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Modeling of Wind Energy Conversion System using PSCAD/EMTDC

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Abstract- This paper aims to model a complete wind energy conversion system (WECS) connected to a grid. The motivation comes from the Distributed Generation System (DGS) installed in the Renewable Energy Lab at UMass Lowell. The objective of this work is to develop universal and standardized manufacturer independent textbook model. Manufacturer specific models are more accurate and detailed, but proprietary and non-disclosure agreements become an issue for research purposes. Since wind turbines installed in the renewable energy lab are VSWT (Variable Speed Wind Turbine) with permanent magnet synchronous generator (PMSG), so such a turbine system is modeled to represent them in general. PMSG requires very less maintenance and has higher efficiency, as it doesn't have rotor current and is without a gearbox. Furthermore, there are two more advantages: firstly, it has the variable speed control capability and rotor speed can be changed in a larger range; secondly, excitation system is independent of the grid and requires another excitation source. In addition to the turbine generator, other main components of WECS are also modeled namely: wind source model, wind turbine, permanent magnet synchronous generator and AC/DC/AC control. The equation governing these models are also discussed. The entire generation system is integrated to the grid and implemented in PSCAD/EMTDC. Moreover, a basic fault analysis is done under different conditions. The proposed model can be used for research purposes on distributed generation issues. This model provides a good software simulation test bed for further research.

Keywords Permanent magnet synchronous generator, grid connection, power electronics interface, reactive power control, variable speed wind turbine (VSWT).

1. Introduction

The modern power system integrates various AC and DC systems in areas of power system distribution, transmission, and generation. Power system handles both centralized and distributed generation sources and must accommodate controllable, variable, and intermittent energy sources such as wind energy, solar energy. The integration of wind power into electrical grid is steadily increasing in United States due to the latest environmental concerns [1] and this trend is expected to continue. There are different technologies for wind turbine system and one such technology is variable speed wind turbine (VSWT). Variable speed wind turbines can operate over a wider range of wind speeds. Speed and power control enables variable speed wind turbines to yield 20 to 30 percent more energy than fixed speed turbines [2].

Recently, several authors have studied the impact of wind energy integration into electrical grid and identified the main problems as power quality, power factor, voltage control, frequency synchronization, reactive power control and harmonics. [11-15]. Shafiullah et. al [16] has introduced simulation models to investigate the potential challenges by using PSS-Sincal. Whereas, Hansen et. al [17] has proposed dynamic wind turbine models by using DIgSILENT. But there is still no universal and standardized manufacturer-independent 'textbook model' for the variable speed wind turbine which can be used as a test-bench for academic and research purposes.

This paper aims at modeling a complete wind energy conversion system (WECS) connected to an electrical grid by using PSCAD/EMTDC. It is a simulation tool used to model and study the transient behavior of electrical systems, with a variable speed wind turbine that employs a permanent magnet synchronous generator. The motivation comes from the distributed generation system (DGS) installed in the renewable energy lab at University of Massachusetts Lowell. The objective of this work is to develop universal and standardized manufacturer-independent ‘textbook model’. As the installed wind turbines in the lab are Variable Speed Wind Turbine (VSWT) with permanent magnet synchronous generator (PMSG), so such a turbine system is used to represent them.

The variable speed operation has many advantages, one is the improved fault response as the wind generator is decoupled from the grid. The turbine can also operate over a wider range of wind speeds, making it to extract more power from the wind. The size of generating unit is reduced since a permanent magnet has no rotor windings, excitation losses [3] and variable speed turbine systems are mostly connected to the distribution system [4]. This makes to study the impact of such a system on the electrical grid and requires simulation from a reliable tool. The schematic diagram of the modeled wind turbine generation system is shown in Fig.1 and consists of following:

- Wind source model
- Wind turbine
- Gearless direct-drive permanent magnet synchronous generator
- Uncontrolled diode rectifier
- DC link
- Current source inverter
- Distribution grid

This paper will proceed as follows: the methodology for wind turbine model is explained in section 2. Subsequently, the permanent magnet synchronous machine (PMSG) and power electronics control is introduced in section 2.3 and 2.5. Then, in section 3 a radial electrical grid has been taken as an example to simulate the effects of the proposed model at constant and variable wind speed condition. Finally, in section 4 the fault analysis and systems response to distributed generation is discussed. The results are concluded in section 5 with an outlook for the future research proposal.

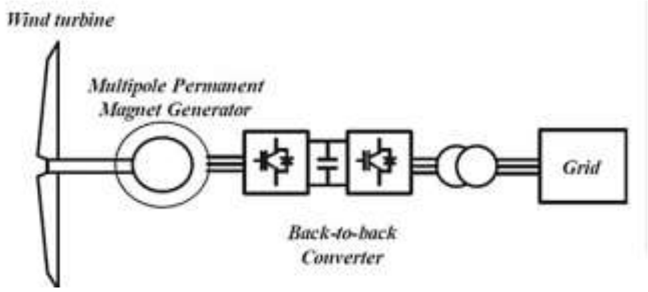


Fig. 1. Schematic representation of modeled wind turbine.

2. Modeling

In this section, the modeling of each component is discussed and most parameters are taken from the model presented in [5].

2.1. Wind source model

A model for wind source should be able to simulate the spatial effect of wind [6] and the model used in this study consider the following:

- mean wind speed
- periodic gust with a sinus form
- noise
- ramp
- damper for all above conditions

The wind source model from PSCAD considers all the above and can be defined by Eq. (1):

$$V_w = V_b + V_g + V_r + V_n \quad (1)$$

Where,

V_b = base wind speed [m/s]

V_g = gust wind component [m/s]

V_r = ramp wind component [m/s]

V_n = noise wind component [m/s]

V_b is the constant speed and assumed to be always present. It is the base component at which the rated characteristics of the turbine and generator are determined [5]. Generally, the mean wind speed is taken as base component, approximately equal to 13 m/s. The gust component V_g can be expressed as a function of sine or cosine [7] and an increasing wind speed is simulated by using the ramp wind component V_r. Finally, the noise wind component models the noise by using equations given in the reference [6]. The cut-in speed is above which mechanical brakes are released and cut-out speed is the limit above which turbine blades are stopped. In this study, the cut-in speed is set at 4 m/s and the cut-out speed is set at 25m/s. These values for the mean wind speed, cut-in and cut-out speed limit are the standard design values for variable speed turbines and used in studies [1-7]. The schematic diagram of wind source model is shown in Fig.2.

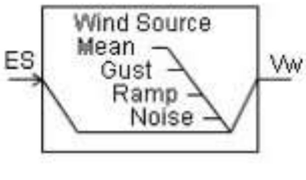


Fig. 2. Schematic representation of the wind source model.

2.2. Wind turbine

Wind turbine is modeled from the built-in models available in PSCAD, which models the mechanical physics of a wind turbine [6]. It takes into the account the blade configuration, coefficient of power, tip speed ratio, blade radius and swept area. However, in this study the shaft dynamics are not taken into consideration as our wind turbine is a three-blade horizontal axis turbine. We have used the MOD 2 model and equations to model the blade dynamics are:

$$\lambda = \frac{\omega_M R}{V_W} \tag{2}$$

$$C_P = (0.44 - 0.0167\beta) sin\,\frac{\pi(\lambda - 2)}{13 - 0.3\beta} - 0.001854\,(\lambda - 2)\beta \tag{3}$$

$$P_M = 0.5\,\rho A C_p V_W^3 \tag{4}$$

$$T_M = \frac{P_M}{\omega_M} \tag{5}$$

Where,

λ = tip speed ratio (TSR)

ω_M = angular mechanical speed [rad/s]

R = radius of turbine blade [m]

V_w= wind speed [m/s]

C_p = power coefficient

β = is pitch angle of blade

P_M = mechanical power from wind turbine blades [kW]

ρ = air density [kg/m3]

T_M = mechanical torque from wind blades [N·m]

The inputs to the wind turbine component are wind speed (V_w), angular mechanical speed (ω_M) and pitch angle (β). Whereas, mechanical torque (P_M) and mechanical torque (T_M) are outputs. The mechanical torque (T_M), is input to the wind turbine generator (PMSG) which converts the mechanical power to electrical power. The PSCAD wind turbine model is shown in Fig.3 and the turbine parameters are given Table 1.

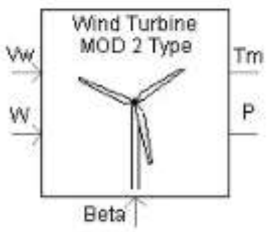


Fig. 3. PSCAD wind turbine model [7].

Table 1. Wind turbine parameters used in this study.

Rated power	3 [MVA]
Rated angular mechanical speed	3.14 [rad/s]
Rotor radius	46.2 [m]
Air density	1.225 [kg/m^3]

2.3. Permanent magnet synchronous generator

The wind turbine is equipped with the permanent magnet synchronous generator (PMSG) and the model is used from [8]. It is a fully developed synchronous machine model which can be used to examine both transient and sub-transient behavior. The generator is a direct drive, having less cost, maintenance, and weight. These generators have usually higher number of poles e.g. 50 to 300 and can even withstand lower speeds from 20 to 60 rpm [4]. But these generator uses an exciter like the IEEE type 1 model [9], which helps the DC bus in maintaining the output voltage of an inverter at adequate level. This is calculated by,

$$V_{dc} \geq \frac{2\sqrt{2}.V_{ac(RMS)}}{D_{MAX}} \tag{6}$$

Where,

D_{MAX} = maximum duty cycle.

$V_{ac(RMS)}$ =line to neutral RMS voltage of an inverter.

The model also contains two additional windings which are short-circuited during modeling to simulate the electromagnetic dampening effect [8]. A gear-less synchronous machine is used in variable speed operation and its electrical speed is not synchronized with the electrical network, but is usually kept lower than that of electrical network. The base electrical frequency (f_B) of the machine must be equal to wind turbine rated speed (RPM) and equations to find the base angular electrical frequency (ω_B) are,

$$f_B = \frac{N_P}{2}.\frac{RPM_{TUR}}{60} \tag{7}$$

$$\omega_B = 2\pi f_B = \pi . N_p . \frac{RPM_{TUR}}{60} \quad (8)$$

Here, N_P is the no of pole pairs. The base electrical frequency (f_B) and base angular electrical frequency (ω_B) values are calculated for the configuration of permanent magnet synchronous generator (PMSG). The parameter used in this study are given in Table 2.

Table 2. PSMG model parameters used in this study.

Rated RMS line to neutral voltage	0.69 [kV]
Rated RMS line current	1.45 [kA]
Base angular electrical frequency	314.16 [rad/s]
No. of pole pairs	100

2.4. Wind turbine model simulation

The wind turbine model is created with connecting the synchronous generator with wind source model and wind turbine model. Upon simulating, when wind turbine starts the torque is greater than the electromagnetic torque and the wind turbine speed initially increases. Upon steady state condition, the wind turbine power is equal to the rated power 3.6 MW and angular mechanical speed is equal to the rated speed 3.1 rad/s. The wind turbine model simulation and curves that follow swing equations are shown in Fig.4, Fig.5.

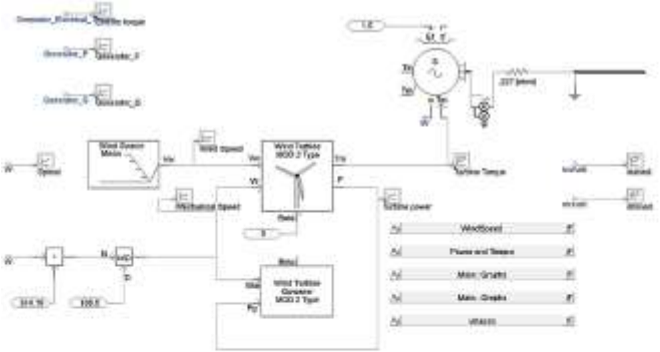


Fig. 4. The wind turbine model.

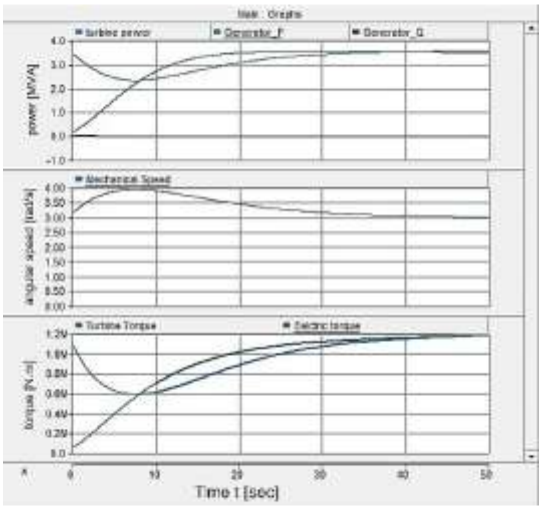


Fig. 5. Turbine power, generator active and reactive power, mechanical speed, turbine torque and electrical torque.

2.5. Power electronics control

An electric grid requires constant voltage and frequency and an AC-DC-AC converter is necessary for modeling a complete wind energy conversion system (WECS) connected to a grid. AC-DC-AC conversion is implemented in the following three stages:

- Uncontrolled Diode Rectifier
- DC bus with storage capacitance
- 6-pulse bridge inverter using thyristors

2.5.1. Uncontrolled diode rectifier

The over-voltages in the power system are expected as the output voltage of wind generator directly depends on the wind speed. As a rule-of-thumb over-voltage of 10% is considered as secure and all voltages above that should be blocked by the rectifier [13-15]. This is implemented by using a ‘Single Input Level Comparator’ available in the PSCAD library. Rated DC voltage is connected to its input and the output is connected to the KB input of rectifier. The ideal average output of three phase full wave rectifier under no-load is calculated by Eq. (9)

$$V_{dc} = V_{av} = \frac{3\sqrt{3}.V_{peak}}{\pi} \quad (9)$$

2.5.2. DC-Bus

The DC bus is used after the diode rectifier. The DC bus uses capacitor to dampen the voltage sags. However, a resistor is included to limit the amount of current flow when capacitor initially starts conducting. The resistance is shunted after capacitor gets charged, usually after 3 time constants. The value of capacitor and resistance is calculated by using:

$$C = 2.\frac{E}{V_{dc}} \quad (10)$$

$$E = P * t \quad (11)$$

$$R = \frac{V_{dc}}{I} \quad (12)$$

Where,

V_{dc}= voltage of the DC bus

t = time which the DC bus must tolerate voltage-sags.

I = rated current.

For calculating the resistance, it is assumed that initially DC bus entire voltage appears across the resistor, as the voltage across the capacitor increases slowly. Then, three time constants (3*RC) are used to calculate the time after which resistance is shunted and the ‘single phase breaker’ is used to shunt the resistor. The DC bus must be protected against overvoltage as the output of the generator is proportional to the variable wind speed. This is done by using a ‘Single Input Level Comparator’ and the sequence is shown in Fig.6.

2.5.3. *6-pulse bridge inverter*

An inverter is modeled by using 6-pulse bridge inverter and a current source thyristor inverter is used for the final stage of AC/DC/AC. A thyristor converter is bi-directional in voltage and mono-directional in current. The 6-pulse bridge inverter should be able to regulate the DC voltage within some range. In case of the fault on distribution system it should be able to limit voltage collapse of DC bus. An inductor is added at the input of inverter for modeling a current source to bear a voltage sag of t seconds. The inductor value is calculated by,

$$W = 0.5 * L * I^2, \text{where } I = 3 * \frac{P_{dc}}{V_{dc}} \qquad (13)$$

2.5.4. *Validation*

The model is simulated after connecting the diode rectifier, DC link capacitor and the 6-pulse inverter to validate the behaviour of the AC-DC-AC converter. It is noticed, the wind turbine power and wind turbine torque decreases with the increase in speed. This can be explained due to decrease in the power coefficient (C_P). The over-voltage regulation limit is applied through the ‘Single Input Level Comparator’ to KB input of rectifier and the DC bus voltage is limited to 1760 V. The rectifier is blocked above 1760 V. We can observe a spike at 7.5s. This is when the breaker shunts the resistance. Finally, the steady state is reached with time and the current at DC bus goes to zero. This can be observed in Fig.7 and Fig.8.

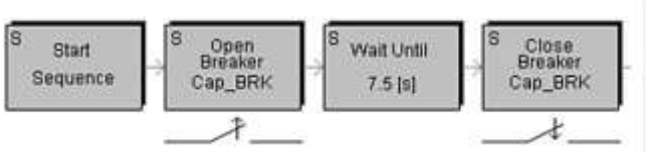


Fig. 6. Sequence used to control breaker.

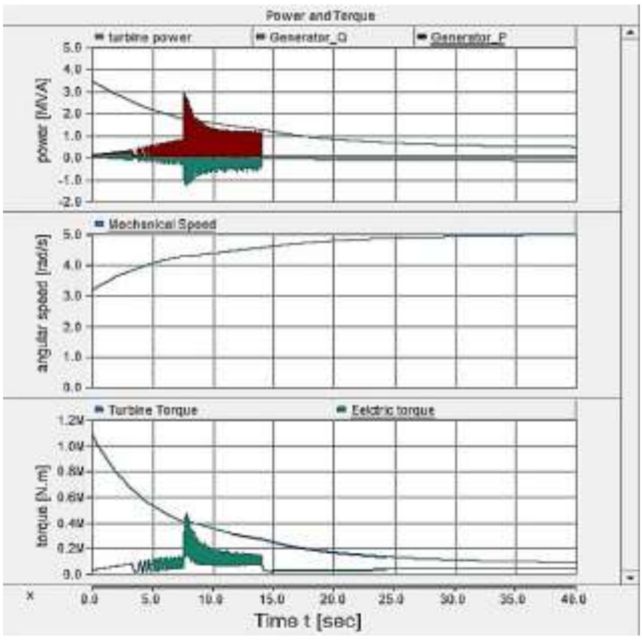


Fig. 7. Turbine power, generator active and reactive power, mechanical speed, turbine torque and electrical torque.

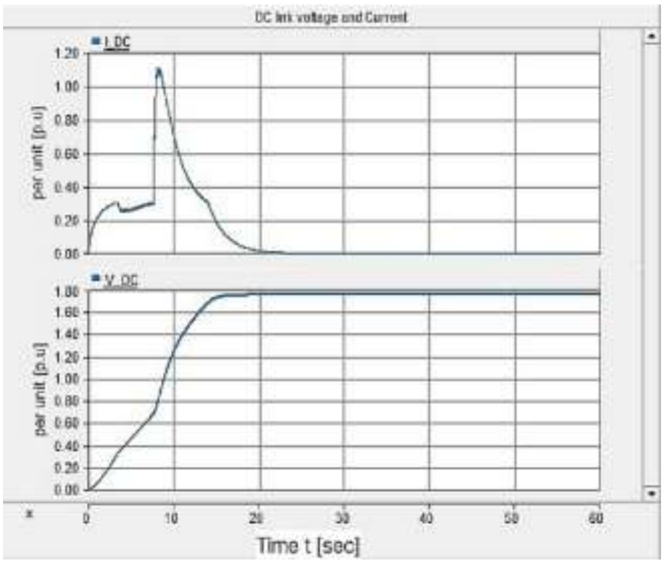


Fig. 8. DC link current and voltage.

2.6. *Voltage Regulation*

The voltage control of network is required either at the connection point of inverter or at the DC bus to cater the wind turbine impact. There is a higher impact for a wind farm and the voltage regulation is done at the connection point. In our case, a single turbine has a weak impact on the network and the voltage regulation is done at DC bus, as in [5]. The DC bus voltage is defined not to fluctuate beyond 0.95pu to 1.05pu of the DC bus voltage and the following two components from the PSCAD Master library are used:

- Voltage dependent current limiter.
- Generic current controller.

2.6.1. *Voltage dependent current limiter*

It has two inputs VD, CI and one output CO. VD is the measured value of the DC bus in kV and CI is the reference current. 'Applying limit' (V_{on}) and 'Removing Limit' (V_{off}) are two defined limits and the DC voltage is maintained between it. A minimum current value is also entered under 'Current Limit' and works as follows:

- if VD > 'Removing Limit'(V_{on}): Current Order CO = Current Input CI, which is current for the rated power
- if VD < 'Applying Limit'(V_{off}): Current Order CO = Current Limit, which is minimum current in the inverter.

2.6.2. Generic current limiter

A generic current controller produces an alpha order for the PI controller which acts on the error between current order (CO) and the measured current on DC bus. It has two inputs, CD, CO and an output DA. CD is the measured current in kA and CO is current order from the 'voltage dependent current limiter'. The output DA gives the firing angle to fire thyristors of the inverter.

3. Simulation

3.1. Radial Grid

This section simulates the complete model and analyses results from this study. First, a radial grid is introduced and then one complete model is simulated with the interconnection of all the earlier defined models in PSCAD/EMTDC. The radial distribution grid has three nodes as shown in Fig.9 and the wind generation system is connected at the node 2. The wind generation system consists of wind turbine model, power electronics control and voltage regulation from section 2.4, 2.5 and 2.6. The proposed system model implemented in PSCAD/EMTDC is shown in Fig.10 and the parameter used in this study are given in table (3).

Table 3. Radial distribution grid parameters same as in [5].

Voltage Source Magnitude (L-L, RMS)	34.5 [kV]
Voltage Source Frequency	50 [Hz]
3 Phase Transformer MVA	300 [MVA]
3 Phase Transformer Winding Voltages	34.5 [kV] / 12.4 [kV]
Node 1 Load Ratings	2.13 [MW], 1.6 [MVAR], 7.2 [kV]
Node 2, Node 3 Load Ratings	0.26 [MW], 0.2 [MVAR], 7.2 [kV]

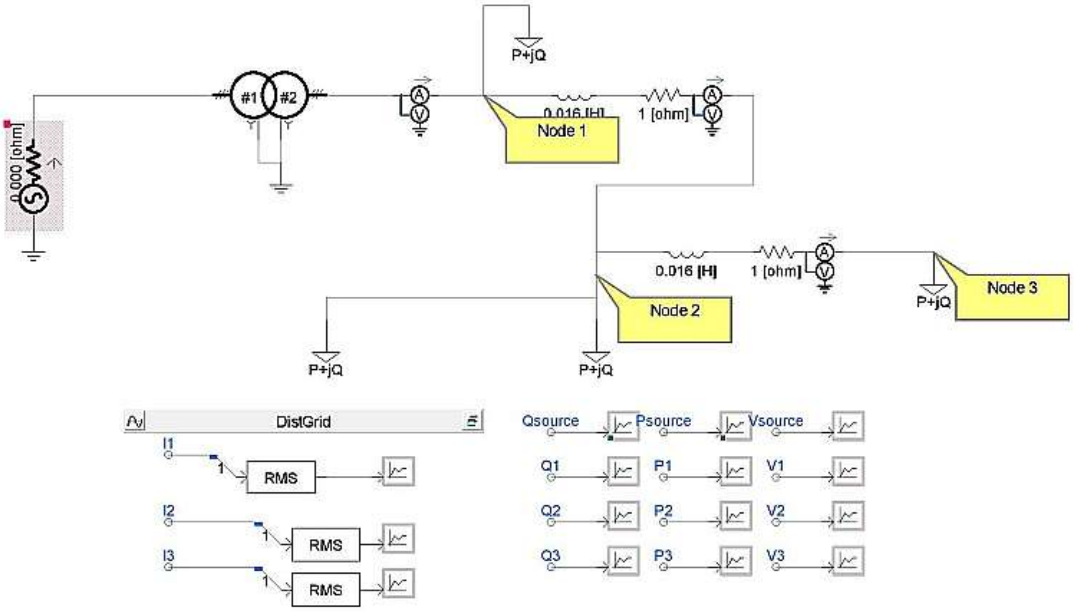


Fig. 9. Radial distribution grid.

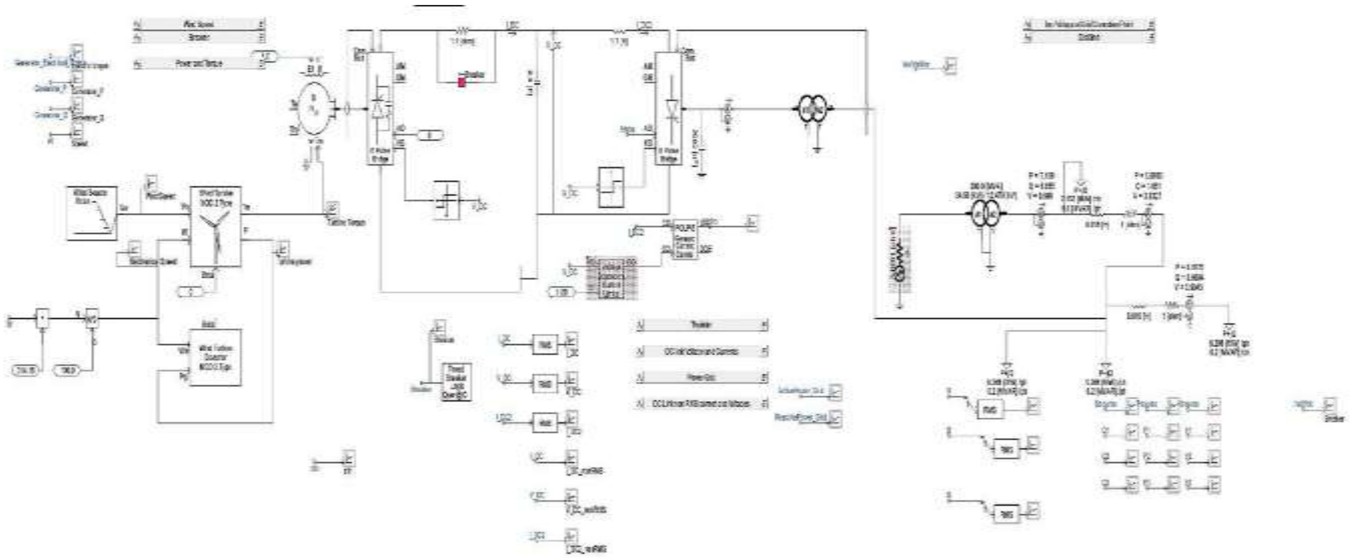


Fig. 10. Variable speed wind turbine (VSWT) implemented in PSACD/EMTDC.

3.2. Constant wind

As explained above, the inverter regulates the DC bus voltage between 0.95 p.u and 1.05 p.u of the rated DC bus voltage. The DC bus voltage is 1600 volts and is maintained between 1520 V and 1680 V. We observe, there is a sudden rise in IDC2 due to the breaker operation at 7.5 sec. This is the point at which the resistance is shunted and capacitor conducts a high current. The current IDC2 doesn't flow to the grid until inverter is unlocked, which happens at 1520 V. The current is 0.06 p.u below this value, as defined in the 'Voltage Dependent Current Limits'. The active power increases as current into the grid increases, which is maintained between 1.5 MW to 1.7 MW. Alpha angle varies with the voltage to keep the DC bus voltage within the limit. Finally, we observe the decrease in the reactive power due to the capacitor and the system response at constant wind speed is shown in Fig. (11) and Fig. (12).

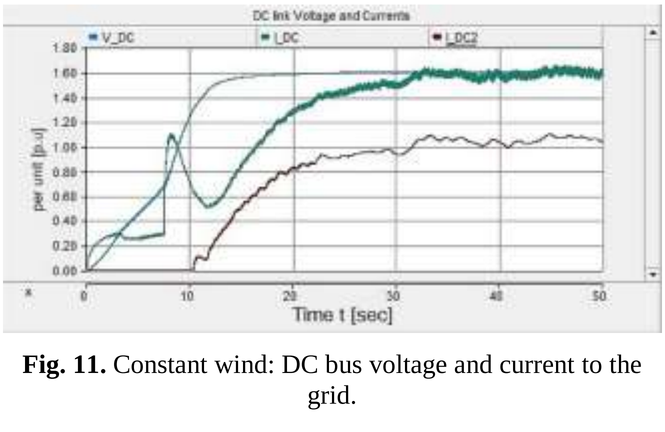


Fig. 11. Constant wind: DC bus voltage and current to the grid.

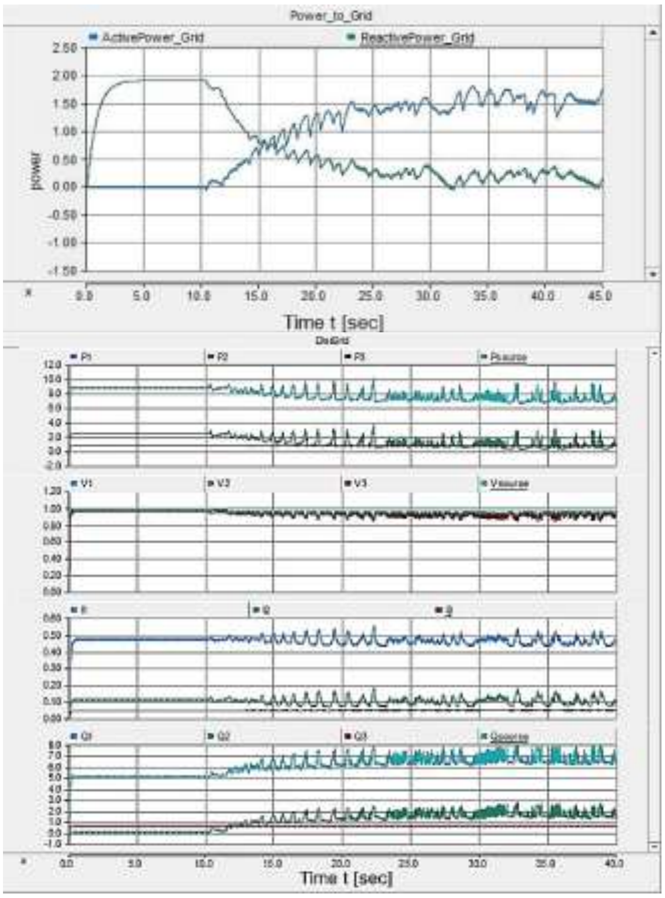


Fig. 12. Constant wind: a) active and reactive power to the grid. b) power, voltages and currents to the grid.

3.3. Variable wind

The behavior of wind turbine is quite fluctuating at variable wind speed. The wind speed is varying from 6-20 m/s. We observe, the wind turbine torque and wind turbine power increases with the wind speed, but the increase in mechanical speed is gradual. The breaker operates same as that with constant wind at 7.5 sec. But, here VDC, IDC and IDC2 have much higher values. The active power is maintained within 1.5 MW to 1.7 MW. Whereas, there is high increase in reactive power into the grid. The system response for variable wind speed is shown in Fig. (13).

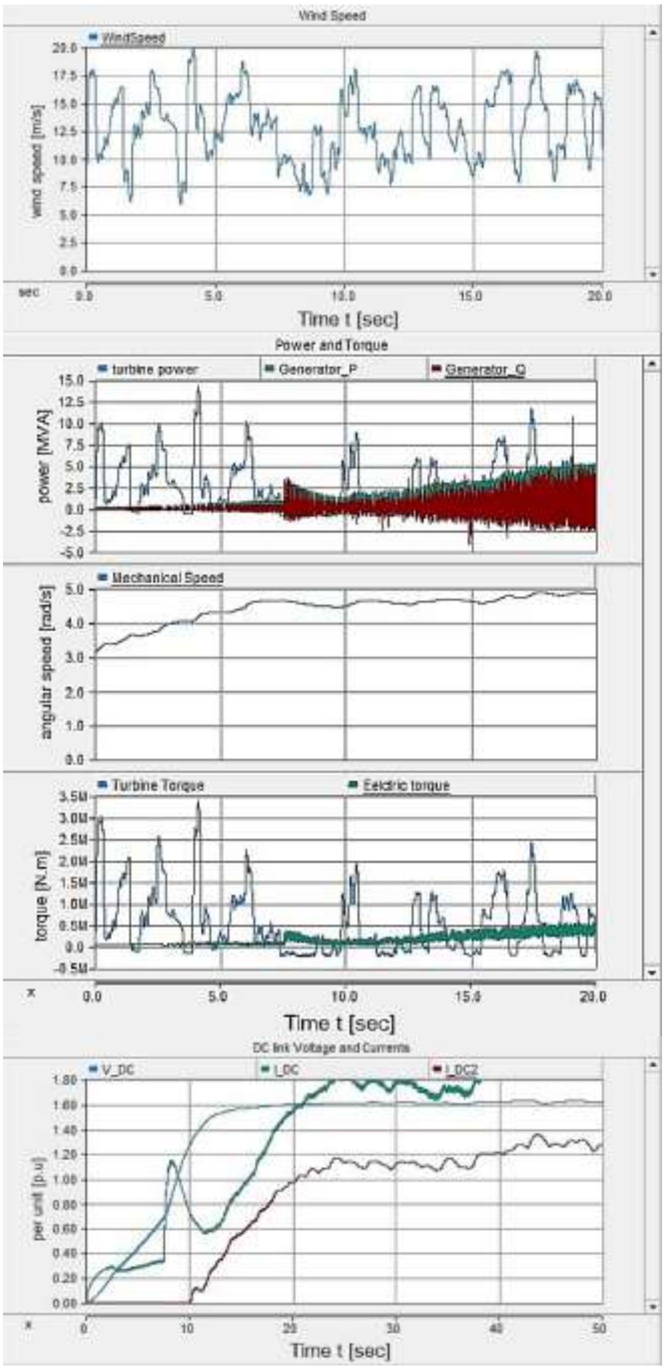


Fig. 13. Variable wind: a) variable wind speed. b) turbine power, generator active and reactive power. c) mechanical speed. d) turbine torque and electrical torque for the variable wind. e) DC bus voltage and currents.

4. Fault analysis: system response to DG faults

The increase in distributed generation penetration impacts the electrical distribution grid. Electrical grids are designed on a concept of conventional centralized generation with the electrical power flow from generation, transmission to the distribution. This impact is attributed to the fact that electrical grid wasn't originally designed to integrate renewable energy generation on the distribution side. Besides, fault detection is another major problem for the distribution generation. The intensity and direction of fault current should be taken care when the distributed generation is present in the system and protection requirements must be re-evaluated.

A simple radial network is taken from the section 3.1 to study the effect of distributed generation on the network. Single line to ground fault is introduced at different points on the distribution network. Fault currents both in the presence and absence of distributed generation are plotted to determine the necessary protection requirements.

4.1. Fault on Node 3 of network with and without DG

A single line to ground fault is introduced at node 3 of the grid. Node 3 is the point at consumers end. The fault current and current is observed in case of the distributed generation (DG) connected and disconnected at the Node 1. It is noticed, the peak value of fault current is around 0.7 kA at t = 15 sec, making the current into the Node 1 as 0.97 kA with DG connected and 1.06kA with distributed generation (DG) disconnected. This difference in the peak value of fault current requires the fault detection level to be defined below the smaller value. Furthermore, the utility company should make sure that normal currents in the absence of distributed generation (DG) must be lower than the fault detection level. The RMS values of the fault current and the current into the Node 1 are plotted in Fig. 14 and Fig.15.

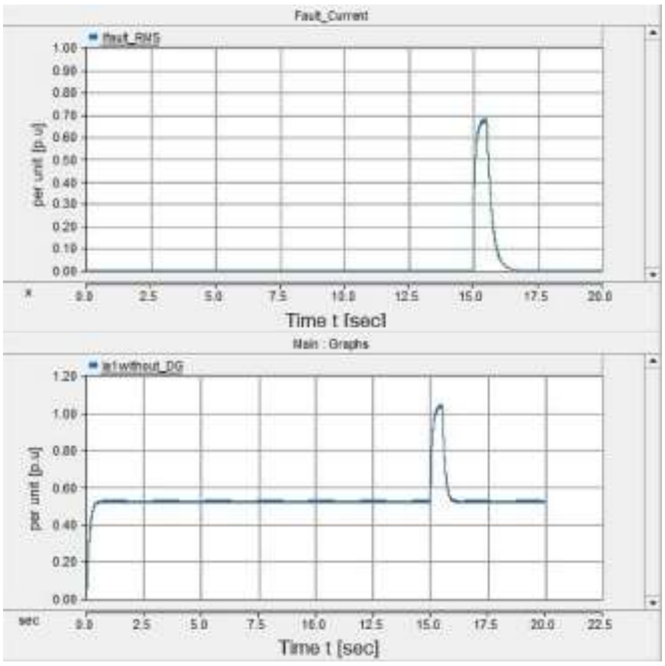


Fig. 14. Fault on Node 3: a) fault current (RMS value). b) phase current at node1 without DG.

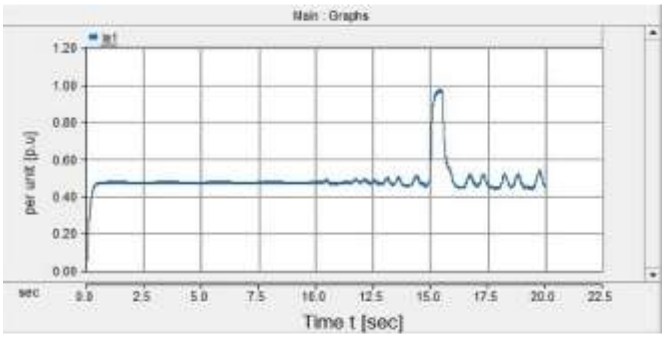
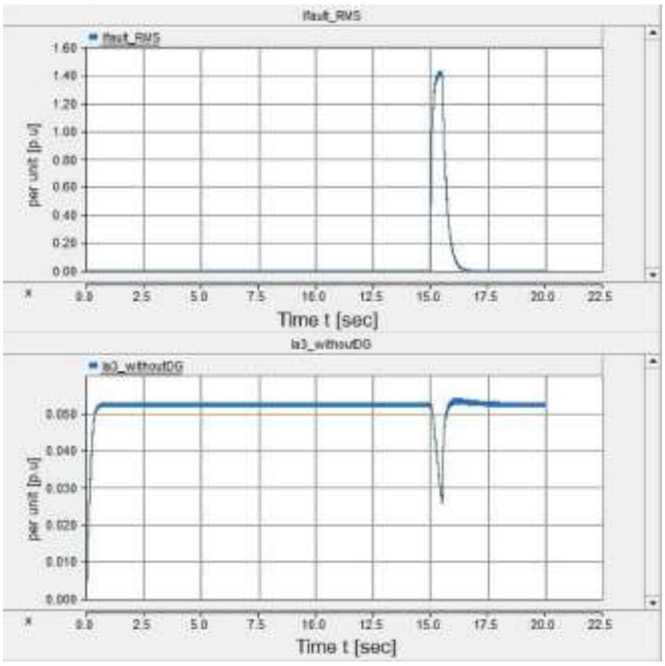


Fig. 15. Fault on Node 3: phase current at node1 with DG.

4.2. Fault on Node 2 of network with and without DG

A single line to ground fault is applied at node 2 of the grid. The network is analysed in the case of distributed generation (DG) connected and disconnected at the Node 3. Plots for the active power, fault current and current into the Node 3 are plotted for both cases. It is noticed, the peak value of fault current is greater than at the Node 1. The peak value of fault current is 1.40 kA at t = 15 sec. The results show the peak value of the current into the Node 3 is positive at 0.26kA with distributed generation (DG) disconnected and negative at -0.09kA with distributed generation (DG) connected to the Node 3. The current is negative because of the negative value of active power. The fault will not be detected if there is a protection system that depends on the direction of power flow. Hence the fault current will keep on flowing. These fault conditions show that the impacts of distributed generation (DG) need to be considered before connecting distributed generation (DG) to the grid as it changes the protection level. The RMS values of the fault current and the current into the Node 3 are plotted in Fig. 16a-16c



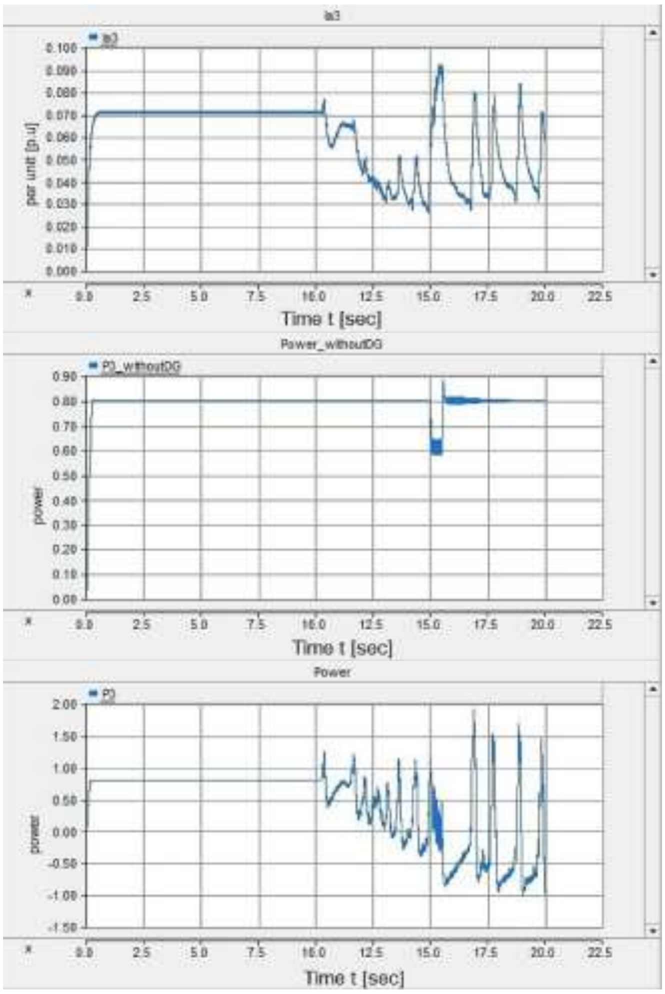


Fig. 16. Fault Node 2: a) fault current (RMS value). b) phase current at node 3 without DG. c) phase current at node 3 with DG. d) active power at node 3 without DG. e) active power at node 3 with DG.

5. Conclusion

A model for the wind energy conversion system (WECS) along with necessary power electronic interface for the grid connection has been presented and implemented in PSCAD/EMTDC at the constant and variable wind speed conditions. The proposed model and power electronics interface is validated and simulations are presented. Results for the power system are performed at the transient time domain.

A step-by-step approach is used to model the system by using MOD-2 wind turbine model with permanent magnet synchronous generator (PMSG). It is concluded that the behavior of wind turbine is quite fluctuating at variable wind speed, particularity the reactive power infeed into the grid. This also creates the fault detection problem, as the protection equipment depends on the direction of power flow. Furthermore, equations for the calculation of network parameters are also discussed along with network's ability to regulate its voltage and results are analysed under constant and variable wind speed conditions.

The challenge for the distributed generation integration into conventional electric grid has been studied and several fault analyses were carried out to analyze the effect of distributed generation system on grid. It changes the system behavior and fault conditions show that the impact of distributed generation (DG) need to be considered before connecting distributed generation (DG) to the grid, as it changes the protection levels. Therefore, a comprehensive study to analyze grid interface requirements before connecting distributed generation is required. This presented model can be useful to study the impact of wind generation system on the power quality of a power network. Furthermore, utility companies can also predict and analyze impacts on the power generation.

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