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Sımulation of Solar Pump and Hydro Generation Standalone Power Supply

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Abstract

The simulation of solar pump and hydro power standalone system has been developed in this paper. Conceptually, as Standalone Power System (SPS) or known as the Remote Area Power Supply System (RAPS) defined as the off-grid power. In this paper, MATLAB SIMULINK is used as the simulation tool. The system is composed of two resources of renewable energy which are solar photo-voltaic arrays and micro hydro units. The energy that form from the solar panel been used to operate the water pump, which pumps the water to water tank and continuous with producing power by the hydro units. All the parameters are adapted from the published research papers.

Keywords: Standalone Power Supply; Solar Photovoltaic arrays; Micro hydro units; integrated renewable energy; MATLAB Simulink;

Introduction

Remote area needs cheap, reliable, energy saving and clean power. Thus, deployment of integrated renewable energy (IRE) system to a remote area increases the reliability. The combination of energy efficiency measures the consumed of renewable sources will save the electricity consumption and the issue of the high demand electricity [1].

Solar energy is the best option in this energy crisis as it is considered as a source of clean and inexhaustible energy. In the past five decades, the solar system has been widely studied and developed to transform it into power and investment in photovoltaic energy is rapidly increasing. Hybrid systems for electricity generation are usually more reliable and less expensive. The indication in the last couple of decayed for increasing interests in wind-PV-diesel hybrid power system for rural electrification shows its large potential market for the system. [2] Reported that the use of PV systems in Palestine is economically valuable with hybrid power. It was found that the generation of power in a small village in the northern part of the kingdom of Saudi Arabia concluded that while the price of diesel has a net gain of hybrid but when compared to other factors of diesel fuel for generators, solar hybrid power system is the most economical.

The Photovoltaic or PV cells can be connected electrically in series or in parallel circuits to generate the higher output voltages, output currents and the output power. The PV modules stand with the PV cell circuits is sealed to an environmentally protective laminate. Several of the tiny cells produce a module and an array is made up by a grouping of modules [3]. In the lower load demand electricity can obtain for single phase while in high load demand the three phases can obtain. Energy storage in battery bank can be used during the night or during the changes of weather that affected the system.

A micro hydro system converts the potential energy of water into electricity through the use of flowing water from the storage by pipelines. This water flow is referring to the size of the storage tank and the pipelines where the different size gives different potential of the flow rate that affected the capacity of output power. Different types of hydropower will produce different output power [4]. Typically, the hardness of water depends on the large or small scales. In turbine selection, the head of the power to operate the turbine need to be determined. A turbine consists of two principles of operation which are the reaction and the impulse. The reaction turbines can produce mechanical energy by converting the potential energy while the impulse turbines will convert the kinetic energy to mechanical energy. Synchronous generator is usually used with a controlled water valve that functioning to shut down the hydro system.

In this paper, MATLAB SIMULINK is used as the simulation tool [5]. The entire block diagram, debugging and testing of the power system is conducted in a simulation environment that enables to provide a safe virtual environment and dramatically reduce the software development time. Moreover, the error can be easily detected and then debugging can be done immediately. In addition, the simulated power system can be detected by referring to the graph or data from the output or the simulation result. The mathematical models are developed to calculate the various parameters of different components needed to produce a 67 kW of power output from which the most efficient components and sizes will be selected for the system. The parameters been used in simulation and verify by the graph.

System Model

The model used in this research is as shown in figure 1. This was implemented in Greece, Nigeria and Japan. Investigation for 67 kW systems suitable for remote area is performed by MATLAB SIMULINK.

The direct current (DC) voltage from PV array will be used for DC motor to pump the water to the tank. The head and cross-sectional of the tank are the input parameters. It will affect the output electric power due to the changing in flow rate of water. The flow rate out from water tank is used as speed reference of Hydraulic Turbine/Generator to produce the mechanical power. The excitation system is used for the input voltage reference to the field winding in the rotor of the synchronous generator. The mechanical power of the turbine is the second input to the generator to produce the electric power that can be supplied the loads. The parameters values of the overall system [6] as well as the calculated variables are given in the appendix.

Photovoltaic Model

There are basically three important characteristics of the PV which are open circuit voltage, short circuit current and maximum power point. There

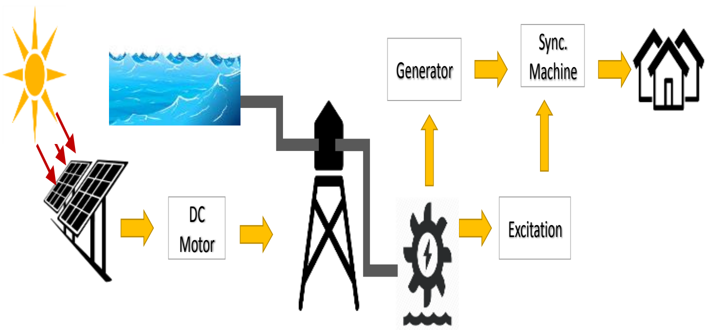

Figure 1: Sketch of solar pump and hydro power supply system.

are five equations that control the photovoltaic characteristics as follows:

Photo-current, $I_{ph} = \left[I_{sc} + k_i \cdot (T - 298) \cdot \frac{G}{1000}\right]$

Saturation current, $I_0 = I_{rs} \cdot \left(\frac{T}{T_n}\right)^3 \cdot \exp\left[\frac{q \cdot E_{go} \cdot \left(\frac{1}{T_n} - \frac{1}{T}\right)}{n \cdot K}\right]$

Reverse saturation current, $I_{rs} = \frac{I_{sc}}{e^{\left(\frac{q \cdot V_{oc}}{n \cdot N_s \cdot K \cdot T}\right)} - 1}$

Current through shunt resistor, $I_{sh} = \left(\frac{V + I \cdot R_s}{R_{sh}}\right)$

Output current, $I = I_{ph} - I_0 \cdot \left[\exp\left(\frac{q \cdot (V + I \cdot R_s)}{n \cdot K \cdot N_s \cdot T}\right) - 1\right] - I_{sh}$

Calculated values are given in table 1.

I_{ph}	photo-current (A)	I_{ph}
I_{sc}	short circuit current (A)	I_{sc}
k_i	short-circuit current of cell at 25°C and 1000 W/m²	.0032
T	operating temperature (K)	T
T_n	nominal temperature (K)	298
G	solar irradiation (W/m²)	G
q	electron charge (C)	1.6×10^{-19}
V_{oc}	open circuit voltage (V)	V_{oc}
n	the ideality factor of the diode	1.3
K	Boltzmann's constant (J/K)	1.38×10^{-23}
E_{g0}	band gap energy of the semiconductor (eV)	1.1
N_s	number of cells connected in series	N_s
N_p	number of PV modules connected in parallel	N_p
R_s	series resistance (Ω);	.221
R_{sh}	shunt resistance (Ω);	415.405
V_t	diode thermal voltage (V).	-----

Table 1: Constants and variables for photovoltaic characteristics

The MATLAB SIMULINK blocks for PV characteristics are given in figures 2 and 3. There are two inputs and two outputs that been used in PV block.

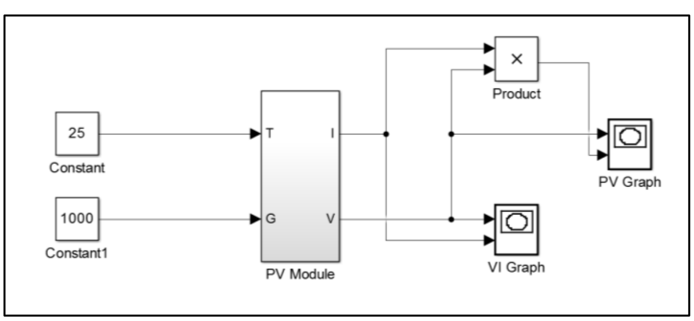

Figure 2: Photovoltaic model

Every data of input will be affected by the outputs that are shown in V-I and P-V graphs of figures 4 and 5, respectively.

The temperature that needs to be used must be undergoing conversion to Kelvin. In the PV array module, has the conversion for every input temperature in Celsius, where 0°C = 273.15°K.

The open circuit voltage is observed at zero current and the short circuit current is observed at zero voltage. The maximum power is the integration of V-I or the area under the V-I curve.

Head Tank Calculations

In micro hydro system, there are basically to determine the required head tank, flow rate of fluid, size of pipe, area of tank, velocity and power

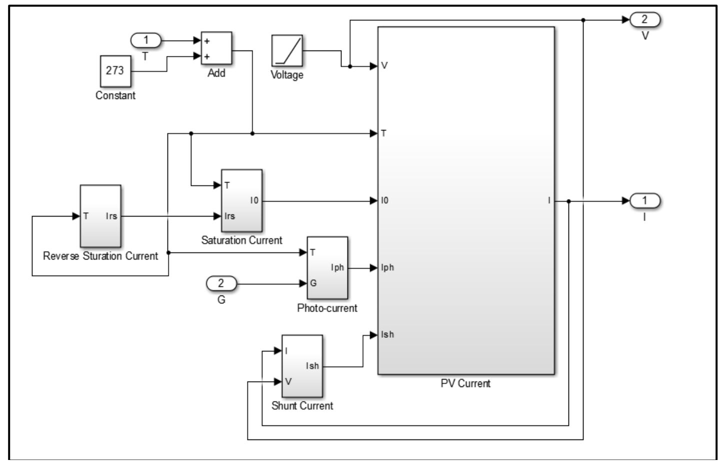

Figure 3: Subsystem under PV

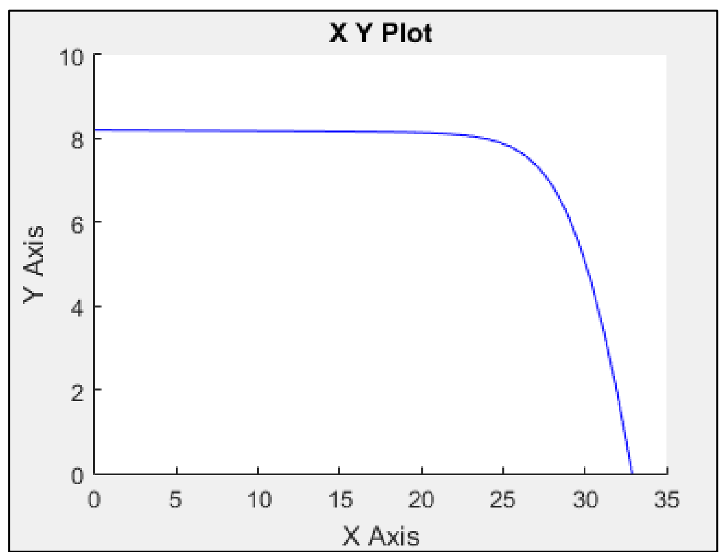

Figure 4: V-I Graph

input to turbine that produces speed and torque to give the final power output

By using the constants $g = 9.81\text{ms}^{-2}$, $\rho = 1000\text{kgm}^{-3}$, $H = 8\text{m}$ and the assumed values of the tank volume, then mass, potential energy, kinetic energy, velocity and flow rate can be calculated.

Pipe diameter $D_{pipe} = 0.294\text{m}$, Tank diameter $D_{tank} = 4\text{m}$,

Tenk height $h_{tank} = 3\text{m}$

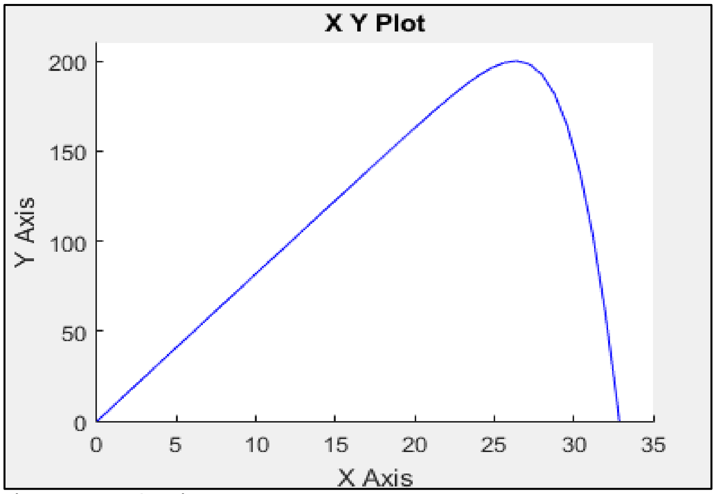

Figure 5: P-V Graph

Calculate area of tank: $\text{Area tank} = \pi r^2 = \pi(2)^2 = 12.566\ \text{m}^2$

Tank volume: $\text{Vol}_{\text{tank}} = A \times h_{\text{tank}} = 12.566\ (3) = 37.698\ \text{m}^3$

$\text{In litres} = 37.698 \times 1000 = 37698\ \text{litres}$

Calculate mass: $\text{Mass} = \rho \times \text{Vol}_{\text{tank}} = 1000(37.698) = 37698\ \text{kg}$

Potential Energy: $\text{PE} = m \times g \times H = 37698(9.81)(8) = 2958.54\ \text{kJ}$

Velocity: $v = \sqrt{2gH} = \sqrt{2(9.81)(8)} = 12.5284\ \text{ms}^{-1}$

Kinetic Energy: $\text{KE} = \frac{1}{2}mv^2 = \frac{1}{2}(37698)(12.5284)^2 = 2958.55\ \text{kJ}$

By using Transverse Internal Area formula, the area of pipe been calculated. $A_{pipe} = 0.7854D^2 = 0{,}7854(0.294)^2 = 0.067886m^2$

Flow rate: $Q = v \times A_{pipe} = 12.5284(0.067886) = 0.85050m^3s^{-1}$

Fluid flow velocity: $v_{fluid} = \frac{1.274Q}{D^2{}_{pipe}} = \frac{1.274(0.85050)}{(0.294)^2} = 12.5357\ ms^{-1}$

Fluid flow rate: $Q_{fluid} = v_{fluid} \times A_{pipe} = 12.5284(0.067886) = 0.8510m^3s^{-1}$

Power developed into the turbine:
$P_{tur} = \rho \times g \times Q \times H = (1000)(9.81)(0.8510)(8) = 66.79kW$

Pump Power Calculations

The pump power is calculated by the overhead holding tank size and balance the amount of water flowing into the turbine.

Pipe diameter $D_{\text{pipe}} = 0.294\ \text{m} = 294\ \text{mm}$,
Material constant $\varepsilon = 0.046$ for commercial steel pipe,
Friction ratio $r = \frac{0.046}{294} = 0.000156$,
Thus, referring to moody diagram the friction factor f = 0.02
Tank dimensions $L_1 = 4.5\text{m}, L_2 = 20.5\text{m}, z_1 = 4\ \text{m}, z_2 = 12\text{m}$
Substitute all values in equation to get the velocity, v

$$f\frac{\rho v^2}{2}\left(\frac{l2-l1}{D}\right) - z_2(1+\rho g) + z_1(1-\rho g) = 0,$$

$$0.02\frac{(1000)v^2}{2}\left(\frac{20.5-4.5}{0.294}\right) - 12(1+(1000)(9.81)) + 4(1-(1000)(9.81)) = 0,$$

Velocity $v = 12\ \text{ms}^{-1}$
Area $A = 0.7854D^2$
Flow rate $Q = vA = 12 \times 0.7854 \times 0.294^2 = 0.8146$

Turbine power input $P_{\text{tur}} = (1000)(9.81)(0.8146)(12) = 95.89\ \text{kW}$

The efficiency been calculated as shown in equation below,
$$\eta = \frac{\text{Required power output}}{\text{Power input to turbine}} = \frac{66.79}{95.89} = 0.70 = 70\%.$$

Primarily, the main focus is to distribute a 70% of energy efficiency with 67 kW of power output requiring the selection of pump efficiency, pump power input and tank power output to turbine efficiency.

DC Motor Model

The input voltage has been applied to the motor's armature and the output is the rotational speed of the shaft. The rotor and shaft are assumed to be rigid with the friction torque is proportional to shaft angular velocity. The model is given in figures 6 and 7.

Physical parameters of DC motor system:
Moment of inertia of the rotor, J = 0.01 kg.m^2

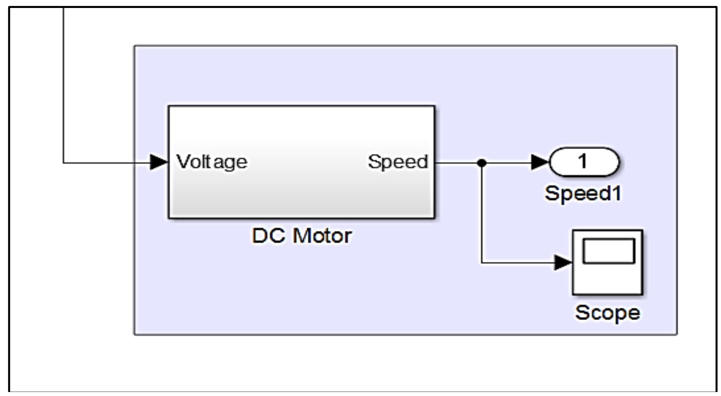

Figure 6: DC motor model

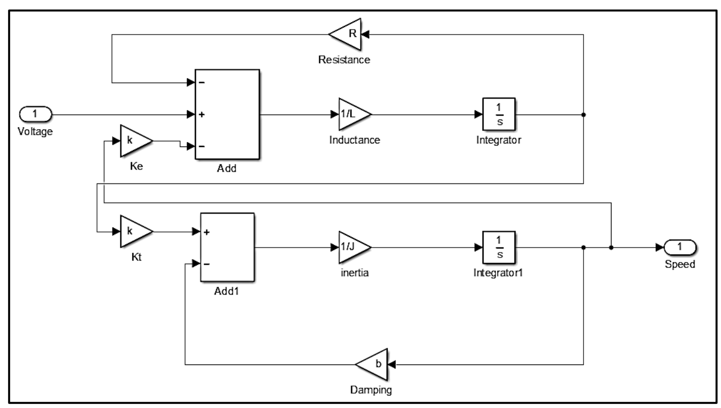

Figure 7: Subsystem under DC motor model

Motor viscous friction constant, b	= 0.1 N.m.s
Electromotive force constant, K_e	= 0.01 V/rad/sec
Motor torque constant, K_t	= 0.01 N.m/Amp
Electric resistance, R	= 1 Ohm
Electric inductance, L	= 0.03 H

Figure 8 shows the speed graph is raising to a rated value of 800 rpm at 0.4s. The efficiency of DC motor can be determined from the pump power to the PV power of figure 5. Pump power can be determined from torque and speed of the pump. The rpm axis of figure 8 is multiplied by 1000.

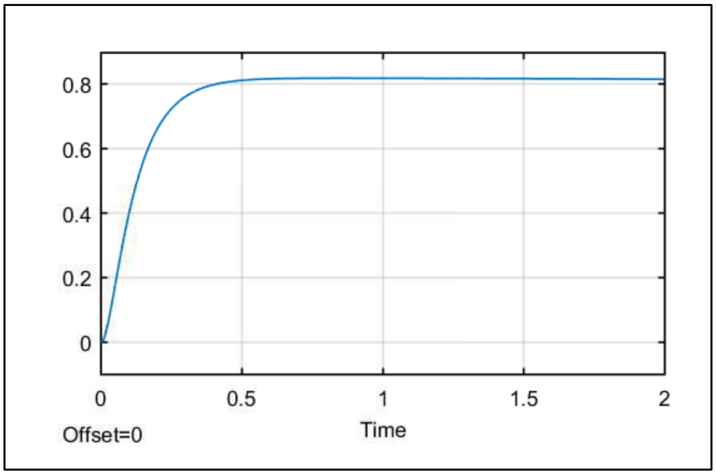

Figure 8: Graph of speed, rpm against time in sec.

Water Tank Model

The model is given in figure 9 and 10.

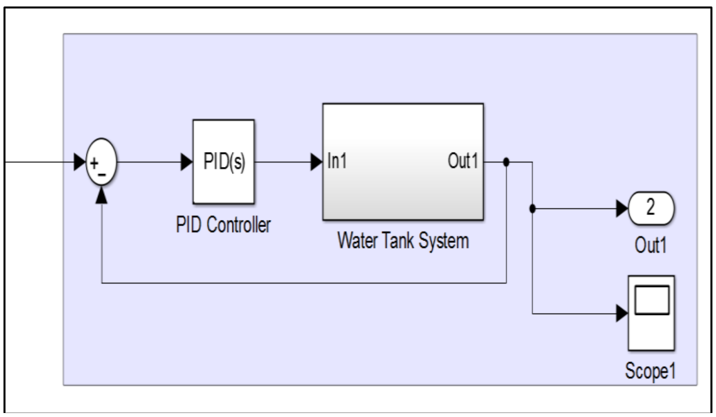

Figure 9: Water tank model

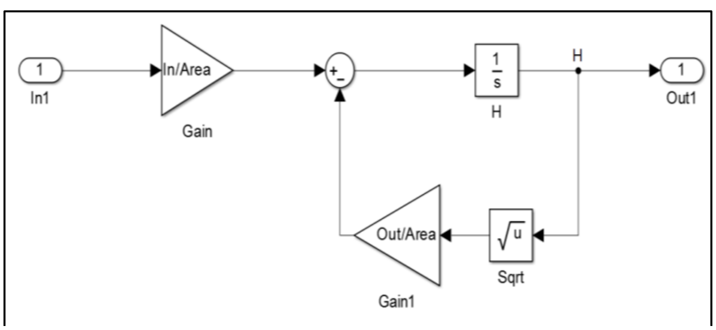

Figure 10: Subsystem under water tank

The motor pumps the water up to the top of the tank and the water leave the tank from its bottom. The flow rate is proportional to the square root of the height of the water inside the tank. Figure 11 shows that within 2 second the tank storage is fulfilled with water in 2 meter height.

Micro Hydro Model

This model has three foremost parts in the simulation which are synchronous machine (SM), hydraulic turbine and governor (HTG), and excitation system (ES).

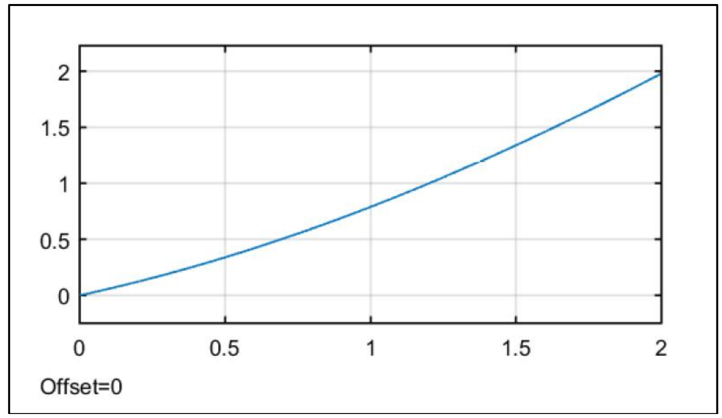

Figure 11: Graph of height of water in water tank against time in sec

Figure 12 shows the SIMULINK model of the Hydraulic Turbine and Governor (HTG) that can be found in the Continuous and Discrete libraries of powerlib models. The HTG block implements a nonlinear hydraulic turbine model, a PID governor system, and a servomotor. The static gain of the governor is equal to the inverse of the permanent droop in the feedback loop. The PID regulator has a proportional gain, an integral gain, and a derivative gain. The high-frequency gain of the PID is limited by a first-order low-pass filter with time constant.

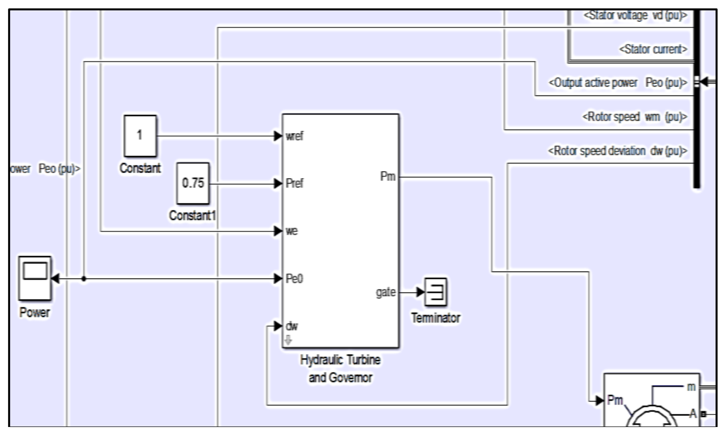

Figure 12: Hydraulic turbine and governor model

The hydraulic turbine is modelled by the nonlinear system. Droop reference specifies the input of the feedback loop either gate position or electrical power deviation. Pm0 indicate the initial mechanical power in per unit at the machine's shaft. This value is automatically updated by the load flow utility of the Powergui block. While the servomotor gate model is in second-order system. The gain and time constant of the first-order system represent the servomotor.

Excitation system (ES) and Synchronous Machine Models

The SIMULINK model of the Excitation system as shown in Figure 13 can be found in the Continuous and Discrete libraries of powerlib models. This excitation system block is used to regulate the terminal voltage of synchronous machine. The basic elements that form the Excitation system block are the voltage regulator and the exciter. The exciter is represented by the following transfer function between the exciter voltage and the regulator's output.

The electrical part of the synchronous machine model is represented

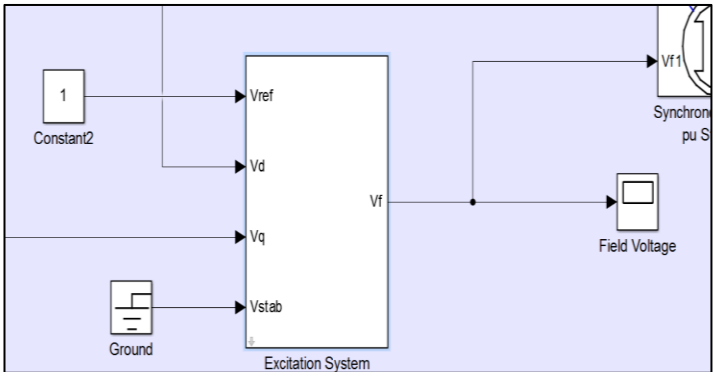

Figure 13: Excitation system model

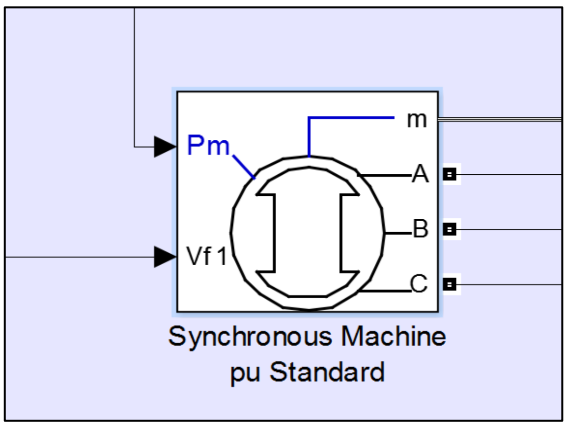

Figure 14: Synchronous machine model

by a sixth-order state-space model and the mechanical part is the same as in the Synchronous Machine block as shown in Figure 14.

The model takes into account the dynamics of the stator, field, and damper windings. The equivalent circuit of the model is represented in the rotor reference frame. All rotor parameters and electrical quantities are viewed from the stator. For stability analysis, it is assumed that the mutual inductances between the armature, damper, and field on direct-axis windings are identical.

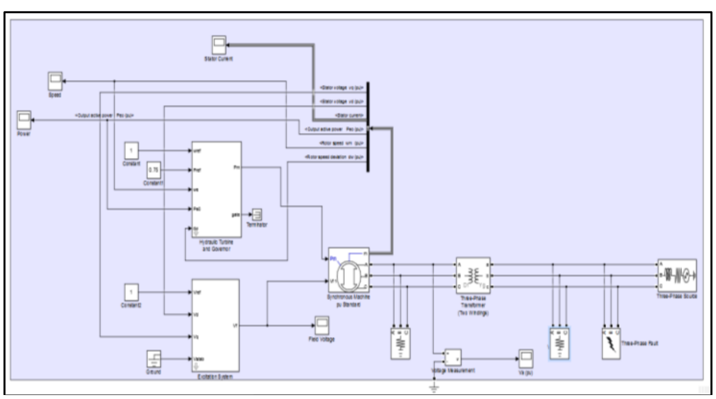
Figure 15: Micro hydro system model

The micro-hydro model is shown in figure 15, and the simulation results of the generator current and output power are given in figures 16, 17. From the result displayed in Figure 17, it shows that the power output is 0.667 pu. Since the base power is 100 kVA, the actual output active power is 66.7 kW.

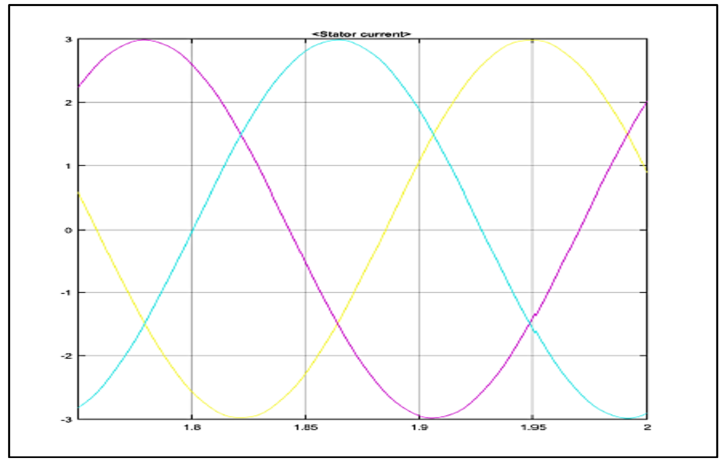

Figure 16: Graph of stator current (pu) against time

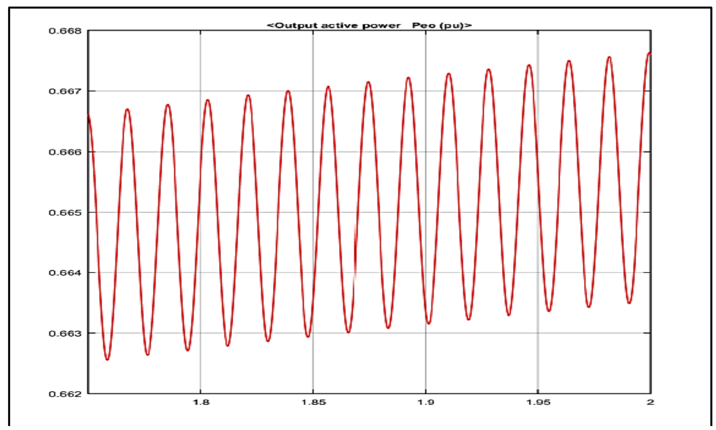

Figure 17: Output active power (pu)

Conclusions

The developing of 67 kW of distributive renewable energy system with 70% energy efficiency is achieved. MATLAB SIMULINK models of the system parts are developed and calculations of power and efficiency are satisfied. Normally, micro hydro system is better than solar photovoltaic system because it has higher efficiency than solar system. Besides, the electrical energy can be produced as long as the water storage is still sufficient with water sources. Every parameters that been selected will affected the output of power generation for both system. In future, when designing, the connections of all components for the system will be needed for verifications and analysis to ensure the required standards for the performance and efficiency of the systems.

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Appendix

In the simulation of solar pump and hydro generation system, the parameters of input and output been selected from previous research publications and mathematical modelling as shown table 2.

Irradiation (w/m^2)	1000
Cell Temperature (Celsius)	25
Tank Radius (m)	2
Net head (m)	8
Height of Tank (m)	3
Tank Area (m^2)	12.566
Tank Volume (litters)	37698
Mass (kg)	37698
Potential Energy (kJ)	2958.539
Fluid Velocity (ms^{-1})	12.5284
Kinetic Energy (kJ)	2958.539
Diameter of Pipe (m)	0.294
Pipe Area (m^2)	0.067886
Flow Rate, Q (m^3s^{-1})	0.85050
Fluid Flow Rate, Q_{fluid} (m^3s^{-1})	0.8510
Power into Turbine (kW)	66.79

Table 2: Parameters value for input and output of simulation