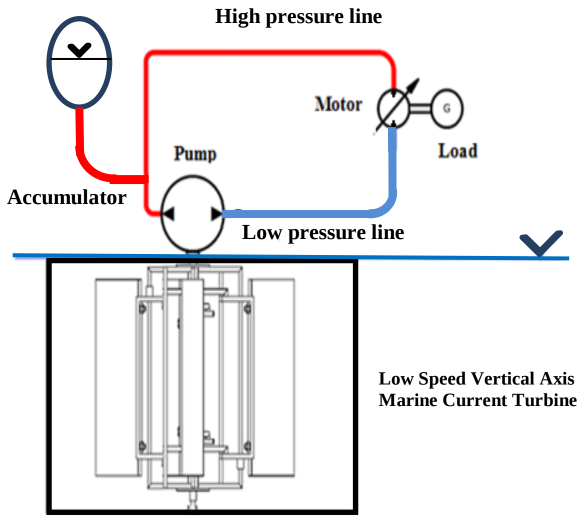


Figure 1 Marine current turbine with hydraulic drive train system

2.1 Concept of Energy Transfer System

Recently, there are many projects under different countries such as Scotland, Norway, USA, Germany, the Netherlands and Japan have adopted and developed this technology.[6] In this technology the concept is that the main shaft connects the rotor of the turbine to the positive displacement hydraulic pump. This pump converts the torque and speed of the turbine into a pressure flow. This fluid power is transferred in a circuit to hydraulic motor where the pressure flow is again converted into torque and speed (mechanical energy) to run and drive a generator at constant speed to produce the electrical energy. The Schematic diagram of the concept is shown in(Figure 2).

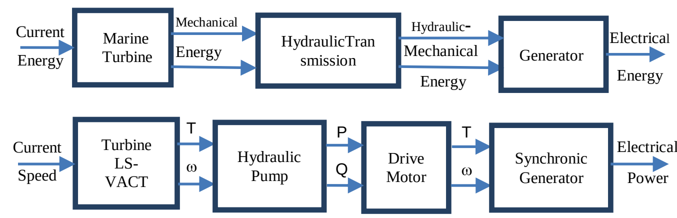


Figure 2 The principle concept of energy transfer system

A gearless hydraulic marine current energy transfer system utilizes the hydraulic power transmission principles to harvest the energy from current flow. The gearless marine current power transfer technology may replace the current energy harvesting system to reduce the cost of operation and increase the reliability of current power generation.

From the literature, the HTS is widely used in the wind energy and summary of some important findings are:

A hydraulic transmission for wind turbines, which offers better characteristics in controlling rotor RPM and damping torque impulses, becomes apparent with the overall efficiency of the system, achieving 86% and its development was duly presented.[7] Enhancement of efficiency is gained by adding another wind-driven fixed displacement hydraulic gear pump to the wind turbine hydraulic power plant. So, increasing efficiency and energy generation of the wind power plant can be achieved by collecting more energy from many wind turbines.[8]

As reported, the solution to overcome the uncertainties with off-the-shelf high pressure oil pumps and motors for hydraulic transfer system with lower efficiency is to combine the power from different sources and the type of hydraulic machine is shown in the design of the variable-displacement machine.[9] The efficiency of the hydraulic machine, variable hydraulic pump and the variable hydraulic motor are functions of pressure, rotating speed, density, dynamic viscosity of the fluid and control angle. [8-10] Also, the optimized control as compared to the traditional control (i.e. controlling the hydraulic machines in sequence) is saving up to 1.5 KW for the same HTS size used. From the simulations, it was found that the best accessible improvements are at low torques (low loads).[10] A continuously variable transmission (CVT) is required to capture the wind marine energy more efficiently. This system in the form of an HTS can be a viable solution for a mid-sized wind turbine. An HTS allows the use of a synchronous generator and hence the generator speed is decoupled from the rotor speed.[11]

Using the technology provided by Digital Displacement TM machine with an HTS, the generator can operate at constant RPM even with a tidal current turbine operating at variable rotor speeds. The generator power output remains uniform and unaffected provided the system does not exceed the rated capacity. Also, the generator does not show any fluctuations even when the incoming power from the pump to the drive motor varies. This is due to the absorption of the fluctuations by the accumulator.[12]

2.2 Advantages of the Marine Turbine System with HTS

The main advantages of the system are:

- Gearless transmission.
- More robust than mechanical gearboxes.
- High power-to-weight ratio.
- Inherently less stiff than mechanical equivalent.
- Damping of dynamic loads.
- Mature technology with high reliability and low maintenance

■3.0 THE SYSTEM USED IN THIS SIMULATION

3.1 The Principal Particulars of The Savonius Turbine

This turbine is based on the full scale prototype of the conventional Savonius turbine with a rotor height of 15 m which is suitable for the Malaysian water requirement; i.e. Low speed current and restricted water depth.[4,14] The parameters of the prototype used in this simulation are based on the experimental and simulated results of model tests which are scaled up to the prototype estimated parameters.[13] The main particulars of the Savonius prototype specifications and estimated parameters will be used for marine current application and its model is presented in the following Table 1 below. The current velocity of the prototype is selected as 0.56 m/s. This is the actual average current speed at the location of the research.[15]

Table 1 Prototype and model specifications for Savonius turbine

No	Description	Model	Prototype
1	Height, H [m]	1.5	15
2	Rotor Diameter, D_P [m]	0.375	3.75
3	Flow velocity U_∞ [m/s]	0.17	0.56
4	Torque, T [Nm]	0.36	3600
5	Angular speed n [RPM]	11.97	3.79
6	Angular speed ω [rad/s]	1.25	0.4
7	Peak Power, P_P [Watt]	0.45	1426.28

In this simulation, the performance characteristic of the Savonius turbine can be quantified by a generic performance coefficient curve or by using the look-up table. The performance coefficient, C_P, expresses the ability of the turbine to extract kinetic energy from the stream flow. It is equal to the ratio of the mechanical power available from the turbine shaft to the power conveyed by the current stream through the swept area of the turbine rotor:

$$C_P = \text{Pshaft mech. avail.} / 0.5\ \rho\ A\ U^3_\infty \quad (1)$$

Where (ρ) is the water density, (A) is the turbine swept area, and (U_∞) is the free stream velocity.[12]The performance coefficient is typically expressed as a function of the tip speed ratio (λ), which is the ratio of the blade tip speed (V) to the free stream velocity (U_∞). (Figure 3)[13] shows the power coefficient C_P curve used for this study from experimental results found in the literature.[13] The curve can be defined by a fifth-order polynomial as shown below in (Figure 3):

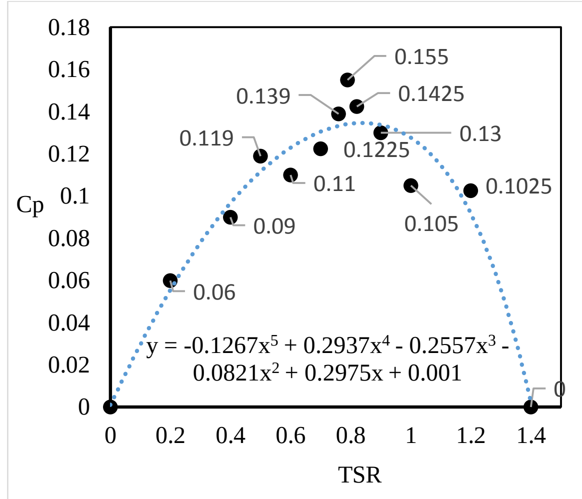


Figure 3 Power coefficient (C_P) Vs TSR (λ)curve

3.2 The Principal Particulars of a Low Speed Modified VACT

This modified turbineas shown in (Figure 4)[17] is a novel concept of VACT based on the Savonius rotor.The turbine is now named asthe Self-rotating Vertical Axis Current Turbine (SR-VACT).[17] In comparison to the Savonius type, the turbine hasfirstly, arms for increasing torque.

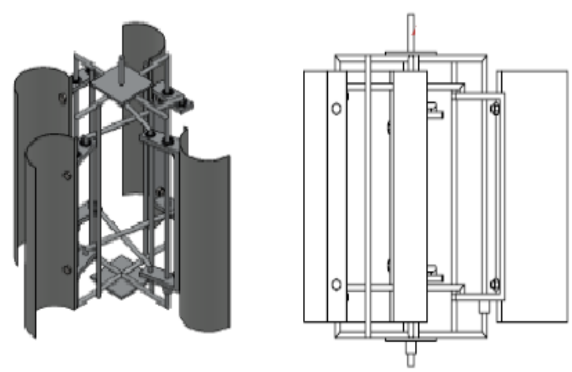


Figure 4 Representation of SR-VACT

Secondly, the self-adjusting or self-rotatingcapability of the four bladesis for increasing the hydrodynamic pressure loads and at the same time decreasing the hydrodynamic resistance and drag forces which leads to enhance in performance and efficiency. Table 2 below illustrates the main estimated parameters of modified design.[13,17]

Table 2 Prototype and model specifications

No	Description	VACT	SR-VACT
1	Height, H [m]	15	15
2	Paddle Diameter, d [m]	1.85	1.85
4	Arm, r (m)	-	0.542
5	Torque, T [Nm]	3600	4914
6	Angular speed n [RPM]	3.79	3.137
7	Angular speed ω [rad/s]	0.4	0.3285
8	Peak Power, P_P [Watt]	1426.28	1614.48

The performance coefficient of this turbine is typically expressed as a function of the tip speed ratio (λ) and torque coefficient (C_m). (Figure 5)[17] shows the torque coefficient (C_m) curve used for this study from simulation results found in the literature.[17]The curvecan be defined by a second-order polynomial as shown in (Figure 5):

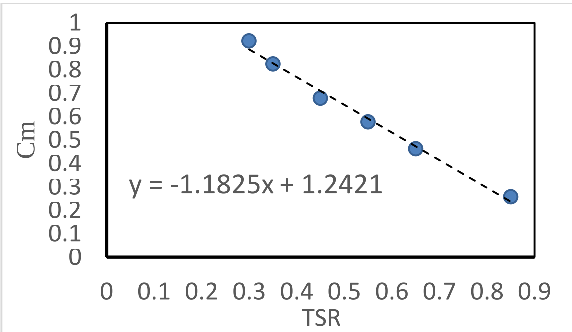


Figure 5 Torque coefficient (C_m) Vs TSR (λ)curve

3.3 The Principal Particulars of the Hydraulic Transmission System (HTS)

Marine Current Turbine drives a hydraulic system based upon oil using axial displacement pumping fluid around the system. This then drives a hydraulic motor which is coupled to a conventional induction machine. Accumulators provide energy storage to compensate for the variations in power.[12] The efficiency of the HTS is dependent on several parameters including volumetric flow rate, rotational speed and torque on the pump shaft, and the pressure difference across the inlet and outlet of the hydraulic pump and motor.[10] The main components of the system and the specifications of the accumulator are shown below in the Table 3.

Table 3 Hydraulic transmission components

Hydraulic Pump	
Working Pressure (Pa)	350 x10^5
Peak Pressure (Pa)	400 x10^5
Volumetric Efficiency	0.97
Hydraulic Motor Drive	
Working Pressure (Pa)	350 x10^5
Peak Pressure (Pa)	400 x10^5
Volumetric Efficiency	0.97
Hydraulic Reservoir(Accumulator)	
Hydraulic Reservoir Max Volume (m^3)	0.5
Max Pressure (Pa)	400 x10^5
Pre-charge Gas Pressure (Pa)	350x10^5
Gas Index	1.25

The conventional hydraulic pumps and motors have good efficiency at full displacement, but their performance drops significantly at partial displacement.[16] In practice more efficient and better performance of the system is achieved when both machines have variable displacement capabilities.[12] There is also a digital displacement technology developed specifically for avoiding the higher losses in the transmission when the input power from the turbine is at its lowest values.[12]

In this simulation study, Simulink Hydraulics library is used to model a hydraulic system and its physical phenomena. The easiest way to model a hydraulic system is to identify all important components, e.g. Pump, valves, orifices, motors, etc. As shown in (Figure 4) below. Connect the models according to the circuit diagram and place a lumped volume at each node (no need to do so if the placement of lumped volumes can be done automatically by the simulation program), the connection of two or more components. This leads to a set of differential equations where the through variable, flow rate, can be easily calculated from the known state variables, i.e. the across variables, which are the pressures in the volumes.

3.4 The Specifications of The Generator

The main electrical characteristics of the generator are presented in the following Table 4. To simulate this generator, a MATLAB, Simulink electric library is used to model a synchronous generator and the load on it.

Table 4 The specifications of the synchronous generator

Synchronous Generator	
Nominal Power (KW)	2.25
Rated Rotation (RPM)	1725
Rated voltage (V)	220
Frequency (Hz)	60
Number of Poles (pcs)	2

3.5 Dynamic Performance Simulation

MATLAB simulation program is developed to simulate Low speed VACT with HTS. In this program the energy is harvested by a low speed-high torque marine current turbine connected to a fixed-displacement hydraulic pump which is connected to a variable-displacement hydraulic motor. This drive motor will provide and maintain constant RPM to the loaded synchronic generator which is integrated into it. In this computer program as mentioned above, the turbine is presented by using a block diagram where the turbine is simulated by gating the power from C_P curve of a fifth-order polynomial using the Equation (1) to power the pump in terms of torque and RPM.

■4.0 RESULTS AND DISCUSSION

4.1 Simulation Results for Low Speed VACT (Savonius)

The current speed used in this simulation is 0.56 m/s and thisis based on the annual average current velocity ofMalaysian sea.[15] The dynamic simulation results as illustrated in Table 5 and in (Figure 6) and (Figure 7) below show that the total power obtained from a synchronous generator is 1675 Watts and RPM remain constant.

Table 5 VACT (Savonius) simulation results

Parameter	Value
Hydraulic Pump	
Pump Displacement (m^3/rad)	9.1543×10^{-5}
Torque at shaft (N.m)	3614
Power rating at 3.75 r/min (KW)	1.445
Hydraulic Motor	
Motor Displacement (m^3/rad)	1.123×10^{-7}
Power rating at 1725 r/min (KW)	1.211
Torque at generator shaft (N.m)	11.15
Hydraulic transmission System with the Generator	
Generator Power P_G (KW)	1.675
Total Efficiency	~ 85 %

Table 6 SR-VACT simulation results

Parameter	Value
Hydraulic Pump	
Pump Displacement (m^3/rad)	0.1375×10^{-3}
Torque at shaft (N.m)	4914
Power rating at 1.57 r/min (KW)	1.6142
Hydraulic Motor	
Motor Displacement (m^3/rad)	1.904×10^{-7}
Power rating at 1725 r/min (KW)	2.227
Torque at generator shaft (N.m)	12.33
Hydraulic transmission System with the Generator	
Generator Power P_G (KW)	1.728
Total Efficiency	~ 85 %

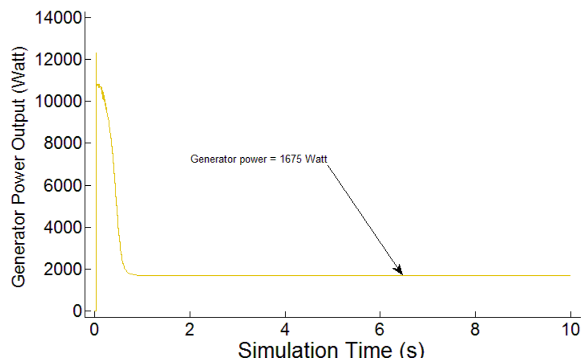


Figure 6 Generator power savoniusturbine output

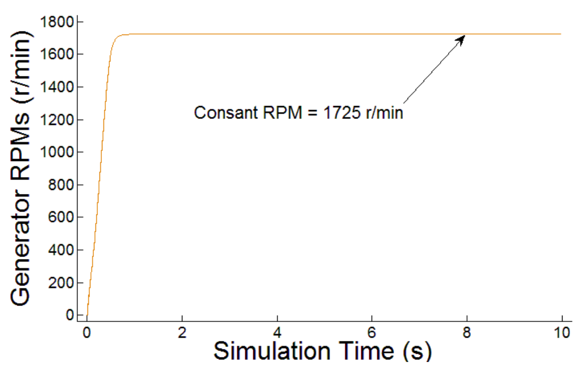


Figure 7 Generator RPM for savonius turbine system

4.2 Simulation Results for Low Speed SR-VACT

The same current speed used in this simulation which is 0.56 m/s and dynamic simulation results are shown in Table 6andin (Figure 8) and (Figure 9) below show that the velocity remains constant and total power obtained from a synchronous generator is 1728 Watts. This is a 3% increase in power as compared to the Savonius Turbine. (Figure 10), (Figure 11) and (Figure 12) show the voltage and current outputs.

Using Math-lab block signal builder as shown in (Figure 13) below, the current speed is changed and stepped from 0.56 to 1 m/s and generator power for both simulations remain without any changes and fluctuations. These fluctuations are absorbed by the accumulator.

The results show that the Low Speed VACT can be integrated with a synchronous generator by means of HTS. In addition, the HTS can be a means of transferring power and having more flexibility than a mechanical and electrical (direct drive) system. Moreover the efficiency of an HTS is dependent on several parameters including volumetric flow rate, rotational speed and torque on the pump shaft, and the pressure difference across the inlet and outlet of the hydraulic pump and motor. Through dynamic performance simulation of the system, an enhanced understanding of the HTS through simulation was gained that lead to an efficient hydraulic energy transmission system for low speed VACT in this case a Savonius rotor.

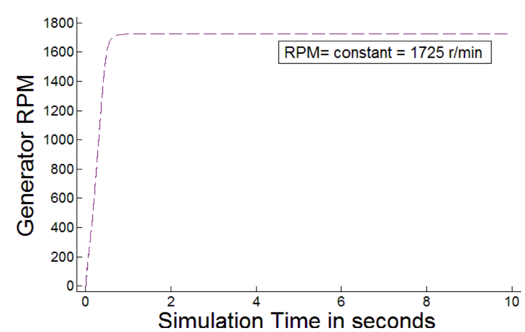


Figure 8 Generator RPM forSR-VACT system

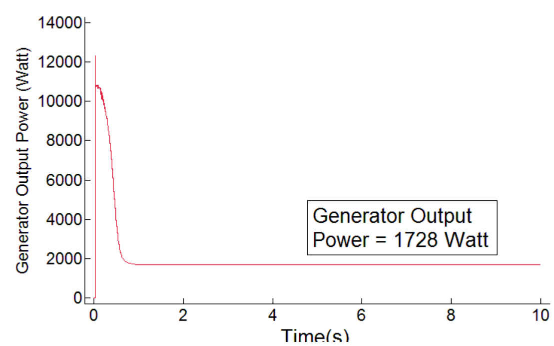


Figure 9 Generator Power SR-VACT output

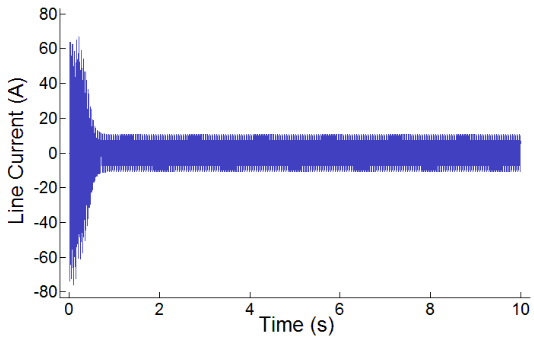


Figure 10 Generator line current

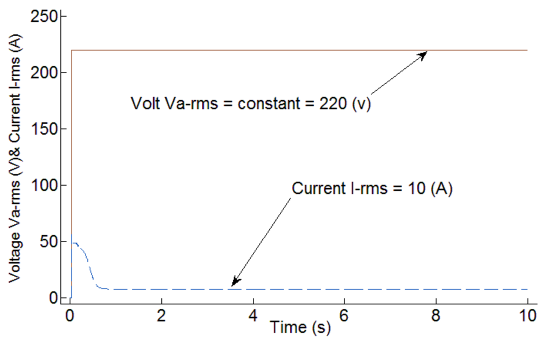


Figure 11 Generator terminal current and voltage

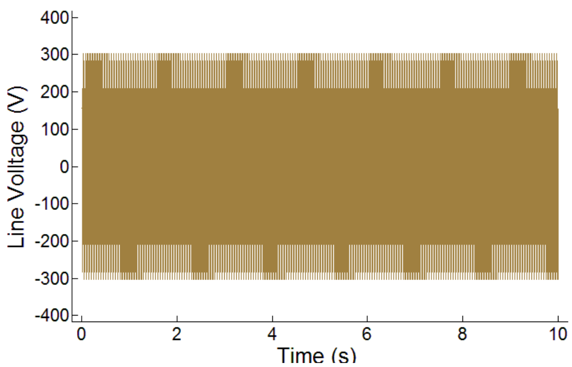


Figure 12 Generator line voltage

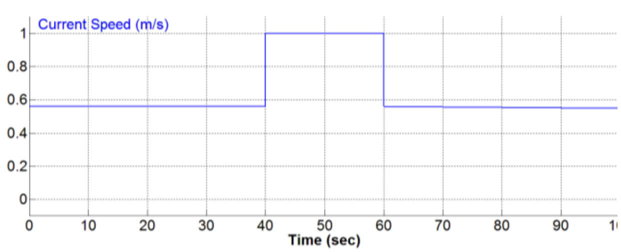


Figure 13 Current speed steps 0.56 to 1 m/s

■5.0 CONCLUSION

- The time domain dynamic performance simulation program for low speed marine current turbine with HTS has been developed.
- Electricity generation from low speed current with high torque is possible with HTS and has acceptable performance under constant and variable current speed conditions.
- A gearless hydraulic marine current energy transfer system that utilizes the hydraulic power transmission principles to harvest the energy from current flow is demonstrated in this paper using two variations of VACT. The gearless marine current power transfer technology has the potential to reduce the cost of operation, increasing the efficiency and the reliability of current power generation.
- The simulation program developed in this paper can be upgraded for further analysis in dynamics and control. For future work, a small prototype of the turbine can be built to validate the results of the simulations.

Acknowledgement

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