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Wind Energy Conversion System for Remote Areas

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ABSTRACT: *The lack of electricity observed over the world, particularly in some parts of Ghana, and pollution due to the exploitation of fossil energy are some motivations of renewable energy development. Properly chosen renewable power sources will considerably reduce the need for fossil fuel, leading to an increase in the sustainability of the power supply. Among the renewable energy, wind energy is well suited today as a solution to the requirements of renewable electricity generation. Standalone wind generation system offers a feasible solution to distributed power generation for isolated localities where utility grids are not available. The aim of this work is to demonstrate the generation of electricity for remote areas using wind energy. The choice of a variable speed wind turbine is mainly based on the ability of the variable speed wind turbine to extract wind energy optimally by deploying doubly-fed induction generator (DFIG) and permanent magnet synchronous generator (PMSG). The entire wind energy conversion system is described along with comprehensive simulation results that help to discover the feasibility of the system. A software simulation model is developed in MATLAB Simulink.*

Key Words: *Permanent Magnet Synchronous Generator (PMSG), Doubly-Fed Induction Generator (DFIG), Wind Energy Conversion System (WECS), Wind Turbine Generators (WTGs)*

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I. Introduction

Energy is an indispensable driver for socio-economic growth and development. However, due to climate change, the fuel sources used for electricity generation are a global concern. The rise in electricity consumption, the depletion of fossil fuels, and greenhouse gas (GHG) emissions have sparked investments in renewable energy technologies for electricity generation [1]. Global warming and air pollution have been identified as some of the key causes of climate change; and CO2 emissions have been generally considered in literature as a significant contributor to these problems [2]. [3] reported that CO2. emissions are a key contributing factor to the high emissions of green-house gases (GHG) globally. The report further emphasized that 76.7% of GHG emissions emanate from emissions of CO2 mainly coming from developing countries such as Ghana in the effort to accelerate economic growth and increase income levels with little or no recourse to environmental provisions.

Beginning 2009, fossil fuel consumption has taken the first position in Ghana's energy consumption mix and continue to rise whiles the consumption renewable energy is on the decline [4]. CO2 emissions in Ghana increased by close to 100% from 12.2MtCO2e to 23.9MtCO2e between 2000 and 2010 [5].

Several attempts have been made through international conventions and intergovernmental agreements to minimize the destructive effects of global warming by advocating for the re-

duction of global emissions by both developed and developing countries. Notable among these international environmental agreements are the Paris convention [6,7] and the Kyoto protocol which were adopted in 1997 under the United Nations Framework Convention on Climate Change (UNFCCC) with the underpinning aim of reducing GHG concentration in the atmosphere in order to minimize the pace of climate change [8]. Ghana is a signatory to the climate change convention [9] and has also ratified the Kyoto Protocol aimed at minimizing climate change and promoting sustainable energy development.

Renewable energy is a promising solution for mitigating global GHG emissions and climate change [10,11]. Most of these wind turbines were installed in developed countries, China and the United States had the largest wind power capacity in the world.

At the beginning of modern industrialization, the use of the fluctuating wind energy resource was substituted by fossil fuel-fired engines or the electrical grid, which provided a more consistent power source [12]. There are several electromechanical devices that can capture this energy and convert it into electrical energy. These devices can be vertical axis or horizontal axis, fixed speed or variable speed. The evolution of power electronics and electrical machines such as synchronous and asynchronous machines, improves the efficiency of wind energy conversion systems. Wind energy conversion system (WECS) consists of three major aspects; aerodynamic, mechanical and electrical [13,14]. The main components which intervene in the electrical power production of WECS in remote areas or stand-alone WECS are: wind turbine generators (WTGs), power electronic converters (PECs) and electrical energy storage (EES). In the past, the majority of wind turbines installed were at fixed speed. These wind turbines nevertheless have many drawbacks: low energy efficiency due to the high dependence of the very fluctuating wind speed and a short life span due to the major stresses on their structure. Variable speed wind turbines have been introduced to provide solutions to these problems. Power fluctuations can be mitigated with a device that allows variable rotational speeds and therefore transforms kinetic energy of wind in large band of rotating speeds [15,16]. It has also been shown that control strategies can have a major effect on the operation of the wind turbine and the electrical system. The control method is an indispensable factor for any type of variable speed wind turbine.

Wind is emerging as one of the world's most promising source of renewable energy. Several studies have shown Ghana has wind speeds suitable for wind power generation. However, Ghana's current electricity generation mix does not have utility-scale wind power plants as part of its power supply. Given the rampant power outages in Ghana, the use of generators is on the increase. Also, the use of generators as a source of electric power proliferates in most rural/remote areas since electricity supply cannot reach majority of rural households or people in remote areas. The negative effect of generators on the environment as well as its obstruction to the global drive to achieve environmental sustainability through 'greening' and plastic circular economy model [16,17] cannot be underestimated. A recent study has established the energy consumption efficiency together with the environmental-friendly effect of an integrated roof coating with a solar PV system as a sustainable source of renewable energy [18]. There is therefore the need to explore wind energy as an alternative environmental-friendly and sustainable source of renewable energy in Ghana. Additionally, given the role of control techniques in the performance of wind turbines, there is the need to develop control strategies to enable wind turbine harness wind energy efficiently and use it to produce quality electrical power. This explains why the paper examines wind energy conversion systems to address the energy needs of remote areas. The paper contributes to knowledge by integrating the blade pitch angle. The value of the blade pitch angle is an inverse determinant of wind generated power [19] hence neglecting it as presented in [20, 21] does not give a complete dynamic representation of wind energy conversion. Thus, integrating the blade pitch angle aids to reflect its effect on the speed of the rotor and to simulate its relationship with wind power generated. Additionally, the paper makes contribution by providing insights on the comparative performances of the DFIG and PMSG. This simulation of comparative performances has not been covered in the literature. Therefore, the study does not only provide insights on the significance of wind energy in remote areas, but also recommends the appropriate wind energy generator to adopt.

II. METHODOLOGY

Design Concept

This section discusses the approach used in modelling of the Wind Energy Conversion System (WECS) for remote areas. It further explains the theory and design concept used based on the selection and specifications of the components.

The concept used in modelling the wind energy conversion system involved modelling the components based on mathematical equations that governed their principle of operation.

The system was designed to generate an AC power for loads in remote areas. The Fig. 1 shows a block diagram representation of the entire Wind Energy Conversion System.

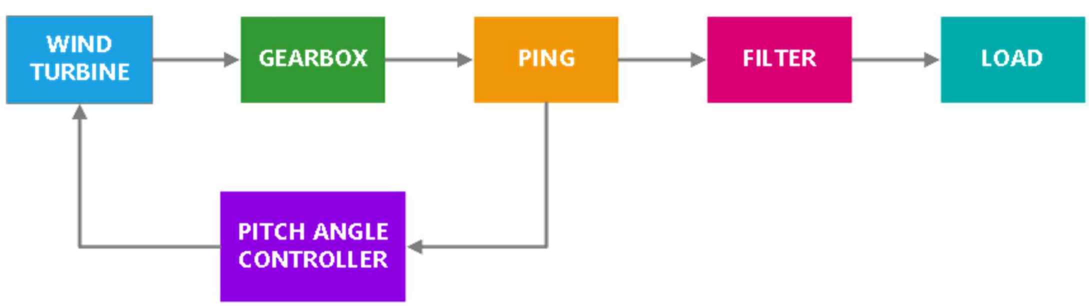

Fig. 1: Block diagram of Wind Energy Conversion System

The system harnesses the kinetic energy of the wind to generate electricity for remote areas. The WECS is made up of a horizontal axis wind turbine, gearbox or drive train, a Permanent Magnet Synchronous Generator (PMSG), a filter and a load. A pitch angle controller is present to control the pitch angle of the turbine blades. The PMSG was chosen for this system by virtue of the fact that it does not need any external source of excitation to produce a magnetic flux. The permanent magnets serve as the source of magnetic flux needed to generate electricity. This makes it suitable for remote areas where there is no connection to the national grid. The wind turbine converts the kinetic energy of the wind into rotational mechanical energy which is used to provide rotation of the PMSG's rotor to generate electrical energy. The generated AC power is supplied to an AC load. In order to get the rotation of the wind turbine's shaft to be the same as the rpm of the PMSG's rotor, a gearbox or drive train is used. Since the AC generated may contain ripples and other unwanted components, a filter is provided to give a smooth sinusoidal AC power for the loads.

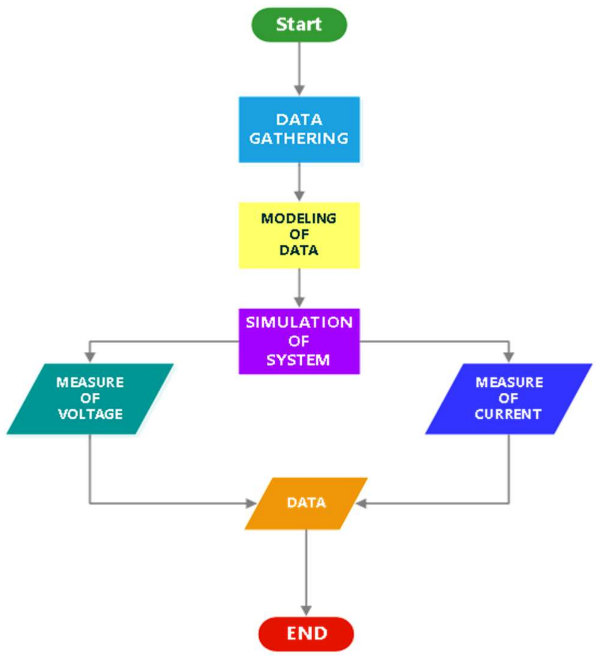

Fig. 2: Flow chart of Wind Energy Conversion System

As shown in Fig. 2, various data on factors that affect the performance of a wind turbine were collected. Such data may include the wind pattern of the area in question, the wind speed, air density of the area, the pitch angle of the wind turbine blades, tip speed ratio of the turbine blades, among others. This data is then used to determine the mechanical output of the wind turbine. The values of these factors are then used to design a model of the wind turbine in Matlab Simulink. Other components of the wind energy conversion system such as the pitch angle controller and the 2-Mass Drive Train were also modelled. After modelling the system in the Matlab Simulink workspace, the system was simulated or run using a run time of 2 seconds. The system was able to determine the output AC voltage and its corresponding current. The resultant power output was also determined by the system

Software used

The system was modelled using blocks from MATLAB Simulink library. The various blocks were picked from the library's subsections Simscape, sinks, continuous, Maths among others of the MATLAB.

Modelling of Parts of The Wind Energy Conversion System

The system is modelled using blocks from MATLAB Simulink library. The various blocks used in modelling each of the parts of the wind energy conversion system are discussed below.

Two Mass Drive Train

Fig. 3 depicts a Simulink model of the two-mass drive train. The mechanical components such as wind turbine rotates at low rpm whereas the rotor rotates at high rpm. The gear box is used to convert the low speed of wind turbine to the required speed of generator turbine. The purpose of using gearbox in the wind energy conversion system is that different mechanical parts need to run at different speeds for efficiency. Some parts of the generating system run fairly faster than other mechanical parts since the generated voltage is a function of rate of change of magnetic fields. In contrast to that the turbine blades rotate slower than other mechanical parts since they will fail to take centrifugal stress. Hence gear box is essential to speed up the slow turbine rotations to the faster generator rotations. The mathematical model for two mass drive train is given by the equations below:

$$2H\frac{d\omega_t}{dt} = T_m - T_s \quad (1)$$

$$T_s = K_{ss}\theta_{sta} + D_t\frac{\theta_{sta}}{dt} \quad (2)$$

Where H is the inertia constant of the triangle, θ_{sta} is the shaft twist angle, ω_t is the angular speed of the wind turbine, ωr is the rotor speed of the generator, ωebs is the electrical base speed, T_s is the shaft torque, is K_{ss} the Shaft stiffness, D_t is the damping coefficients.

The following paragraph gives a step-by-step procedure of the modelling process of the two-mass drive train: The Input block is connected to the input port 1 (+) of the Sum block. The output port of the Sum block is connected to a Gain block (1_2H_WT). The output of the gain is connected to a Discrete Time Integrator (DTI). The output port of the DTI is connected to the Input port 1 (+) of the Sum block 2. The output of the DTI is again connected to an Output block. An Input block is connected to the input port 2 (-) of the Sum block 2. The output port of the Sum block 2 is connected to the input of a Gain. The output of this Gain is connected to the Input port of a DTI block 2. The output port of the DTI block 2 is connected to the input port of a gain. The output of this Gain is connected to the input port 1 of the Sum block. The output port of Sum block 2 is connected to a Gain block, whose output is then connected to the input port 2 (+) of Sum block 3. The output of Sum block 3 is connected to a Gain block, whose output is connected to an Output block. This output from the Sum block 3 is also connected to the input port 2 (-) of Sum block 1.

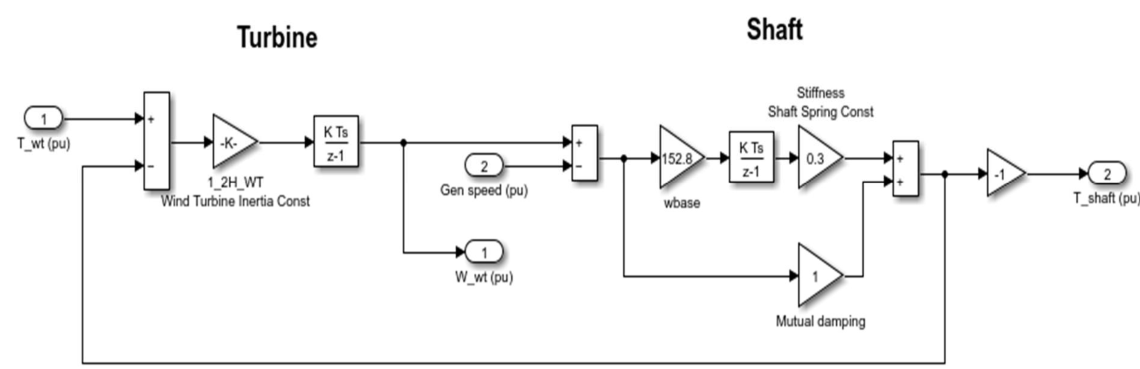

Fig. 3: Simulink Model of Two Mass Drive Train

Wind Turbine model

The Wind Turbine block models the steady-state power characteristics of a wind turbine. The stiffness of the drive train is infinite and the friction factor and the inertia of the turbine must be combined with those of the generator coupled to the turbine. The output power of the turbine is given by the following equation:

$$P_m = \frac{1}{2}C_p(\lambda, \beta)Av^3 \quad (3)$$

Where:

P_m = Mechanical output power of the turbine (W)

C_p = Performance coefficient of the turbine

ρ = Air density (kg/m^3)

A = Turbine swept area (m^2)

V = Wind speed (m/s)

λ = Tip speed ratio of the rotor blade tip speed to wind speed

β = Blade pitch angle (deg)

A generic equation was used to model C_p (λ, β). This equation, based on the modeling turbine characteristics of the equation above, is:

$$C_p\,(\lambda, \beta) = C_1\left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\right)e^{-\frac{C_5}{\lambda_i}} + C_6\lambda \quad (4)$$

With,

$$\frac{1}{\lambda_i} = \frac{1}{\lambda+0.08\beta} - \frac{0.035}{\beta^3+1} \quad (5)$$

The coefficients C_1 to C_6 are: $C_1 = 0.5176$, $C_2 = 116$, $C_3 = 0.4$, $C_4 = 5$, $C_5 = 21$ and $C_6 = 0.0068$. The Simulink model of the turbine is illustrated in the following fig 4:

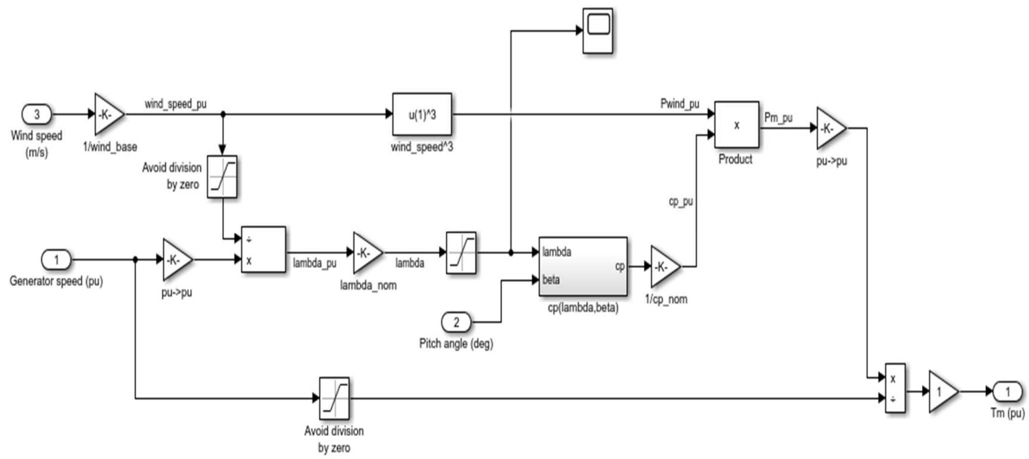

Fig. 4: Simulink Model of Wind Turbine

PMSG model

The permanent Magnet Synchronous Machine block implements a three-phase permanent magnet synchronous machine. The stator windings were connected in wye to an internal neutral point. The three-phase machine can have a sinusoidal or trapezoidal back electromotive force (EMF) waveform. The rotor can be round or salient-pole for the sinusoidal machine. The rotor is round when the machine is trapezoidal. Preset models are available for the sinusoidal back EMF machine. The Permanent Magnet Synchronous Machine block operates in either generator or motor mode. The mode of operation is dictated by the sign of the mechanical torque (positive for motor mode, negative for generator mode). The electrical and mechanical parts of the machine are each represented by a second-order state-space model.

A Simulink model of the permanent magnet synchronous generator is shown in Fig. 5.

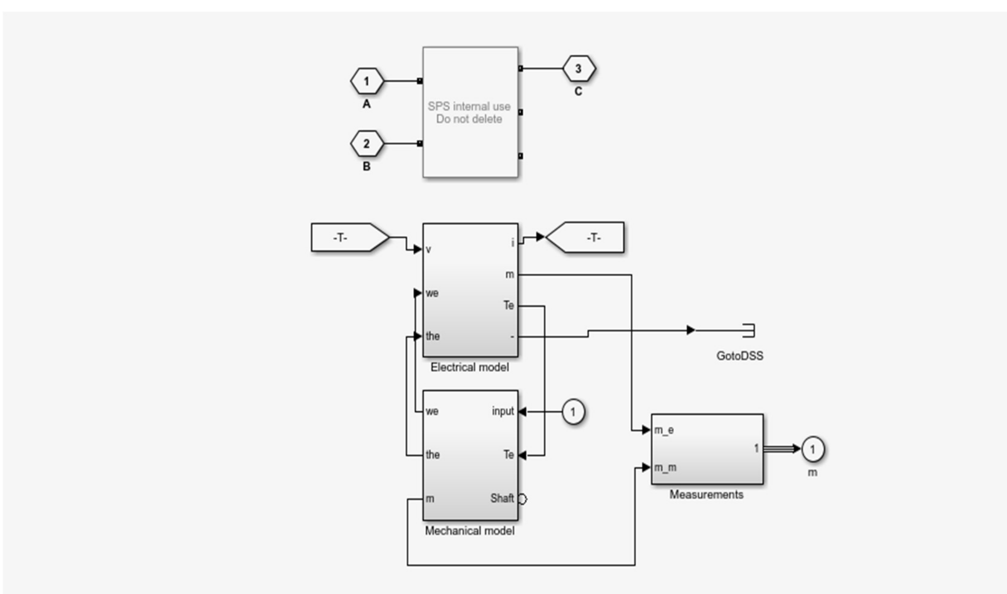

Fig. 5: Simulink Model of Permanent Magnet Synchronous Generator

Modelling of Pitch Angle Controller

The following steps were involved in modelling of the Pitch angle Controller subsystem:

An Input port was connected to the input port 1 (+) of a Sum block. A Constant block was connected to input port 2 (-) of the Sum block. Output port of the Sum block was connected to the input port of Saturation block, through a Gain block (pitch gain). The output of the Saturation block was connected to the input port of a Rate Limiter block, whose output was then connected to an Output block. The output of the Rate Limiter block was connected to input ports of a Scope block to display the graphical representation of the pitch angle.

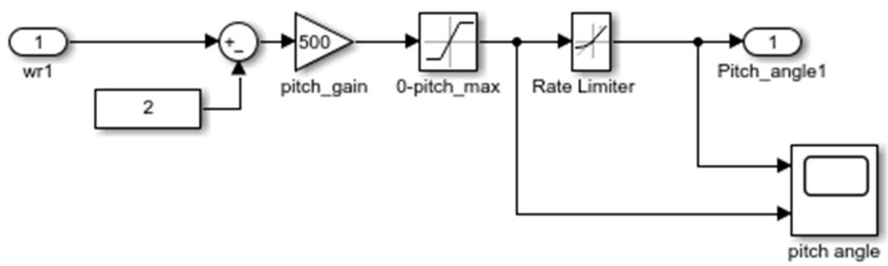

Fig. 6: Simulink Model of a Pitch Angle Controller

Modeling of WECS

The entire Simulink model of the wind energy conversion with all components put together is shown in the Fig. 6. The procedure involved in modelling the system is discussed in the paragraph below: The output port of the Pitch Angle Controller was connected to the input port 2 (pitch angle) of the Wind Turbine Model. An Input block (representing wind speed) was connected to input port 3 (wind speed, m/s) of the Wind Turbine Model. Output port 1 of the Two Mass Drive Train was connected to input port 1 (Generator speed, p.u.) of the Wind Turbine Model. Constant blocks 1 and 2 were connected to input ports 1 and 2 of the Product block respectively. The output (base torque) port of the Product block was connected to input port 2 of Product block 2. Output port 2 (T-shaft) of the Two Mass Drive Train was connected to input port 1 of Product block 2. The output of the Product block 2 (mechanical torque, Tm) was connected through a Gain block (-1) to the input port (Tm) of the PMSG model. Output port 1 (m) of the PMSG was connected to a Bus Selector block with two output ports (rotor speed and electromagnetic torque, Te). Output port 1 (rotor speed) of Bus Selector block was connected through a Gain to the input port of the Pitch Angle Controller subsystem and input port 2 (Gen speed, p.u.) of the two mass Drive Train. Output port 2 (Te) of the Bus Selector block was connected to a First Order Filter block through a Gain block. Output ports A, B and C of the PMSG model were connected through a 3 – phase LC filter to the input ports of a 3 – phase V-I Measurement block. Output ports A and B of the PMSG were connected to the input ports of a Voltage Measurement block.

The output port of the Voltage Measurement block was connected to the input port of a Discrete RMS block, whose output was connected to input port 1 of a Product block. Output port A of the PMSG was connected to the input port of a Current Measurement block. Output port 1 of the Current Measurement block was connected to the port of a Discrete RMS block 2, whose output was connected to input port 2 of the Product block. The output port of Product block was connected through a Gain block to the input ports of a Scope block and a Display block.

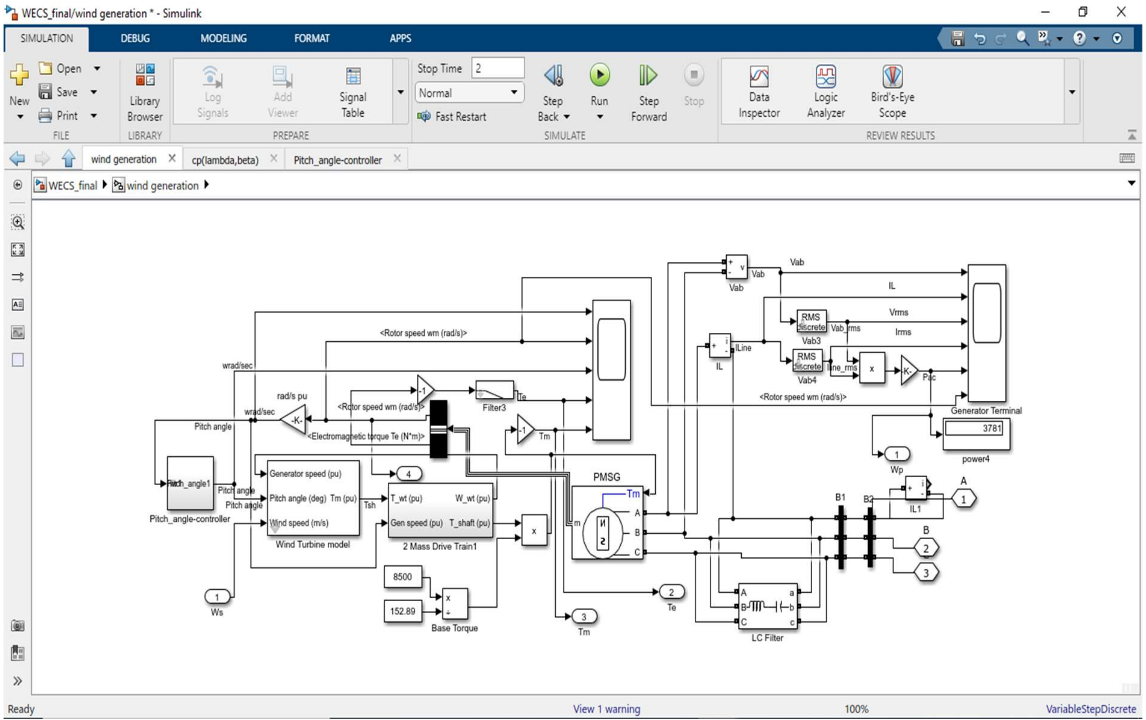

Fig. 7: Simulink Model of Wind Energy Conversion System

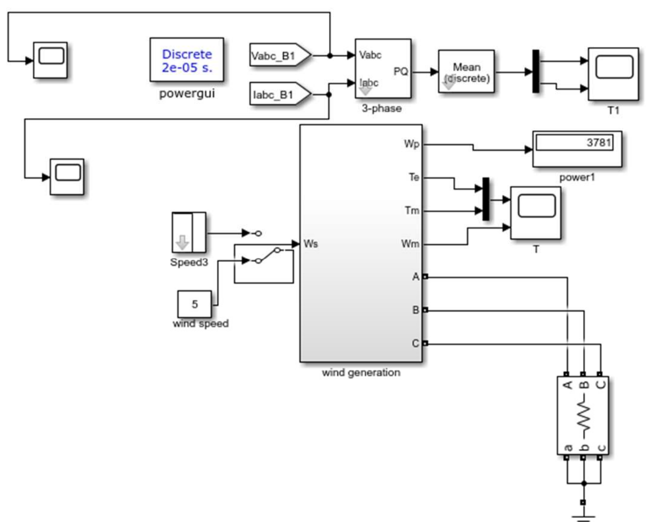

Fig. 8: A Simplified General View of the WECS

Summary
Entailed in this chapter are details of how the various parts as well as the entire Wind Energy Conversion System was modelled using MATLAB Simulink. The various models show how each of the ports of the blocks were connected to each other to get the system.

III. RESULTS AND DISCUSSIONS

4.2 Results and Discussions

In this section, the simulated results of the wind energy conversion system which was modelled in the MATLAB Simulink environment are presented. The results are then discussed to determine the feasibility and operability of a standalone wind energy conversion system based on a permanent magnet synchronous generator for remote areas

In the following graphs, the signal waveforms in Red represent the waveform generated by the PMSG-based wind energy conversion system, whiles the waveform in Blue represents a system that used a DFIG.

Fig. 9 depicts the pitch angle of the wind turbine blades used for the simulation of the wind energy conversion system of the method used (in red) and that of another bench mark system (in blue) that uses a DFIG imported into the workspace. For optimal power generation, a pitch angle of around 5 degrees is encouraged.

In the following graphs, the signal waveforms in Red represent the waveform generated by the PMSG-based wind energy conversion system, whiles the waveform in Blue represents a system that used a DFIG. The PMSG was preferred over the DFIG.

Fig 9 shows the pitch angle of the wind turbine blades used for the simulation of the wind energy conversion system (in red) and that of another system (in blue) that uses a DFIG imported into the workspace.

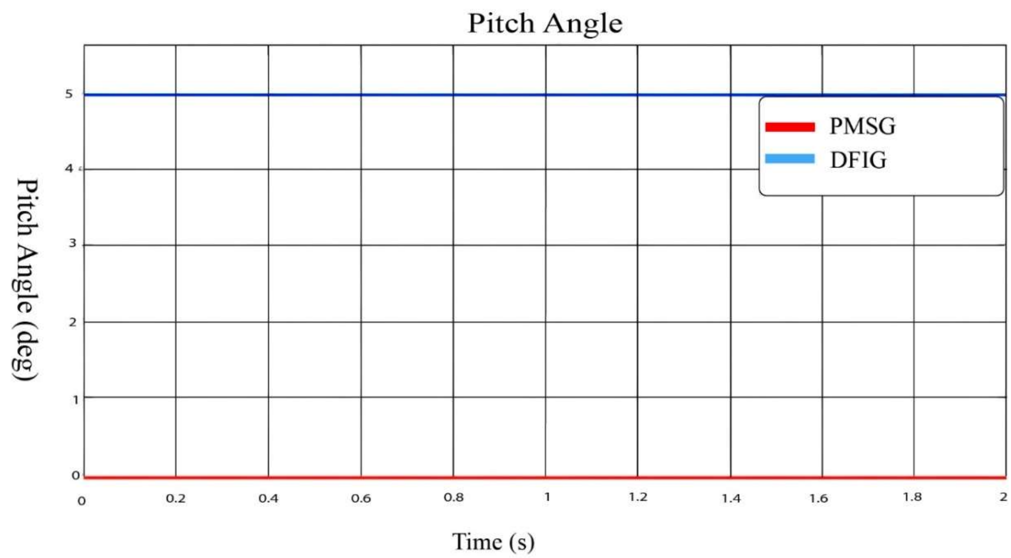

Fig. 9: A graph showing the pitch angle of the wind turbine blades

In Fig.10, a graph of the waveform of the rotor speed of the PMSG is shown. It has an initial value of 0, reaching an overshoot of around 196rad/sec before finally settling at a value of 140 rad/sec at 2 sec. Also, at DFIG 0 sec reaches an overshoot of 196 rad/sec and gradually 123 rad/sec at 2 sec. The higher the rotor speed the greater the power generated. An increase in the base wind speed efficiently results in an increase in the rotor speed and hence an increased power output.

As shown in the graph, the wind energy conversion system which uses a PMSG has a slightly faster settling time than the system that using the Doubly-fed induction generator, making it preferable. An increase in the base wind speed efficiently results in an increase in the rotor speed and hence an increased power output.

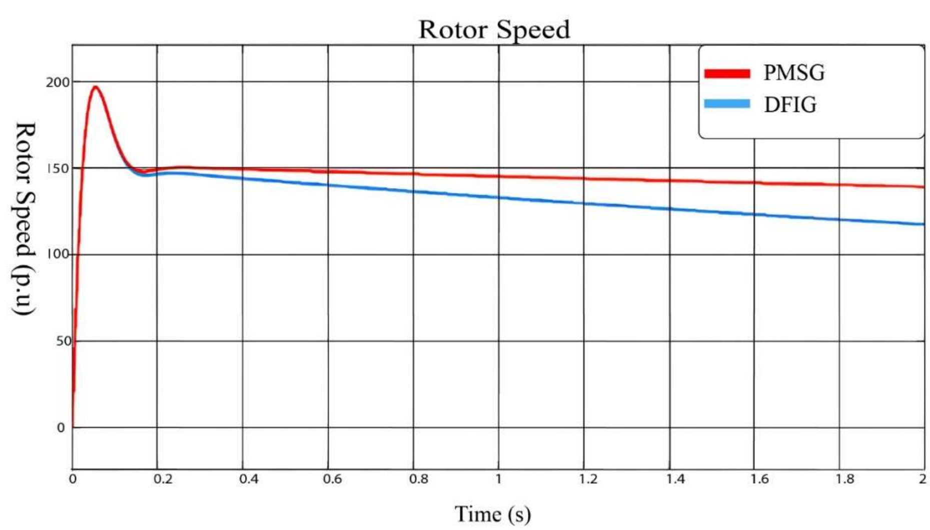

Fig. 10: A graph showing rotor speed of the PMSG

The graph illustrates Fig. 11 shows the speed produced in the PMSG by the two-mass drive train. It reaches an overshoot of 1.3 p.u at 0.15 sec before finally reaching a value of 94. And also 1.3 p.u DFIG reached its overshoot at 0.15 sec. and finally reached at 0.78 p.u at 2sec.

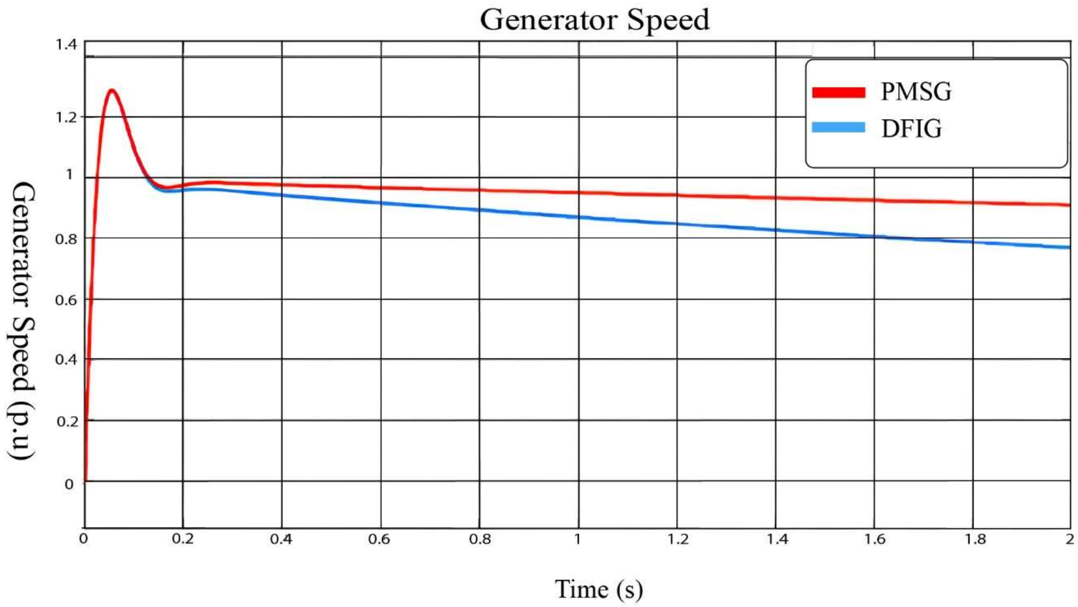

Fig.11: A graph showing the generator speed of the PMSG

The mechanical torque produced by the wind turbine was observed to be around 38 p.u. at 2 after an overshoot to a value of around 110 p.u. a higher mechanical torque value will result in higher performance, increase power output and enhanced efficiency. For the DFIG at 32 p.u it recorded an overshoot of 110 p.u as well A graph of the mechanical torque generated is shown in Fig.12.

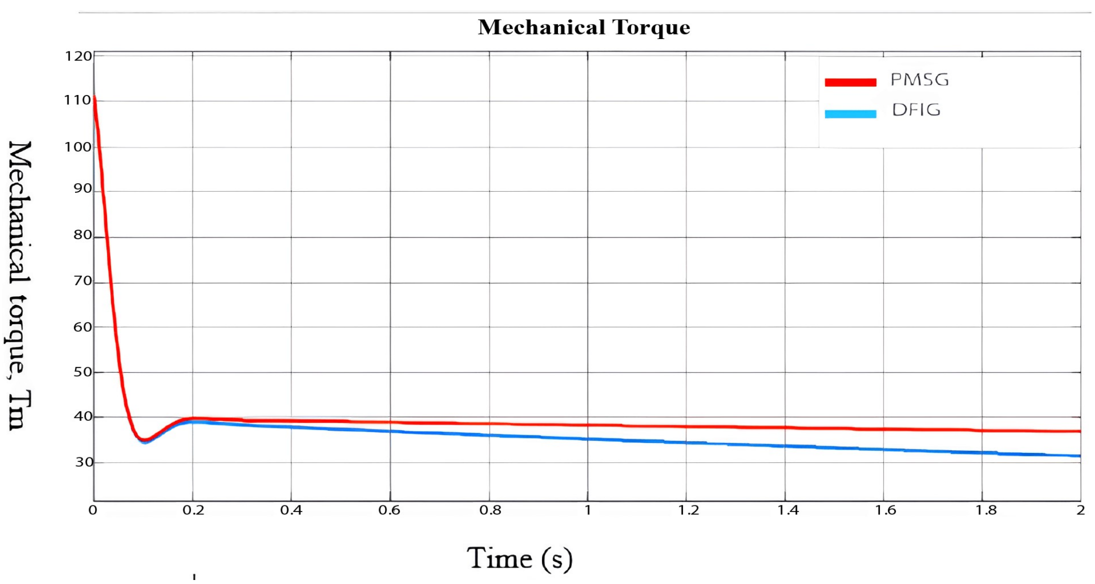

Fig. 12: A graph showing the mechanical torque generated by the action of the wind turbine

The Fig.13 shows the waveform of the electromagnetic torque generated in the PMSG. It was observed to reach a final value of 32 p.u after an overshoot of 48 p.u.

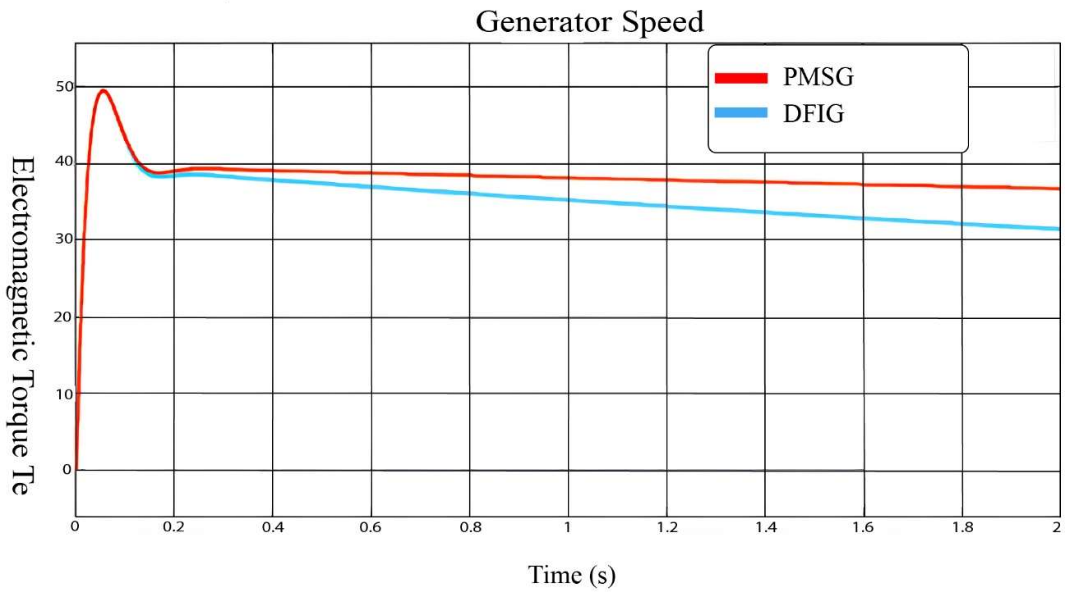

Fig. 13: A graph showing the electromagnetic torque generated in the PMSG

A graph of the torques (mechanical and electromagnetic) combined and the rotor speed of the PMSG is displayed in Fig. 14.
An AC voltage of 240 V with a frequency of 50 Hz was desired, Fig. 14 shows a smooth sinusoidal waveform of the output AC voltage with a value of 239.2 V. This output voltage value is good for the intended use. High electromagnetic torque will lead to increase in power output and improve the efficiency of the system.

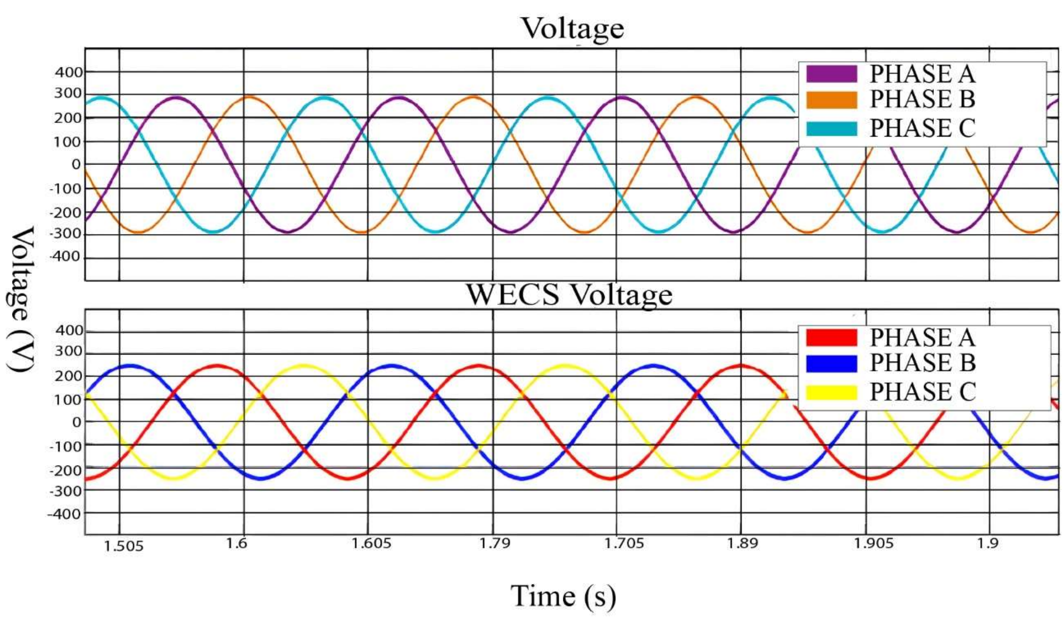

Fig. 14: A graph showing the waveform of 3 – phase voltage to be supplied to the load

The waveform of the corresponding AC current obtained from the simulation is depicted in the in Fig 15. The current was seen to reach a value of around 10 A

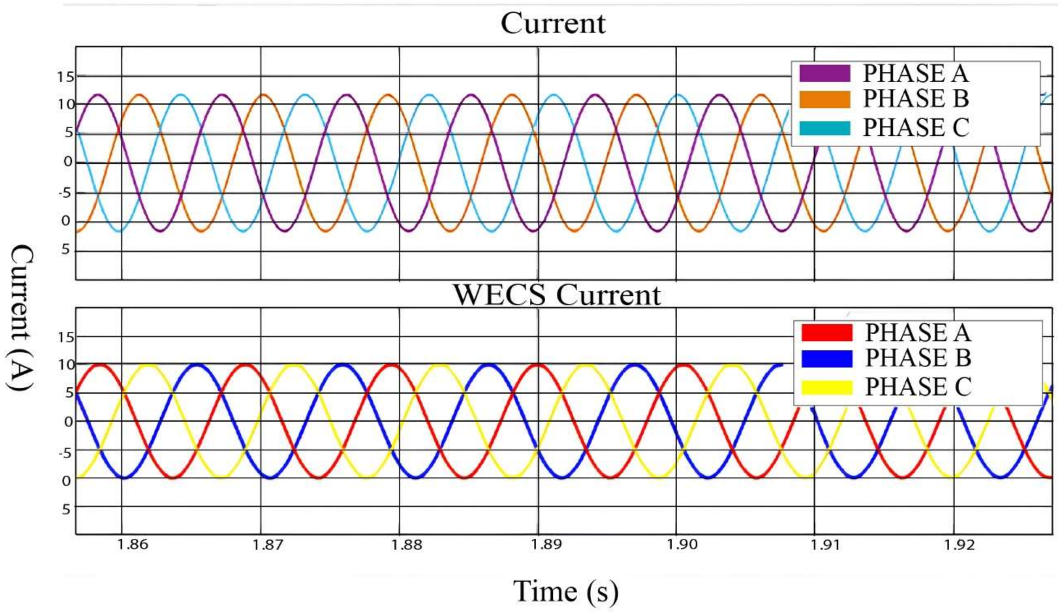

Fig. 15: A graph showing the waveform of the 3 – phase current

The AC power generated by the base wind speed of 5 m/s was observed to be around 3871 kW, after an overshoot of value 9400 kW. This is shown in Fig.16. This can subsequently be increased by an increase in the wind speed. A wind speed of 12m/s generated an output power of 6100 kW. DFID reached the its highest of power of 9000 kW at a wind speed of 12 m/s. After 2 sec the PMSG declined to a power range between 4900 to 5500 kW. The DFIG has a lower power range of 3750 to 3900 kW in 2 sec.

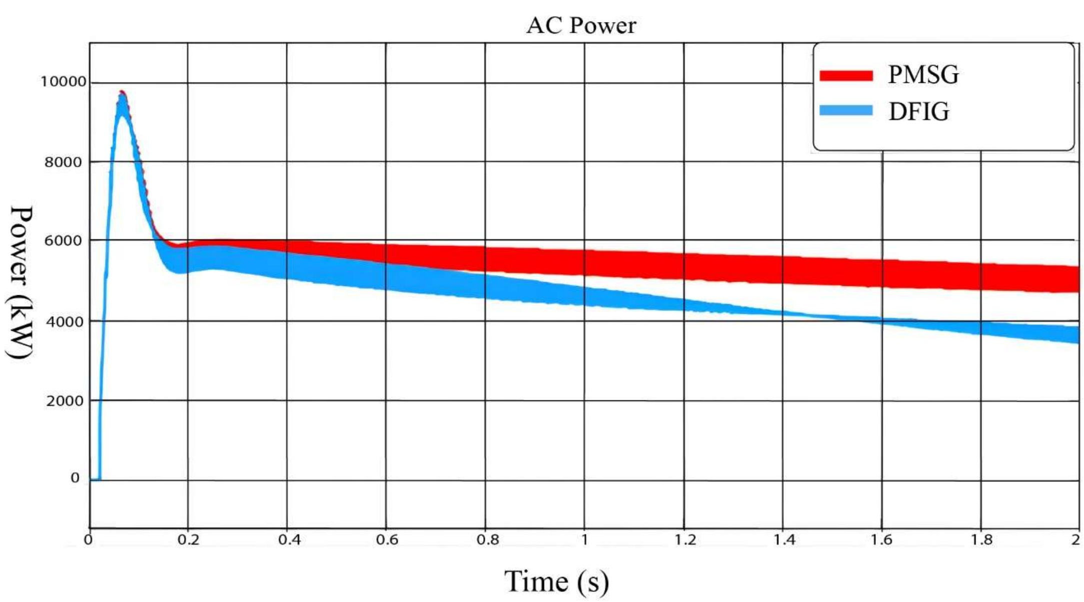

Fig.16: A graph showing the AC power generated

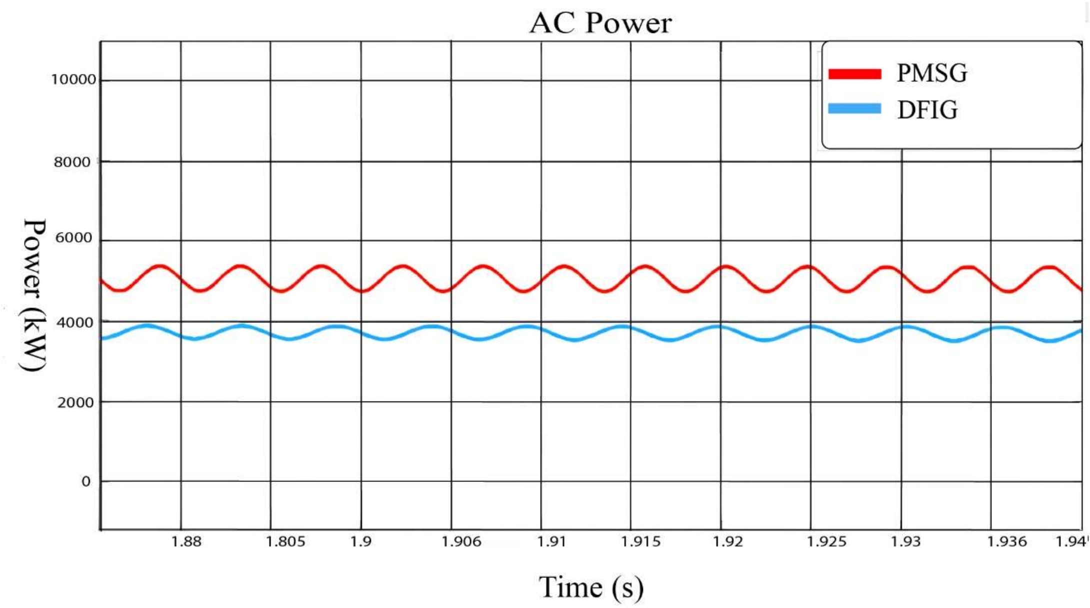

Fig.17: A graph showing an expanded view of the AC power generated

IV.CONCLUSION

Studies of wind energy for power generation purposes have a great interest in the electricity market. The good exploitation of wind energy may enhance the renewable power generation capabilities, increase its capacity factor, and participate in generating electricity at good costs. Many parameters are to be taken into consideration during manufacturing or installation of wind turbines, such as air density, wind speed, and power coefficient as a function of pitch angle and blade tip speed.

In this work, modelling and simulating of a standalone wind energy conversion system has been successfully accomplished. The model can be easily understood and its ability to supply electrical power to a load further proves its operability in remote areas.

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