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Dynamic Compensation Studies using RTDS for Large Wind Farm Integration with Grid

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Amongst all renewable energy sources so far identified in India for commercial exploitation, wind energy is the one, which has been found to be more viable for generation of grid quality power. Following recent growth of wind generation, utilities have responded by developing various interconnection requirements/guidelines to which the wind farm must abide. The guidelines provide for penalty to be levied by State Electricity Boards, if the projects fail to achieve minimum monthly average power factor of specified value at the coupling point. Suitable penalties are also levied for reactive power to discourage drawl of reactive power from the grid and to avoid free wheeling of the machine.

Majority of wind generator topologies are asynchronous machines, which draws reactive power from the grid. Thus, there is a requirement that the wind farms be self sufficient with respect to the needs of reactive power of the wind farm. The methods of reactive power control may be provided in the form of capacitor banks, static power converter based devices (SVC, TSC, or STATCOM) or by employing machines capable of reactive power control, such as the doubly-fed induction machine topology.

This paper discusses the results of grid integration studies of wind farms, based on three phase dynamic simulation utilizing the real time digital simulator (RTDS). It investigates the application of STATCOM for a typical wind farm for providing an effective means in dynamic voltage control of the wind farm, meet the reactive power requirements of the wind farm and enhance the capability of the wind farm to ride through the grid disturbances.

Keywords: *Wind turbine induction generator (WTIG), Wind energy, Real time digital simulator (RTDS) and Static compensator (STATCOM).*

1.0 INTRODUCTION

In the past, the amount of wind power integrated into power systems formed only a small part of the total electrical generation. Most of the electricity was still being generated by conventional sources, such as thermal, nuclear and hydro generators. Therefore, it was not necessary for wind turbines to provide voltage and frequency support. During a large disturbance, such as a grid fault, the wind turbines are rapidly disconnected from the grid and reconnected when normal operation has been resumed. This is acceptable as long as the wind penetration is low. However, with increasing wind penetration levels, it influences the overall system behavior. In view of this, it has become necessary that wind farms maintain continuous operation during grid operation and thereby support the network voltage and frequency.

Existing wind farms are onshore sites with turbines that use the fixed speed induction generator (FSIG). This type of wind turbines draw substantial reactive power from the grid during start-ups and

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part-load operation which occur several times in a day. Its reactive power consumption depends on active power production. With the variation in the wind speed, the active power generation and hence the reactive power drawn by wind turbine induction generators from the grid varies. This, in turn, causes an unacceptably large voltage drop at or near the wind farm interconnection point with the grid. When viewed from very narrow perspective of simply managing VARs, capacitor banks are undoubtedly the lowest cost option of any power compensation solution. Fixed speed induction generators may be fitted with switchable shunt capacitors, such that the steady state reactive power conditions can be adjusted as necessary. However, during dynamic conditions this control would not be sufficiently fast to assist the AC network. If necessary, a dynamic reactive power compensation device - STATCOM could be provided for that purpose.

Although the demand for VARs is variable, capacitors are able to switch only fixed amounts of VARs, so it is nearly impossible to achieve optimum amounts of reactive compensation. In addition, the traditional remedial action of switching banks of capacitors to regulate voltage levels causes excess stress on the wind turbine gearboxes. This unavoidable source of gearbox stress contributes largely to making gearboxes the number one maintenance item for wind farms and the costliest.

It has been observed that in spite of installing switched capacitor banks to minimize the drawl of reactive power from Grid, utilities are paying large amounts in penalties to Electricity Boards for importing reactive power from grid. The payment of such penalty throughout the lifetime of the project shall substantially influence the economics of the project. Experience has revealed that faults which occur on the transmission line can lead to generator over speed and instability of the network if the short circuit ratio (SCR) at the interconnection point is too low [1]. After the fault is cleared, large amounts of reactive power are required by the induction generator. If this is not available, the machine will speed out of control and needs to be disconnected from the Grid. While the loss of a small capacity wind farm may be acceptable, large wind farms are subject to grid code requirements [2] and must be able to ride through disturbances. Studies have shown that by controlling the voltage and thereby the reactive power requirements within the wind farm installation, allows large wind farms to be connected to the grid.

Dynamic reactive compensation techniques (SVC or a STATCOM) completely resolve VAR demands caused by the operation of wind farm. It does this by using advanced power electronics, sometimes in combination with traditional capacitor banks, to dynamically inject or absorb precise amounts of VARs into the system. The STATCOM responds to changes in AC voltage within a few power frequency cycles, and can thus eliminate the need for rapid switching of capacitor banks or transformer tap changer operations. The rapid response of the STATCOM can also reduce the voltage drop experienced by the wind farm during remote AC system faults, thereby increasing the fault ride through capability of the wind farm. Similarly, the STATCOM can reduce the over voltage amplitude on the clearance of a fault, or under light load conditions thereby reducing the risk of wind farm trip due to over voltage.

In this study the effect of wind speed changes, on the penetration of active and reactive power to the grid is investigated. Variations in wind speed changes namely, constant wind speed and linear change of wind speed is considered in the present study. Further the application of Dynamic compensation device STATCOM in a wind farm equipped with only induction generators in minimizing the reactive power exchange with the grid under steady state and transient condition is investigated. Simulation results show that STATCOM gave a much better dynamic performance, and provided better reactive power and voltage support to the network.

2.0 STUDIED NETWORK

The power system network considered in this investigation is shown in Figure 1. The case study illustrates two wind farms each of 300 MW 3×100) and 250 MW (2×85 + 1×80 MW) aggregate capacities interfaced with transmission grid at 220 kV. All of the wind generators employed is of the induction generator (IG) type. Power from each of the wind farms connected to Bus A and Bus B is evacuated over 33 kV lines. The voltages are then stepped up to 220 kV (Bus A, Bus B). Power from Wind Farm A and Wind Farm B is pooled together at Bus B and then evacuated to the 220 kV grid (Bus C) over 220 kV, 37 km double circuit line. The 3-phase short circuit level at the grid interconnection point is assumed to be 1768 MVA.

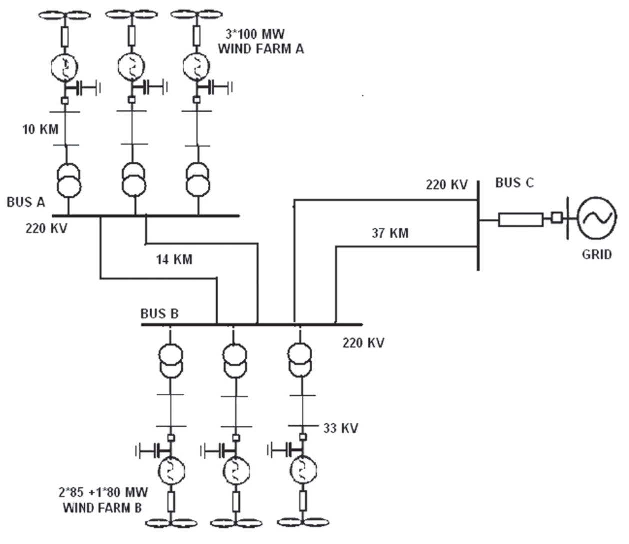

FIG. 1 SINGLE LINE DIAGRAM OF WIND FARM NETWORK.

3.0 SYSTEM MODELING

Each wind farm is simulated as an aggregated wind turbine generator, as the study concerns not on the effect of individual wind turbines but on the aggregate effect of the entire wind farm on the grid [1]. It is assumed that all generators within the wind farm are identical and are at the same operating point. Each wind farm is represented as a classical wind turbine generator driven by a single equivalent wind turbine. The basic configuration of IG driven by a wind turbine is shown in Figure 2.

The wind turbine model employed in the present study is based on the steady-state power characteristics of the turbine [3].

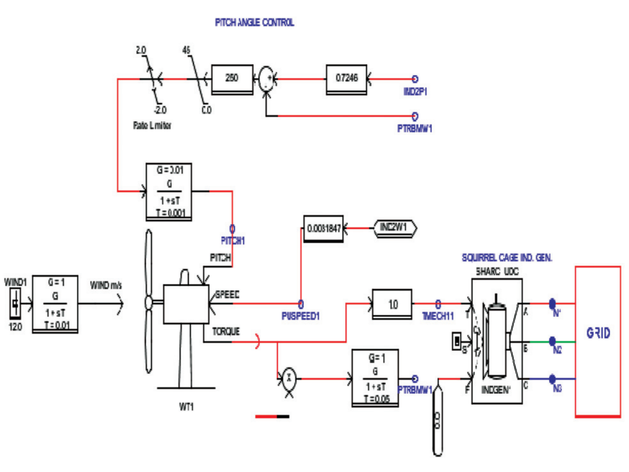

FIG. 2 INDUCTION GENERATOR DRIVEN BY A WIND TURBINE.

The wind turbine mechanical power output is a function of rotor speed as well as the wind speed and is expressed as:

$$P_m = Cp(\lambda, \beta)\frac{\rho A}{2}V^3_{wind} \qquad .... (1)$$

where,

Pm – Mechanical power output of the turbine (MW)

Cp – Power co-efficient of the turbine (p.u.)

λ – Tip speed ratio of the rotor blade tip speed to wind speed (p.u.)

B – Blade pitch angle (Degrees)

ρ – Air density (kg/m^3)

V_{wind} – Wind speed (m/s)

A – Turbine swept area (m^2)

A generic equation is used to model Cp (λ. β) as given below:

$$Cp(\lambda, \beta) = C_1\left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\right)e^{\frac{-C_5}{\lambda_i}} + C_6\lambda \qquad .... (2)$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\,\beta} - \frac{0.035}{\beta^3 + 1} \qquad .... (3)$$

The relevant parameters are given in Appendix I.

Phase-compensating capacitors are used to compensate for the no-load reactive consumption of the generator. The induction generators are assumed to be compensated to 0.99 power factor by shunt capacitor compensation (29.8 MVAr) at the terminals of 100 MW machine, and 25.34 MVAr and 23.85 MVAr for the 85 MW and 80 MW machines respectively. A lumped wind farm model is used and the wind turbine generator parameters are outlined in the Appendix II.

The STATCOM is modeled as a shunt connected two level voltage source converter (VSC) and its associated coupling transformer connected in shunt with the AC system as shown in Figure 3. The STATCOM operates in voltage control mode with sinusoidal PWM techniques being adopted for generation of gating signals. A simple Proportional Integral (PI) controller is used to offer the AC voltage control and thereby the necessary reactive power. The other elements of the STATCOM are voltage and current measurement units, DC voltage controller, AC bus RMS voltage controller and current controller that can individually control the d-axis and the q-axis currents of the STATCOM, to produce V_d and V_q representing the phase and magnitude components of the AC voltage to be synthesized at VSC terminals. Figure 4 shows the control logic adopted in the STATCOM model.

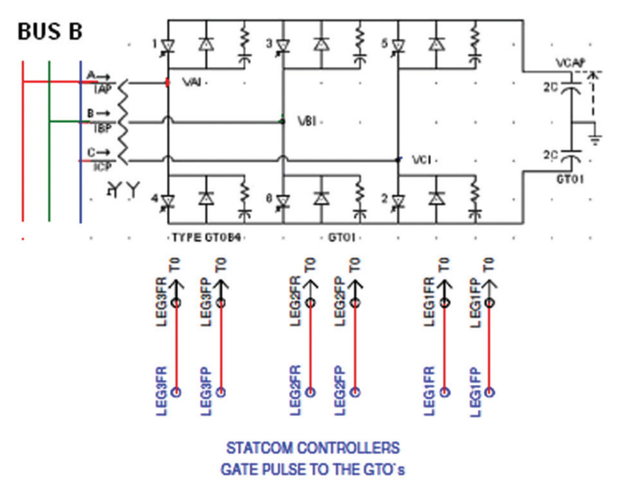

FIG. 3 SHUNT CONNECTED STATCOM.

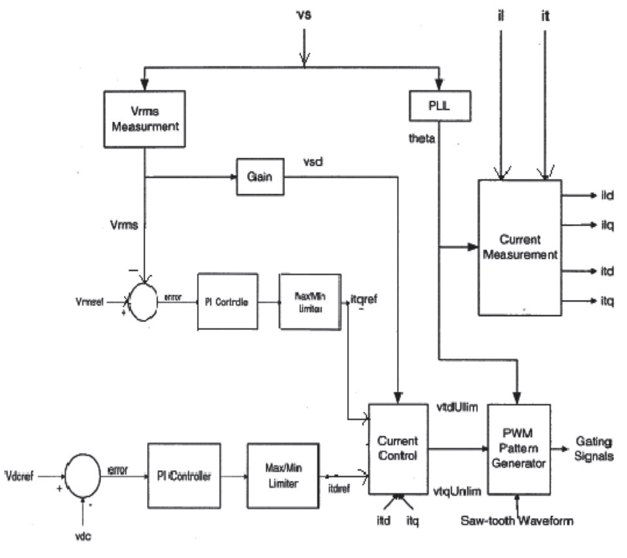

FIG. 4 STATCOM CONTROL SYSTEM.

4.0 SIMULATION TOOL

RTDS is a power system simulator for real-time power system studies. The simulator environment utilizes a combination of custom hardware and software. Hardware of the RTDS comprises different types of processor cards, signal channels and communication modules. An Ethernet connection is used to transfer data between the hardware and the controlling computer. Physical devices can be connected to the system via digital and analog Input / Output channels. The system performs power system simulations with a typical time step of fifty microseconds. Software used to control the physical system called RSCAD provides a graphical user interface for controlling the hardware. It also provides libraries for typical power system components and models [5]. RTDS can be used both for off-line simulation and closed-loop real time simulation.

5.0 SIMULATION RESULTS AND DISCUSSIONS

The dynamic behavior of the Wind Turbine Induction Generator (WTIG's) and the amount of active/reactive power drawn/injected from/to grid during wind speed changes and contingencies is analyzed and presented in this section. Two types of wind speed namely - constant wind speed and linear change of wind speed is considered as shown in Figure 5. A constant wind speed of 10.7 m/s is applied to WTIGs to produce approximately 70% of the rated power.

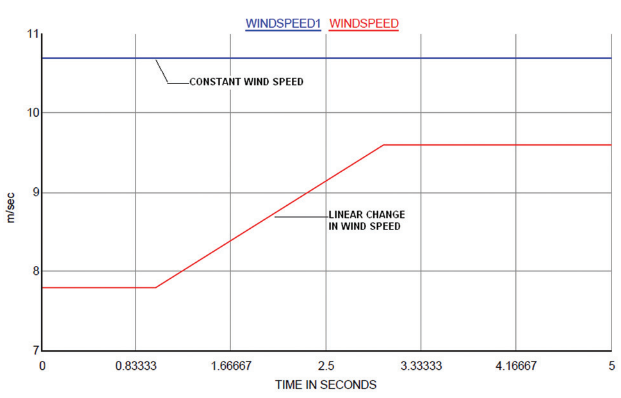

FIG. 5 WIND SPEED VARIATIONS (A) CONSTANT SPEED (B) LINEAR WIND SPEED VARIATION.

The corresponding active and reactive power generations of WTIG's and at the grid terminals are shown in Figures 6 (a–b) respectively. As seen from the oscillograms, the power generated by WTIG's connected to bus A is 69.03×3 MW and those connected to Bus B is 58.42×2 MW and 55.27 MW from 85 MW and 80 MW Wind Generators. Power exported to the grid is 357.84 MW, and 110.17 MVAr is drawn from the grid with no extra reactive compensation provided in the system other than the no load compensation at WTIG terminals. The negative reactive power generation of the WTIG's indicates that 100 MW Wind Generator connected to bus A consumes 27.94 MVAr of reactive power at constant wind speed of 10.7 m/s, and similarly the 85 MW and 80 MW generators connected to Bus B absorbs 23.83 MVAr and 22.40 MVAr respectively. Negative value of active power at grid terminals indicates power being exported to the grid from the wind farm, while the positive MVAr indicates reactive power export from grid to the wind farm. Figure 6(c) shows the 220 kV bus voltages (phase-to-ground).

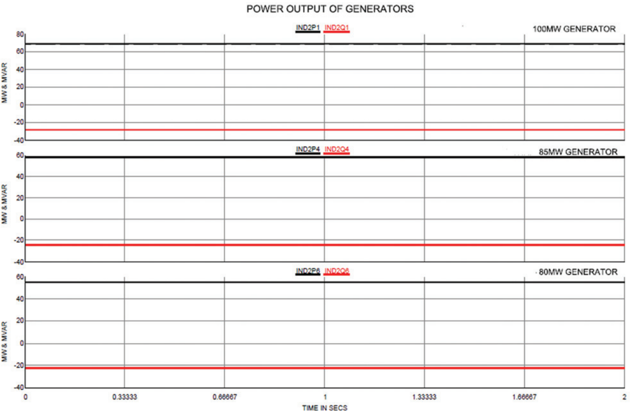

FIG. 6(A) ACTIVE AND REACTIVE POWER OF WTG'S FOR CONSTANT WIND SPEED – 70% POWER OUTPUT.

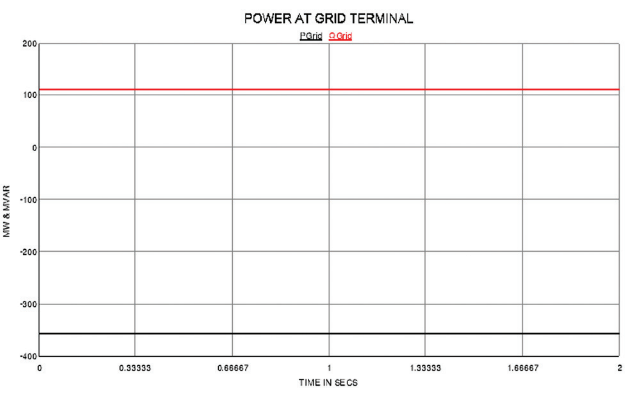

FIG. 6(B) ACTIVE AND REACTIVE POWER AT GRID TERMINALS FOR CONSTANT WIND SPEED – WITHOUT STATCOM.

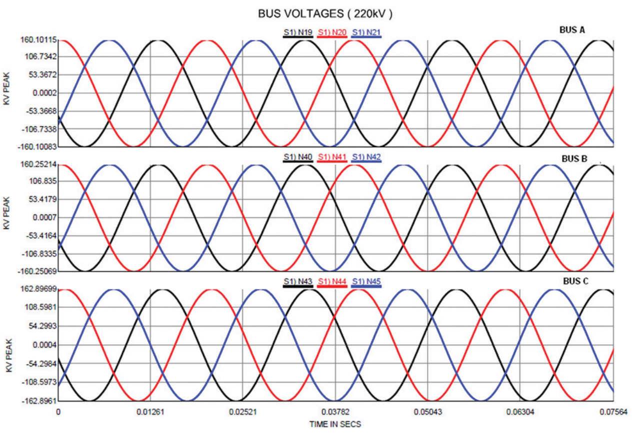

FIG. 6(C) BUS B - 220 kV BUS VOLTAGES.

A linear change of wind speed as shown in Figure 5 is applied to the WTIG's. A wind speed of 7.8 m/s produces 20% of the rated power and 9.6 m/s corresponds to 50% power generation. It was observed that at lower wind speed of 7.8 m/s, the real power generation and reactive power consumption of 100 MW, WTIG is 20.72 MW and 11.79 MVAr respectively. But as the wind speed increases to 9.6 m/s, the realpower generation of WTIG increases to

50.02 MW and hence the reactive power consumption also increases to 24.94 MVAr. The additional reactive power required is drawn from the grid. As seen from Figure 7 the reactive power import from grid has increased to 45.07 MVAr.

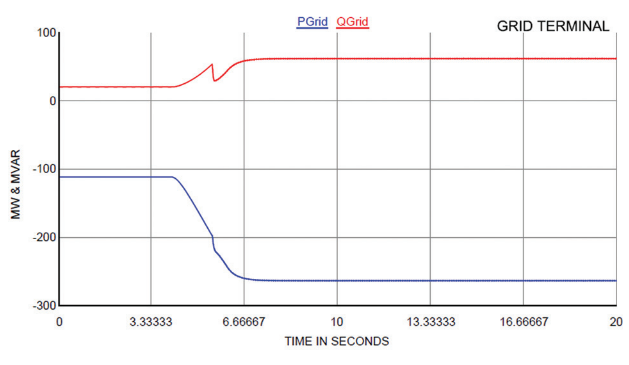

FIG. 7 ACTIVE AND REACTIVE POWER AT GRID TERMINALS FOR LINEAR CHANGE IN WIND SPEED – WITHOUT STATCOM.

With a view to minimize the reactive power drawn from the grid, and wind farm sustaining its operation under contingency cases such as faults, suitable sized STATCOM 60 MVA with 15 MVAr filters is provided at the 220 kV pooling point (Bus B). Figure 8(a) shows the active and reactive power at grid terminals with STATCOM placed at 220 kV pooling point to provide steady state as well as transient voltage support for the wind farm It can be observed from this oscillogram that the reactive power drawn from the grid is almost reduced to zero and Figure 8(b) shows that the 220 kV bus voltages are almost one per unit.

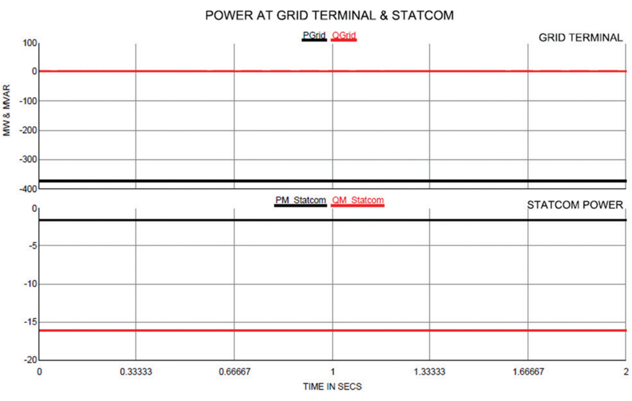

FIG. 8(A) ACTIVE AND REACTIVE POWER AT GRID TERMINALS AND STATCOM FOR CONSTANT WIND SPEED.

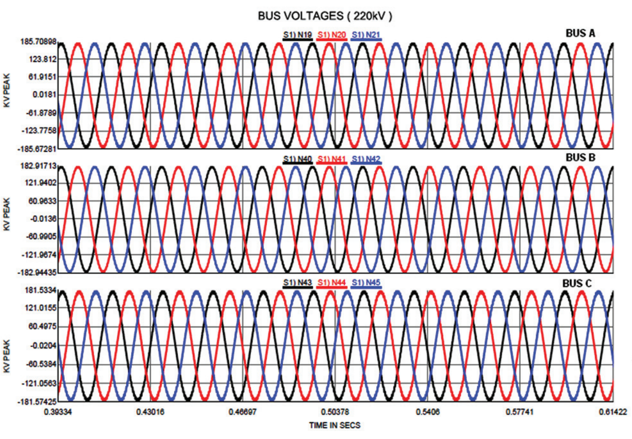

FIG. 8(B) BUS B - 220 kV BUS VOLTAGES-WITH STATCOM.

The voltage recovery following fault on one of the transmission lines evacuating power to the grid followed by 3-phase line tripping is shown in Figure 9(a). As seen from this figure, during the fault, the AC voltage drops resulting in the electric torque to decrease. Consequently the rotor speeds up. Immediately after the fault clearance, due to the high rotor slip, the reactive power demand is greatly increased. Thus the AC voltage dips to 0.8 p.u. The reactive power drawn from the grid reaches almost 250 MVAr for the case of no reactive compensation provided, while when STATCOM is provided it draws only 28 MVAr. After clearance of the fault the STATCOM provides the necessary reactive power support and normal operation resumes.

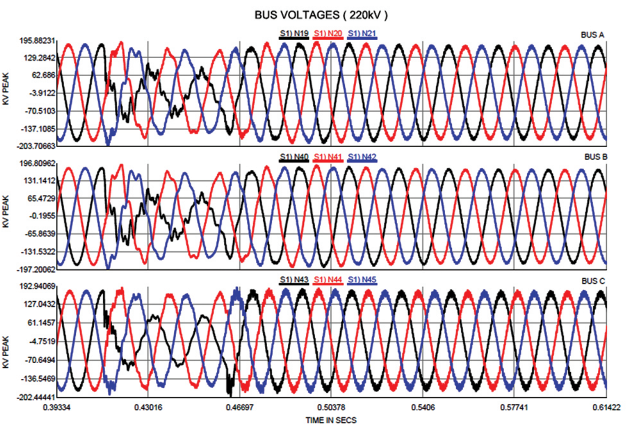

FIG. 9(A) BUS VOLTAGES – SLG FAULT.

Figure 9(a) shows the 220 kV bus voltages for a single line to ground fault at the midpoint of one of the lines followed by line outage followed by recloser after one second.

Figure 9(b) shows the power evacuation at grid terminals and the reactive power supplied by STATCOM.

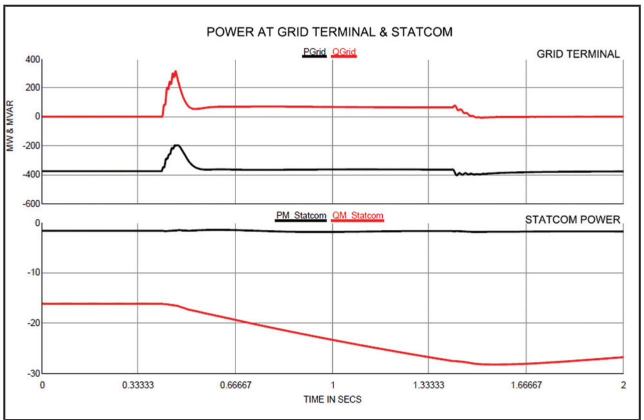

FIG. 9(B) ACTIVE AND REACTIVE POWER AT GRID TERMINALS AND STATCOM – SLG FAULT FOLLOWED BY LINE RECLOSER.

6.0 CONCLUSIONS

The study reported in this paper investigates the possibility of integrating 300 MW and 250 MW wind farms to the 220 kV transmission network, as well as their impacts on the system. When considering the impacts, special attention is paid to the exchange of reactive power with the grid. The effectiveness of the STACOM used as the dynamic reactive compensation device for the WTIG's is also studied. Real Time Digital Simulator has been used in the study.

The active power generated by the WTIGs varies with the wind speed. The reactive power consumption varies with the variation in active power generation. Reactive power is either supplied or drawn from the grid depending on the requirement by WTIG's and the capability of the fixed capacitor compensation to meet these requirements.

Based on the simulation study results, it is technically feasible to integrate both the wind farms with an aggregate capacity of 550 MW with the 220 kV grid. But, the reactive power constraints at the interconnection point are violated. It is found that 110.17 MVAr is imported from the grid when 357.84 MW wind power is exported to the grid. Also, under contingency case, of one line being faulted and tripped, the MVAr drawl further increases to 250 MVAr.

The results showed that the presence of STATCOM gave a much better dynamic performance, and provided better reactive power support to the network, as its maximum reactive current output was virtually independent of the bus voltage to which it is connected. In this particular case it was found that a STATCOM rated 60 MVA had completely compensated the reactive power drawn from the grid during steady state condition. In contingency case of one of the evacuating lines being tripped, it is found that the reactive power drawn from the grid has drastically reduced to 28 MVAr.

When wind farms of larger size are to be connected to the grid, properly located and sized dynamic compensation devices such as the STATCOM is essential in order to provide sufficient reactive power support so that the wind farms can meet Grid Code requirements.

ACKNOWLEDGEMENT

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APPENDIX I

POWER COEFFICIENT - CONSTANTS
C1 : 0.5176
C2 : 116
C3: 0.4
C4 : 5.0
C5 : 21.0
C6 :0.0068

APPENDIX II

WIND TURBINE DATA

1. Rated Turbine Power: 100 MW
2. Rated Wind speed: 12 m/s
3. Cut in wind speed: 3.5 m/s
4. Rated Voltage: 33 kV line-to-line
5. Stator Resistance: 0.0063 p.u.
6. Stator Leakage Reactance: 0.0974 p.u.
7. Unsaturated Magnetising reactance: 5.35 p.u.
8. Rotor resistance : 0.15 p.u.
9. Rotor Leakage reactance: 0.0911 p.u.
10. Inertia Constant: 0.87 MWs/MVA

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