Abstract

In this paper the wind energy operations in addition to its all vital issues during transients are presented. A Type III or class C type wind turbine system with induction generator is implemented which is fed from both the side of rotor and grid. As the T-III-WT-DFIG wind turbine system is effective over normal speed variation among all sustainable power sources; with variable-pitch control for variable speed it is main criteria for the motive of the research. The major issue in wind energy system design is variable speed in the power generation sectors; so this research can play an important role to define the transient analysis and fault clearances. The system is integrated with 1.5MW grid system for the analysis. Using the MATLAB Simulink, the type-III WT DFIG with variable speed wind turbine integrated with the grid system is simulated and the control action is performed by conventional PI controller in the generator and turbine coupling. In this research paper three cases such as voltage dip or sag, 3 phase fault analysis and wind speed variation are executed and the stability of the power system are discussed.

Keywords: Type- III WT, DFIG, WECS, SVOC, wind turbine, Auto Regressive Moving Average, decoupled control

I. Introduction

On the basis of cost and effective renewable energy source; Wind energy system can play a vibrant role among other sustainable energy develop systems like photo voltaic, geothermal or tidal. It is the most inexpensive and effective alternative
energy source. Wind energy is sufficient, so no harmful chemicals or gasses are emitted into the atmosphere. The Wind Energy is an effective and zero harmful to our environment which makes it a more favorable option for renewable energy. Different control techniques have been proposed to run the WECS in stable and reliable mode. On basis of control action the stator voltage can be control all the aspects of active and reactive power during the transients and make the system faster towards stability. In this control the Stator is directly assembled to the grid system and made the parameters of the voltage constant [I]. The whole model is consists of grid side and rotor side controllers into the grid tie up and the mechanism is fully controlled by the conventional control action using PI controller [III]. The grid side with stator maintained with unity power factor with dc link attachment with parallel to the both grid and rotor controller. The converter at the rotor side can control the torque and both the powers of active and reactive in the system under the stator voltage control action. The MPPT controller is implemented at the stator terminal used to supply the actual values of the reference parameters for the control over active power [IV]. Pitch angle controller also used in the wind energy model to work under the high speed of wind which is the major factor of implementing the Type III DFIG system to the wind model. The research paper of this study is used to the highlight the control actions of the controllers and the effective study during the transients [XII][XV].

II. Wind Generator Model

As the wind system shows the fast and better performance, such as high energy transmission capacity, low maintenance and operational cost over the versatile control, the DFIG (double fed induction generator) plays superior in industrial technology for analyzing the impact of the wind farms link on the power grid. DFIG provides many benefits, such as decoupling the active and reactive power control [V][VI]. Figure 1 displays the overall diagram of a wind generator based on DFIG modeled in MATLAB.

III. Type-III WT DFIG Model

Type I FSIG (Fixed Speed Induction Generator) system is based on fixed speed rather a Type II WT DFIG wind system is operated under partial variable speeds. In Type III WT DFIG system it can work under variable wind speed in partial scale control action shown in figure 1 below. The Type IV WT PMSG system is variable speed of operation in full scale controller. The Type-III WT DFIG equations according to axis d and q scheme can be expressed as below [XII]:

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Fig. 1: Type III WT DFIG-based wind generator [IV]

The model shown in the figure 1 depicts the control action of Type-III DFIG under the transients and the rotor side, grid side control operations on the stator voltage control mechanism. The control is also use a conventional PI controller of control system for the steady state and transient actions of settling time during fault clearances [III][IV].

\[
\begin{align*}
\dot{v}_{ds} &= -R_s x_{ds} + (x_s + x_m) i_{qs} + x_m \dot{v}_{qr} \\
\dot{v}_{qs} &= -R_s i_{qs} - (x_s + x_m) x_{ds} + x_m \dot{x}_{dr} \\
\dot{v}_{dr} &= -R_s x_{dr} + (1-\omega)x((x_r + x_m) x_{dr} + x_m \dot{x}_{qs}) \\
\dot{v}_{qr} &= -R_s x_{qr} + (1-\omega)x((x_r + x_m) x_{dr} + x_m \dot{x}_{ds})
\end{align*}
\]

Where: \(\dot{v}_{ds}, \dot{v}_{qs}\) are d and q axes of the stator voltages; \(\dot{v}_{dr}, \dot{v}_{qr}\), d and q axes of the rotor voltages; \(i_{ds}, i_{qs}\), d and q axes of the stator currents; \(i_{dr}, i_{qr}\), d and q axes of the rotor currents; \(R_s, R_r\), stator and rotor resistance; \(x_s, x_m\), stator self-reaction; \(x_r\), rotor self-reaction; \(x_m\), rotor speed. The inserted active and reactive forces in the network can be expressed as given blow [VI]:

\[
P = v_{ds} x i_{ds} + v_{qs} x i_{qs} + v_{dr} x i_{dr} + v_{qr} x i_{qr}
\]

\[
Q = - \frac{x_m v^2}{x_s + x_m} - \frac{v^2}{x_m}
\]

Here \(v\) is the magnitude of grid voltage.
The Type-III WT DFIG has the mechanical motion system associated with the wind gear box and coupled to the blades [VII]. The motion equation of the wind turbine system derives the torque due to electromagnetic effect and the mechanical torque. The equations are shown as follows:

\[
\begin{align*}
J \frac{d\omega_m}{dt} &= T_e - T_m \\
T_e &= \frac{3P}{2} \text{Re}(j\lambda_s i_s^*) = -\frac{3P}{2} \text{Re}(j\lambda_r i_r^*)
\end{align*}
\]

Here \( J \) = MI-moment of inertial of the rotor (Kgm^2)

\( P \) = number of poles

\( T_m \) = Mechanical Torque (N.m)

\( T_e \) = Electromagnetic Torque (N.m)

\( \omega_m \) = Rotor Mechanical Speed (rad/s)

The mathematical modeling of Type-III base on dq frame of reference conversion in dq axis representations [VII]. The modeling equations are present below:

\[
\begin{align*}
\overline{v}_s &= v_{ds} + jv_{qs} \\
\overline{v}_r &= v_{dr} + jv_{qr} \\
\overline{i}_s &= i_{ds} + ji_{qs} \\
\overline{i}_r &= i_{dr} + ji_{qr} \\
\overline{\lambda}_s &= \lambda_{ds} + j\lambda_{qs}; \quad \overline{\lambda}_r = \lambda_{dr} + j\lambda_{qr}
\end{align*}
\]

Voltage equations for stator and rotor in dq axis frame are:

\[
\begin{align*}
v_{ds} &= R_s i_{ds} + p\lambda_{ds} - w\lambda_{qs} \\
v_{qs} &= R_s i_{qs} + p\lambda_{qs} + w\lambda_{ds} \\
v_{dr} &= R_r i_{dr} + p\lambda_{dr} - (w - w_r)\lambda_{qr} \\
v_{qr} &= R_r i_{qr} + p\lambda_{qr} + (w - w_r)\lambda_{dr}
\end{align*}
\]

Flux linkages to stator and rotor in dq axis reference frame are:
Motion due to mechanical rotation is shown in equations in dq reference frame are:

\[
\begin{align*}
\lambda_{ds} &= (L_{ds} + L_{ms})i_{ds} + L_{ms}i_{dr} = L_s i_{ds} + L_m i_{dr} \\
\lambda_{qs} &= (L_{qs} + L_{mq})i_{qs} + L_{mq}i_{qr} = L_s i_{qs} + L_m i_{qr} \\
\lambda_{dr} &= (L_{dr} + L_{mr})i_{dr} + L_{dr}i_{ds} = L_r i_{dr} + L_m i_{ds} \\
\lambda_{qr} &= (L_{qr} + L_{mq})i_{qr} + L_{mq}i_{qs} = L_r i_{qr} + L_m i_{qs}
\end{align*}
\]

(12)

IV. Wind Turbine Model

The wind turbine mechanical torque can be presented as \( T_m \):

\[
T_m = \frac{P_w}{\omega}
\]

(14)

The wind turbine system can extract the as \( P_w \): 

\[
P_w = \frac{1}{2} \rho c_p A V_w^3
\]

(15)

Where: \( c_p \) - power coefficient, \( \omega \) - rotor speed, \( \rho \) - air density (kg/m\(^2\)), \( A \) - rotor area (m\(^2\)) and \( V_w \) (m/s) - wind velocity. Thus the electrical torque \( T_e \) and the mathematical link between \( T_m \) and \( T_e \) results:

\[
T_e = x_m (i_q i_{ds} - i_d i_{qs})
\]

(16)

\[
\frac{d\omega}{dt} = \frac{1}{2H} (T_m - T_e)
\]

(17)

Here \( H \) is denotes rotor inertia.

V. Wind Speed Model

Mathematically wind speed \( V_w(t) \) is characterized by four components of its controls: i) Initial and average value of wind speed \( V_{wa} \) (m/s); ii) Ramp component \( V_{wr} \) (t); iii) The gust component \( V_{vg} \) (t) iv) Turbulence of wind speed \( V_{wt} \) (t). Therefore the mathematically wind speed \( V_w(t) \) represented as follows: 

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\[ V_w(t) = V_{wa} + V_{wr}(t) + V_{wg}(t) + V_{wt}(t) \] (18)

Fig.2: Typical configuration of ARMA wind speed model [III]

The figure 2 shown above represents the generation of wind speed in artificial manner through the Gaussian noise generator using ARMA (autoregressive moving average) technique taking unity delay function [VI].

VI. Modelling of Grid Connected WECS

Grid network is equipped with a variable speed wind turbine generator network is shown in below figure 3. The doubly fed induction generator type-III has three-stage stator windings are directly associated with the network. In this system a bi-directional converter with a three phase transformer is connected with the rotor frame.

Fig.3: Wind Turbine Design with Type-III-WT-DFIG [VI]

GSC-Grid side converter gives a steady and bi-directional voltage over the capacitor and as a unity preserves operating power factor. Be that as it might, the WECS force component usually maintains the rotor side converter [IX][XI]. In the stator terminals the dynamic and responsive power is controlled by the rotor side converter which
controls the DFIG speed and its torque. If there is over current situation occurs, here a crowbar protection system is used to give protection to it [X].

VII. Stator Voltage Oriented Control Technique

In wind energy system the stator side of the DFIG under normal operating speed variation when connected to the grid its voltage and frequency parameters are constant with reference values [V][XI]. The diagram figure no. 4 below shows the phasor diagram of the stator voltage control with its frame of references. When the stator frame is considered the q axis is phase with zero to inactive during the operation. This makes the full control action of the stator voltage on the system [X].

![Stator voltage oriented control technique (SVOC)Phasor Diagram](image)

VIII. Grid Side Converter (GSC)

A control technique with a reference edge balanced along the inverter air conditioning voltage is obtained for the matrix side converter, so that the dynamic power and receptive power transmitted to the grid lattice from DFIG-WT can be freely controlled [III][VIII]. The lattice side converter utilizes two external Proportional-Integral (PI) control circles characterizing the id* and iq* reference esteems for two inward current control circles controlling the current segments of the d-and q-axis decoupling. The inward-current control circles then determine the inverter control files for the PWM switch. A network side converter can keep the DC-interface voltage steady along these lines, and control the reactive power at the ideal value. In addition, the inverter will operate in solidarity power factor mode to produce the most extreme dynamic power yield when the receptive power comparison estimate is set as 0. As per the lattice codes, the grid side converter keeps the DC-interface voltage set and satisfies the sensitive power requirement. As shown on Fig. 3, the complex and receptive power can be limited only by the d-axis and the q-axis current using the voltage-situated control system [VII]. This monitoring technique involves two circles of fillings. The inner circle deals with the lattice current; for the network side converter, the outer circle guides the DC-interface voltage and the
sensitive power. The voltage of the DC-interface is firmly dependent on the dynamic power; the change can then be viewed as the reference of the d-pivot current. A solidarity power factor is usually needed, as it is the q-pivot relation is set to zero except where the system administrator requires sensitive power pay. In addition, the space vector modulation (SVM) is used to generate the exchange signals in order to allow proficient use of the DC voltage [XI].

**Fig.5:** GSC block diagram representation [II]

**IX. Rotor Side Converter (RSC)**

The RSC- rotor side converter is triggered by injecting a three phase voltage on the rotor circuit at slip recurrence. The converter controller infused voltage in both magnitude and orientation and this immediately regulates the rotor flows [V][VII].

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This power provides two substantial capabilities. The first is the variety of electromagnetic torque generators, and then the speed of the rotor. The second may be steady stator receptive power yield control, stator power factor control or stator terminal tension control. Normal speed control run for a cutting edge wind turbine Class MW doubly encouraged enlistment generator may be anywhere within the range of 70 percent and 120 percent of synchronous speed with the 120 percent more often than not stated as the approximate speed at which the measured MW yield is supplied [XI][XIII].

X. Pitch Angle Control

The PAC stands for pitch angle controller which is inactive at low speed or natural wind speed but it will activate when the wind speed is much more than that of reference or actual speed. This means the PAC will operate at over speed condition.

Fig. 6: RSC block diagram representation [III]

Fig. 7: Pitch Angle controller (PAC) [II]
This control scheme at high speed condition decreases the mechanical power of the rotor to establish the full control during transients [XI]. The simulink diagram and the block diagrams of PAC and its control action are represented in figure no. 7 and 8.

**XI. Transient Behavior Study of DFIG Based WECS**

The transients due to the over speed cause unhealthy operation to the wind system shown in the figure 9 with detail model which is cause voltage sag. In this study there will be given faulty which represents the wind variation actions. There are three major cases are drawn here for complete study. In case-1, terminal voltage recovery is done by the controller action. In case-2, inductive load cause the disturbances in the system and study on it is done. During case-3, here the wind speed variation on cut-in and cut-out are studied.
XII. Simulink Results

The simulink block diagram shown below highlights the control action of PI controller on the rotor side and the grid side to make the operation smooth and maintain the stability during the faults and transients.

- **Case 1**: A three-ph fault is created for 100 msec in the center of Grid and WECS, from 8 sec - 8.1 sec. Here the WECS for PI controller is activated for steady state operation over transients. Results of the simulation indicated as follows:

![Fig.10: DFIG side voltage Vs time](image1)

![Fig.11: DFIG side current Vs time](image2)

![Fig.12: DFIG rotor current Vs time](image3)
Fig.13: Stator Active Power Vs time

Fig.14: Stator Reactive Power Vs time

Fig.15: Electromagnetic Torque Vs time

Fig.16: DC link Voltage Vs time

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The simulink for the first case shown in figure 10 to 17 which highlights the control action of the PI controller during the fault is being given. During the fault time the system parameters are changed and the PI controller controls the steady state values. As 0.1pu decreases to 0.05pu, the failure interruption is known to be. As initially Crowbar protection system is not implemented, the DC link voltage activates itself during the issue to a high esteem. After the shortcoming was removed from the system, after a certain transitory time the structure went to the enduring state.

- **Case 2:** An excessively inductive RLC strain in the centre of Grid and WECS is all of a sudden associated (8.0 sec to 8.35 sec) of 350ms with the target that voltage drop occurs about that time with WECS perform with PI controller.
The outcome shown in figure 18 to 24 refers to the effects of the extremely inductive constraint being associated between matrix and DFIG at 8 sec and being evacuated at
8.35 sec. DFIG stator as rotor current rises to a high value during high inductive load condition and DFIG voltage decreases to 0.65PU resulting in DFIG side voltage drop.

- **Case 3:** During this case the cut in speed (4m/s) and the value of cut out speed (12m/s) are taken under the consideration of wind speed variations. For this PI a conventional controller is activated for the steady state values to be appeared during transient conditions. The effects of the control scheme simulink results are shown as follows:

![Fig.25: Wind Speed Vs Time](image)

![Fig.26: Stator active Power Vs time](image)

![Fig.27: Electromagnetic Torque Vs time](image)

Figures 25 and 27 of the simulink tests relate to the after effects of dynamic and electromagnetic torque during wind speed change. A control action result shows that WECS powered by PI has great power following capability during wind speed variations.

**XIII. Discussion**

In this section the parameters are shown and the results from the simulations are discussed. This make the validation of the system modeling of T-III-DFIG driven wind turbine and the power analysis during transients due to wind speed variations with fault clearances produce for this effects.

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Table 1: Wind Turbine Parameters

| Sl no. | Parameter                        | Value   |
|--------|----------------------------------|---------|
| 1.     | Mutual damping (D)               | 4.2pu   |
| 2.     | Stiffness constant (K)           | 144pu   |
| 3.     | Turbine inertia constant (Ht)    | 3.2     |
| 4.     | Gearbox ratio                    | 45.75   |
| 5.     | Generator inertia constant (Hg)  | 0.34    |
| 6.     | Rotor Diameter                   | 42.5m   |
| 7.     | Rotor rated speed                | 50rpm   |
| 8.     | Hub height                       | 40m     |

Table 2: Type-III WT DFIG Parameters

| Sl no. | Parameter                        | Value   |
|--------|----------------------------------|---------|
| 1.     | Rotor leakage inductance (Xr)    | 0.017pu |
| 2.     | Mutual inductance (Xm)           | 2.76pu  |
| 3.     | Rotor resistance (Rr)            | 0.008pu |
| 4.     | Stator leakage inductance (Xs)   | 0.07pu  |
| 5.     | Stator resistance (Rs)           | 0.012pu |
| 6.     | Rated voltage                    | 690V    |
| 7.     | Rated power                      | 1.5MW   |

Table 3: Wind Turbine Parameters (1.5MW System)

| Wind speed variation (m/sec) | RSC Power (kW) | GSC Power (kW) | Real Power (Kw) (Type-III WT) |
|-----------------------------|----------------|----------------|-------------------------------|
| 4                           | 85             | -21.09         | 63.91                         |
Table 4: PI Control Parameters during transients

| Controller          | Wind Speed Variation (m/sec) | Settling Time (ms) |
|---------------------|------------------------------|--------------------|
| Conventional PI Controller | 4                            | 0.0061             |
|                      | 6                            | 0.0139             |
|                      | 8                            | 0.5410             |
|                      | 10                           | 0.01263            |
|                      | 12                           | 1.25709            |

From the above diagnosis on wind power it is concluded that the PI controller can maintain the voltage sag due to the transients and stability of the wind energy system is maintained. The reactive power can be compensated using DC link filter acts like a compensator. This can be done by the mathematical modeling of RSC and the stator side converter in the wind model. The PI controller settles the fault at cut in and cut out speed and makes the system more responsive and faster towards the steady state with variation in wind speeds. The research finds that the Type-III wind turbine system is faster for steady state operation and the reactive power can be controlled during Grid integration.

XIV. Conclusion

On the base of this study of wind energy using a Type-III DFIG turbine the voltage regulation under synchronous and asynchronous rotating frame under the transients is described in this research paper. The study on the variable partial scale controlled Type-III DFIG system associated with wind system has the synchronous frames and asynchronous frame for the control action of rotor and stator side which connected through a bi directional power converter for the reduction of harmonics and switching losses. The DC interface of capacitor helps in balancing the actual power flows between grid and the wind system. The GSC helps in compensation of reactive power and its strength to create stability during grid integrations. The converter at rotor side able to control the active power (P) and reactive power (Q) of the stator or grid side with full control over d-q axis frame of reference. From the
above case studies this can be confirmed that the Type-III DFIG within the wind energy system integrated with the grid power system can give faster response and more stable under transient analysis. The grid under sudden disturbances can perform more responsive with the voltage variations and reactive power compensation for the high inductive load as faults. The simulink results show the faster voltage recovery capabilities using this Type III DFIG into the wind energy conversion system. The implementation of Type-III DFIG system in wind energy is provide better response under wind speed fluctuations and maintain the power system stability.

References
I. AbdulhamedHwas, Reza Katebi, Wind Turbine Control Using PI Pitch Angle Controller, IFAC Proceedings Volumes, Volume 45, Issue 3, 2012, Pages 241-246, ISSN 1474-6670, ISBN 9783902823182, https://doi.org/10.3182/20120328-3-IT-3014.00041.

II. B. P. Ganthia, S. Mohanty, P. K. Rana and P. K. Sahu, "Compensation of voltage sag using DVR with PI controller," 2016 International Conference on Electrical, Electronics, and Optimization Techniques (ICEEOT), Chennai, 2016, pp. 2138-2142, doi: 10.1109/ICEEOT.2016.7755068.

III. B. P. Ganthia, V. Agarwal, K. Rout and M. K. Pardhe, "Optimal control study in DFIG based wind energy conversion system using PI & GA," International Conference on Power and Embedded Drive Control (ICPEDC), Chennai, 2017, pp. 343-347.

IV. Bekhada, HamaneDoumbia, Mamadou, BOUHAMIDA, Mohamed Draou, Azeddine CHAOUI, HichamBenghanem, Mustapha, “Comparative Study of PI, RST, Sliding Mode and Fuzzy Supervisory Controllers for DFIG based Wind Energy Conversion System”, International Journal of Renewable Energy Research (IJRER), Volume - 5, 2015/12/26, Page 1174 - 1185.

V. Djeriri, Youcef&Meroufel, Abdelkader&Massoum, Ahmed &Boudjema, ZinelabaBidine. (2014). A comparative study between field oriented control strategy and direct power control strategy for DFIG. Journal of Electrical Engineering. 14. 169-178.
VI. Iulian Munteanu, Antoneta Iuliana Bratcu, Nicolaos-Antonio Cutululis and Emil Ceanga, “Optimal Control of Wind Energy System”, Springer, London, 2008.

VII. Lei, Yazhou, et al. "Modeling of the wind turbine with a doubly fed induction generator for grid integration studies." Energy Conversion, IEEE Transactions on 21.1 (2006): 257-264.

VIII. Power conversion and control of wind energy systems by Bin Wu, Yongqiang Lang, Navid Zargari, Samir Kouro. IEEE publication.

IX. Qiao, Wei. "Dynamic modeling and control of doubly fed induction generators driven by wind turbines." Power Systems Conference and Exposition, 2009. PSCE’09. IEEE/PES. IEEE, 2009.

X. S. M. Muyeen, Md. Hasan Ali, R. Takahashi, T. Murata, Y. Tomaki, A. Sakahara and E. Sasano, “Comparative Study on Transient Stability Analysis of Wind Turbine Generator System Using Different Drive Train Models”, IET Renewable Power Generation, Vol. 1, No, 2, pp. 131-141, June 2007.

XI. Siraj, Kiran, Haris Siraj, and Mashood Nasir. "Modeling and control of a doubly fed induction generator for grid integrated wind turbine." Power Electronics and Motion Control Conference and Exposition (PEMC), 2014 16th International. IEEE, 2014.

XII. T. Ghennam, E.M. Berkouk, B. Francois, “Modeling and Control of a Doubly Fed Induction Generator (DFIG) Based Wind Conversion System” IEEE 2009.

XIII. Tao Sun, “Power Quality of Grid-Connected Wind Turbines with DFIG and Their Interaction with the Grid”, Ph.D. dissertation, Aalborg University, Denmark, May 2004.

XIV. Yang, Jin. “Fault analysis and protection for wind power generation systems”. Diss. University of Glasgow, 2011.

XV. Zhang, B.; Hu, W.; Hou, P.; Tan, J.; Soltani, M.; Chen, Z. “Review of Reactive Power Dispatch Strategies for Loss Minimization in a DFIG-based Wind Farm” Energies 2017, 10, 856.