Modelling And Simulation of Wind Farm for Voltage Regulation of a Mini-Grid

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Abstract- This paper presents the modelling and simulation of wind farm driven by doubly-fed induction generator (DFIG) which feeds alternating current (AC) power to the utility grid. Here, two pulse width modulated voltage source converters are connected back-to-back between the rotor terminals and utility grid via common direct current (DC) link. The grid side converter controls the power flow between the DC bus and the AC side. It allows the system to be operated in sub-synchronous and super synchronous mode of operation. The machine side converter provided the proper rotor excitation needed. The complete system is modelled and simulated in the MATLAB Simulink environment. The modelling was done in such a way that it can be suited for modelling of all types of induction generator configurations. Using dynamic vector approach for machine model, the model makes use of rotor reference frame. The results of the simulations showed that the voltage stability of the system was improved by 66.7% using the DFIG wind turbines. This is through their ability to control reactive power and decouple control of active and reactive power by independently controlling the rotor excitation current. It was observed that the system voltage was increased from 0.99p.u to 1.01p.u.

Indexed Terms- Doubly-fed Induction Generator, Wind Farm, Pulse Width Modulation Converter, Voltage Sag, Reactive Power

I. INTRODUCTION

Wind energy is one of the extraordinary sources of renewable energy due to its free availability and clean characteristic. Wind is produced by uneven heating of the earth by the sun making wind a renewable and free source of energy. Wind turbines are alternative sources of energy that harnesses this renewable wind power to make electricity. They (wind turbines) cause no pollution since they run solely on wind, making them environmentally friendly.

All over the world, research on wind power as a vital and promising renewable source of energy is being widely carried out. Recently doubly fed induction generator has become more popular in wind power due to its various advantages over other types of wind turbines. These advantages include variable speed, controllability, lower power electronic cost and so on (Takahashi, Ichita, Tamura, at el, 2010). It is a standard, wound rotor induction machine with its rotor windings connected to the grid through an AC/DC/AC Pulse Width Modulation (PWM) converter and its stator windings directly connected to the grid.

Many investigations in recent researches have been channeled to the use of the doubly fed induction machines, especially in generator mode for the wind turbine. It is important that the generator can function at variable speed but the presence of converters between the generator and the network reduces the efficiency of the system (Lei, Mullane, and Lightbody, 2006). The DFIG proposes a good compromise between the variable speed range which it handles and the converters size visa vis the machine nominal power. Several strategies are being established to control the power exchange between the machine and the network which it is connected to (Rodriguez-Amenedo, Arnalte, and Burgos, 2002). The induction generator is used with a two-stage AC-DC-AC inverter.

The alternating power of variable frequency can be modulated into that of constant frequency, by the rectifier and the inverter, to be used by loads. Therefore, this can effectively solve the issue of the amount of output power varying with the rotating speed and the load of the induction generator. In doubly-fed machine, it is possible to control both the active power and reactive power through modifications of magnitude and phase in excitation currents, while only the magnitude of terminal voltage can be controlled as a vector by means of modification of excitation currents in doubly-fed machine (Wei, Qiu, Xu, and Li, 2010). The three stages through which the development of the wind turbine system has gone through include (Thomas Ackermann, 2012):

a) Fixed speed stall-controlled induction generator.
b) Variable speed pitch controlled synchronous generator.
c) Variable speed, pitch controlled doubly-fed induction generator (DFIG).

The variable nature of the wind makes the DFIG suitable and important. Through power electronic converter control, the DFIG can be operated in any desired power factor. Moreover, a lower converter cost and also a lower loss can be achieved through a special connection of rotor windings (Sun, Chen, and Blaabjerg, 2005). The stator of DFIG is directly connected to the grid while the rotor is indirectly to the grid through back-to-back converters which are capable of providing 10-40% of the generators rated power. The back-to-back converters are controlled by pulse width modulation (PWM).

Control strategy proved to be effective by the simulation results in Matlab/Simulink environment (see Figure 2). For large- scale electromechanical conversion of wind power to mechanical power, the use of a DFIG is a preferred option. For control, the DFIG requires a two-sided controller; a rotor-side controller (RSC) to control both the speed of operation and the reactive power, and a grid-side controller (GSC) using a grid- side voltage-source converter which is responsible for regulating DC-link voltage as well as the stator terminal voltage (Lujano-Rojas, Monteiro, Dufo-López., Bernal-Agustín 2012). The RSC functions include:

a) Maintaining stable operation by regulating the rotor speed.
b) By means of current control, regulates the reactive power and holds the stator output voltage frequency constant.
c) Ensuring maximum wind power capture by altering the speed set-point.

The function of the GSC is to ensure regulation of the DC-voltage bus, and thereby indirectly controls the stator terminal voltage (Tapia, Tapia, Ostolaza, Saens, 2003). The commonly used induction machines by the wind turbine industry today are the doubly-fed wound rotor induction machines with d-q vector control and very are attractive to the high performance (Lie, Cartwright, 2006). There are several reasons for using variable-speed DFIG wind turbines, among those are:

a) To reduce the mechanical structure stresses.
b) The back-to-back PWM converter, connected between the grid and the induction machine rotor circuit, only to handle a fraction (20-30%) of the total system power (Lie, Cartwright, 2006)

A decoupled d-q control approach is the general control technique for the grid-side converter control, widely used in wind power industry. It uses the quadrature axis current component for reactive power control and direct axis current component for real power control (Peña, Cardenas, Asher 2013).

The power quality problems may become a serious concern, in the case of smaller installations connected to weak electric grids such as medium voltage distribution networks, because of the proximity of the generators to the loads. One of the main disturbances related to power quality in distribution networks is the existence of voltage dips. In developed countries, it is known that from 75% up to 95% of the industrial sector claims to the electric distribution companies are related to problems originated by this disturbance type (Touaiti, Azza, Jemli, 2015). These problems emanate from the fact that many electrical loads malfunction during voltage dip. The main aim of this paper is to model and simulate wind farm for voltage regulation of a mini-grid using an iterative power system simulation package, to evaluate the impact of strategically placed wind generators on distribution systems with respect to the critical voltage variations and collapse margins. This work concludes with the discussion of wind generators excellent options (the doubly fed induction generator) for voltage regulation.

II. WIND TURBINE MODELLING

By means of torque production, the wind turbines are able to convert the kinetic energy present in the wind into mechanical energy. Its magnitude depends on the air density and the wind velocity since the energy contained by the wind is in the form of kinetic energy. The wind power developed by the turbine is given by the equation 1 (Slootweg, Polinder and Kling, 2011):

$$P = \frac{1}{2} C_P \rho A V^3. \qquad (1)$$

Where; C_P is the Power Co-efficient,
ρ is the air density in kg/m^3,
A is the area of the turbine blades in m^2 and
V is the wind velocity in m/sec.

The fraction of the kinetic energy which is converted into mechanical energy by the wind turbine is given by the power coefficient C_P. It is a function of the tip speed ratio λ and depends on the blade pitch angle for pitch-controlled turbines. The tip speed ratio may be defined as the ratio of turbine blade linear speed and the wind speed

$$\lambda = \frac{R\omega}{V}. \qquad (2)$$

Substituting (2) in (1), we have:

$$P = \frac{1}{2} C_P(\lambda) \rho A \left(\frac{R}{\lambda}\right)^3 \omega^3. \qquad (3)$$

The output torque of the wind turbine $T_{turbine}$ is calculated by the following (3).

$$T_{turbine} = \frac{1}{2} \rho A C_P V / \lambda. \qquad (4)$$

Where R is the radius of the wind turbine rotor (m). There is a value of the tip speed ratio at which the power coefficient is maximum. By operating variable speed turbines at a blade speed that gives the optimum tip speed ratio, they can be made to capture this maximum energy in the wind. This can be achieved, by changing the speed of the turbine in proportion to the change in wind speed.

III. MODELLING OF WIND FARM CONNECTED TO A MINI-GRID

The overall single line diagram of DFIG-based wind power system is as shown in Figure 1, it consists of wind power model and DFIG model.

Figure 2 shows the Simulink model of the single line diagram of the wind farm. Here, a 9-MW wind farm consisting of six 1.5 MW wind turbine connected to a 11kV distribution system exports power to a 33kV grid through a 30km, 11kV feeder. A 2.3kV, 2 MVA plant consisting of a motor load (1.68MW induction motor at 0.93PF) and of a 200kW resistive load is connected on the same feeder at bus B11. The DC link voltage of the DFIG is also monitored.

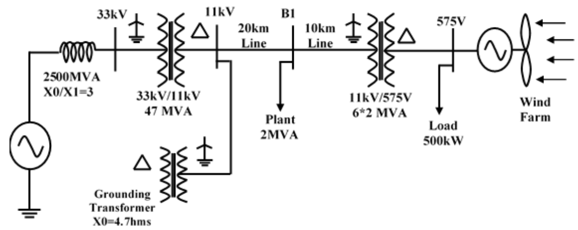

Figure 1: Single-line diagram of the wind farm connected to a distribution system

A doubly-fed induction generator (DFIG) consisting of a wound rotor induction generator and an AC/DC/AC IGBT-based PWM converter is used in the wind turbines. The rotor is fed at variable frequency through the AC/DC/AC converter while the stator winding is directly connected to the 50Hz grid. The DFIG technology is suitable for extracting maximum energy from the wind for low wind speeds. It does this, by optimizing the turbine speed, while minimizing mechanical stresses on the turbine during gusts of wind. The optimum turbine speed which produces maximum mechanical energy for a given wind speed is proportional to the wind speed. The rotor runs at sub-synchronous speed for wind speeds lower than 10m/s. When the wind speed is high, it runs at hyper-synchronous speed.

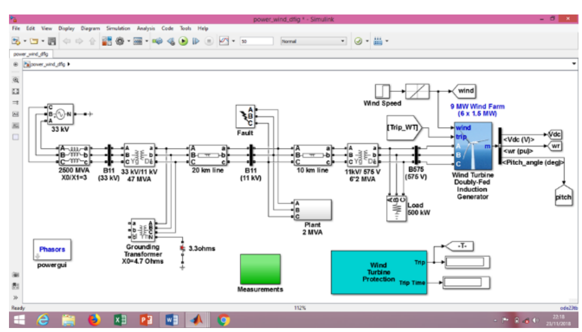

Figure 2: Simulink model of the DFIG wind farm connected to a distribution system

As a phasor model, the wind turbine permits transient stability studies with enough simulation times. Here, in this work, the system is observed for 50 seconds. The four sets of parameters specified for the turbine, the generator and the converters (grid-side and rotor-side) are considered, from the wind turbine block menu. The six-wind-turbine farm is simulated by a single wind turbine block by multiplying the following three parameters by 6, as follows:

i From the turbine data menu, the nominal mechanical output of the wind turbine is specified thus: $6 * 1.5e6$ watts.
ii From the generator data menu, the generator rated power is set thus: $6 * 1.5/0.9$ MVA $(i.e. 6 * 1.5$ MW at 0.9 PF).
iii From the converter data menu, the nominal DC bus capacitor is set thus: $6 * 10e3$ microfarads.

IV. RESPONSE OF THE TURBINE AS WIND SPEED CHANGES

The single-line diagram of the system under study is illustrated in Figure 1 while the equivalent Simulink model of the system is shown in Figure 2. First, the wind speed is set at 8 m/s, then to observe the response of the turbine to a change in wind speed, at time t = 5 seconds, wind speed was increased suddenly to 14 m/s. The wind turbine generated active and reactive powers are presented in Figure 3 while Figure 4 shows the DC bus voltage. It can be observed that, at time t = 5 seconds, the generated active power starts increasing smoothly (together with the turbine speed) to attain its rated value of 9 MW in approximately 20 seconds as shown in Fig. 3.

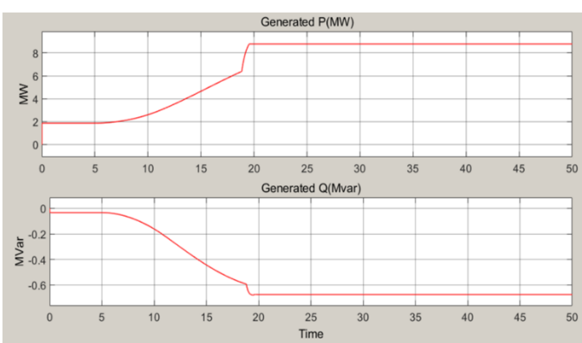

Figure 3: Generated active and reactive power of the turbine under sudden increase of wind speed (Time is seconds)

The reactive power is controlled to maintain a voltage of 1 pu. It can be observed that, at the nominal power, the wind turbine absorbs 0.68 Mvar (generated Q = -0.68 Mvar) to control voltage at 1pu (see Figure 3).

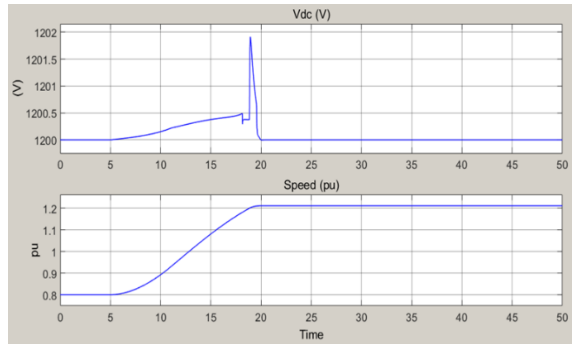

Figure 4: DC bus voltage and turbine speed under sudden increase of wind speed (Time is seconds)

The turbine speed increased from 0.8pu to 1.21pu over that time frame as presented in Figure 4. Initially, the pitch angle of the turbine blades is at zero degree and the turbine operating point follows the normal cubic relationship of the turbine power characteristics. Then, in order to limit the mechanical power, the pitch angle is increased from 0 deg to 0.76 deg as presented in Figure 5.

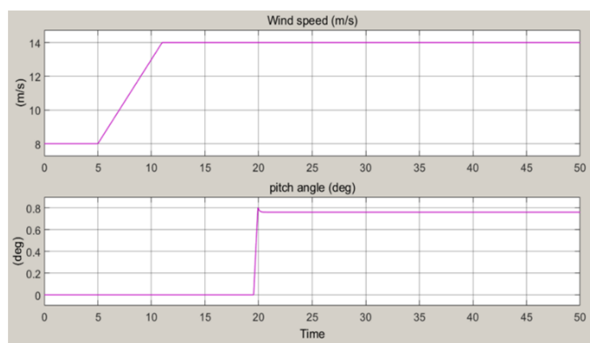

Figure 5: Wind speed and turbine pitch angle (Time is seconds)

When the wind turbine mode was changed to “Var regulation” with the “Generated reactive power Qref” set to zero, it was observed from Figure 6 that the plant voltage increased to 1.01 pu when the wind turbine generates its nominal power at unity power factor.

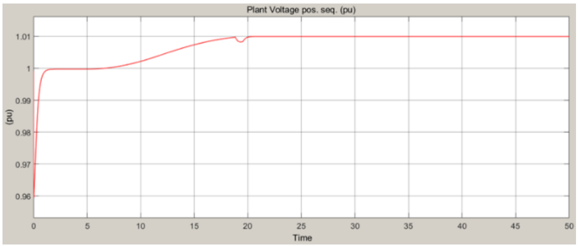

Figure 6: Response of the plant voltage when the wind turbine is at "Var regulation" mode (Time is seconds)

V. SIMULATION OF A VOLTAGE SAG ON THE 33KV SYSTEM

The impact of a voltage sag resulting from a remote fault on the 33kV system is investigated. First, the wind speed step is disabled by changing the final value from 14m/s to 8 m/s, from the wind speed step block. Then, a 0.15 pu voltage drop lasting for 0.5 s is programmed to occur at time t =5 seconds, from the programmable voltage source.

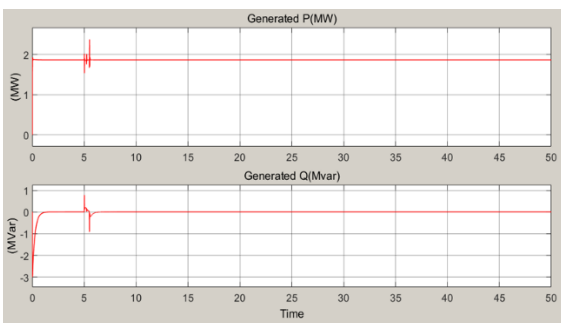

Figure 7: Generated active and reactive power of the system during voltage sag (Time is seconds)

It can be observed from Figure 7, that the wind farm produces 1.87MW. Also, at time t = 5 seconds, the voltage falls below 0.9 pu as shown in Figure 8. The protection system trips the plant at time t = 5.22 seconds because an undervoltage lasting more than 0.2 s has been detected (as in the protection settings and status in the ''Plant'' subsystem).

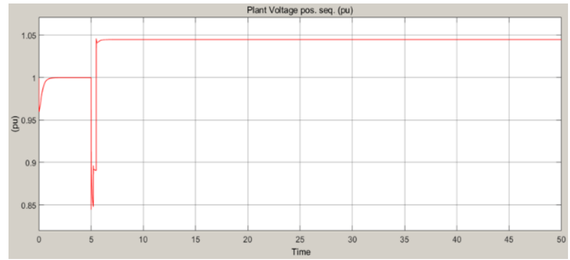

Figure 8 The plant Voltage (when the wind turbine control mode was changed to "Voltage regulation"), due to voltage sag resulting from a remote fault (Time is seconds)

As shown in Figure 9, while the wind farm continues generating at a power level of 1.87 MW, the plant current falls to zero and motor speed gradually decreases. About 1.25 MW of power was exported to grid after the plant has tripped, as evidently shown in Figure 10.

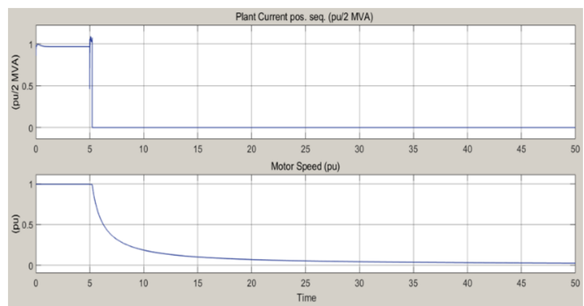

Figure 9: The plant current and motor speed due to voltage sag resulting from a remote fault (Time is seconds)

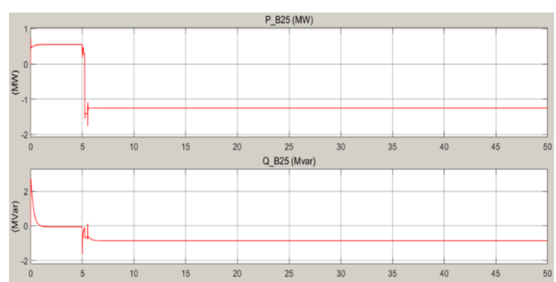

Figure 10: Generated active and reactive power of the system after the DFIG has tripped during the voltage sag

Now, it was observed from Figure 11, when the wind turbine control mode was changed to "Voltage regulation", that the plant does not trip anymore. This is because during the voltage sag the voltage support provided by the 5MVar reactive power generated by the wind-turbines keeps the plant above the 0.9 pu protection threshold. During the voltage sag, the plant voltage is now 0.93pu as shown in Figure 12.

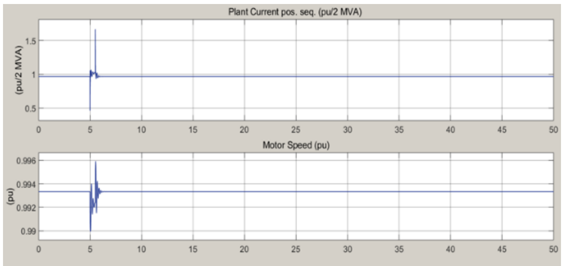

Figure 11: The plant current and motor speed (when the wind turbine control mode was changed to "Voltage regulation"), due to voltage sag resulting from a remote fault

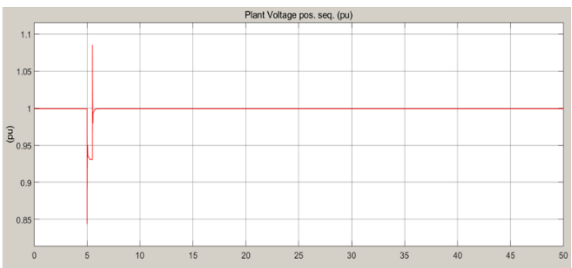

Figure 12: The plant Voltage (when the wind turbine control mode was changed to "Voltage regulation"), due to voltage sag resulting from a remote fault.

CONCLUSION

The variation of wind turbine causes change of operation mode in the wind turbine system. The wind turbine is operating in maximum power point tracking mode, when the wind is less than rated speed, so Cp = 0.48 while tip speed ratio = 8.1 with pitch angle = 0. When the wind speed is more than rated speed, pitch control starts operating as a result, Cp < 0.48, tip speed ratio < 8.1 and pitch angle > 0. The detailed modeling of DFIG has been carried out for a wind energy conversion system. The DFIG has been found capable to work for a wide speed range and it is clear that power fed to the grid can be controlled by controlling the rotor current's components. The vector control allowed decoupled or independent control of both active and reactive power of doubly-fed induction generator.

Using DFIGs in wind turbines instead of other asynchronous generators offers the following advantages:

a) Sudden variations in the generator power output and rotor torque can be virtual eliminated,
b) At lower wind speeds, electrical power can be generated,
c) While the amplitude and frequency of the generated voltages remain constant, it can be operated at variable rotor speed,
d) The power factor can be controlled. For instance, in order to maintain unity power factor, and
e) The amount of power generated can be optimized as a function of the wind available up to the nominal wind turbine generator output power.

As a challenge asynchronous generator does not require complex power conversion circuitry, while the DFIG does require it. Secondly, the rotor of the squirrel-cage induction machine used to implement the asynchronous generator require no rings while the slip rings on the wound-rotor induction machine used to implement the DFIG require periodic maintenance.

The work has been able to implement voltage regulation and Var regulation during a voltage sag on a 33kV line using AC/DC/AC IGBT-based PWM converter in DFIG. The grid system voltage stability regulation was actually demonstrated by observing the response of the turbine to change in wind speed and through simulating the model for a fault on the 11kV system.

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