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IMPACT OF VARIABLE SPEED WIND ENERGY SYSTEMS ON POWER SYSTEM TRANSIENT STABILITY

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ABSTRACT

This paper investigates the effect of grid-connected variable speed wind turbine (VSWT) generators on the transient stability of a power system network. The wind generators considered are the doubly-fed induction generator (DFIG) and the direct driven synchronous generator (DDSG).Studies were conducted on a standard three-machine, 9-bus system augmented by a radially connected wind power plant (WPP). The critical clearing time (CCT), rotor angle deviation, rotor speed deviation, voltage magnitude, active power and reactive power of the system under fault condition were examined and compared with conventional synchronous generators (CSG). From the simulation results, it is observed that large scale integration of VSWT generators at the transmission level has the potential to improve the transient stability of the grid.

Keywords

VSWT, DFIG, DDSG, transient stability, CCT, rotor angle deviation, rotor speed deviation, active power, reactive power.

1.INTRODUCTION

Wind has proven to be one of the most successful of all available sources of renewable energy offering relatively high capacity, with generation costs competitive with conventional energy sources. In recent years, the technologies for generation of electrical energy from renewable energy sources, especially wind energy, have evolved. In the early stage of wind power development, most wind farms were equipped with fixed-speed wind turbines and cage type induction generators. Since, such generators can only operate at a constant speed; the power efficiency is fairly low for most wind speeds [1].

Modern wind turbine generator (WTG) systems usually are of variable speed type. Variable-speed wind generators produce constant-frequency electric power from a variable speed source [2]. Nowadays, for WTGs above 1 MW ranges, variable speed types are usually employed that are either doubly fed induction generators (DFIG) or direct drive synchronous generators (DDSG). The use of DFIG is receiving increasing attention for wind generation purposes [3]. DFIGs are useful in applications that require varying speed of the machine's shaft for a fixed power system frequency. The wound rotor DFIG is the only electric machine that operates with rated torque to twice synchronous speed for a given frequency of excitation. In concept, any electric machine can be converted to a wound-rotor DFIG by changing the rotor assembly to a multiphase wound rotor assembly of equal stator winding set rating. In the DFIG connected wind energy conversion system (WECS), the stator terminals of the generator is connected to the grid and the rotor terminals are connected to the grid via a partial variable frequency AC-DC-AC voltage source converter (VSC) and a transformer. DDSG tend to be very large due to the large number of poles. Here, a full-scale power electronic converter is interfaced between DDSG and grid.

Maintaining the transient stability of the system is one of the major issues in the operation of power system. It is the ability to maintain synchronous operation of the machines when subjected to a large disturbance.

This paper attempts to investigate how the power electronic controllability of modern variable speed wind turbines DFIG and DDSG can be utilized to improve the power system transient stability. The wind turbine systems have been tested on IEEE 9-bus test system.

2. WIND ENERGY CONVERSION SYSTEMS

2.1Configuration of WTGs

There are two electrical generating systems that dominate the variable speed wind turbines in operation today: DFIG and DDSG. The (Figure1) and (Figure 2) illustrate the configurations of DFIG and DDSG respectively.

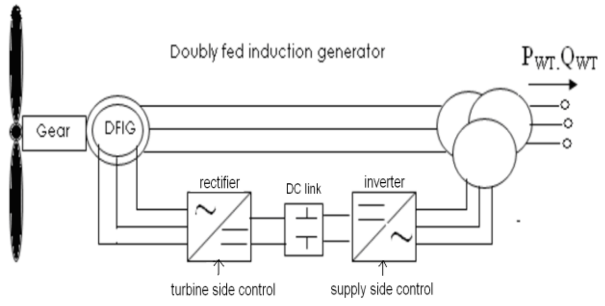

Fig 1: Schematic representation of the DFIG

In the DFIG system shown in (Figure 1), a back-to-back PWM converter concept is used. A frequency converter is connected to the rotor circuit of the induction generator. For the rotor side, the choice of decoupled control of the electrical torque and the rotor excitation current given in [4] is utilized. The machine is controlled in a synchronously rotating reference frame with the d-axis orientated along the stator-flux vector, providing maximum energy transfer. Rotor-side converter control employs the use of PI controllers. The control of the supply-side converter is simply just keeping the dc-link voltage constant. PWM switching techniques are used in both converters. The supply -side converter now controls the transfer of real power between the grid and the battery, as the DC voltage is now fixed. The supply-side controller is made up of three PI controllers, one for outer loop power control, and the other two for the d–q-axis inner current control loop. Energy is stored during high winds and is exported to the grid during calm conditions to compensate for the drop in stator power.

Variable speed is achieved by controlling rotor currents. The possible speed variation of the generator is proportional to the power of the converter i.e. a speed variation of ±20% gives a power rating of the converter of 20 % of the rated system power. In this system, just a part of the power passes through the frequency converter and thereby the cost of the converter is less, also the system losses are lower compared to the full power converter where all the power passes through the converter.

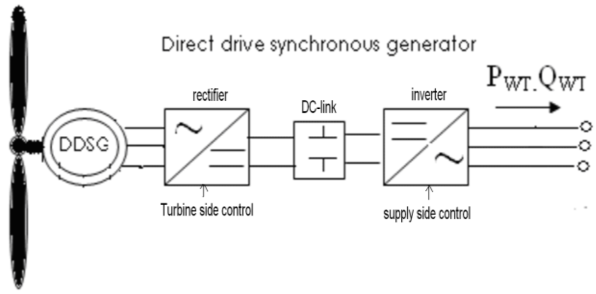

Fig 2: Schematic representation of the DDSG

In the gearless DDSG system shown in (Figure 2), a back-to-back PWM converter concept is used. The supply side PWM inverter allows for control of real and reactive power transferred to the grid. The generator side converter is used for electromagnetic torque regulation. The controllers used in these systems are designed to achieve maximum power transfer to the grid. These generators have a high efficiency since the whole of the stator current is employed during electromagnetic torque production. With a full power converter the control of the current is total and thereby the control of active and reactive power is very precise. Another advantage is the minimization of stator current through the direct control of generator power factor. Here it is also possible to control the reactive power to the grid. Common for both the above systems are they are able to control reactive to control the reactive power to the grid.

2.2 Power conversion system

The power conversion system in variable speed WECS is composed of a six- IGBT rectifier and a six-IGBT VSC. The VSC includes a *LC* harmonic filter at its terminal to reduce harmonics it generates. The rectifier converts ac power generated by the wind generator into dc power. A current-controlled VSC can transfer the desired real and reactive power by generating an ac current with a desired reference waveform.

Reactive power control is implemented in such a manner that the voltage magnitude of the VSWT terminal is kept constant at a specified level. Therefore, the target for reactive control is the desired voltage magnitude *V*ref. It must be set as the nominal voltage of the ac grid, where possible addition of the VSWT is considered. Whether the mode controls power factor or voltage, the reactive power generation is limited by reactive power capability of the VSWT. The limits of reactive capability are determined by rating of the inverter and are given in (1).

$$Q_{limits} = \pm\sqrt{\left(S_{inv}^2 - P_{inv}^{\ 2}\right)} \qquad (1)$$

where S_{inv} is grid side inverter's apparent power and P_{inv} is grid side inverter's active power.

2.3 Modeling of WECS

2.3.1 Wind Turbine

The wind turbine is described by the following equations (2-5).

Tip speed ratio = $\lambda = \dfrac{\omega_M R}{V_W}$ (2)

Mechanical power from wind turbine =

$$P_M = \frac{1}{2}\rho\pi R^2 C_P V_W \quad (3)$$

Mechanical torque from wind turbine =

$$T_M = \frac{P_M}{\omega_M} = \frac{1}{2}\rho\pi R^5 C_P \frac{\omega_M^2}{\lambda^3} \text{ N·m.} \quad (4)$$

where ω_M is the mechanical speed of wind turbine in rad/sec., R is the blade radius in m, V_W is the wind speed in m/sec., *ρ is the a*ir density in kg/m^3 and C_P is the coefficient of performance. C_P is expressed as a function of the tip speed ratio (TSR) λ.

$$C_P = (0.44 - 0.0167\beta)\sin\frac{\pi(\lambda-2)}{13-0.3\beta} - 0.00184(\lambda-2)\beta \quad (5)$$

where β is the blade pitch angle. The mechanical torque expressed by the equation (4) enters as input torque to the synchronous generator, and is driving the generator.

2.3.2 Modeling of DFIG and DDSG

Based on the assumptions that the wind turbine system is equipped with a voltage dip ride-through facility and a rapid current controller, both systems DFIG and DDSG are modeled as negative loads [5] at the connection point with negative conductance and positive susceptance, as shown in (Figure 3).

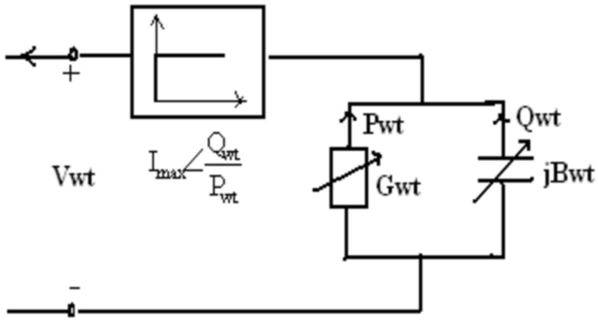

Fig 3: Model of DFIG and DDSG

For a given wind speed, WECS acts like a constant megavolt ampere (MVA) source as long as the converter current limit is not violated. A voltage source inverter can respond very quickly to a voltage disturbance, which justifies the assumption of modeling it as a constant MVA source. The active power production during a voltage dip will thus be limited by the converter current limit. The conductance (G_{WT}) and susceptance (B_{WT}) are given by

$$Y_{WT} = -G_{WT} + jB_{WT} = \frac{P_{WT} + jQ_{WT}}{V_{WT}^2} \quad (6)$$

where P_{WT} and Q_{WT} are the active and reactive power production of the wind farm, respectively, V_{WT} is the wind farm connection point voltage. The current injection from the wind farm is accordingly

$$I_{WT}^2 = (P_{WT} + jQ_{WT})Y_{WT} \quad (7)$$

It is considered that the generator is equipped with an exciter identical to IEEE type 1 model. The exciter plays the role of helping the dc link to meet the adequate level of inverter output voltage as given in (8) below

$$V_{dc} \geq \frac{2\sqrt{2}\cdot V_{AC\_RMS}}{D_{MAX}} \quad (8)$$

where $V_{AC\ RMS}$ is RMS line to neutral voltage of the inverter and D_{MAX} is maximum duty cycle.

3.TRANSIENT STABILITY OF POWER SYSTEM

Short circuit fault is a very common disturbance in a power system which upsets the rotating machines in the vicinity of the fault, causing the speeds of these machines, and the power flows in the network to oscillate. When the short circuit is cleared by disconnecting the faulted line, the generators that have accelerated will decelerate and come back into synchronism with the rest of the system. If they do not, the system becomes unstable and there is a risk of widespread blackouts and of mechanical damage to generators.

Stability depends strongly upon the magnitude and location of the disturbance and to a lesser extent upon the initial state or operating condition of the system.Rotor angle oscillations can also arise in the grid without any obvious reason. High power flows over weak transmission lines, fast and powerful voltage regulators and other types of controls may cause standing oscillations in the grid.

To assess the system stability under various operating conditions, a transient stability indicator is needed. In this paper, the following indicators are used to quantify the rotor speed oscillations of the large generators, [6]:

- the maximum rotor speed deviation, and
- the oscillation duration.

The maximum rotor speed deviation is defined as the maximum rotor speed value achieved during the transient phenomenon. The oscillation duration is defined as the time interval between the application of the fault and the moment after which the rotor speed stays within a bandwidth of 10^{-4} pu during a time interval longer than 2.5 seconds. The (Figure 4) shows the typical allowable maximum rotor speed deviation and oscillation duration.

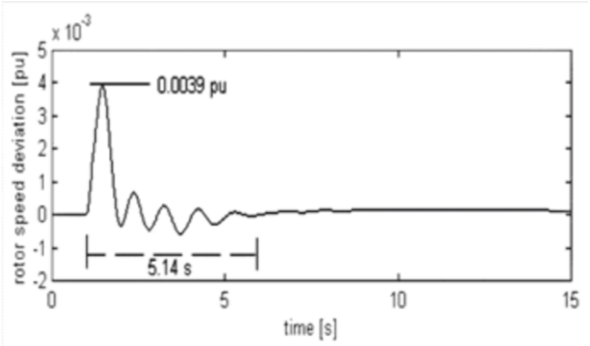

Fig 4: Typical allowable maximum rotor speed deviation and oscillation duration.

Critical Clearing Time is the maximum time interval by which the fault must be cleared in order to preserve the system stability [7,8].CCT is one of the most important basic criterions of the transient stability assessment for the reliable and secure system operation. Every generator connected to the power system should have CCT longer than the operational time of circuit breaker in power system.

3.1 Transient stability in the presence of WECS

The (Figure 5) shows the equivalent circuit of the power system setup with variable speed WECS [9].

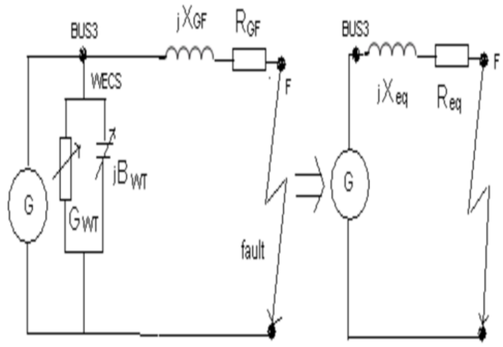

Fig 5: Equivalent circuit of the power system setup with variable speed WECS

R_{GF} is the resistance of the generator and X_{GF} is the inductive reactance of generator when a fault occurs at position F without the presence of a wind farm. During a fault, R_{GF} is the only resistance seen by the generator. The active loss associated with this R_{GF} is supplied by the generator. If the active power transfer is higher, accelerating energy gained by the generator will be lesser. With the connection of wind farm, active current can be injected and thus the equivalent impedance seen by a generator can be changed. The equivalent impedance Zeq is given by the following eq.(19).

$$Z_{eq} = R_{eq} + jX_{eq} = \frac{(G_{GF} - G_{WT})}{(G_{GF} - G_{WT})^2 + (B_{GF} - B_{WT})^2} + j\frac{(B_{GF} - B_{WT})}{(G_{GF} - G_{WT})^2 + (B_{GF} - B_{WT})^2} \quad (9)$$

where $G_{GF} = \frac{R_{GF}}{(R_{GF}^2 + X_{GF}^2)}$ and

$$B_{GF} = \frac{X_{GF}}{(R_{GF}^2 + X_{GF}^2)}$$

DFIGs and DDSGs have the possibility to control the active and reactive current injection during a grid fault. They can change the active current injection to zero (G_{WT} =0) and in this way keep the resistance seen by the generator to its initial value. They also have the possibility to inject reactive current during a fault (making the value of (B_{GF} - B_{WT}) lower, i.e. reduce the reactive impedance seen by the generator). During a grid fault, the combined effect is a reduced X_{eq}/R_{eq} ratio. Thus by setting the active current injection from a WECS to zero and injecting reactive current during a

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grid disturbance, the active power transfer from a nearby generator could be increased which would reduce the available accelerating energy for the generator during and immediately after a grid fault (when the generator rotor angle accelerates). DFIGs and DDSGs can increase the active power transfer from a nearby conventional generator and thus increase the transient stability of the generator.

On the other hand, when the generator rotor angle decelerates, it is beneficial to reduce the load seen by the generator either by injecting active power from an alternate energy source or by absorbing reactive power. DDSG has the possibility of exchanging reactive power during a rated power operation). This contingency operation of a WECS will increase the transient stability of a nearby conventional generator and also improve the damping of power oscillations. After the fault clearing, by reducing the active current injection from a WECS to zero, the effective load seen by the generator is increased and vice versa.

In transmission networks and distribution grids, node voltage and reactive power are correlated. DFIGs and DDSGs have the capability to change its reactive power generation or consumption and thus can control node voltages. This can increase the electromagnetic torque and reduce the rotor acceleration. This could increase the critical clearing time which in turn could enhance the rotor speed stability.

4. RESULTS AND DISCUSSION

When the penetration of WTG is strongly high, its impact is no longer restricted to the distribution network but begins to influence the whole system. Therefore, analyzing the influence on the transmission system transient stability is very much essential. The performance of the system with DFIG and DDSG are implemented in Matlab with GUI interface components and tested by connecting them at bus-1 of IEEE 9 bus power system network. A three-phase to ground fault (200 ms duration) is applied near bus-4.

4.1 Power system with CSG alone

In this case, the system was simulated with CSG `alone without including the wind generator. The (Figure 6a) shows the rotor angle swing occurred with only CSG. The generator maximum rotor angle swing is 100^o when the system is connected with only CSG.

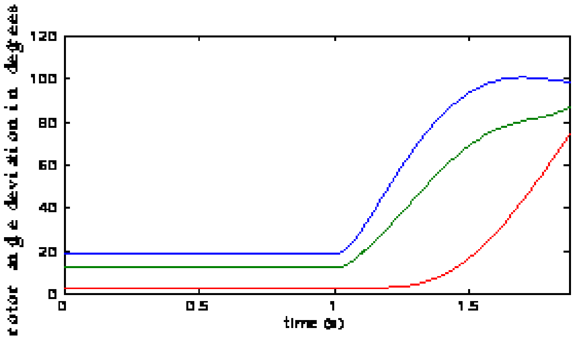

Fig 6a: Rotor angle swing occurred with only CSG

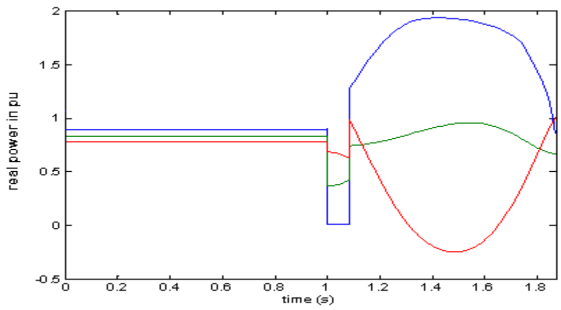

Fig 6b: Active power support with CSG alone.

The (Figure 6b) shows the active power support with CSG alone. During fault, active power dropped to 0pu and after clearing also, the active power injection is less than 1pu with no WTG connected to the system.

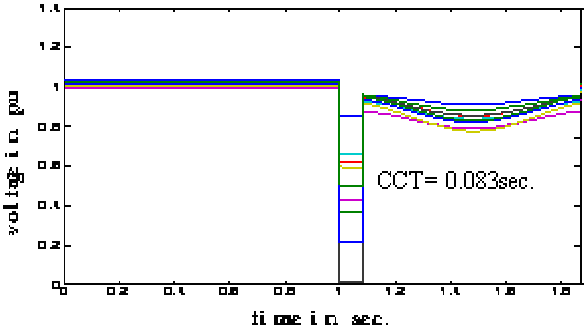

Fig 6c: Voltage magnitude of all the buses and the CCT with CSG alone

The (Figure 6c) shows the voltage magnitude of all the buses and the CCT with CSG alone. When severe fault occurs, the terminal voltage of the CSG falls. This will reduce the electrical torque. Also, the rotor will oscillate, and the slip of the CSG will increase gradually. Once the fault is cleared, the terminal voltage and electrical torque will again increase to its nominal value and thereby, the rotor will decelerate. If the fault is cleared after the critical clearing time (t_{cr}), the rotor

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may accelerate to a higher than critical slip (s_{cr}) value. In this case, although the fault is cleared and the terminal voltage is recovered back, the rotor will continue to accelerate (beyond s_{cr}), and therefore, the CSG will enter into the unstable region.

The CCT represents a useful measure for characterizing the transient stability performance of a given scenario. Without any WTG, it is seen that the voltages dropped to a very low value of 0 initially and does not recovered to 1pu. It settles down at a low value of 0.8pu. The CCT value in this case is 0.083sec. It means that if the fault at F exists longer than 0.083sec., the generator will loose synchronism.

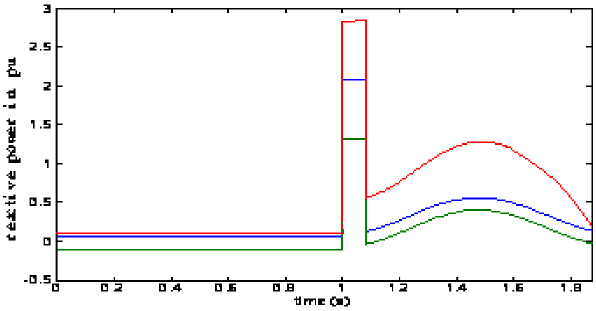


Fig 6d: Reactive power support with CSG alone

The (Figure 6d) shows the reactive power support provided with CSG alone. Reactive power generated is very minimum when only CSG are connected. It shows the absorption of local reactive power.

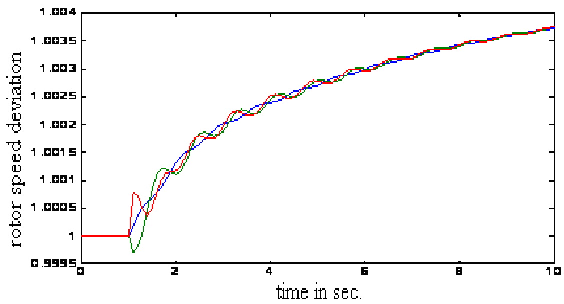


Fig 6e: Rotor speed deviation with CSG alone

The (Figure 6e) shows the rotor speed deviation without WTG. From figure 6(e), it is seen that the rotor speed of the CSG monotonically increases and has not settled down, which indicates clear instability. The rotor speed simulation is taken upto 10 sec. of time to show the rotor oscillation settling time. The rotor speed deviation is 1.0038 pu.

4.2 Power system including WTG system

Next, the system was simulated along with WTGs at bus-3. Again the three-phase to ground fault was simulated near bus-4.

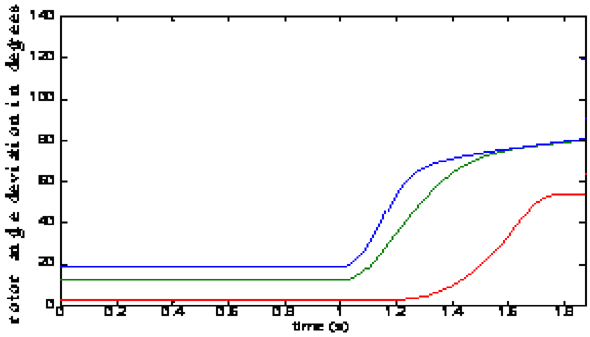


Fig 7a: Rotor angle swing with DFIG

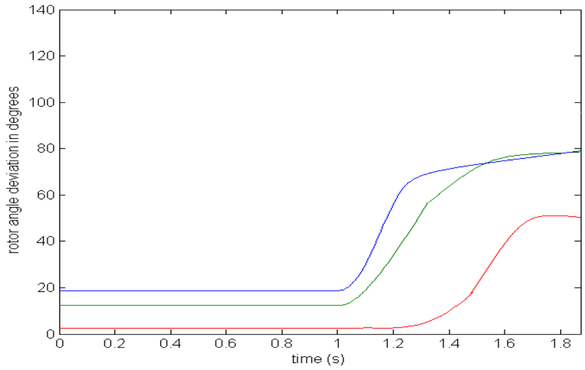
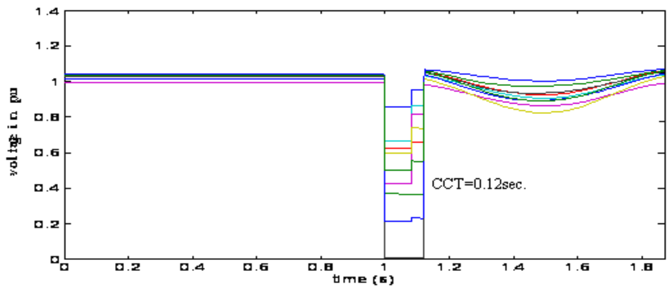


Fig 7b: Rotor angle swing with DDSG



The (Figure 7a) and (Figure 7b) show the rotor angle swing of generator at bus-3 when DFIG and DDSG are connected to the system.

The maximum rotor angle swing is reduced to 80^o when DFIG is connected. The maximum rotor angle swing is further reduced to 79^o when the connected WECS is DDSG installation which is shown in (Figure 7b).

The reduced maximum rotor angle swing of all generators connected in the power system, when subject to a grid fault, in presence of variable speed

WECS show the transient stability enhancing property. But when comparing both the variable speed systems, it is more capable of reducing the rotor angle swing.

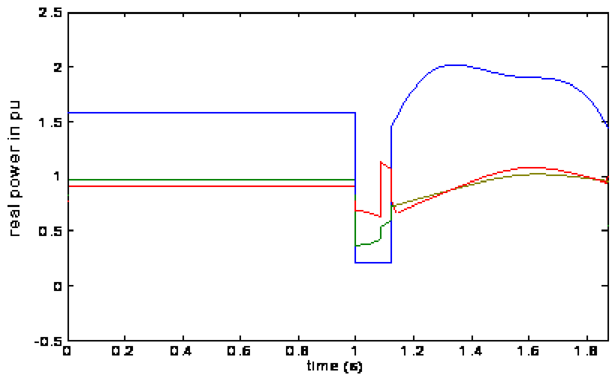


Fig 8a: Active power support with DFIG

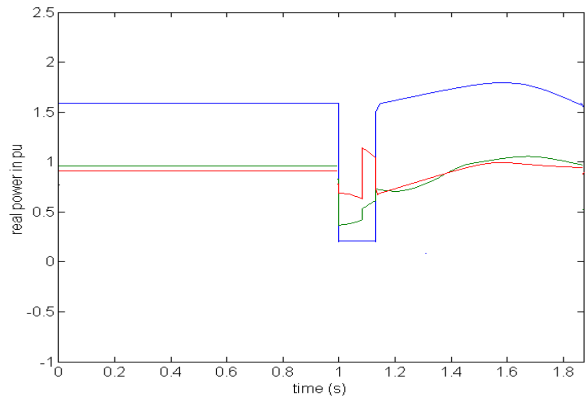


Fig 8b: Active power support with DDSG

The (Figure 8a) and (Figure8 b) show the active power support when DFIG and DDSG are connected to the system. With both DFIG and DDSG, during fault, the active power dropped to even 0.25 pu, but regained to 1pu and above after clearing. With respect to active power support, both system's performance are almost the same.

After the fault is cleared the active power control of the DFIG and DDSG are acting very fast helping the system to recover quickly. Due to the reduced inertia, the rotor angle is reaching a lower maximum, increasing the transient stability of the system considerably.

Fig 9a: Voltage magnitude with DFIG

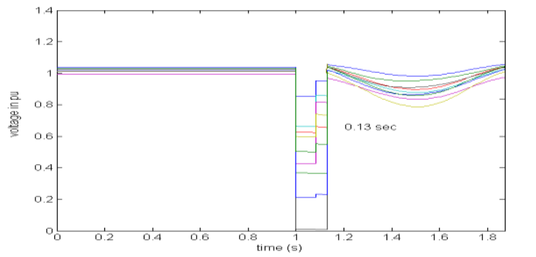


Fig 9b: Voltage magnitude with DDSG

The (Figure 9a) and (Figure9 b) show the voltage magnitude of all the buses and the CCT when DFIG and DDSG are connected to the system. When system DFIG is connected, voltages dropped during disturbance and regain their voltage at 1pu. A CCT of 0.12sec. is obtained in this case, which shows that the system stability has further improved. It is observed that the DFIG system gets stabilized and regained its original voltage after fault clearance.When system DDSG is connected, voltages dropped during disturbance and regain their voltage at 1 pu. In this case the CCT has improved to 0.13sec. which shows the further improved system stability.

From the results it is observed that, variable speed WECSs enable enhanced power capture. The injection of reactive power at Bus 3 by variable speed systems DFIG and DDSG could control voltage in the system can ease the reactive power burden on CSG connected in the network, and minimize angular separation in the system following a contingency event.

Reactive power support provided by the DFIG and DDSG systems could be analysed from (Figure 10a) and (Figure 10b). With DFIG and DDSG systems, reactive power supplied is nearly 0.25pu which elevated the voltage.

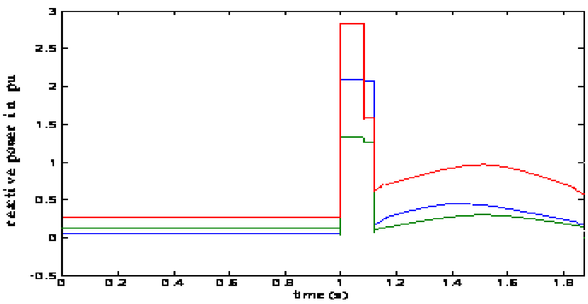


Fig 10a: Reactive power support with DFIG

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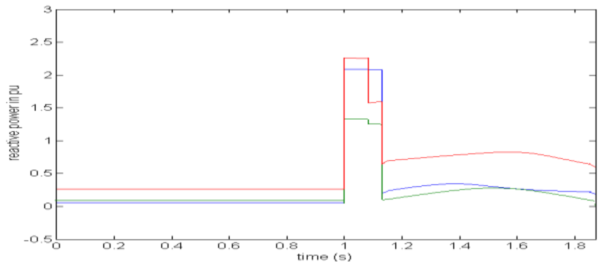

Fig 10b: Reactive power support with DDSG

The (Figure 11a) and (Figure 11b) show the rotor speed deviation occurred when DFIG and DDSG systems are connected. With system DFIG, the rotor speed deviation is 1.0025rad/sec. and rotor speed oscillations get settled down at nearly 6 sec. With System DDSG, the rotor speed deviation has reduced to 1.002rad/sec. and rotor speed oscillations get settled down at nearly 5 sec. It is observed that the systems DFIG & DDSG get stabilized and regained their original speed after fault clearance.

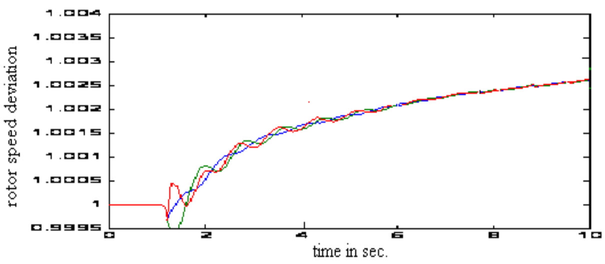

Fig 11a: Rotor speed deviation with DFIG

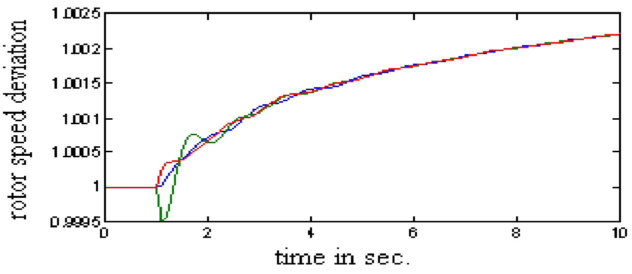

Fig 11b: Rotor speed deviation with DDSG

When comparing the performances of systems DFIG & DDSG, with respect to active power support, reactive power support and voltage, their values are same. But with respect to rotor speed deviation, rotor angle deviation and CCT, the performance of DDSG is better. Table-I gives the variable speed direct driven synchronous generator parameters.

Table-I gives the variable speed direct driven synchronous generator parameters.

Power, voltage and frequency ratings	100 MVA, 16.5kV, 50Hz
Stator resistance Rs	0.01p.u.
Direct and Inverse reactances (Xd and Xq)	0.146 p.u, 0.0969 p.u
Constant field flux Psi_p	1 p.u
Inertia constants Hm	2*23.64KWs/KVA
Voltage control gain and time constant Kv, Tv	10p.u, 1 sec
Pitch control gain and time constant Kp, Tp	10p.u, 3 sec
Active and reactive power control time constants Tep, Teq	0.01 sec, 0.01 sec
Number of poles	4
Blade length and number	75m, 3
Pmax and Pmin	1p.u., 0p.u.
Qmax. And Qmin	+0.7 p.u, -0.7 p.u

5. CONCLUSION

The effect of variable speed WECS on the transient stability of power system has been investigated in this paper. CSG and variable speed systems DFIG & DDSG are compared by connecting them at IEEE 9 BUS test system. The systems are compared with respect to active power support, reactive power support, voltage magnitude, CCT, rotor angle swing and rotor speed deviation. From the simulation results it is observed that, variable speed WTGs have much higher transient stability margin as compared to CSG. Also it is found that, DDSG has more capability in reducing rotor angle swing and rotor speed deviation and increasing the CCT when compared with DFIG. Thus it is very clear that systems

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DFIG & DDSG could contribute to the transient stability enhancement, and thus would bring an additional value to the installation.

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