Modeling and simulation of a DFIG RES generation system for small and growing grids

L.O. Mogaka, G.N. Nyakoe, M.J. Saulo

Abstract
The increasing population and hence increase in the demand for electric power calls for ways for increasing power generation most especially from the Renewable Energy Sources (RES) like wind and solar PV. That is why the integration of these RESs of power to the grid is on the increase. This is as a result of favorable government policies, effort of minimization of greenhouse gases production and the natural abundance of RES. This is also in line with the grid's evolution to smart grid requirements. Among the many RESs the Doubly Fed Induction Generators is the most used wind energy conversion system because of high efficiency, environmentally clean and ease of being integrated to the grid. In addition to this, the DFIG is gaining popularity in applications because its speed can be varied hence cops up very well with the wind speed variation for different places and times. However, these RESs have different characteristics and thus poses different operating challenges. This calls for proper prior investigations and analysis of these challenges for particular grids in mind before actual integration to the system. In line with this smart grid concept, in this paper we have designed, modelled and simulated the various aspects, different load condition of DFIG wind system integration to small and growing grids for countries like Kenya in MATLAB/Simulink platform.

Keywords-DGs, RESs, Rotor Side Control, Grid Side Control, PWM, DFIG

I. INTRODUCTION

The first power generation using wind was installed in the United States of America in the year 1890. Next, in the year 1979 a 2 MW wind turbine generator was installed in a place called Howard Knob Mountain. A third wind power project was a 3 MW turbine that was in Orkney, Scotland in the year 1988. In all these projects, the power that was generated was small and was only used in lighting buildings in the vicinity and was not grid connected.

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Wind energy can be described in simple terms as the mechanism through which the kinetic energy from blowing wind is converted to useful mechanical and electrical power using wind turbines [1]. A wind generator plant generally comprises of three main components; a wind turbine, an electric generator and control mechanism. Examples of the most commonly used wind generator types include permanent magnet synchronous generator (PMSG), squirrel cage induction generator (SCIG), doubly-fed induction generator (DFIG) and wound field synchronous generator (WFSG) [2]. Additionally, wind turbines can also be categorized into fixed or variable speed turbine based on their speed of rotation.

When coming up with a model of a wind generation system, there are two main aspects that must be put into consideration; the generator and converter system should must ensure that the generated voltage frequency conforms to the grid frequency and the control mechanism should regulate the speed of the rotor since this depends on the wind speed.

The rest of the paper is organized as follows; section II describes the general wind power generation scheme and its numerical design point of view, section III describes the system design used for this study, while IV describes the results from the simulations and V conclusions.

II. WIND POWER GENERATION SCHEME

Schematically, the power generation and its various components can be illustrated as shown in the figure 1 below.

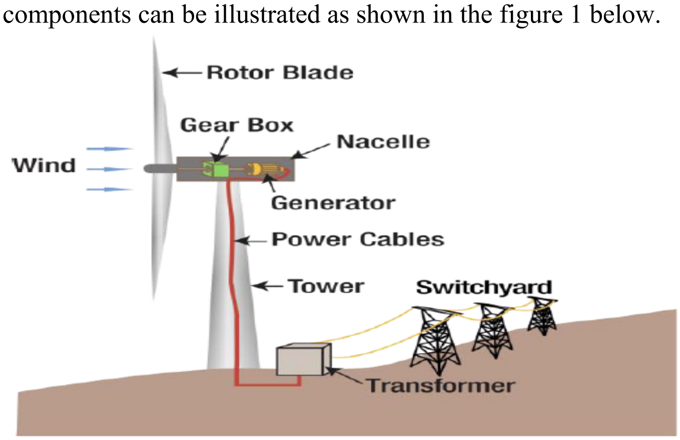

Figure 1: Wind power generation scheme

There are two broad categories of wind generators; synchronous and induction type generators. Their main differences lie mainly in their interface to the grid. When used to generate power, synchronous generators use power electronic converters interface in grid connection. On the other hand, the generated power from induction generators is directly fed to the main grid from the stator and use a small power electronic converter to feed power from the rotor to the grid. In other words, power is doubly fed to the grid from induction generators. Figure 2 below is a sketch of a DFIG wind power generator.

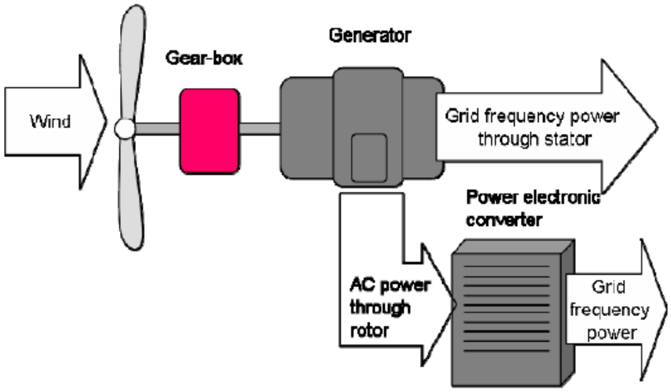

Figure 2: DFIG wind power generation

A. Wind turbines

Wind turbines are used to convert the kinetic energy from the wind to electrical energy. Using the orientation of the axis of the blade, the wind turbines can be classified into two categories; i.e. the horizontal axis and vertical axis wind turbine[2]. This is as illustrated by figure 3 and 4 below.


Figure 3: Horizontal axis turbine type


Figure 4: Vertical axis turbine type

Principally, the wind rotates the wind turbines which in turn makes the generator shaft also rotate. The motion of the rotor does the conversion of the shaft's mechanical power to electrical power. This power generated depends of the speed of the wind, air density, blade area covered and the type of generator used. The expression for the power generated from wind is as shown below [1] [3].

$$P_M = \frac{1}{2}\rho A C_P V^3 \tag{1}$$

This can be expanded as follows;

$$P_M = \frac{1}{2}\pi\rho C_P(\lambda.\beta)R^2V^3 \tag{2}$$

Where

A is the area swept by turbines blades, V is the speed of the wind (m/s), Pm wind turbine power, R is the radius of the blade, ρ is the air density (kg/m3) and β is the pitch angle measured in radians. The tip speed ratio is represented by the term **λ**. CP is the power coefficient of the wind turbine. This coefficient is not a constant parameter. It can be expressed in terms of β and **λ** as follows.

$$C_P = \frac{1}{2}\left(\frac{116}{\lambda_1} - 0.4\beta - 5\right)e^{\frac{-16.5}{\lambda_1}} \tag{3}$$

Where $\lambda_1$is a constant that can be expressed as follows;

$$\lambda_1 = \left(\frac{1}{\frac{1}{\lambda+0.089} - \frac{0.035}{\beta^3+1}}\right) \tag{4}$$

The MPPT of a wind generation system is shown in the diagram below.

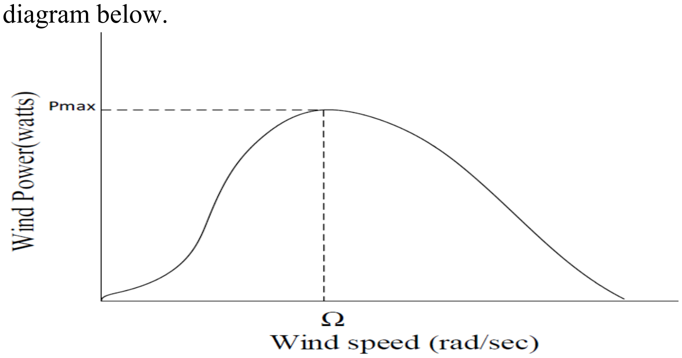

Figure 5: Wind Power-Speed characteristic curve

For maximum power production point,

$$\frac{dp}{d\Omega} = 0 \tag{5}$$

Applying the chain rule,

$$\frac{dP}{d\Omega} = \frac{dP}{dD} \times \frac{dD}{dV_w} \times \frac{dV_w}{d\Omega_e} \times \frac{d\Omega_e}{d\Omega} \tag{6}$$

Where D is the duty cycle of the converter, P the wind power, Vw the output voltage of the rectifier, **Ω** is the speed of the rotor and **Ω**eis the phase voltage angular speed of the generator.

The driving torque of the wind turbine can be expressed mathematically as follows;

$$T_m = \frac{1}{2}\rho A R C_T V_w^2 \tag{7}$$

Where C_T is the torque coefficient of the generator given be the equation below.

$$C_T = \frac{C_P}{\lambda} \quad (8)$$

The wind turbine output power versus pitch angles and Power coefficient of the turbine versus tip ratio for varying pitch angles outputs can be illustrated as shown in figure 6 and 7 below.

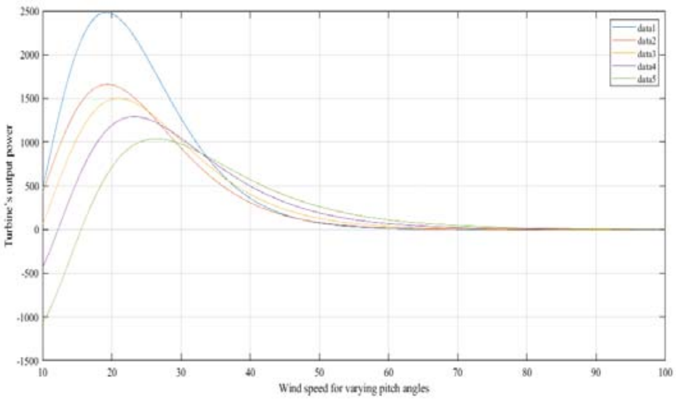

Figure 6: Turbine output power versus pitch angles

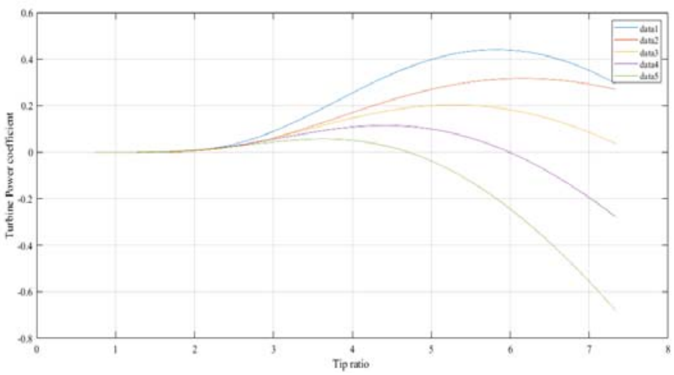

Figure 7: Power coefficient of the turbine versus tip ratio for varying pitch angles

The wind energy conversion system can be controlled using two methods to enhance maximum power extraction as the wind speed varies; aerodynamic power control and electric power control. The aerodynamic control method uses the information provided by the wind turbine manufacturer in the power curve that shows how the system performs at various wind speed levels. An example of a wind power curve is illustrated by figure 8 below.

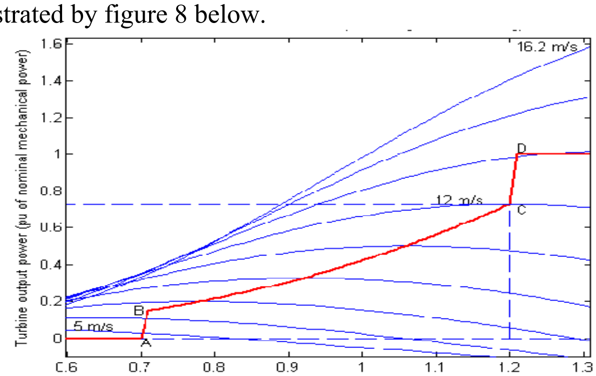

Figure 8: Wind power curve

For best performance of the wind generation system, the turbine speed should be controlled so as to be within the curve described by O-A-B-C-D where point A and D are known as the cut-in and cut-out speeds respectively. On the other hand, the electric power control method of wind generators uses pulse width modulated inverters in an effort to ensure constant voltage is supplied at a constant rated frequency.

B. DFIG wind generator

The application of this type of wind generator is increasing day by day due to its versatility, small converter rating requirement (30% of generator rating) and cost, ability to control both active and reactive power [4] and robustness [5]. The figure 9 below shows the topology for the DFIG generator.

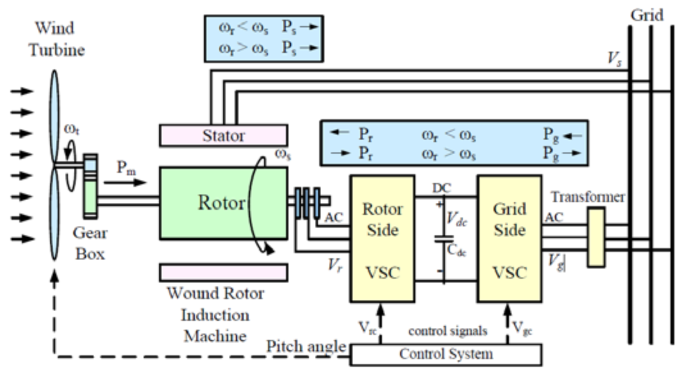

Figure 9: DFIG topology

Briefly the following are the functions of the various components of the DFIG generator shown in figure 9 above.

i. Wound Rotor Induction Machine (WRIM) whose rotor winding is connected to the voltage source converter (VSC) while the stator winding has a direct connection to the grid.
ii. Voltage Source Converters (VSC) of IGBT technology. The output from these VSCs are stepped up to conform to the voltage at the grid. The rating of these VSCs is proportional to the speed variation range of the WRIM.
iii. The DC-link with a capacitor is used to store energy, provide reactive power and remove ripples from the voltage. It also helps to stabilize two AC networks that are not synchronized. Its voltage is controlled by the grid side VSC.
iv. The control system does a number of functions in the DFIG topology. To start with, it regulates the wind turbines so as to ensure extraction of maximum power as much as possible and also avoid overloading of the system by controlling the pitch in case the wind speed exceeds the limits. It also regulates the rotor side VSC to maintain the rotor speed of the generator and the reactive power output from the stator.

When modelling DFIG type of wind generator, the wound rotor induction generator is modelled in a way that its rotor winding voltage is not zero at all times. Then, the park's transformation equations are used in d-q axes for the machine as shown in equations that follows [6] [7].

$$V_{ds} = -R_s i_{ds} - \omega_s \varphi_{qs} \quad (9)$$
$$V_{qs} = -R_s i_{qs} + \omega_s \varphi_{ds} \quad (10)$$
$$V_{dr} = -R_r i_{dr} - s\omega_s \varphi_{qr} \quad (11)$$
$$V_{qs} = -R_r i_{qr} + s\omega_s \varphi_{dr} \quad (12)$$

Where V is the machine voltage, φ is the machine winding flux, s the machine slip, ω_s the electrical frequency of the stator, R the resistance of windings and I the phase current of the system [8].

III. SYSTEM DESCRIPTION

A 10 MW DFIG wind farm driven by the wind turbine connected to an 11kV distribution system through a 5km feeder was modelled with the following characteristics;

- AC-DC-AC IGBT based PWM converter
- The stator windings are directly connected to the grid while the rotor is connected through an AC-DC-AC converter
- The speed of the wind flow is regulated at 15 m/s

The grid is modelled as a three-phase power source with internal Resistor–Inductor (RL) impedance. The ratings of the system transformer are 47MVA, 50 Hz, 120/25 KV and the wind farm transformer ratings are 10MVA, 50 Hz, 575 V/25 KV as illustrated in figure 10 below.

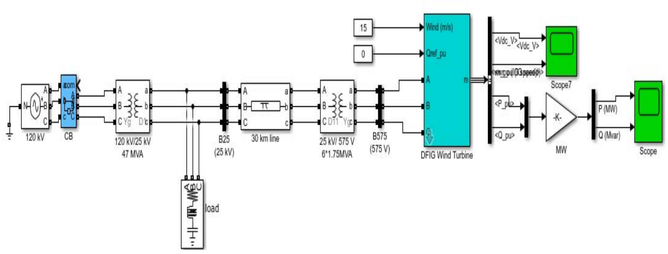

Figure 10: Grid connected DFIG wind farm

IV. SIMULATION RESULTS

The DFIG wind generation system was modelled and simulated using a MATLAB/Simulink software platform. The various operating conditions such as normal operation and loss of mains were simulated as shown in the subsections that follows. All system measurements were carried at the Point of common coupling (PCC).

A. Normal operation measurements

During the normal operation, the wind farm operates in parallel with the grid and both feed the loads. The voltage at the PCC is the grid voltage. Figure 11-14 below shows the measurements at the PCC under normal operating condition.

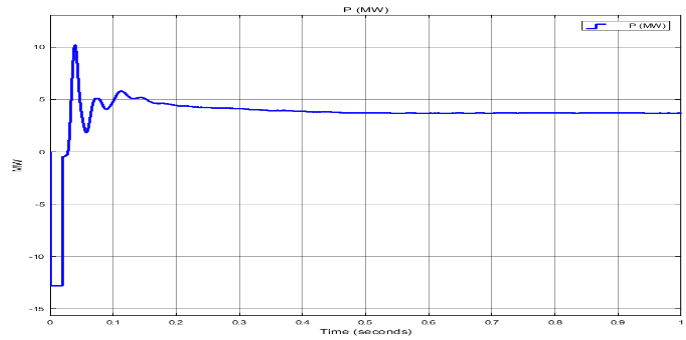

Figure 11: DFIG active power

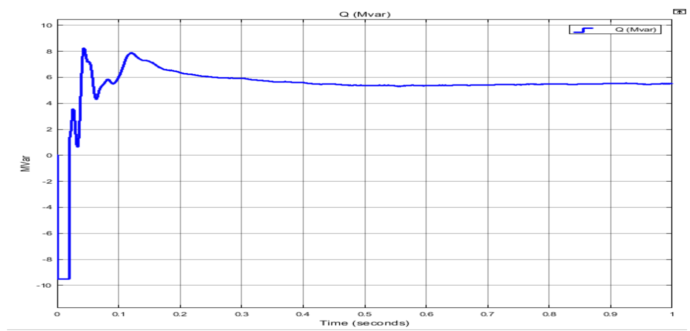

Figure 12: DFIG reactive power

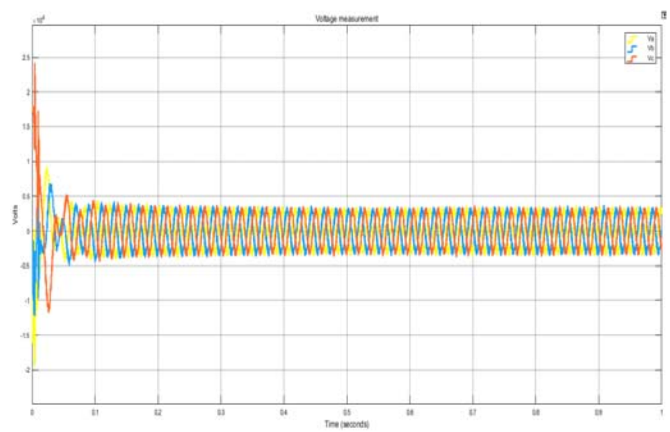

Figure 13: DFIG Voltage output

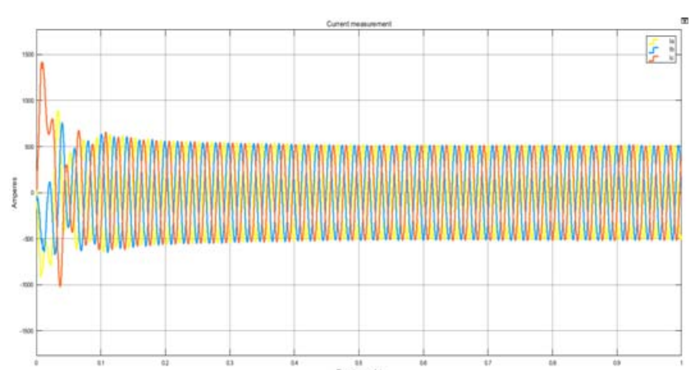

Figure 14: DFIG current output

B. Measurements during loss of mains

The mains were disconnected by creating a three-phase fault and the generator output observed as shown by the following graphs.

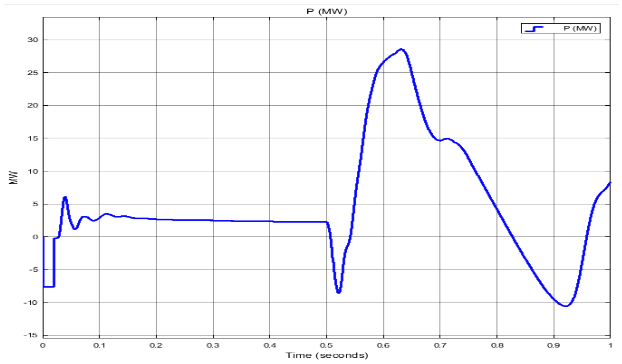

Figure 15: DFIG generator active power output

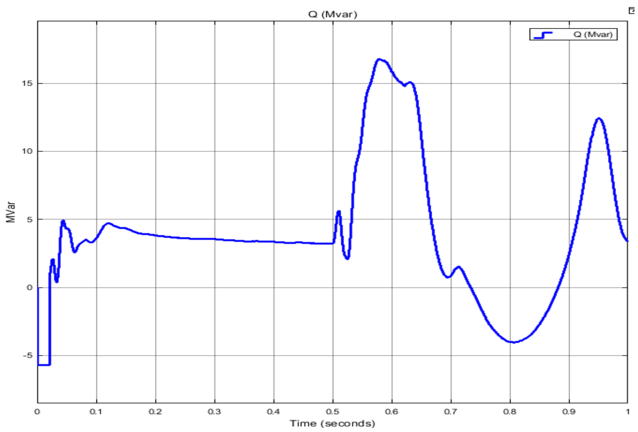

Figure 16: DFIG Reactive power output

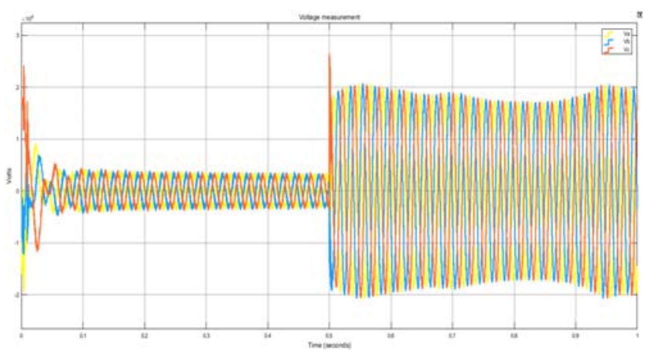
Figure 17: Voltage output

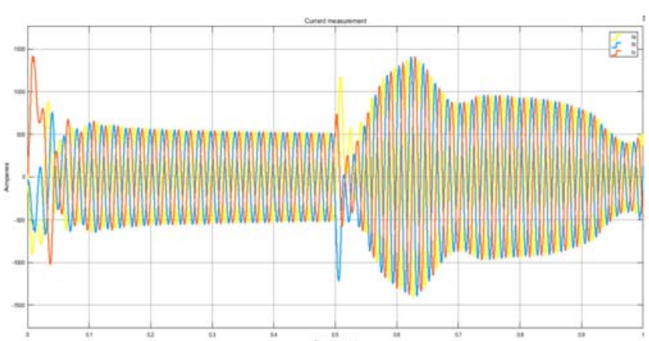
Figure 18: Current measurement

V. CONCLUSION

This paper discussed the modeling and simulation of a variable speed wind turbine using DFIG under MATLAB/Simulink platform. Firstly, an analytical model of wind turbine was presented and system behavior were measured and analyzed. This model of DFIG wind turbine can later serve as a basis to build hybrid energy supply in combination with other renewable energies like solar PV that could also be modeled in MATLAB/Simulink software.

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REFERENCES

[1] A. Amevi and B. H. Essel, "A Wind Turbine System Model using a Doubly-Fed Induction Generator (DFIG)," *International Journal of Computer Applications (0975 – 8887),* vol. 90, no. 15, pp. 6-11, 2014.

[2] P. Vishal, P. Sanket, T. Pushprajsinh and T. Chaudhary, "Modeling and simulation of solar PV and wind hybrid power system using MATLAB/SIMULINK," *International Research Journal of Engineering and Technology (IRJET),* vol. 5, no. 4, pp. 619-623, 2018.

[3] S. Khajuria and J. Kaur, "Implementation of Pitch Control of Wind Turbine using Simulink (Matlab)," *International Journal of Advanced Research in computer Engineering and technology (IJARCET),* vol. 1, 2012.

[4] K. Rajesh, A. D. Kulkarnib and T. Ananthapadmanabha, "Modeling and Simulation of Solar PV and DFIG Based Wind Hybrid System," *Procedia Technology* , vol. 21, p. 667 – 675, 2015.

[5] H. Elsherbiny, A. Hamdy, M. Shatla and A. Refky, "Efficiency Improvement for A Hybrid PV-Wind Energy System," *Current Science International,* vol. 5, no. 3, pp. 256-265, 2016.

[6] B. Abdolreza, K. Mehrdad and R. Omid, "Islanding Detection in Microgrid with wind turbine and reduce non detection zone," *ARPN Journal of Engineering and Applied Sciences,* vol. 15, no. 12, pp. 4340-4350, 2017.

[7] D. Velasco, C. Trujillo, G. Garcer´a and E. Figueres, "An Active Anti-Islanding Method Based on Phase-PLL Perturbation," *IEEE Transaction on Power Electronics,* vol. 26, no. 4, pp. 1056-1066, 2011.

[8] N. Senthil Kumar and J. Gokulakrishnan, "Impact of FACTS controllers on the stability of power systems connected with doubly fed induction generators," *Electrical Power and Energy Systems,* vol. 33, pp. 1172-1184, 2011.