Modelling and Simulation of Permanent Magnet Synchronous Generator Wind Turbine: A Step to Microgrid Technology

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Abstract Since the beginning of the electrification, the fossils have been exploiting for the last hundred years on the generation of electricity. However, now in twenty first century, there is a dilemma that the reserve of combustible fossil fuel has been almost depleted and the combustion has an inevitable consequence on the environment. Hence, the renewable energy sources can be the fuel of choice for the next generation since it is easily available, environment-friendly, and cost effective in all manners. There are several types of renewable energy resources such as solar, wind, geothermal, tides, and biomass. In this paper, the concentration is limited to the wind energy resources and wind turbine. Specifically, this letter is associated with the mathematical modeling of the permanent magnet synchronous generator wind turbine and simulation for the different aspects and cases of the system. After that, the performance of the PMSG wind turbine is analyzed for the different parameters. All of these analysis would contribute in a significant way towards implementing this technology in practical fields. All the results are verified by Matlab simulations with appreciable aftermaths.

Keywords Microgrid; Renewable Energy Resources; Wind Energy; Permanent Magnet Synchronous Generator (PMSG); Wind Turbine; System Modeling.

1. Introduction

The next generation power system is moving towards the possible fuel shift rather than depending on the conventional fuel sources because of two major reasons. First, from the environmental point of view, the more combustion of the fossil fuel, the more the carbon emission in the environment. It eventually aggravates the environmental issues. From the point of resource availability, the conventional fossil fuels have almost been depleted and cannot meet the next generation power demand. To fix these challenges, renewable energy resource-based power system has been developing into the choice to meet the next generation power demand and to ensure mass electrification around the world. Renewable energy sources have a number of advantages over the conventional fuel sources. First, it doesn't require any fuel combustion, therefore, it doesn't have any negative impact on environment. Second, the renewable energy resources- unlike the conventional fuel sources- provides inherently the unlimited resource facility. Third, since it is freely available in the environment, the renewable energy-based systems do not require any fuel cost. Hence, these systems are cost-effective since these require only the manufacture cost and the maintenance cost. After that, the renewable energy resource-based system can be implemented independently in the remote area where utility grid connection cannot be reached [1-5].

There are several types of renewable energy resources such as solar, wind, geothermal, tides, and biomass. Renewable energy sources are basically implemented by the microgrid technology which incorporates distributed generation units. Distributed generation units are based on the available resources of the particular locality. Solar energy-based generation technique contributes majorly to the microgrid system since solar energy is available almost all the day everywhere in summer. Besides that, wind energy has significant portion though it is actually appropriate for the coastal area where the high velocity wind is easily available all the day and night. Geothermal resources are based on the thermal energy and its long term consequences are not favorable to the environment since it dislodges minerals in its process and it hampers the underground thermal balance. Tides are one the most excellent way to generate electricity. It's of quick starting and easy maintenance, but it's architecture is relatively complex and construction is necessarily costly. On the other hand, the tide-based hydroelectricity offers significant amount of generation. Biomass-based generation has continually increasing growth specially in the rural areas. Besides the electricity generation, it has an important role in waste management [6-9].

A microgrid system integrates the several types of renewable energy sources, such as solar system (PV), wind turbine, fuel cell, to the household and industrial load [10,11,12,13]. It is a distributed generation-based system and it requires secure communication for safe and uninterrupted generation [14-17]. In this paper, the concentration will be limited to the wind energy resources and wind turbine. Specifically, this letter is associated with the mathematical modeling of the permanent magnet synchronous generator wind turbine and simulation for the different aspects and cases of the system. The reason is the wind turbine is operated according to various wind speed by assuming that are installed in different geographical sites [8-11]. A low cost and low weight design of PMSG with higher efficiency was modelled and simulated by Omijeh et al [18]. Another wind power system was modelled with double PWM control circuit [19]. Another optimized simulation model was introduced by floren et al at their novel design [20]. MPPT Controller was intriduced in Modeling and Simulation of Microgrid Connected Renewable Energy Resources by govinda et al [21].

The contribution of this paper is as follows. In section two, the microgrid model is presented. Later, in section three, the modeling of the 12 KW PMSG wind turbine is illustrated with necessary mathematics and schematics. After that, in section four, the simulation results are presented considering different aspects and cases of the system. There, its behavioral characteristics, noise analysis, load profile, typical performance analysis, and many other things are delineated.

2. Microgrid Model

Microgrid system incorporates several distributed generation units and it is possible to operate microgrid autonomously. The sources of microgrid generation are wind energy, solar energy, fuel cells and other energy sources. The multiple and isolated sources of microgrid helps a lot to run it autonomously and as per the requirements of any circumstances of demand. In figure 1, the microgrid system is modelled with the renewable energy sources and some storage system. Here, a 12 kW wind turbine, 100 kW solar panel, two 45 kW natural gas generator, and 50 kW fuel cell are connected to a bus-bar in left side, which is known as source side. And on the right side of the bus-bar, several loads are connected such as the electric vehicle charging station, 200 kW passive load etc. The parameters of each generator, plants, and load are given in the tabular form in respective section. Using those parameter simulation work has been done in the later part of the paper.

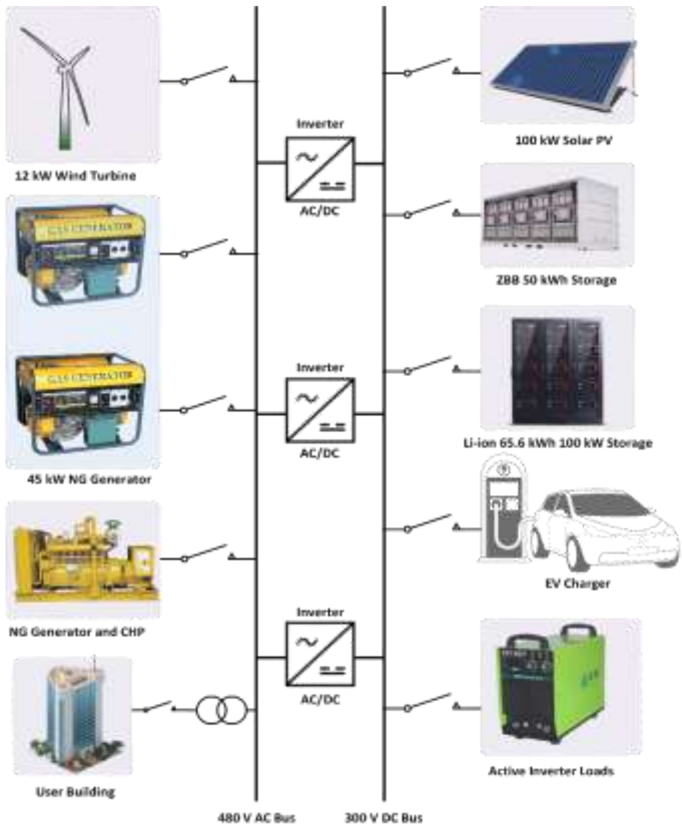


Fig. 1: Proposed framework for microgrid system.

3. Modeling of 12 kw pmsg Wind Turbine

In this paper, a PMSG generator is used for microgrid modeling. The basic advantage of PMSG over induction generator is its considerably higher efficiency and better reliability. Besides that, there is no need of external excitation, it's compact in size, and relatively easier to control. Because of having the variable speed configurations, the permanent magnet synchronous generators are used around the world in small-scale wind turbines. The direct-drive PMSG wind power system consists of the following several basic components: wind turbine, generator, DC/AC inverter, and control systems [14]. The basic structure of the direct-drive permanent magnet synchronous wind power generation system is shown in Figure 2.

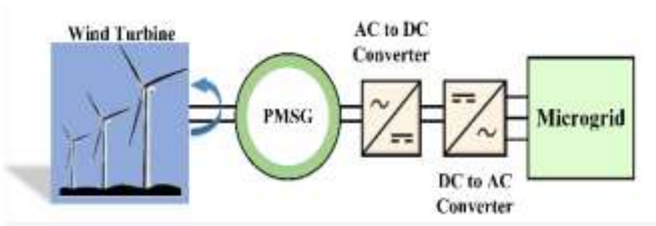


Fig. 2: Wind turbine with full scale converter connected to the grid/microgrid.

A. Mathematical Modeling of the Wind Turbine

The overall mechanical power extracted from the wind is essentially a combined function of the wind and the rotor speeds of the generator unit. This is denoted by Pω and can be expressed as:

$$P_{\omega} = 0.5\,\rho A_r C_p(\alpha,\beta)v^3 \tag{1}$$

$$\lambda = \frac{\omega m}{v} R \tag{2}$$

$$C_p = C_1\left(\frac{C_2}{\gamma} - C_3\beta - C_4\right)e^{\frac{C_5}{\gamma}} + C_6\lambda \tag{3}$$

Where, ρ is Air density, v is Wind speed, A_r is Area swept by the rotor, Λ is Tip-speed ratio, C_p is Power coefficient, Β is Pitch angle, R is Rotor radius.

The mechanical torque output of the wind turbine is denoted by Tm and be expressed as:

$$T_m = \frac{P_\omega}{\omega_m} = \frac{0.5\rho A_r C_p(\alpha,\beta).v^3}{\omega_m} \tag{4}$$

B. Modeling of the PMSG

To simplify the response study of the PMSG, it is convenient to transform the equations from the stationary stator frame into the d-q axis using Park transformations. The mathematical model of PMSG can be described in the d-q reference system as follows [14]:

$$\begin{cases} \frac{di_d}{dt} = \frac{-R_s I_d + L_q p\omega_r i_q + u_d}{L_d} \\ \frac{di_q}{dt} = \frac{-R_s I_q - L_q p\omega_r i_d - p\psi_f\omega_r + u_q}{L_q} \end{cases} \tag{5}$$

$$T_m = 1.5p(\psi_j i_q - (L_d - L_q)i_d i_q) \tag{6}$$

$$\omega_e = p\omega_r \tag{7}$$

Where, u_d is d-axis voltage, u_q is q-axis voltage, i_d is d-axis current, i_q is q-axis current, Rs is Stator resistance, Ld is d-axis inductance, Lq is q-axis inductances, ωr is Mechanical angular speed, Te is Electromagnetic torque, Ψf is Magnitude of the flux.

The drive train mathematic equation of the DDPMSG is:

$$\frac{d\omega_r}{dt} = \frac{1}{J_{eq}}(T_e - B\omega_r - T_m) \tag{8}$$

The wind turbine- by slowing the wind down- extracts energy and the maximum amount of energy by a wind turbine rotor can be collected theoretically by Betz limit is approximately 59%. But, in practical case, the collection efficiency of a rotor is not as high as 59% and merely varies between 35% to 45%. Realistically, a complete wind energy system, consisting of rotor, transmission system, generator, storage and other devices, can supply between 10% to 30% of the original energy available in the wind. The efficiency factor denoted by Cp can be expressed as [22]:

$$C_p = \frac{Power\ output\ by\ wind\ turbine}{Power\ in\ the\ wind} \tag{9}$$

This can roughly be estimated for simulation purpose [22]:

$$C_p = \eta_{rotor} \times \eta_{mechanical} \times \eta_{electrical} = 40\% \times 80\% \times 90\% = 28.8\% \tag{10}$$

Finally, the electrical power equation for A HAWT is obtained by

$$P_{out} = \frac{1}{2}\rho\pi r^2 v^3 C_p \tag{11}$$

From this equation, the radius of the wind turbine can be derived as

$$r = \sqrt{\frac{2P_{out}}{\rho\pi v^3 C_p}} \tag{12}$$

Considering 11 m/s as the rated wind velocity, a 10 kW wind turbine which has a radius (r) of the blade:

$$r = \sqrt{\frac{2x10000}{1.225x3.1416x11^3x0.288}} \approx 3.5m$$

The Power map of wind turbine is depicted in the figure 3 below.

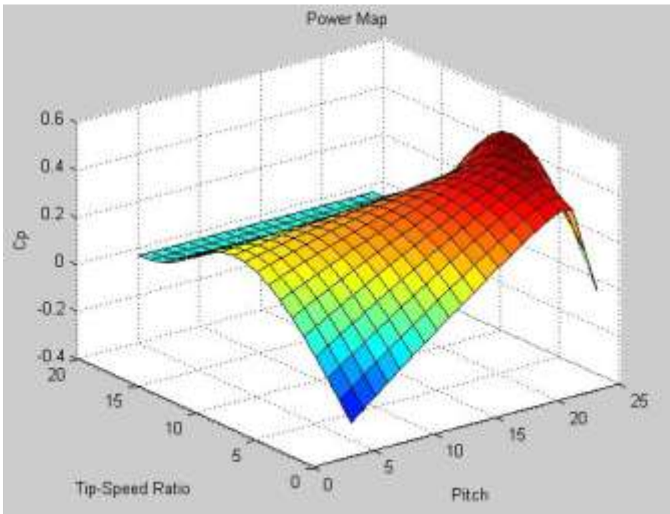


Fig. 3: Power map of wind turbine.

Based on the above assumption and calculation, a 10kW wind turbine model is simulated for 10m/s rated wind speed using MATLAB/Simulink. The results for the variation of the wind power according to the wind velocity obtained from the simulation are represented in the Figure 4.

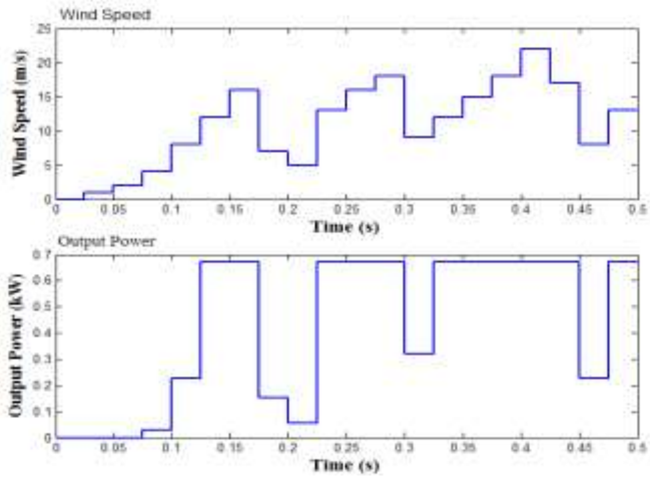


Fig. 4: Simulation results for 10 kW HAWT using 24 hour real data. Top: Wind Speed (m/s); Bottom: Output Power (kW).

4. Simulation and Analysis

The output power vs wind speed characteristics is shown in Figure 5, where there is four different region of operation. In the region 1, the wind velocity is very low (less than 2.2m/s), and the wind turbine cannot develop enough usable power, this speed is termed as cut in speed. Region 2 is the proportional portion of the graph. In this region, the output power is proportional to the wind velocity until 13m/s and it’s called the rated wind speed or the normal speed. Above 13m/s, the blade pitch is controlled such a way that output power is constant irrespective of wind velocity until the cut out velocity of 25m/s. Above this, the wind mill is shut down to prevent the unintentional damage of the machineries.

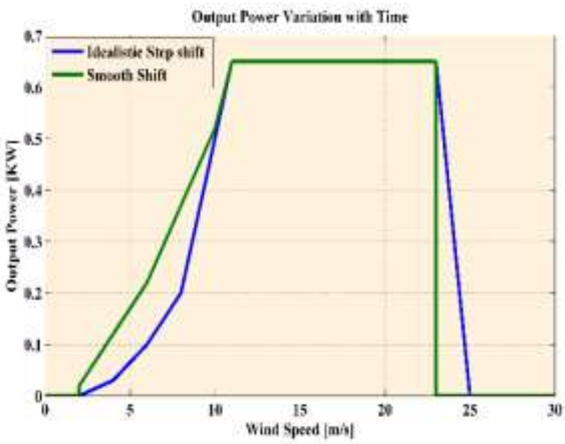


Fig. 5: Wind Speed vs. Output power. Blue curve showing idealistic step shift and green one indicating smooth shift

Figure 5 depicts characteristics of output power with wind speed for two different cases. For the purpose of practical implementation, a survey was conducted around the Milwaukee area for the annual variation of the wind velocity. The result from the statistical analysis is represented in figure 6. From this illustration, the average wind velocity of the Milwaukee area can be estimated.

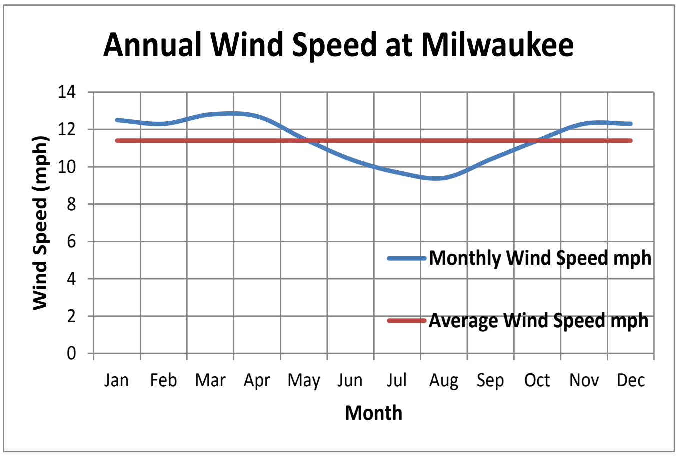


Fig. 6: Annual Speed data at Milwaukee.

Now, the relation among the hub height with the wind velocity and the output generated power is presented in figure 7.

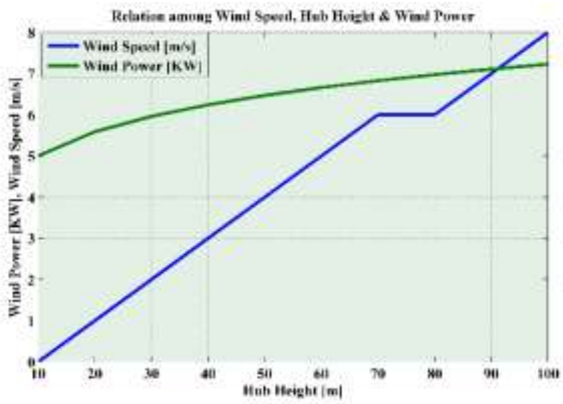


Fig. 7: Relation between hub height and wind speed (blue), wind power (green).

Then, the power carried by the wind, the maximum power from the Betz Limit, and the power produced in the UWM (University of Wisconsin Milwaukee) using this setup are compared in the figure 8.

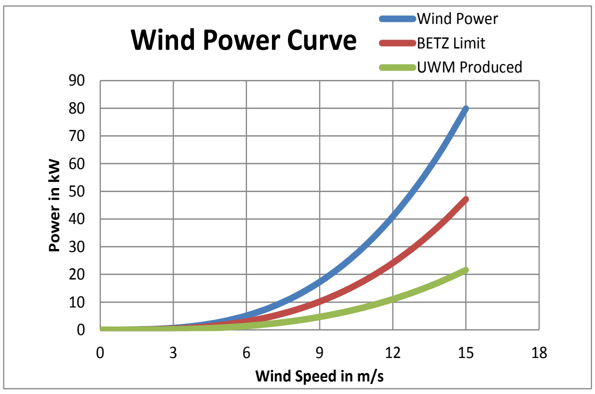


Fig. 8: Comparison of wind power.

After that, a complete wind profile including the variation of the wind power depending upon the wind velocity, the hub height, and the maximum possible power output for different wind velocity condition are estimated and presented in figure 9. Here, the maximum power behaves as a function of the root diameter and the wind speed. In this course, the power increases as the square of the rotor diameter and more significantly as the cube of the wind speed.

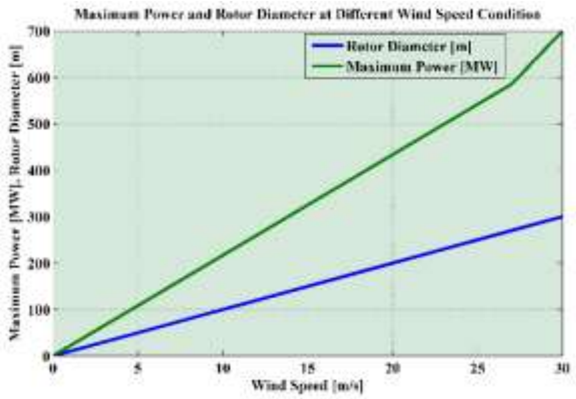


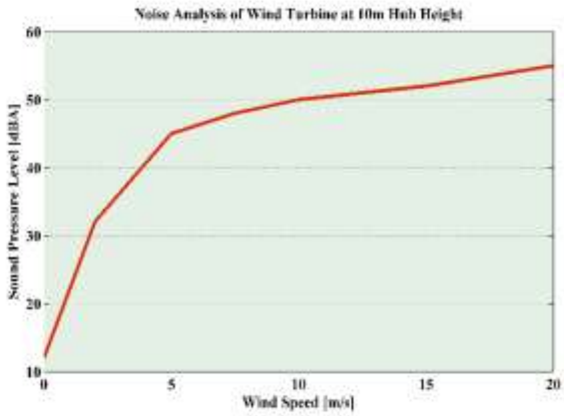
Fig.9: Maximum power for the different speed condition where green plot showing the relation for maximum power whereas the blue plot showing Rotor diameter relation.

Next, the following table is presented to illustrate the specifications of the wind turbine.

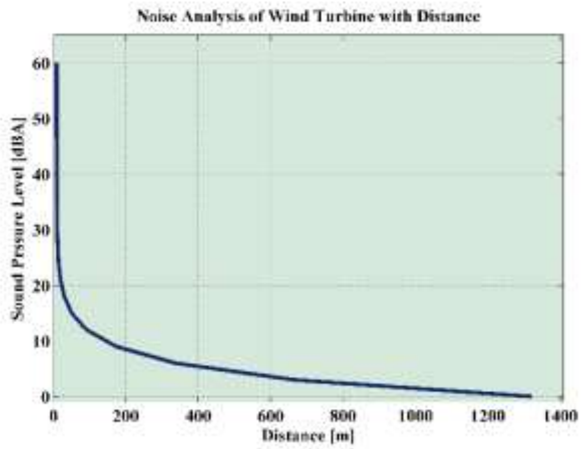
Table 1: The Specifications of the wind turbine

Wind Turbine Specification			
AWEA Rated Power	8.9 kW at 11m/s (25 mph)	Type	3 Blade Upwind
AWEA Rated Sound Level	42.9 dB	Rotor Diameter	7 m (23 ft)
AWEA Rated Annual Energy	13600 kWh at 5 m/s (11 mph)	Blade Pitch Control	None, Fixed Pitch
Start-up Wind Speed	2.2 m/s (5 mph)	Overspeed Protection	Auto Furl
Cut-in Wind Speed	2.2 m/s (5 mph)	Temperature Range	-40 to +60 deg C
Nominal Power	10 kW at 12 m/s (27 mph)	Generator	Permanent Magnet Alternator
Cut-Out Wind Speed	None	Gearbox	None
Furling Wind Speed	15.6 m/s (35 mph)	Power Processor	Powersync II inverter
Max. Design Wind Speed	60 m/s (134 mph)	Output Form	240 VAC, 1-Phase, 60 Hz

As a consideration of the environmental impact of the wind turbine, the noise impact of the wind turbine is illustrated in the figure 10.



(a)



(b)

Fig.10: Noise Impact analysis of the wind turbine. (a) wind speed vs sound pressure analysis and (b) sound pressure vs distance.

After that, the simulations are carried out in order to verify the wind turbine model and PMSG model by MATLAB/Simulink. The simulation platform for this purpose is presented in the figure 11. It includes different parts of the wind energy conversion system and depicts the grid tied operation of a 12 KW wind turbine in the designed microgrid. A 12 KW wind power conversion unit is modeled followed by the directly driven PEMG. The wind turbine power characteristics for the various wind velocity/ turbine speed (pu) is presented in the figure 12.

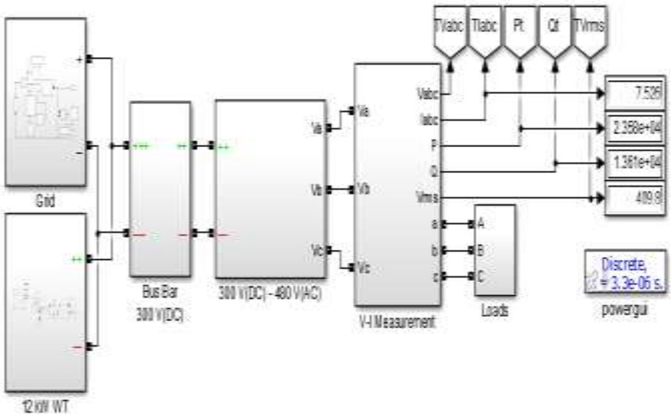


Fig. 11: Complete Model of the Grid Tied Wind Energy Conversion System.

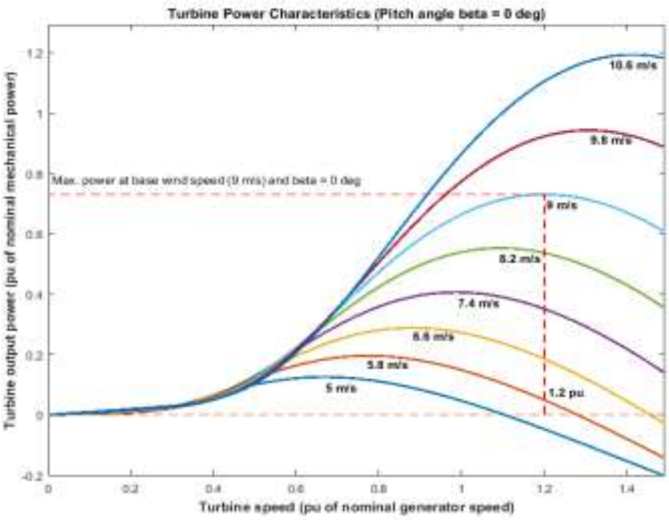


Fig. 12: Wind Turbine Power Characteristics for various wind speed/ turbine speed (pu of nominal generator speed).

From this figure, the maximum power output of the wind turbine at 9m/s can be estimated. Due to the variation in the wind velocity and its random nature, directly driven PMSG will generate variable electrical frequency. To avoid this phenomena, 3 phase AC output voltage from PMSG is converted into the DC power and then a 300 V DC stabilization technique is implemented. Later, this 12 KW wind power conversion unit is coupled with a DC power grid. This 300 V DC bus is coupled with a 300 V DC to 480 V AC three phase inverter to connect the generation side to the distribution network. The load profile for the designed microgrid is illustrated in the figure 13.

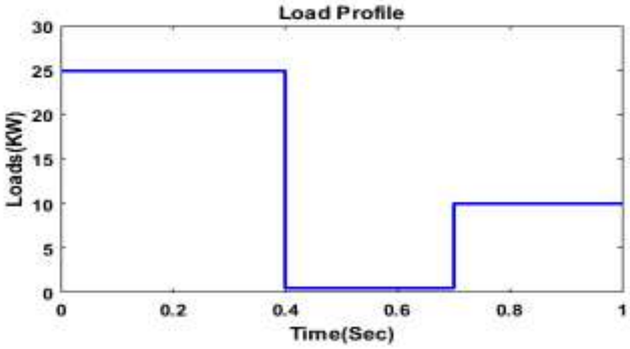


Fig. 13: Load profile of small scale grid tied microgrid

At 0.4 second of the simulation, when the load falls to 500 W and the WEC rated power moderates the load demand, the rest of the power feedback to the grid. Finally, at 0.7 second of the simulation, when the microgrid load demand is nearly equal to the WECS Power generation, grid power contribution falls to zero. The power characteristics is shown in figure 14. Here, figure 14(a) shows the power generated by the 12KW PMSG wind turbine at 9 m/s base wind speed and figure 14(b) shows the power contribution of the grid as grid is functioning like both source and sink of the power. Finally, figure 14(c) represents the overall load demand of the designed microgrid. After that, figure 15 shows the terminal voltage and current for both the WECS and the supply grid and figure 16 shows the RMS voltage, current, real power and reactive power of the microgrid after the conversion of the 300V DC Bus into the 480 V three phase AC system to couple with the distribution network.

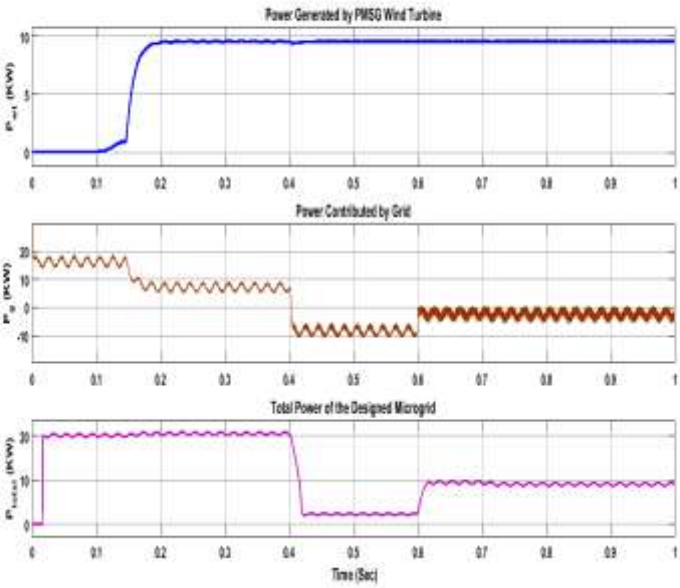


Fig. 14: (a) Power Generated by PMSG12 KW Wind Turbine at 9m/s Base wind speed (b) Power contributed by Grid (c) Total power of designed microgrid.

In figure 14, the curve shows the power generated by the turbine at 9 m/s wind speed. Since the system is grid connected in figure 14(b), its response with a grid tied system is also presented. By observing the curve it is visible that from .4 to .6 second the power contributed by the grid becomes became negative as it starts consuming power from the system.

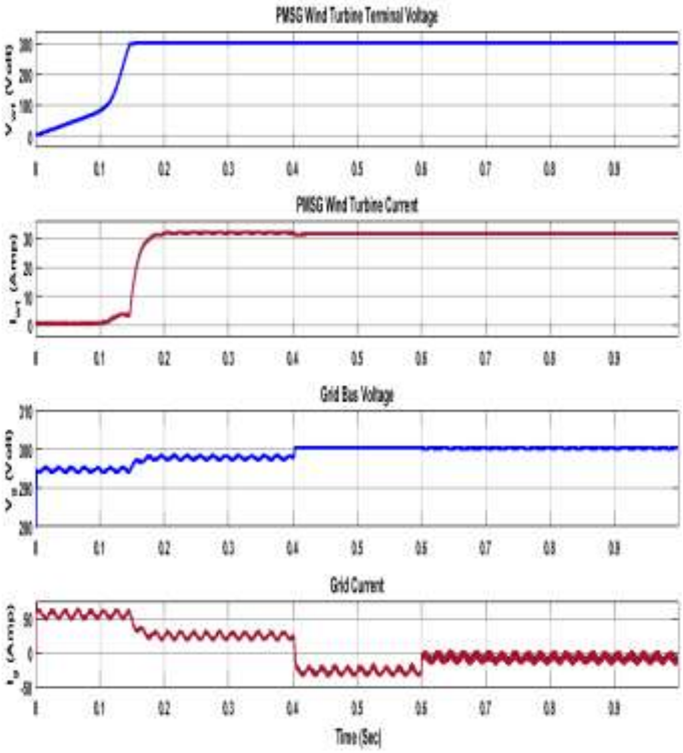


Fig.15: (a) Terminal Voltage of PMSG Wind Turbine (b) PMSG Wind Turbine Current (c) Grid Bus Voltage (d) Grid Current.

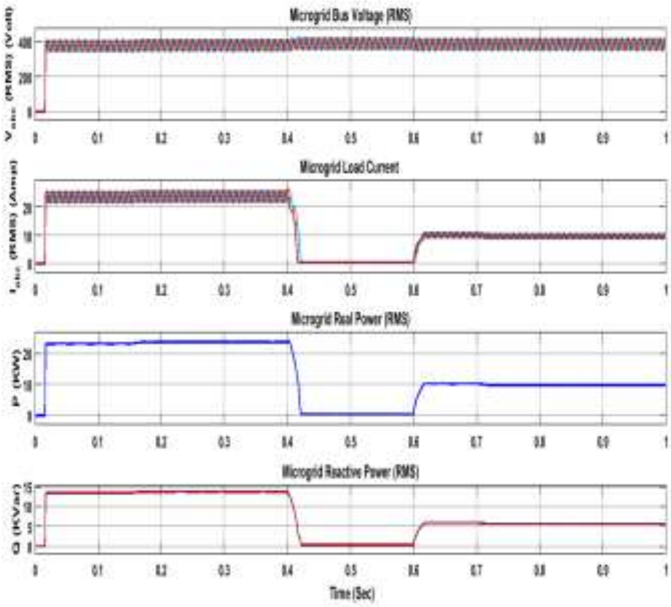


Fig. 16: After Conversion into 300V DC to 480V AC (a) Microgrid Bus Voltage in RMS (b) Microgrid Load Current (c) Microgrid Real Power in KW (d) Microgrid Reactive Power in KVar,

5. Conclusion

To meet the next generation power demand, renewable energy sources are the most reasonable fuel-shift taken over the naturally limited conventional fuels. Among all the available renewable energy resources, wind energy has been developing as one of the most significant contributors of the power industry. In this paper, the mathematical modeling of the permanent magnet synchronous generator wind turbine has been delineated. After that, the simulations and analysis have been presented to explain the different aspects and the cases of the system. To verify the performance of the permanent magnet synchronous generator wind turbine, the simulation results have been demonstrated on the virtual platform such as Matlab/Simulink.

References:

[1] Farid Chaaban, Mohammad Akkawi & Ibrahim Nassar (2015) Transferring Power Sectors from Aging Utilities into Smart Grids—The Case of Lebanon, Electric Power Components and Systems, 43:16, 1793-1802.

[2] Eklas Hossain, Ersan Kabalci, Ramazan Bayindir and Ronald Perez “Microgrid testbeds around the world: State of art”, Energy Conversion and Management 86 (2014) 132–153.

[3] Farhan H. Malik, Matti Lehtonen, A review: Agents in smart grids, Electric Power Systems Research, Volume 131, February 2016, Pages 71-79, ISSN 0378-7796.

[4] Aushiq Ali Memon, Kimmo Kauhaniemi, A critical review of AC Microgrid protection issues and available solutions, Electric Power Systems Research, Volume 129, December 2015, Pages 23-31, ISSN 0378-7796, http://dx.doi.org/10.1016/j.epsr.2015.07.006.

[5] C.N. Papadimitriou, E.I. Zountouridou, N.D. Hatziargyriou, Review of hierarchical control in DC microgrids, Electric Power Systems Research, Volume 122, May 2015, Pages 159-167, ISSN 0378-7796.

[6] Eklas Hossain, Ersan Kabalci, Ramazan Bayindir and Ronald Perez “A Comprehensive Study on Microgrid Technology”, International Journal of Renewable Energy Research, Vol.4, No.4, 2014 1094–1107.

[7] Ersan Kabalci, Eklas Hossain and Ramazan Bayindir “Microgrid test-bed design with renewable energy sources”, International Conference on Power Electronics and Motion Control Conference and Exposition (PEMC), 2014, Pg. No. 907-911.

[8] E. Kabalci, R. Bayindir and E. Hossain, "Hybrid microgrid testbed involving wind/solar/fuel cell plants: A desing and analysis testbed," Renewable Energy Research and Application (ICRERA), 2014 International Conference on, Milwaukee, WI, 2014, pp. 880-885.

[9] V.A. Evangelopoulos, et al., Optimal operation of smart distribution networks: A review of models, methods and future research, Electr. Power Syst. Res. (2016).

[10] Nazmus Sakib, Jakir Hossain, H. Ibrahim Bulbul, Eklas Hossain, Ramazan Bayindir, “Implementation of Unit Commitment Algorithm: A Comprehensive Droop Control Technique to Retain Microgrid Stability”, Renewable Energy Research and Applications (ICRERA), 2016 International Conference on, Accepted.

[11] J. Hossain, S. S. Sikander and E. Hossain, "A wave-to-wire model of ocean wave energy conversion system using MATLAB/Simulink platform," 2016 4th International Conference on the Development in the in Renewable Energy Technology (ICDRET), Dhaka, 2016, pp. 1-6.

[12] Nazmus Sakib, jakir Hossain, Eklas Hossain, Ramazan Bayindir “Modelling and Simulation of Natural Gas

Generator and EV Charging Station: A Step to Microgrid Technology”, International Journal of Renewable Energy Research, Accepted.

[13] Eklas Hossain, Mashrur Zawad Xahin, Khondokar Rakibul Islam, MD. Qays Akash, “Design a Novel Controller for Stability Analysis of Microgrid by Managing Controllable Load using Load Shaving and Load Shifting Techniques; and Optimizing Cost Analysis for Energy Storage System”, International Journal of Renewable Energy Research, Vol 6, No 3 (2016), 772-786.

[14] L. Sun, C. Gong and F. Han, "Design and optimization of control parameters based on direct-drive permanent magnet synchronous generator for wind power system," 2013 IEEE 8th Conference on Industrial Electronics and Applications (ICIEA), Melbourne, VIC, 2013, pp. 1238-1243.

[15] Magdi Ragheb and Adam M. Ragheb (2011). Wind Turbines Theory - The Betz Equation and Optimal Rotor Tip Speed Ratio, Fundamental and Advanced Topics in Wind Power, Dr. Rupp Carriveau (Ed.), ISBN: 978- 953-307-508-2

[16] A. Harrouz, A. Dahbi, O. Harrouz and A. Benatiallah, "Control of wind turbine based of PMSG connected to water pumping system in South of Algeria," *Environmental Friendly Energies and Applications (EFEA), 2014 3rd International Symposium on*, St. Ouen, 2014, pp. 1-4.

[17] R. S. Pukale, K. U. Jadhav and A. G. Thosar, "Data collection of variable wind speed to study the change in power and power coefficient," *Energy Efficient Technologies for Sustainability (ICEETS), 2013 International Conference on*, Nagercoil, 2013, pp. 387-392.

[18] Omijeh, B. O., C. S. Nmom, and E. Nlewem. "Modeling of a vertical axis wind turbine with permanent magnet synchronous generator for Nigeria." international Journal of Engineering and Technology 3, no. 2 (2013): 212-220.

[19] Li, Nan, Y. U. Bing, Lei Liu, and Bing Kong. "Simulation study on permanent magnet wind power generation system based on PSIM." SIMULATION 3, no. 4 (2014).

[20] Iov, Florin, Frede Blaabjerg, Zhe Chen, Anca Daniela Hansen, and Poul Sorensen. "A new simulation platform to model, optimize and design wind turbines." In IECON 02 [Industrial Electronics Society, IEEE 2002 28th Annual Conference of the], vol. 1, pp. 561-566. IEEE, 2002.

[21] Chukka, Govinda, Swarupa Pinninti, and P. Sri Venkatesh. "Modeling and Simulation of Microgrid Connected Renewable Energy Resources with MPPT Controller and by Using SVPWM Technique." In International Journal of Engineering Research and Technology, vol. 3, no. 1 (January-2014). IJERT, 2014.

[22] Fu, Qiang, "Modeling, Analyses and Assessment of Microgrids Considering High Renewable Energy Penetration" (2013). Theses and Dissertations. Paper 248