

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

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ABSTRACT

For Malaysia, 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, moreover the reserves of fossil fuels are being depleted and there is no accurate way to determine how much 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 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 using 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 Turbines, hydraulic transmissions, Simulink, Time domain simulation

NOMENCLATURE

A_s	Turbine swept area (m^2)
C_p	Performance coefficient
T	Torque (Nm)
Q	Flowrate (m^3/s)
P	Pressure (Pa)
D_p	Rotor Diameter, (m)
d	Paddle Diameter, (m)
r	arm, (m)
H	Rotor Height, (m)

P_p	PeakPower (Watt)
n	Rotation rate (RPM - Revolutions per minute)
U_∞	Current velocity (m/s)
ω	Angular velocity (rad)
λ	Tip speed ratio -TSR
ρ	water density (Kg/m^3)

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 forms of these 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 as stated in [3]. Many studies and researches are 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. In other hand, the vertical-axis turbines 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 of the vertical-axis turbine types is a conventional Savonius turbine which has good potentials and suitable for the Malaysia's waters requirement; low speed current and shallow water depth [4, 5]. But this turbine has a main drawback which is low tip speed ratio TSR (λ) and difficult to integrate it with a generator.

Recently, large wind turbines are using speed-increasing gearboxes to connect the high speed RPMs of generator to the slow motion rotors. However, these gearboxes are heavy and got a lot of mechanical problems. Also their maintenance work and replacement process is costly and very expensive. Other wind/marine turbines use direct drive low-speed generators which is connected direct to the generator. But these machines are expensive and very heavy even they are efficient and reliable. In another hand they need full-power electronic frequency and voltage converters to condition their power to

supply the grid to avoid the network instability. Convictional hydraulic transmission systems have long been considered for wind turbines and to make them attractive some companies and researchers have developed new high 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 best 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.
- A save and reliable operation.
- Good damping characteristics

For Malaysian sea which has low current speed and shallow depth, 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 low tip speed ratio TSR (λ) and difficult to integrate it with a generator. So, this paper presents a dynamic performance simulation of matching the Low Speed Vertical Axis Marine Current Turbine with synchronic generator using the hydraulic transmission system.

1.0 HYDRAULIC TRANSMISSIONS SYSTEM

Currently power transmission systems used are heavy with high cost of components moreover the Concept of the energy transfer system experiences dynamic loads and requires high maintenance, hence using hydraulic power transmission is the solution. Moreover the hydraulic transmission has a steeples gear ratio which enables the rotor to change speed independent of the generator. To illustrate that, a functional principal sketch of the hydraulic drive train system for current turbine is shown in fig.1.

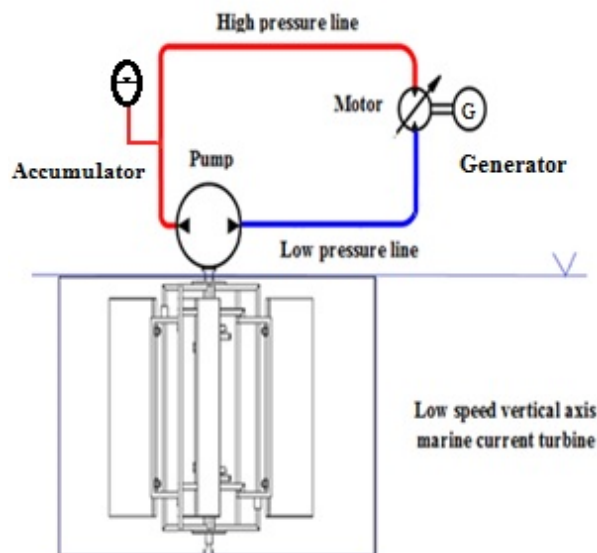


Figure1: A functional principal sketch of the system.

Concept of the Energy Transfer System

Recently, there are many projects under different countries such as Scotland, Norway, USA, Germany and Netherlands stated in [6] and Japan are developed and adopted this technology. In all of 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 the figure 2.

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.

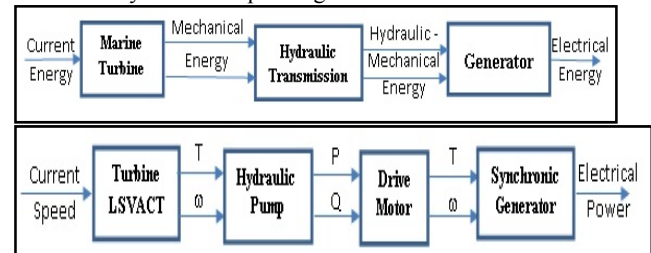


Figure 2. Concept of energy transfer

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

A hydrostatic transmission for wind turbines which offers good characteristics in controlling rotor RPM and damping torque impulses becomes apparent due to the overall efficiency of the system which was reached to 86% and its development is presented in the reference [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 the energy from more wind turbines [8].

In reference [9] reported that solution to overcome the uncertainties with off-the-shelf high pressure oil pumps and motors for hydraulic transfer system such as low efficiency to combine power from different sources and the type of hydraulic machine described in his paper which is the design of the variable-displacement machine [9]. Efficiency of the hydraulic machine, variable hydraulic pump and the variable hydraulic motor are function of pressure, rotating speed, density dynamic viscosity of the fluid and control angle as stated in [8, 10]. Also the optimized control comparing with traditional control (control the hydraulic machines in sequence) is saving up to 1.5 KW for his HTS size used in simulations and found that the best accessible improvements are at low torques (low loads). But, the traditional control still operating well on most working points [10]. A continuously variable transmission (CVT) is required to capture the wind marine energy more efficiently. This system in the form of a hydrostatic transmission (HST) can be a viable solution for a mid-sized wind turbine. A hydrostatic transmission allows to use a synchronous generator, hence the generator speed is decoupled from the rotor speed [11].

Using the technology based on Digital DisplacementTM machine for hydraulic transmission system maintains the generator to operate at the constant RPM even a tidal current turbine operates at variable rotor speeds. So, the generator power output remains uniform and unaffected until the system does not exceed the rated capacity, besides the generator does not show any fluctuation even the incoming power from the pump to the drive motor varies, due to the absorptions of the fluctuations by the accumulator [12].

Advantages of the Marine Turbine System with the Hydraulic Transmission

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/low maintenance

2.0 THE SYSTEM USED IN THIS SIMULATION

The principal particular of the Low Speed VAMCT:

This turbine is based on the full scale prototype of the conventional Savonius turbine with a rotor height 15 m height which is suitable for the Malaysia's waters requirement; low speed current and 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 scaled up to obtain prototype estimated parameters [13]. The main particular of the Savonius prototype specifications and estimated parameters will be used for marine current application and its model are presented in the following table.1 below. The current velocity of the prototype is 0.56 m/s and it is regarding the actual averaged current speed in the location of the research [15].

Table 1: Prototype and model specifications

No	Description	Model	Prototype VAMCT
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

Simply in this simulation, the performance characteristic of the Low Speed VAMCT can be quantified by a generic performance coefficient curve or by using the lock-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

$$C_p = \text{Shaft mechanical power avail.} / 0.5 \rho A U_\infty^3 \quad (1)$$

Where ρ is the water density, A- the turbine swept area, and U_∞ 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 shows the power coefficient C_p curve used for this study from

experimental results done by [13]. The curve can be defined by a fifth-order polynomial as shown below:

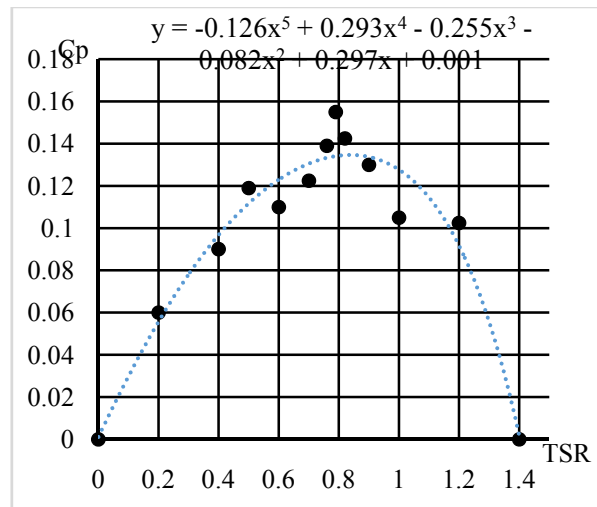


Figure3: Power coefficient (C_p) Vs TSR (λ) curve

The principal particular of modified LS-VAMCT:

This modified turbine as shown in figure 4 a new novel concept of vertical axis water current turbine based on modified Savonius rotor proposed by [17] called self-rotating vertical axis current turbine SR-VACT.

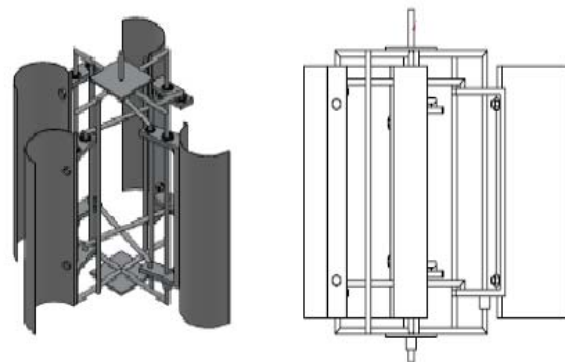


Figure 4: Representation of SR-VACT

In this design a self-movement or self-rotating four blades technique is applied for increasing the hydrodynamic pressure loads and at the same time, to decrease the hydrodynamic resistance and drag forces which leads to enhance performance and efficiency of this type of turbine. Table 2 below illustrates the main estimated parameters of modified design.

Table 2: Prototype and model specifications

No	Description	VAMCT	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 shows the torque coefficient C_m curve used for this study from simulation results done by [17]. The curve can be defined by a second-order polynomial as shown:

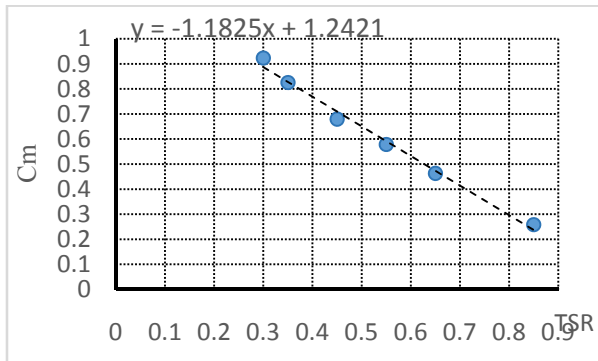


Figure 5: Torque coefficient (C_m) Vs TSR (λ) curve

The principal particular of the Hydraulic Transmission System (HTS)

Marine Current Turbine is driving a hydraulic system based upon oil using axial displacement pumping fluid around the system to drive a hydraulic motor, which is then coupled to a conventional induction machine. Accumulators provide energy storage to compensate for the variations in power [12]. The efficiency of a HTS is dependent on several parameters including volumetric flow rate, rotational speed and torque at 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 used have variable displacement capabilities [12]. There is also a digital displacement technology is developed specifically for avoiding the higher losses in the transmission when the input power from the turbine is lower as stated in [12].

In this simulation study, Simulink Hydraulics library is used to model a hydraulic system and to describe the physical phenomena of it. The conceptive 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.

The specifications of the generator

The main electrical characteristics of the generator are presented in the following table 4.

To simulate this generator in this study a Simulink electric library is used to model a synchronic generator and the load on it.

Table 4: The specifications of the synchronic generator

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

3.0 Dynamic Performance simulation

Mat-lab simulation program is developed to simulate LS-VAMCT with the hydraulic transmission system. 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 variable-displacement hydraulic motor. This drive motor will provide and maintain constant RPM to the loaded synchronic generator which is integrated to 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

Simulation Results for low Speed VAMCT

The current speed used in this simulation is 0.56 m/s and that based on the annual average current velocity of Malaysian sea as reported in [15]. The dynamic simulation results as illustrated in table 5 and in figures 7 below show that the RPM remains constant and total power obtained from a synchronic generator is 1675(Watts).

Table 5: VAMCT simulation results

Parameter	Value
Hydraulic Pump	
Pump Displacement (m ³ /rad)	9.1543x10 ⁻⁵
Torque at shaft (N.m)	3614
Power rating at 3.75 r/min (KW)	1.445
Hydraulic Motor	
Motor Displacement (m ³ /rad)	1.123x10 ⁻⁷
Power rating at 1500 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 %

Simulation Results for modified LS-VAMCT

The same current speed used in this simulation which is 0.56 m/s and dynamic simulation results are shown in table 5 and in figures 6, 7 below show that the velocity remains constant and

total power obtained from a synchronic generator is 1728(Watts).

Table 6: LS-VAMCT simulation results

Parameter	Value
Hydraulic Pump	
Pump Displacement (m ³ /rad)	0.1375x10 ⁻³
Torque at shaft (N.m)	4914
Power rating at 1.57 r/min (KW)	1.6142
Hydraulic Motor	
Motor Displacement (m ³ /rad)	1.904x10 ⁻⁷
Power rating at 1500 r/min (KW)	2.227
Torque at generator shaft (N.m)	12.33
Hydraulic transmission System with the Generator	
Generator Power P _G (Kw)	1728
Total Efficiency	~ 85 %

Using Math-lab block signal builder as shown if figure8 below the current speed is changed and stepped from 0.56 to 1 m/s and generator power for both simulations remain without changes and any fluctuations. These fluctuations are absorbed by the accumulator.

As result, the LS-VACT has been integrated with synchronous generator. In addition, a hydraulic transmission system can transfer amounts of power and has more flexibility than a mechanical and electrical (direct drive) system. Moreover the efficiency of a HTS is dependent on several parameters including volumetric flow rate, rotational speed and torque at 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 vertical axis marine turbine in this case a Savonius rotor.

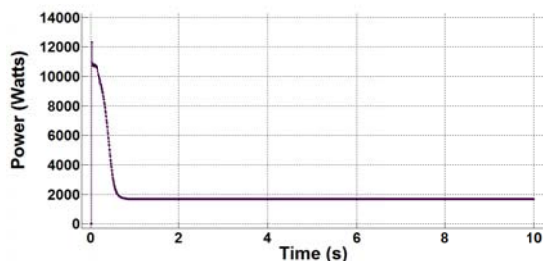


Figure 6: Generator Power RS-VACT

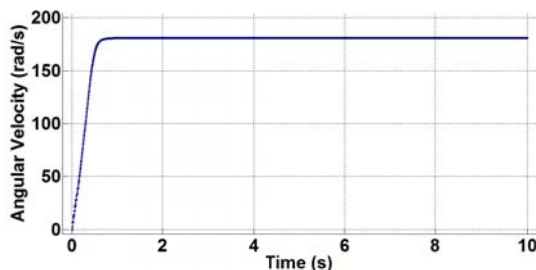


Figure 7: Generator angular velocity

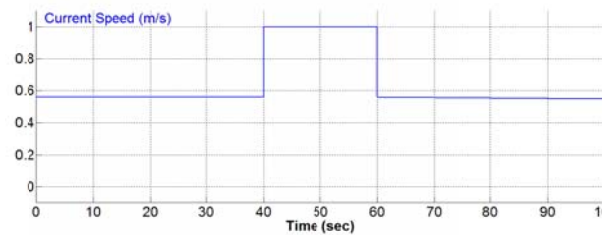


Figure 8: Current speed steps 0.56 to 1 m/s

5.0 CONCLUSION

The time domain dynamic performance simulation program for low speed marine current turbine with the hydraulic transmission has been developed.

Electricity generation from low speed current and high torque can be possible with hydraulics transmission and has decent performance under constant and variable current speed conditions.

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, increase the efficiency and the reliability of current power generation.

In the future, this simulation can be upgraded for the purpose of further analysis in dynamics and control. Moreover the Simulation is not supported by experimental results of the whole system, so for future work a small system prototype can be built and comparison between the results obtained from tests conducted and simulations can be demonstrated and validated.

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