Transient Stability Enhancement of Wind Farm Connected to Grid Supported with FACTS Devices

Qusay Salem and Ibrahim Altawil
Yarmouk University/Power Engineering Department, Irbid, Jordan
Email: qusi_salim@yahoo.com, ialtawil@yu.edu.jo

***Abstract*—In recent years, a remarkable and numerous improvements have been achieved because of electric energy generation by utilization of wind energy. However, these achievements are accompanied by several problems such as grid stability and security. The transient stability issues of the grid connected wind farms have increased especially in case of severe disturbances and contingences. The aim of this paper is to investigate the transient stability at the grid point and at point of common coupling of the proposed system in different operating conditions. A wind farm of 15 MW consisting of five wind turbines which are based on fixed speed induction generators connected to grid has been proposed. A Static Var Compensator (SVC) and Static Synchronous Compensator (STATCOM) have been attached at the transmission system for reactive power support. It was noticed from the simulation results that STATCOM and SVC have strongly supported the point of common coupling voltage and reactive power as well as the grid voltage and reactive power particularly when the system has subjected to severe disturbances. In addition, it was also noticed that STATCOM is more robust and faster than SVC in recovering the system back to a stable operation.**

***Index Terms*—wind energy, fixed speed induction generator, static synchronous compensator (STATCOM), static var compensator (SVC), transient stability**

I. Introduction

Increasing of power demands and economic growth as well as the rapid increase of CO_2 emission which creates the global warming problem have stimulated the desire for renewable energy sources like wind energy, solar energy etc. Electric power generation using wind turbines has attracted the attentions of utilities due to high generation capacity and low maintenance and cost of such turbines.

The most common type of wind turbine is the fixed speed turbine with squirrel cage induction generator directly connected to the grid. These wind turbines based induction generators require reactive power for compensation. The needed reactive power of induction generator can be provided either by the grid or self capacitor bank in parallel with the generator stator terminals [1]. If sufficient reactive power is not supplied, then the electromagnetic torque of wind generator decreases significantly. Then the difference between mechanical and electromagnetic torques becomes large and the wind generator and turbine speeds increase rapidly. As a result, the induction generator becomes unstable and it requires to be disconnected from the power system. However, the recent trend is to decrease the shut down operation because a shutdown of large wind farm can have a serious effect on the power system operation such as loss of generation and load demand, voltage and frequency variations, power imbalance [2].

If a disturbance occurs at the transmission line which connects the power system to a remote wind farm, the wind turbines usually do not participate in voltage or reactive power control; they are often disconnected and then reconnected after the power system restore the normal operating conditions [3]. With the recent development of FACTS devices, SVC and STATCOM have been used for transient stability augmentation of power system in order to support the power system voltage and reactive power during and after disturbances where they actually increase the electric torque produced by the fixed speed induction generators and makes generators less like to over-speed and thus to increase system stability [4].

This paper has studied a normal case and a transient case (two successive three phase to ground faults) in a grid connected wind farm based on fixed speed induction generators. The impact of integration of STATCOM and SVC in improving the transient stability of the grid as well as the point of common coupling is considered. A performance comparison between the two kinds of FACTs devices is also considered.

II. Wind Turbine Model

Fig. 1 shows a Squirrel-Cage Induction Generator (SCIG), which is an asynchronous machine and it is connected directly to the grid because of its simplicity, robust operation and comparatively low-cost system [5]. For an induction generator, it is necessary to use a gearbox in order to join the generator and turbine speed. Reactive power compensation by capacitor bank, and using of soft-starter for facilitate grid connection are also necessary. Power and speed are assigned aerodynamically by stall or pitch control [6]. In this research paper, the used wind speed was the base wind speed which is 9m/s.

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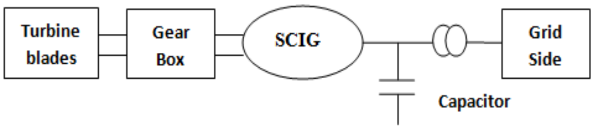

Figure 1. Wind turbine system with SCIG [1]

Eq. (1) and Eq. (2) respectively depict the mechanical power and mechanical torque on the wind turbine rotor shaft [7].

$$P_T = \frac{1}{2}\rho A_r C_p(\beta,\lambda)V_w^3 \quad (1)$$

$$T_T = \frac{1}{2\,W_T}\rho A_r C_p(\beta,\lambda)V_w^3 \quad (2)$$

where, P_T is the mechanical power extracted from the turbine rotor, T_T is the mechanical torque extracted from the turbine rotor, A_r is the area covered by the rotor which is equal to πR^2, R is the turbine rotor radius in [m], V_w is the wind velocity in [m/s], C_p is the power coefficient or performance coefficient, ρ is the air density in [kg/m^3], λ is the tip speed ratio (TSR), β is the rotor blade pitch angle in [rad], W_T is the angular speed of the turbine shaft in [rad/s].

III. Modeling and Structure of FACTS Devices

For wind farm integration, this research study uses both the static var compensator (SVC) and the static synchronous compensator (STATCOM). Providing dynamic reactive power compensation using SVC and STATCOM can possibly raise the network voltage during and after fault. As a result, the electric torque produced by the fixed speed induction generator will increase. So, generators will over-speed and thus increasing system stability.

A typical SVC configuration is shown in Fig. 2(a). It consists of a number of thyristor switched capacitors (TSC) shunted with a thyristor controlled reactor (TCR). Step change of connected shunt capacitance is provided by the TSC, while continuous control of the equivalent shunt reactance is provided by the TCR. The SVC can be operated to provide reactive power control or closed loop AC voltage control. Fig. 2(b) shows a typical STATCOM, which consists of a voltage source converter (VSC) and coupling transformer connected in shunt with the AC system. STATCOM DC voltage is usually controlled to a fixed value so as to operate satisfactorily [8]. The STATCOM performs the same function as the SVC. However at voltages lower than the normal voltage regulation range, the STATCOM can generate more reactive power than the SVC. This is due to the fact that the maximum capacitive power generated by a SVC is proportional to the square of the system voltage (constant susceptance) while the maximum capacitive power generated by a STATCOM decreases linearly with voltage (constant current). This ability to provide more capacitive reactive power during a fault is one important advantage of the STATCOM over the SVC. In addition, the STATCOM will normally exhibit a faster response than the SVC because with the VSC, the STATCOM has no delay associated with the thyristor firing [9].

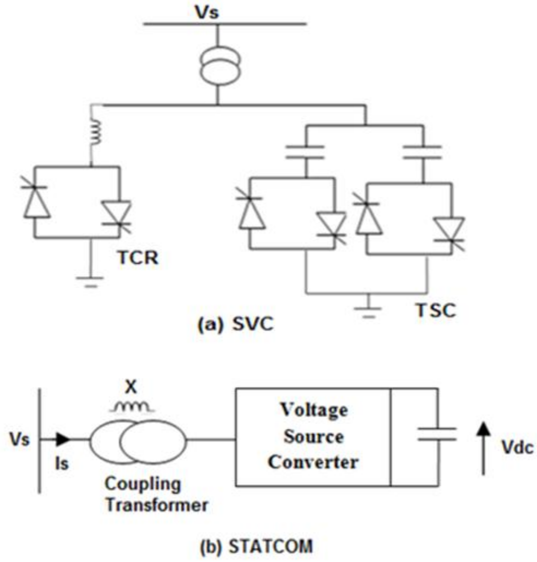

Figure 2. Schematic diagram of SVC and STATCOM [8]

Fig. 3 demonstrates the reactive current characteristics output from SVC and STATCOM. From this figure we can see that when the system voltage down to certain value or raises to a certain value, SVC characteristics will become the characteristics of pure reactance. The reactive current output from SVC is proportional to the system voltage. But STATCOM characteristics become the characteristics of constant current. That is, STATCOM produce the maximum capacitive reactive or inductive reactive current. It is also worth noting that most SVC types produce certain amount of harmonics due to incomplete conduction of the thyristor in for example the TCR type SVC. It is difficult to design a filter for SVC system but STATCOM adopt power electronics inverter technology which can effectively suppress the harmonic components in the output voltage and output current through the circuit structure and pulse triggering [10].

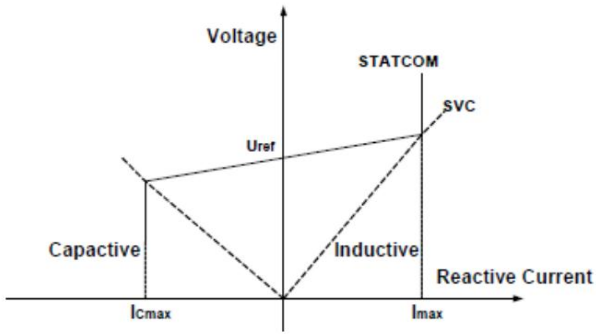

Figure 3. Reactive current characteristics output from STATCOM and SVC

IV. Transient Stability Impact

An increasing capacity of integrated wind power has negative effects on large-scale integrated wind farms. The security and stability issues of grid connected wind farms have become an urgent need to be resolved. The steady-state and transient simulation based on the wind turbine model is one of the important means to study the interaction of the wind farms and power system [11]. There are several researches and studies which have been done by researchers in analyzing and investigating in depth the influence of the grid connected wind farm on the grid security and stability. Analyzing the influence of power flow after wind power connected to the grid, particularly the impact on system voltage and reactive power balance was studied in [12]. The study has developed power flow analysis in terms of voltage and reactive power so as to investigate the results efficiently.

Short circuits or loss of production capacity as well as tripping of transmission lines can be treated as power system faults which are related to system transient stability. Such kind of faults affects the balance of both real and reactive power and change the power flow. Even though the capacity of the operating generators is suitable, when large voltage drops occur, the unbalance and redistribution of real and reactive power in the network may force the voltage to vary beyond the boundary of stability. After that, a period of low voltage may occur and possibly be followed by a complete loss of power. A wind farm nearby will see this problem. If a fault strikes the transmission line and causes the voltage at point of common coupling of local wind turbines to drop, then local wind turbines will be simply disconnected from the grid and reconnected when the fault is cleared and the voltage returned to normal operating conditions. Earlier, wind power penetration was low. Therefore, a sudden disconnection of wind turbine or even a wind farm from the grid did not cause any noticed impact on the stability of the power system. As the penetration of wind energy increases, the significance of wind power generation by wind farms is also increase. Production capability will be lost if a large power wind farm is suddenly disconnected. The system may suffer a drop in voltage or frequency and possibly followed by a blackout unless the remaining power plants replace the loss within very short time. As a result, to avoid total disconnection from the grid, there might be a new generation of wind turbines that can ride through the disturbances and faults. It is important to ensure that the wind turbine can restore the normal operation in a simple way and within suitable time in order to keep system stability. Optimization of different types of wind turbine technologies may result in adequate design so as to face the future problems. Dynamic reactive power compensation devices such as STATCOM, SVC, and interface power electronics may also limit these problems and support system stability [13].

V. System Description

Fig. 4 presents the schematic diagram of the proposed system. The system consists of a 15MW wind farm; 5 wind turbines rated at 3MW for each WTIG, and the induction generators connected with the turbines operate at 0.9 power factor.

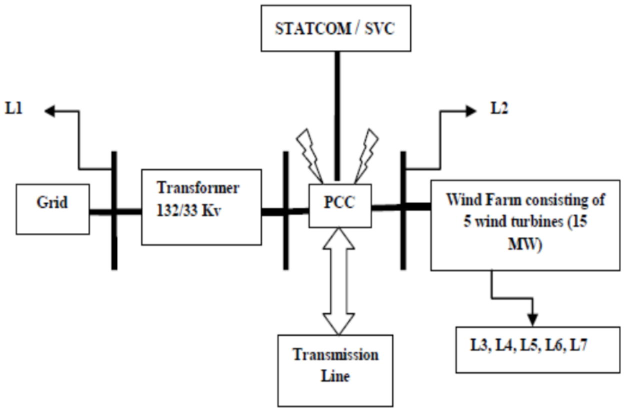

Figure 4. Schematic diagram of the proposed system

A 25km overhead transmission line is proposed, a 132/33KV (47MVA) transformer represents the grid side. The wind farm side includes Five transformers of 33/0.575KV (4MVA) attached to each WTIG and a shunt capacitor banks of 400-500-600-700-800KVAR connected at each WTIG terminals respectively.

The grid is formed by a three-phase balanced A.C voltage source, 2500MVA short circuit power and (X/R) ratio of 3 at 132KV voltage. The parameters of all components are presented in Table I, Table II, Table III and Table IV.

TABLE I. Wind Farm Parameters

Wind Turbine	Symbol	Value	Unit
Base power	*SB*	3	*MW*
Base wind speed	*VB*	9	*m/s*
Max power at base wind speed	*Pt max*	1	*p.u*
Base rotational speed	*WB*	1	*p.u*
Pitch angle controller gain	*Kp, Ki*	5, 25	
Generator			
Base power	*SB*	3/0.9	*MW*
Base voltage	*UB*	0.575	*Kv*
Stator resistance	*Rs*	0.004843	*p.u*
Stator inductance	*Ls*	0.1248	*p.u*
Rotor resistance	*Rr*	0.004377	*p.u*
Rotor inductance	*Lr*	0.1791	*p.u*
Magnetizing reactance	*Lm*	6.77	*p.u*
Inertia Constant	*H*	5.04	*S*

TABLE II. TRANSFORMER DATA

Parameter	Value	Unit
Wind farm side transformer data (33/0.575KV)		
Rated power	4	*MVA*
Vsecondary L-L (RMS)	0.575	*Kv*
Vprimary L-L (RMS)	33	*Kv*
Inductance	0.025	p.u
Grid side transformer data (132/33 KV)		
Rated power	47	*MVA*
Vsecondary L-L (RMS)	33	*Kv*
Vprimary L-L (RMS)	132	*Kv*
Inductance	0.08	p.u

TABLE III. TRANSMISSION LINE PARAMETERS

Parameter	Value	Unit
Resistance	0.1153	*Ω / Km*
Inductance	1.05	*mH/ Km*
Capacitance	11.33	*nF/ Km*

TABLE IV. LOAD DATA PARAMETERS

	P (MW)	QL (KVAR)	Qc (KVAR)
Load 1 (L1)	1.5	20	120
Load 2 (L2)	1.5	20	120
Load 3 (L3)	1.2	20	0
Load 4 (L4)	1.2	20	0
Load 5 (L5)	1.2	20	0
Load 6 (L6)	1.2	20	0
Load 7 (L7)	1.2	20	0

SCIG is used in this study, and the 25Km overhead transmission lines was modeled as π section, the lines between point of common coupling and wind farm transformers which are 1km long were also modeled as π sections.

STATCOM and SVC are connected at point of common coupling (PCC) for reactive power compensation. Wind turbines, transmission systems, transformers and grid models as well as SVC and STATCOM models are all developed in Simulink interface included in Matlab Program [14].

VI. DISCUSSION OF SIMULATION RESULTS

A. Simulation Results in Healthy Conditions

A wind farm consisting of five wind turbines connected to medium voltage grid is considered firstly without taking into account the occurrence of any short circuit. The generated power is then transferred to the high voltage grid with rated voltage of 132KV through a 25Km overhead line. The stator winding of the SCIG is directly connected to the 60Hz grid and the rotor is driven by a variable pitch wind turbine. The pitch angle is controlled in order to limit the generator output power at its rated value for the wind speeds exceeding the nominal speed. The induction generator speed must be slightly above the synchronous speed so as to generate power. So, speed varies approximately between 1p.u at no load and 1.005p.u at full load. The nominal wind speed producing the nominal mechanical power is 9m/s where 1p.u equals 3MW.

Reactive power compensation varies with the variation in wind speed. Therefore, fixed capacitor banks are assumed to be connected at the terminals of each generator but they partly compensate the reactive power absorbed by the IGs. Consequently, In order to support the voltage and provide reactive power compensation at PCC as well as at grid, STATCOOM and SVC of equal converter ratings (17MVA) are attached at PCC. Ratings of both FACTs below 17MVAR did not work satisfactorily in maintaining system stability.

The voltage and reactive power at point of common coupling as well as at grid point with the integration of STATCOM and SVC are shown in Fig. 5, Fig. 6, Fig. 7 and Fig. 8. As seen from Fig. 5 and Fig. 6, with the integration of STATCOM the voltage at PCC and grid reaches approximately 0.995p.u and 0.999p.u respectively. However, with the integration of SVC, the voltage at PCC and grid were approximately the same of the STATCOM case. It is worth noting from these figures that STATCOM has less oscillation than SVC.

Fig. 7 and Fig. 8 depict the reactive power at PCC and grid point with the integration of STATCOM and SVC. It can be seen from the former that the reactive power at PCC and at grid reaches approximately 1.6MVAR and 0.4MVAR respectively. Fig. 8 depicts the reactive power at PCC and grid with the integration of SVC. It can be shown from this figure that the reactive power at both locations was approximately the same as of the STATCOM case.

It is obviously shown from Fig. 8 that SVC has more oscillation than STATCOM. Even though they have approximately the same performance at healthy conditions, but it is clear that STATCOM is more stable and has less harmonic content than SVC.

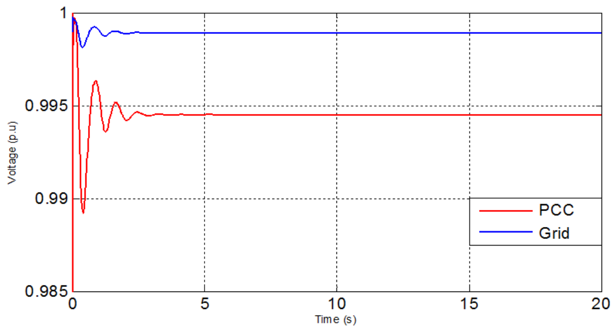

Figure 5. Voltage at PCC and grid with STATCOM

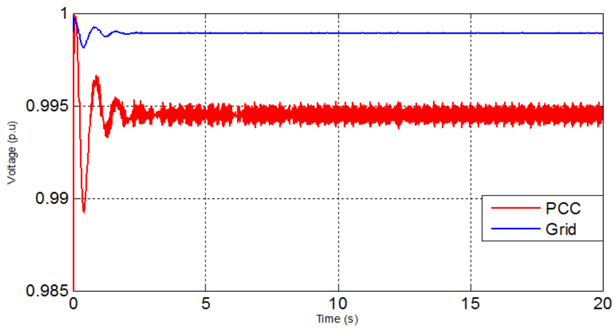

Figure 6. Voltage at PCC and grid with SVC

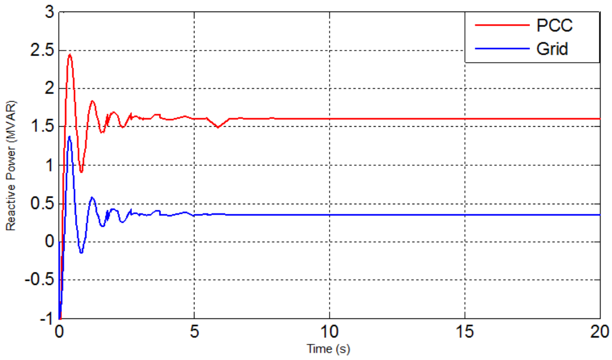

Figure 7. Reactive power at PCC and grid with STATCOM

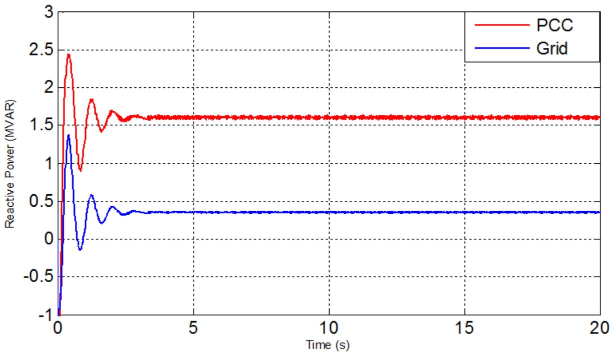

Figure 8. Reactive power at PCC and grid with SVC

B. *Simulation Results in Faulty Conditions*

Due to the severity of the three phases to ground fault than other types of faults, it is worthy to investigate the behavior of the power system during and after such kind of faults. A transient condition by means of two successive three-phase to ground fault was simulated at PCC in this study. Improving the transient stability margin of the grid and PCC can be obtained by the utilization of the given two FACT devices (STATCOM, SVC).

In order to investigate as well as compare the performance of these two FACT devices, four parameters were monitored during these transient conditions. These parameters are the voltage and reactive power at PCC and at grid and the induction generator rotor speed as well as the reactive power of wind farm induction generator.

Point of common coupling which represents the overhead transmission line has experienced two successive three-phase to ground faults. The first one occurs at t=3s and stills to t=3.2s and the other one occurs at t=8s and stills to t=8.2s.

Voltage recovery time at both PCC and grid was compared relatively when FACTS devices (STATCOM, SVC) of equal converter rating are integrated to the power system.

Fig. 9 shows the voltage recovery performance of SVC and STATCOM at PCC after subjected to the two transient conditions. It is clearly shown that after the fault recovery, the voltage at PCC gets back to the pre-fault value which is indicated by Fig. 5 and Fig. 6. From transient stability point of view, it is worth noting that STATOM is faster than SVC in recovering the voltage to its pre-fault value.

As seen from Fig. 10, STATCOM & SVC have successfully recovers the voltage back to the pre-fault value at grid point which is indicated by Fig. 5 and Fig. 6. It is clearly shown from this figure that STATCOM is also better and faster than SVC in maintaining voltage stability of the grid.

The reactive power at PCC with the integration of FACTs devices are shown in Fig. 11. This figure depicts the reactive power at point of common coupling with the integration of FACTs.

It is shown from the figure that STATCOM and SVC have recovered the reactive power back to the pre-fault value as indicated in Fig. 7 and Fig. 8. Furthermore, STATCOM has approved a better and faster performance than SVC not only in voltage recovery time but also in reactive power stability as indicated from the last figure. Fig. 12 depicts the reactive power at grid point with the integration of FACTs.

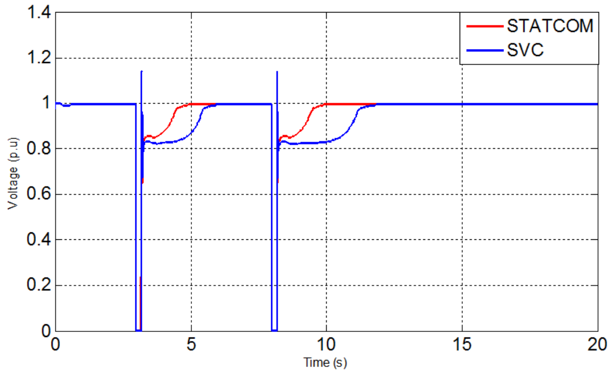

Figure 9. Voltage at PCC with STATCOM & SVC

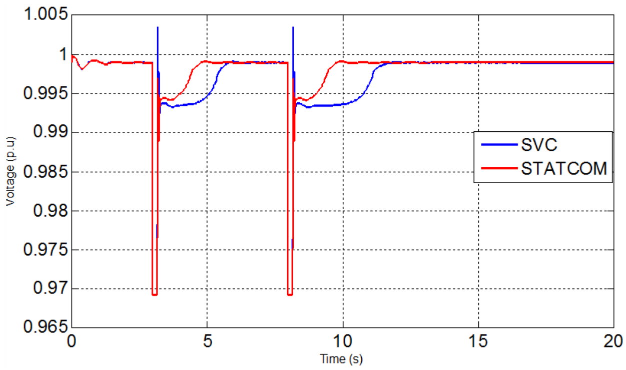

Figure 10. Voltage at grid with STATCOM & SVC

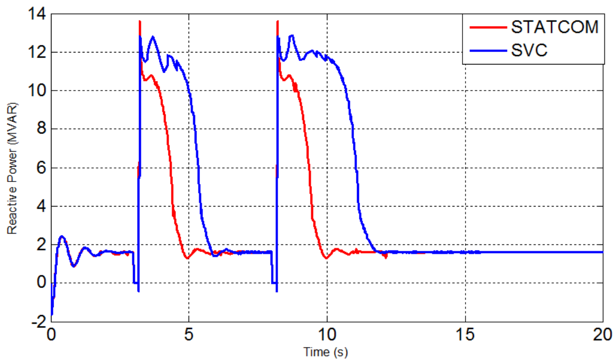

Figure 11. Reactive power at PCC with STATCOM & SVC

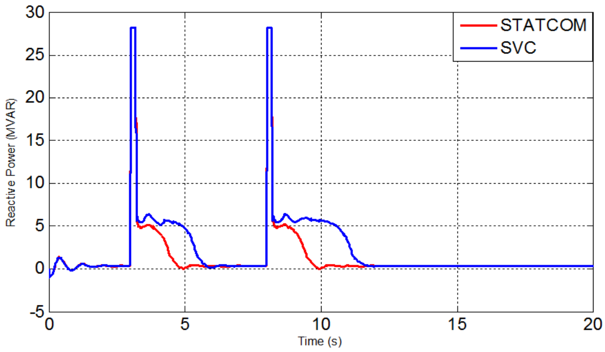

Figure 12. Reactive power at grid with STATCOM & SVC

It is obvious from Fig. 12 that the pre-fault value of the reactive power at grid point after subjected to the transient conditions has been successfully recovered due to the support of FACTs devices. STATCOM is faster than SVC in recovering the reactive power at grid point to the pre-fault value.

As known, wind generator rotor speed must be slightly above the synchronous speed in order to generate power. So, speed varies approximately between 1p.u at no load and 1.005p.u at full load. During a transient condition in a power system with wind farm based on fixed speed induction generators, the generator rotor speed increases rapidly making impossibility of the wind generator to remain connected to the power system unless suitable control mechanism or dynamic var compensators such as FACTs devices take part in maintaining system stability.

Fig. 13 depicts the wind farm generator rotor speed supported with STATCOM and SVC during and after subjected to the transient conditions. It is clearly shown that STATCOM and SVC have a robust role in recovering the rotor speed to the steady state condition. It is also shown from this figure that STATCOM is faster and has less oscillation compared to SVC.

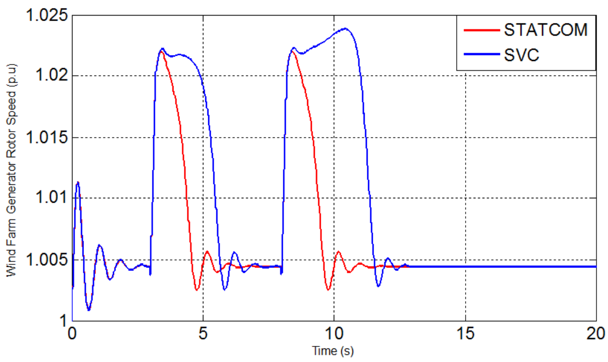

Figure 13. Wind farm generator rotor speed with STATCOM & SVC

The fourth parameter which is monitored during the transient conditions is the reactive power of the wind farm induction generator. Fig. 14 shows the reactive power of the wind farm induction generator with the integration of FACTs.

It can be noticed from Fig. 14 that the reactive power is reduced to the pre-fault value with the support of FACTs devices. Also it is obviously shown that STATCOM has a better performance than SVC in maintaining reactive power stability.

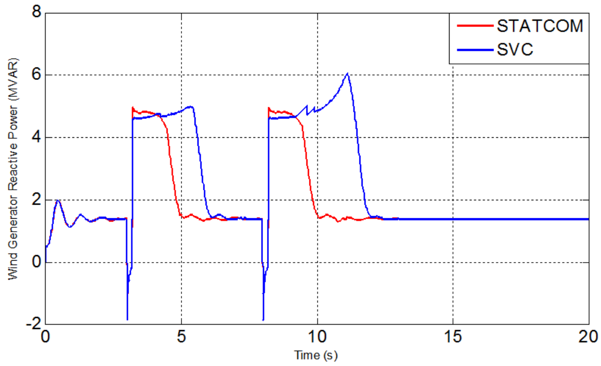

Figure 14. Reactive power of wind farm induction generator with STATCOM & SVC

Finally, it is clearly shown from the simulation results in faulty conditions that SVC takes more time in the second transient condition than the first transient to get back to the pre-fault value while STATCOM has approximately the same performance for the two transients.

VII. Conclusion

Study of transmission conditions and it's usage in electrical grids is function of wind farms connection conditions to the power system. FACTs devices are the most common power electronics based reactive power compensators that can be connected at PCC so as to improve the transient performance of the power system and support the grid voltage.

The transient performances of a grid connected to wind farm equipped with shunt capacitor banks and both of the FACTs devices which have equal converter ratings have been studied. As indicated from the obtained results, it's worth noting that the FACTs devices such as (STATCOM, SVC) can be used prosperously in a wind farm connected to medium voltage grid for improving transient stability of the grid as well as point of common coupling. It can also be concluded that STATCOM can withstand the successive disturbances of the system more efficiently than SVC.

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Qusay Salem was born in Irbid, Jordan, in 1986. He received the B.S degree in Electrical Power Engineering from Mutah University, the M.Sc degree in Electrical Power Engineering from Yarmouk University, Jordan in 2013. His research interests are in the areas of Stability of Power Systems connected to Distributed Generation, Smart Grid Applications, FACTS Devices Applications, Security of Power Systems, and Advanced Transmission Systems.

Ibrahim Altawil received the B.S. and M.S. degrees in Electrical Engineering from Fairliegh Dickinson University, NY, USA, in 1987 and 1990 respectively. He received his Ph.D. degree in Electrical Engineering from University Collage of Swansea, Wales, UK, 1996.

His research interests are in Condition monitoring, fault diagnosis and preventive maintenance of electrical machines and power electronics drive, Dc-to-Dc converters, variable speed drives, developing educational techniques for teaching power electronics and electrical machines.