Voltage stability enhancement for large scale squirrel cage induction generator based wind turbine using STATCOM

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ABSTRACT

A stable operation of wind turbines connected to the grid is an essential requirement to ensure the reliability and stability of the power system. To achieve such operational objective, installing static synchronous compensator static synchronous compensator (STATCOM) as a main compensation device guarantees the voltage stability enhancement of the wind farm connected to distribution network at different operating scenarios. STATCOM either supplies or absorbs reactive power in order to ensure the voltage profile within the standard-margins and to avoid turbine tripping, accordingly. This paper present new study that investigates the most suitable-location to install STATCOM in a distribution system connected wind farm to maintain the voltage-levels within the stability margins. For a large-scale squirrel cage induction generator squirrel-cage induction generator (SCIG-based) wind turbine system, the impact of STATCOM installation was tested in different places and voltage-levels in the distribution system. The proposed method effectiveness in enhancing the voltage profile and balancing the reactive power is validated, the results were repeated for different scenarios of expected contingencies. The voltage profile, power flow, and reactive power balance of the distribution system are observed using MATLAB/Simulink software.

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1. INTRODUCTION

Wind energy as the second most commonly used renewable resource contributes effectively to the reduction of global environmental pollution, where the electrical power generated by wind turbines does not pollute the air nor the water. Expressly, wind energy does not accelerate pace of the global warning [1]. Due to the unpredictable changes in weather and climate, the stability and quality of power produced by wind turbines are threated, hence, the efficiency of the whole power system may be degraded [2]. To continue the operation without being isolated by protection devices, wind turbines should satisfy the grid codes while operating in transient conditions. Consequently, an efficient fault ride through capability and a stable voltage profile are the essential requirements for higher penetration of wind generation [3].

SCIG is directly connected to the network through a coupling transformer as illustrated in Figure 1. The wind turbine speed is constrained by the frequency of the network, subsequently, SCIG operates within a narrow band around the synchronous speed. For this type of wind turbines, the generator consumes reactive power from the grid to create the magnetic field in the stator windings, for this reason SCIG is equipped with a capacitor bank to improve power factor close to unity.

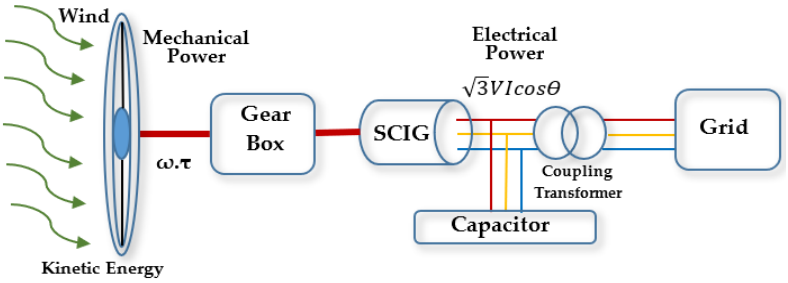

Figure 1. Prime mover and connections of squirrel cage induction generator

Grid codes are a set of standards, regulated by certain agencies, that include the technical requirements the wind-based power systems should meet for well synchronized grid interconnection. Generally, during faults and extreme loading cases, system inability to balance the produced and demanded reactive power leads to voltage instability problems [4]. SCIGs consume reactive power from the grid to create the magnetic field in the stator windings, while SCIGs have a steep torque speed characteristic, fluctuations in the wind power are reflected directly to the grid producing transients. This may cause a voltage disturbance during the turbine-grid connection [5].

Voltage stability is a crucial issue for wind farms connected to power systems due to the fact that most of wind farms are located far away from load centers where weak grid characteristics can be observed. Therefore, the danger of voltage instability in weak grid becomes significant and wind turbine is subjected to be disconnected during faults and disturbances [6]. Large compensation capacitor banks could help to improve the voltage profile of SCIG wind farm at steady state conditions. However, if the reactive power supported by capacitors drops sharply in cases of contingencies and low voltage conditions, wind turbine generators disconnection from the grid may occur.

Voltage stability is defined as the ability of the system to sustain constant voltage at all buses at normal conditions and after being subjected to a disturbance from a given initial operating point [7]. The overvoltage in alternating current (AC) power system can be controlled by adjusting the amount of the absorbed reactive power, while adjusting the injected reactive power will control the under voltage at certain point in the system. The main reasons for voltage stability problems in power system are: High reactive power consumption at heavy loads, generation plants are too far from load centers, and large disturbances between generation and load centers.

It is essential to maintain the power system voltage stability by a proper voltage control mechanism, in order to avoid improper operation conditions for the system equipment that may include overheating, increase of losses, and voltage collapse. When the system starts supplying a load which exceeds its capability to preserve the voltage within the rated limit, the load current increases at the same pace as the voltage decreases. Consequently, reactive power consumption is increased, and more voltage drop until reaching to a state of voltage collapse [8].

Wind farms must be qualified to operate continuously within the voltage and frequency boundaries that may be experienced in typical operating conditions. Moreover, wind farms should stay in service producing reduced power for a certain period when the frequency exceeds the limits [9]. Two main control modes collaborate on controlling the voltage of wind turbine: 1) Turbine based control, by which, the turbine should be equipped by specific control system such as those controlling the reactive power or power factorand; 2) substation based control: where flexible AC transmission systems flexible alternating current transmission system (FACTS) or switched capacitors are installed to compensate the reactive power.

To ensure the system stability according to grid codes requirements, for certain duration, wind farms must be able to withstand voltage dips to specific percentage of the nominal voltage. These requirements are known as low voltage ride through (LVRT), which guarantee a quick active and reactive power restoration to the normal values as they were before disturbances. Moreover, another grid code requirement is the ability of wind power plant (WPP) to supply reactive power at the point of the common coupling (PCC). Because of losses in connection cables and line losses between WPP and PCC, installing reactive power capability in every turbine may be not enough to satisfy the requirements of grid codes [10].

One common solution is to use an external reactive power compensator. The installation of large compensation capacitor banks helps improve voltage profile of the system at steady state conditions. Nevertheless, capacitor banks do not provide the best dynamic response at contingency situations and disturbances when the voltage drops dramatically. Moreover, while the reactive power generated by a shunt capacitor is proportional to the square of the applied voltage, voltage instability may cause the reactive power supported by the capacitors drops sharply. As a result, the wind turbine may be isolated from the grid, to avoid such event during contingency and disturbance situations, large amounts of reactive power can be injected or absorbed to improve the electrical transient response of the wind turbine [11].

Over the past years, research papers investigated the issues related to voltage instability problems and system reactive power balance, that offered different methods and approaches to improve the quality of the generated power. Authors Ahmad *et al*. in [12], investigated the performance of SCIG based wind farm, during three-phase grid fault, the SCIG is equipped with static synchronous series compensator (SSSC). Moreover, [13] presents the impact of connecting SCIG-based wind farms to power system through a unified inter-phase power controller (UIPC), the power system stability, as well as the enhancement of the low-voltage ride-through LVRT capability is presented. Karoui *et al*. [14] starts by modeling a SCIG based wind farm while connected to a network, through simulation, the impact of connecting STATCOM on voltage dips mitigation is discussed. A fuzzy logic-based approach to enhance the steady state voltage stability for a grid connected wind farm including multi type wind generators, by reducing the deviation in the voltage of the load bus [15]. A fuzzy based controller supporting the controller of the SVC controller is implemented to enhance the low voltage ride through LVRT capability as well as the voltage stability of the farm [16]. SVC controller based on adaptive neuro-fuzzy interface system (ANFIS) is designed to improve the voltage profile of the wind connected power system [17]. The effect of implementing superconducting magnetic energy storage (SMES) with the wind energy generation system is studied to improve the voltage stability of radial distribution system [18]. A model-free adaptive control (MFAC) is developed in order to enhance the response of a unified power flow controller unified power flow controller (UPFC), that mitigates the effect of wind gusts and some contingency conditions may disturb the operation of the operation of wind energy conversion system [19]. The operation of the on-load tap changers (OLTCs) is coordinated using Tagushi method to improve the voltage stability of a system including wind generation by such an interaction between OLTCs and the wind turbines [20]. The impact of installing UPFC on the power quality issues, improving transmission capacity, and the grid dynamic response is studied when connected at the point of common coupling PCC [21].

This work studies the impact of installing STATCOM at different locations and voltage level points on the voltage stability of a distribution system, a large scale SCIG based wind turbine is adopted, while the voltages at different system buses are observed at some proposed contingency cases. This paper is organized is being as: In part 2, proposed method and equipment are presented in detail. In part 3, research method, parameter identification and modeling of the case study system and proposed contingency cases are discussed. In part 4, simulation results for different operation scenarios are described and discussed, and finally, conclusions are drawn in part 4.

2. PROPOSED METHOD

To achieve the previously mentioned system requirements, flexible AC transmission system devices FACTS such as STATCOM and UPFC are being used widely in control of power systems due to their ability to provide reactive power balance and flexible power flow control [22]. STATCOM has the ability to override voltage stability threats, this paper explores the impact of installing STATCOM at different voltage points to mitigate the adverse effect of some common contingencies on the operation and the stability of the distribution system connected to SCIG wind turbines, where system voltage profile and reactive power balance are compared for both healthy and contingency scenarios.

2.1. Static synchronous compensator (STATCOM)

FACTS devices are installed in wind farm connected networks to enhance the dynamic and the transient stability of the power system. They are classified according to the way they are connected to grid; 1) shunt-connected devices like STATCOM and static Var compensator (SVC), and 2) series-connected devices like static synchronous series compensator (SSSC) [23]. Shunt-connected FACTS devices have a vital task in enhancing the voltage stability of the network by reducing reactive losses, damping of power system oscillations, and controlling power flow and transmission line voltage [24].

STATCOM is a controlled reactive power source aims to improve the transient stability of systems by regulating the bus injected current [25]. Installing STATCOM contributes to the compensation for sag/swell effects, suppressing of line currents harmonics, correction of power factor, mitigation of bus voltage fluctuations, and transmission line reactive power compensation [26]. STATCOM as shunt connected FACTS controller is a power electronic-based synchronous Var compensator that generates a three-phase reactive power in synchronism with the transmission line voltage. STATCOM is connected through coupling transformer and acts as a source of reactive power (capacitor) or a sink of reactive power (inductor). For weak grids operation conditions, STATCOM transient response is more efficient than that of SVC, based on its lower overshoots and faster response compared with those for the SVC [27].

2.2. STATCOM construction

STATCOM consists of the following parts:

a. Voltage-source inverter (VSI), serves to transforms the input voltage as a direct current (DC) to an AC voltage at the output, based on one of the following VSI types:
   - Insulated gate bipolar transistors (IGBT) based PWM inverters, create a sinusoidal waveform from a DC voltage source according to pulse-width modulation (PWM). Passive filters at the AC side of the VSI are installed in order to mitigate harmonic.
   - Gate turn-off Thyristors based square-wave inverters, include four sets of three-level inverters that compose a 48-step voltage waveform. They are able to control reactive power flow by adjusting the
   - DC input voltage.

b. DC-link capacitor to supply the inverter with the DC voltage.

c. Inductive reactance (X) which represents the leakage inductance of a coupling transformer between inverter and power system.

d. Harmonic filters are installed to mitigate the high frequency components produced by the inverters [28].

2.3. STATCOM operation

A distribution system supplying a load with installed shunt compensator (STATCOM) is shown in Figure 2, the current drawn from STATCOM is defined as I_c and is given by [29]:

$$I_C = I_L - I_S \tag{1}$$

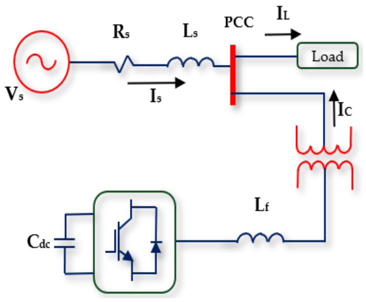

Figure 2. STATCOM general system diagram

The desired compensation current I_c equals to the difference between the load (I_L) and the source (reference) currents (I_s). The basic operation of a STATCOM depends on two important facts: 1) active power flows from the leading point toward the lagging point and 2) reactive power flows from the higher to the lower voltage magnitude point. According to that, STATCOM serves to regulate the reactive power flow by adjusting the voltage produced by the VSI with respect to the system voltage. STATCOM has two modes of operation:

2.3.1. Voltage regulation mode

In this mode, voltage regulation is achieved by controlling a value of reactive power that absorbed from or delivered to the power system through a VSI. To ensure that active power flow is zero, the voltage V_S generated by the VSI through the DC-link capacitor should be in phase with the system voltage ($\delta = 0$).

2.3.2. Var control mode

Where the reactive power output is preserved constant independently from other system parameters. As shown in Figure 3, the d-q components of reference currents can be obtained by [29]:

$$i_{Sd}^{*} = \bar{\imath}_{Ld} + i_{Cd} \tag{2}$$

$$i_{Sq}^{*} = K_q \bar{\imath}_{Lq} + u i_{Cq} \qquad (3)$$

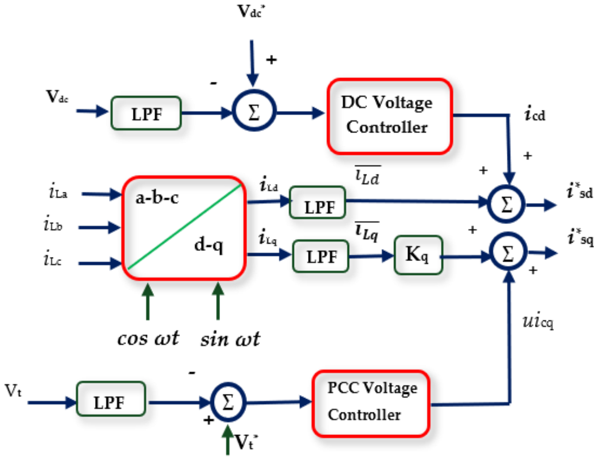

Figure 3. Computation of reference source currents (d and q components)

i_{Ld} and i_{Lq} are the load current average values of the d-and q-axis components. i_{Cq} is the output of the AC voltage controller and i_{Cd} is the output of the DC voltage controller. (u) is a logical variable equal to either zero in Var-control mode or one in voltage-regulation mode. K_q is one in voltage regulation mode where in Var control mode is defined by (4). For unity power factor Q_S^* is zero and K_q is 0 as well [29].

$$K_q = \frac{Q_S^*}{\bar{Q}_L} \qquad (4)$$

Where (Q_S^*) is the source reference reactive power and ($\bar{Q}_L$) the average reactive power that can be obtained by:

$$\bar{Q}_L = |V_t| \bar{\imath}_{Lq} \qquad (5)$$

The average value of $\bar{\imath}_{Ld}$and $\bar{\imath}_{Lq}$is the outputs of two identical low pass filters (G (s) is transfer function) [29].

$$\begin{bmatrix} \bar{\imath}_{Ld} \\ \bar{\imath}_{Lq} \end{bmatrix} = G(s) \begin{bmatrix} i_{Ld} \\ i_{Lq} \end{bmatrix} \qquad (6)$$

The d-q components are obtained as:

$$\begin{bmatrix} i_{Ld} \\ i_{Lq} \end{bmatrix} = \begin{bmatrix} \cos\omega t & -\sin\omega t \\ \sin\omega t & \cos\omega t \end{bmatrix} \begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} \qquad (7)$$

$$\begin{bmatrix} i_{S\alpha}^* \\ i_{S\beta}^* \end{bmatrix} = \begin{bmatrix} \cos\omega t & \sin\omega t \\ -\sin\omega t & \cos\omega t \end{bmatrix} \begin{bmatrix} i_{Sd}^* \\ i_{Sq}^* \end{bmatrix} \qquad (8)$$

3. RESEARCH METHOD

Using MATLAB/Simulink, a distribution system supplying a wind farm is the subject of this paper. Figure 4 shows a 132 kV grid supplies a 33 kV distribution system connected to a wind farm and other loads. System parameters are listed in Table 1.

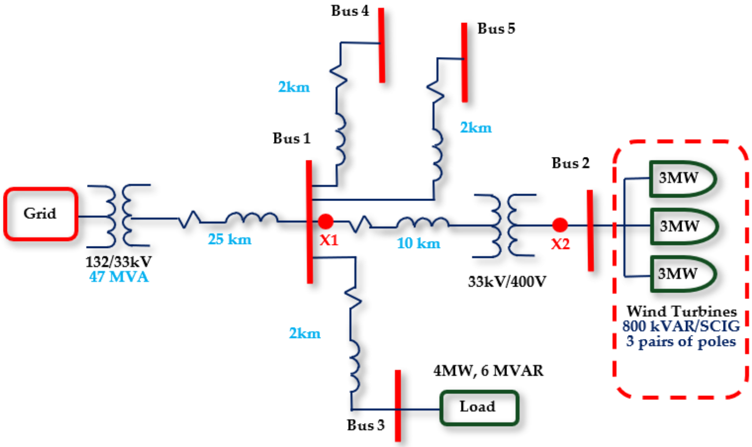

Figure 4. Circuit diagram of the case study

The voltage response and the reactive power balance of the distribution system will be observed under each of the following normal and contingency cases [30]: 1) at the instant of connecting the wind turbines to the grid (normal conditions); 2) sudden load changes; 3) sudden interruption of some electrical loads for specific time; 4) connecting fluctuating loads such as arc furnaces; and 5) single line to ground fault at medium voltage level. Each contingency case in addition to normal case will be applied under the following three operation scenarios:

a. System without compensation devices.
b. System with STATCOM installed at low voltage level close to wind turbine (point X_2).
c. System with STATCOM installed at medium voltage level (33 KV busbar-point X_1).

The simulation parameters of the STATCOM controllers are listed in Table 2. The results include the power generated by the wind turbines, active power flow, balance of reactive power, voltage profile at low voltage level 400 V and at medium voltage busbar 33 KV.

Table 1. Distribution line parameters

Parameter	$^{+}$Ve Sequence	Zero Sequence
Resistance	0.1153 Ω/km	0.413 Ω /km
Inductance	1.05 mH/km	3.32 mH/km
Capacitance	11.33 nF/km	5.01 nF/km

Table 2. Parameters for STATCOM controllers

Parameter	Symbol	Value
AC Voltage Controller (PI Controller)	K_P	5
	K_I	1000
DC Voltage Controller (PI Controller)	K_P	0.1 e^{-3}
	K_I	20 e^{-3}
Current Controller (PI Controller–d and q channels)	K_P	0.3
	K_I	10
Converter impedance	R (pu)	0.007
	L (pu)	0.22
Reference Voltage (*pu*)		1.0
STATCOM Converter Rating		18
DC-link total equivalent capacitor		375 µF

4. RESULTS AND DISCUSSION

This paper explores the effect of STATCOM on voltage stability and reactive power balance for a large-scale wind turbine connected distribution system. The results and the recommendations will include system voltage response and a comparison of the impact of installing STATCOM at low voltage level and medium voltage level for different disturbance situations and load conditions in addition to normal operation case.

4.1. Case (1)

In this case, the system operates at normal conditions, system parameters (voltage, active power flow, and reactive power balance) are obtained without and with installing STATCOM at low and medium voltage levels, Table 3 and Table 4 show both voltage values and reactive power balance at each operating scenario. Maintaining the voltage within the normal limits, leads the wind turbine to generate the rated real power (3 MW) and to consume a reactive power of 1.4 MVAR. As shown in Table 4, the reactive power flow from grid to distribution has been reduced from 3.20 MVAR to 2.65 MVAR by installing STATCOM at point (X_2) and reduced further to 1.3 MVAr when the STATCOM is installed at point (X_1). Which means that installing STATCOM at medium voltage level generates more reactive power than that generated when it is installed at low voltage level.

Table 3. A summary for system voltage results at normal and turbulated cases

Operation Scenario	Without STATCOM		STATCOM at low Voltage		STATCOM at 33 kV	
	Bus 1 Voltage	Bus 2 Voltage	Bus 1 Voltage	Bus 2 Voltage	Bus 1 Voltage	Bus 2 Voltage
Case 1	0.968	0.987	0.975	0.998	0.993	1.014
Case 2	0.91	0.92	0.95	0.992	0.98	1.01
Case 3	1.085	1.14	1.005	1.01	1.01	1.03
Case 4	0.95	0.968	0.968	0.995	0.988	1.01
Case 5	0.76	0.8	0.84	0.96	0.92	0.95

Table 4. Reactive power (Mvar) from grid to distribution area at normal and turbulated cases

Operation Scenario	Without STATCOM	STATCOM at Low Voltage	STATCOM at 33 kV
Case 1	3.2	2.65	1.3
Case 2	7	4.45	2.3
Case 3	-7.34	1.2	0.8
Case 4	4.26	4.08	3.875
Case 5	3.2	-4.05	-11.2

4.2. Case (2)

For this case, the system will experience a sudden increase in the reactive power demand (Mvar) at bus 4 for 1.0 second. Figure 5 shows the voltage at 33 kV busbar (bus 1). Both voltages at 33 kV and 400 V buses will affect the operation of wind turbine, the reactive power (Mvar) imported from grid for the three operating scenarios is illustrated in Table 3.

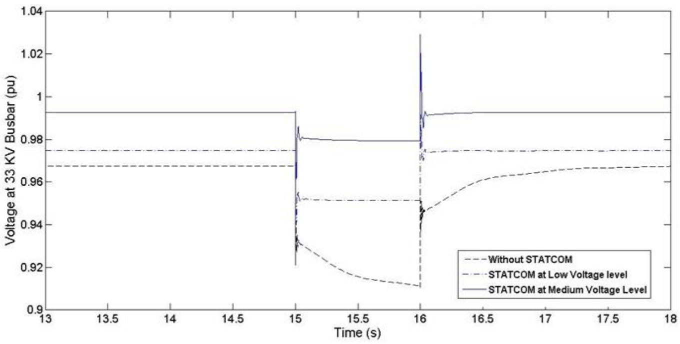

Figure 5. Voltage (pu) at bus1

The high reactive power demand at bus 4 (during the time period from 15 sec to 16 sec) leads to a voltage drop at bus 1 (0.91 pu) and at bus 2 (0.92 pu), while these voltages are improved to reach (0.95 pu) and (0.992 pu) respectively by installing STATCOM at low voltage side (point X_2), and to (0.98 pu) and (1.01 pu) when it is installed at medium voltage side (point X_1) as listed in Table 3. Voltage variation on wind turbine busbar affects the turbine output power which varies from 2.85 MW to 3.15 MW. The STATCOM narrows the gap of output power to be 2.93 MW until 3.04 MW. This variation includes the reactive power consumed by wind turbine as well. The reactive power varies from 1.1 MVAR to 1.9 MVAR, but by using STATCOM the value remains close to 1.4 MVAR. Table 4 shows the impact of STATCOM on reducing the reactive power imported from the grid at different installation scenarios. Moreover, by increasing the reactive power demand at bus 4, the increment in the active power flows from distribution system to grid is obviously affected by installing STATCOM, which reaches to 600, 300, and 100 kW for the scenarios of operation without STATCOM, with STATCOM at low voltage, and with STATCOM at medium voltage, respectively.

4.3. Case (3)

A sudden interruption of some electrical loads at bus 2 is applied on the system for short period of time (1.0 second). As concluded in case 2, the voltage variation at bus 1 and bus 2 could be reduced by installing STATCOM at low or medium voltage side, in more efficient manner when it is installed at the medium voltage side, results are listed in Table 3. The voltage variations will affect the operation of the wind turbine as shown in Figure 6, and thus the resultant turbine generated power will affect the power flow and reactive power balance in the distribution system.

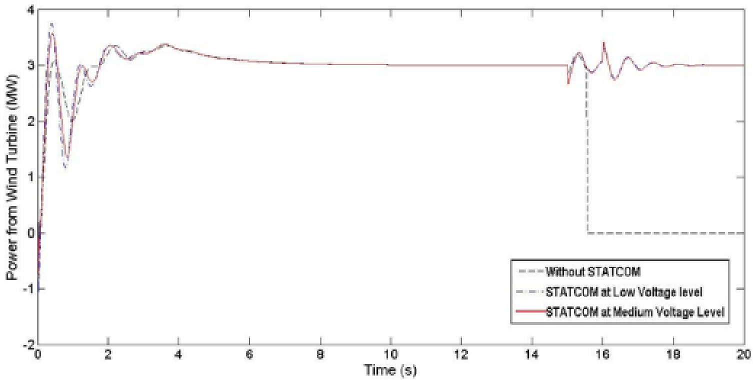

Figure 6. Active power generated by wind turbine (MW)

Due to loading disturbance, a considerable voltage increase takes place at main bus1 (1.09 pu) and bus 2 (1.15 pu). Such voltage increase could cause tripping of the wind turbines by the operation of turbine overvoltage protection system; this tripping forces the distribution system to import 6.0 MW from grid to supply the demand at bus 3. Moreover, a reflection of reactive power flow towards the grid is observed due to the significant contribution of wind farm capacitor banks in generating reactive power, which are no longer supplying the isolated wind turbines. On the other hand, by installing STATCOM, the voltage increase produced by load interruption is limited to acceptable values at low voltage bus and no no over voltage will be experienced, which keeps the wind turbine in service in normal operation mode, where 3 MW output will be generated accordingly.

4.4. Case (4)

The system will be exposed to a variable inductive load at bus 5 for 10 seconds. Voltage variation at bus 2 is illustrated in Figure 7. The continuous variations on voltage values affect the operation of wind turbine and reactive power balance in the distribution system. Installing STATCOM contributes to the reduction of these changes in voltage significantly, which in turn mitigates the variations in the in the wind turbine output active and reactive power, and thus modify the power flow status and reactive power balance in the distribution system as illustrated in Table 4.

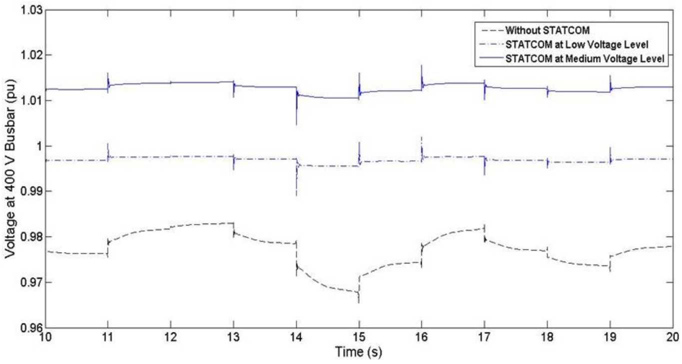

Figure 7. Voltage (pu) at wind turbine bus (bus2)

4.5. Case (5)

The system will experience a single line to ground fault at a point located between bus 1 and bus 5 for a period of time (from 14 sec to 14.4 sec). The Voltage dips at bus1 and bus 2 during that time period are listed in Table 3. The voltage response during the fault affects the operation of the wind turbine as shown in Figure 8, and thus wind turbine output affects the power flow and reactive power balance in the distribution system as listed in Table 4.

A considerable voltage drop takes place at bus 1 that reaches (0.77 pu), while the voltage at bus 2 shows a value of (0.82 pu), such a voltage drop leads to disconnect the wind turbine from the grid by the under voltage protection system. Tripping of wind turbine forces the distribution system to import 6 MW from grid to cover the demand at bus 3. Also due to the significant contribution of the capacitor of the wind turbine in reactive power producing, reactive power flow reflection will be experienced that leads to export the reactive power to the grid. Installing STATCOM at point x2 limits the voltage drops at bus 1 and bus 2 to values of (0.85) and (0.96) respectively, while installing STATCOM at x1 enhance the voltage profile to the values of (0.92 pu) and (0.95) respectively. The acceptable voltage values at bus 2 leads the wind turbine for a normal operation condition at rated output power of (3 MW).

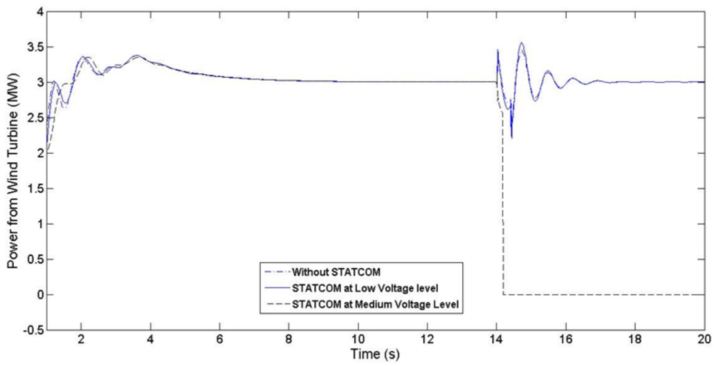

Figure 8. Active power (MW), from wind turbine

Acceptable voltage level at bus 2 ensures the normal operation of wind turbine to generate the rated output power. Severe voltage drop due to fault occurrence leads to the operation of the under-voltage protection which isolates the wind turbines from the grid. Accordingly, 6.0 MW should be imported from the grid to cover the demand at bus 3. Moreover, a reactive power flow reflection takes place towards the grid, to drain the significant contribution of the reactive power produced by the capacitor banks in the wind farm. While Installing STATCOM helps to keep the turbine connected, and so no power inversion will be experienced.

For more clarity, the numerical data listed in Tables 3 and 4 summarize the simulation results of the mentioned five scenarios for the normal and turbulated system behaviors, the results show a considerable improvement in bus voltage by installing STATCOM at medium voltage side especially for a faulty system condition at case 5. A small error in the magnitude of the results mentioned above is due to the ignorance of the connection cables impedance between the wind turbines at the wind power plant. This error does not affect the listed comparison results between the different scenarios of system operation as long as the percentage ratio of the different scenarios voltages is figured. The results listed take into consideration not only the impact of STATCOM installation but also the location of installation in the wind turbine connected distribution system. Like the most surveyed similar works, authors in Karoui *et al*. [14] cares about the stability improvement by only STATCOM installation process, a constrain of review for many similar studies show a lack of comparative analysis results to that figured in this study.

5. CONCLUSION

This paper explores the feasibility of installing a STATCOM to a large-scale squirrel cage induction generator-based wind turbine, distribution system supplying a wind farm is simulated according to different proposed disturbance scenarios, while the busbar voltage and wind farm generated real and reactive power are observed. The installation of STATCOM provides a stable voltage profile to meet grid codes by injecting or absorbing the reactive power as a response to several contingencies and disturbances at different voltage level locations. Simulation results show that STATCOM provides better network voltage characteristics while the system experiencing faults and unstable load conditions. Accordingly, the installation improves the dynamic performance of wind farms. The results conclude that the location at which STATCOM is installed, affects optimistically the performance and the voltage profile in the distribution network. STATCOM installation at medium voltage level has better impact on voltage stability for all sections in the distribution system than that at low voltage level. Conversely, installing STATCOM close to the wind farm at low voltage level is more suitable for voltage profile improvement on the wind turbine bus bar.

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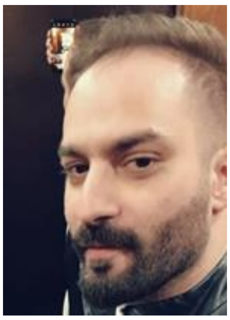

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