Stability Study of Grid Connected to Multiple Speed Wind Farms with and without FACTS Integration

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Abstract—**Integration of wind power into power grid has developed several problems like lack of reactive power at point of common coupling which leads to voltage stability problems for the utility owner. Due to the weakness of shunt capacitor banks in maintaining voltage stability as well as reactive power improvement at point of common coupling and wind turbine generator bus, STATCOM and SVC as dynamic var compensators have been attached at the transmission network to support the stability of the proposed system. In this paper, three wind farms of different wind speed connected to grid with and without flexible AC transmission systems have been proposed. Simulations are carried out using Matlab/Simulink to investigate the performance of the proposed system under normal and abnormal conditions.**

Index Terms—**wind power integration, squirrel cage induction generator, static synchronous compensator (STATCOM), Static Var Compensator (SVC), system stability**

I. Introduction

Wind energy has attracted large attention because it is classified as the most cost effective source to produce electricity with efficient growth of power capacity. On the other hand, the rise in fossil fuel prices as well as the attitude toward a clean and abundant source of energy is another concern for researchers and utilities [1]. Fixed speed wind turbine based induction generator directly connected to the grid is the most common type of wind turbines. For such kind of generators, the compensation of reactive power is needed so as to maintain the rated voltage of the system which is connected to the remote wind farm [2].

In areas far away from the main power transmission system, the integration of wind power generating units to the utility grid by these transmission systems will impose several connection conditions such as voltage control and reactive power compensation. In this case, voltage stability of the proposed network is a major concern [3].

When the power system has not the ability to meet the demand of reactive power due to heavy loads or system disturbances, instability or collapse in system voltage will be developed. For such wind farms connected to weak grid, Flexible AC transmission Systems (FACTs) such as STATCOM and SVC is the key paradigm to support the weak power network [4] [5].

In literature, a lot of researches and studies have been performed in order to investigate the system stability performance using FACTs devices and other controllers or compensators. In [6], the system stability of fixed speed wind farms has been investigated. The transient performances with PFC only, with SVC, and with STATCOM have been studied for different network strength and compensation device rating. In [7], the transient performance of a large wind farm equipped with PFC only and equal converter rating of FACTs like SVC and STATCOM has been studied for a solid three phase fault at point on the transmission line connecting the wind farm with the grid.

In this paper, three wind farms of different wind speed (low wind speed, base wind speed, high wind speed) connected to the grid have been proposed. Each wind farm has a capacity of 9 MW and each WTIG is provided by shunt capacitor banks. STATCOM and SVC have been attached to the transmission system at point of common coupling in order to support the system stability. Simulations are carried out with and without FACTs in normal and abnormal operating conditions. Two successive faults (line to line fault followed by three phases to ground fault) have been proposed in the case of abnormal operating conditions. Voltage, reactive power and rotor speed have been monitored during and after this event in order to investigate the performance of the considered FACTs used in this study.

II. Wind Generator System Modeling

The wind turbine based induction generator system is shown in Fig. 1. The figure consists of a horizontal axis turbine generator connected to the power grid as well as the converters, filter and the transmission system. The local load including the compensating capacitor is located at the generator terminals. The models for the different components of the wind turbine generator system are given below.

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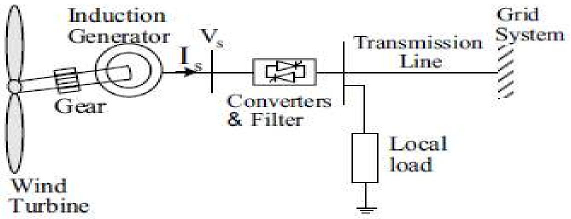

Figure 1. Wind turbine generator system

A. Wind Turbine Model

The mechanical power output of a wind turbine is related to the wind speed V_ω by [8],

$$P_m = \frac{1}{2}\rho A C_p(\lambda, \beta) V_\omega^3 \quad (1)$$

where, ρ is the air density and A is the swept area of the turbines blades. C_p is the power coefficient and it is a function of both tip speed ratio (λ) and blade pitch angle (β). The tip speed ratio (λ), which is the ratio of linear speed at the tip of blades to the speed of wind, is expressed as,

$$\lambda = \frac{\omega R}{V_\omega} \quad (2)$$

where, R and ω are the radius and mechanical angular velocity of the wind turbine rotor. Expression of C_p as a function of λ and β is related to wind turbine design specifications [9].

B. Induction Generator and Drive Train Models

The induction generator is modelled as an equivalent voltage source as, $E' = e'_d + je'_q$ behind the transient impedance, $Z' = R_x + jx'$ [10], and is represented as,

$$E'_d = -\frac{1}{T'_\circ}\left[e'_d - (x_s - x')i_{qs}\right] + s\omega_b e'_q - \frac{x_m}{x_{rr}}\omega_b v_{qr} \quad (3)$$

$$E'_q = -\frac{1}{T'_\circ}\left[e'_q - (x_s - x')i_{ds}\right] + s\omega_b e'_d - \frac{x_m}{x_{rr}}\omega_b v_{dr} \quad (4)$$

where, v_{dr} and v_{qr} are the residual voltages in the rotor circuit, $T'_\circ$ is the rotor circuit transient time constant. The stator voltages and currents are as follows,

$$V_{ds} = -R_s i_{ds} + x' i_{qs} + e'_d \quad (5)$$

$$V_{qs} = -R_s i_{qs} + x' i_{ds} + e'_q \quad (6)$$

The electromagnetic torque is given by,

$$T_e = e'_d i_{ds} + e'_q i_{qs} \quad (7)$$

The subscripts d and q stands for direct and quadrature axis values respectively. The slip used in the above equations is defined as,

$$s = \frac{\omega_s - \omega_r}{\omega_s} \quad (8)$$

For drive train, two mass model is used and by neglecting the damping terms, the equations of motion can be expressed as [11].

$$2H_t\frac{d\omega_t}{dt} = \frac{P_m}{\omega_t} - K_s\theta_s \quad (9)$$

$$2H_g\frac{d\omega_r}{dt} = K_s\theta_s - T_e \quad (10)$$

$$\frac{d\theta_s}{dt} = \omega_b(\omega_t - \omega_r) \quad (11)$$

where, θ_s is the shaft twist angle, K_s is the shaft stiffness, ω_t and ω_r are respectively the turbine rotor and generator rotor angular speed.

C. Transmission Line and Load Models

The transmission line and load equation can be expressed as,

$$V_s = V_B + (R + jX)(I_s - V_s(g11 + jb11)) \quad (12)$$

where, $(R + jX)$is the transmission line impedance, and $(g11 + jb11)$ is the admittance of local load including excitation capacitor. V_s is the induction generator terminal voltage, I_s is the stator current, and $V_B$is the infinite bus voltage.

III. Overview on FACTS Devices

Flexible AC transmission systems were developed to give the same performance as traditional power system controllers such as passive reactive compensators, transformer tap changers, etc [12]. Controlling of reactive power at transmission system as well as voltage magnitudes and angles control can be achieved using these devices [13]. Static var compensator (SVC) is one of the shunt compensating devices that can provide reactive power and support the system voltage which can be seen as a variable susceptance with a smooth control over a wide range from capacitive to inductive [14]. Static synchronous compensator (STATCOM) is another shunt compensating device which behaves like a synchronous voltage source which can inject or absorb reactive power. It was observed that STATCOM has a better performance than SVC in the ability of maintaining the reactive current output at its nominal value over a wide range of node voltages, where SVC has limited current capability when voltage is reduced [15]. The SVC consists of a number of thyristor switched capacitors (TSC) in parallel with a thyristor controlled reactor (TCR). The TSC provides step change of connected shunt capacitance while the TCR provides continuous control of the equivalent shunt reactance. SVC can be operated to provide reactive power control or closed loop AC voltage control. The STATCOM consists of a voltage source converter (VSC) and coupling transformer connected in parallel with the AC system. DC voltage of STATCOM is usually controlled to a fixed value so as to operate satisfactorily. Controlling the voltage generated by the converter to control the generated reactive power represents the basic operation of STATCOM. The synchronous d-q reference frame with the d-axis fixed to the network voltage represents usually the STATCOM control system. So, independent control of active power and reactive power by controlling the q-axis and d-axis currents can be enabled [16].

IV. Power System Stability Concerns

Increasing of wind power capacity has resulted in negative effects on large scale integrated wind farms. Therefore, stability issues of grid connected wind farms have attracted the research attention in order to be investigated and analyzed [17]. Faults during the system operation or loss of production capacity as well as tripping of transmission lines are one of the examples of power system faults which can be classified into transient stability. If a network on the power system is affected by disturbance or being heavy loaded, the unbalance and redistribution of real and reactive power in the network may force the voltage to vary beyond the boundary of stability. If a disturbance 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. Short circuits or a drop in voltage or frequency at the transmission line of a network can drive the system toward a blackout or a total disconnection from the grid. Therefore, the availability of dynamic var compensators such as STATCOM or SVC may ride through disturbances or system faults, in addition to the reactive power and voltage support that can be enhanced by these compensators [18].

V. Test Model

The schematic diagram of the proposed system is shown in Fig. 2. The system consists of three wind farms connected to the grid and each wind farm includes three wind turbine induction generators. The wind turbines are running at wind speeds of 9 m/s (base wind speed) for the first wind farm, 7 m/s (low wind speed) for the second wind farm, 11 m/s (high wind speed) for the third wind farm. The induction generators connected with the wind turbines operate at 0.9 power factor. A 20 Km overhead transmission line is used to connect the grid with each wind farm. A 132/33 KV (47 MVA) transformer connects the grid to the 20 Km overhead transmission lines. The wind farms side includes transformers of 33/0.575 KV (4 MVA) attached to each wind turbine induction generator (WTIG) that connects the wind farms to the transmission network. Shunt capacitor banks of 500 KVAR are connected at each WTIG terminals of the proposed wind farms.

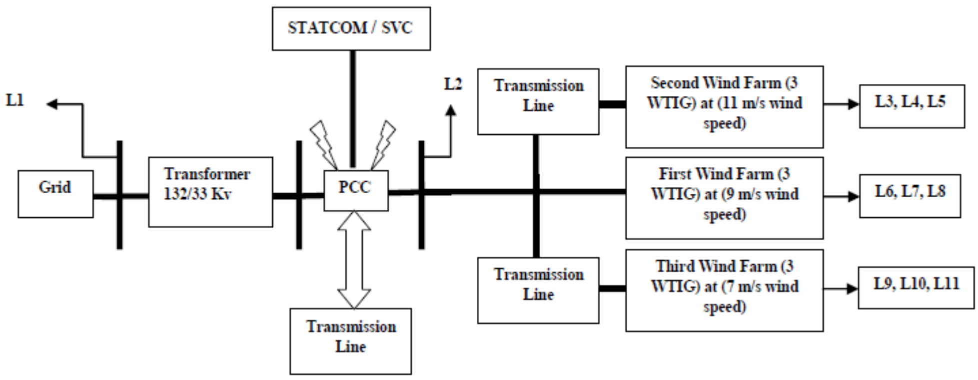

Figure 2. Test model

TABLE I. Transformer Data

Parameter	Value	Unit
Wind farm side transformer data (33/0.575 KV)		
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

The grid is formed by a three–phase balanced A.C voltage source, 2500 MVA short circuit power and (X/R) ratio of 3 at 132KV voltage. Squirrel cage induction generator (SCIG) is used in this study, and the 20 Km overhead transmission lines were modelled as π section. STATCOM and SVC are connected at point of common coupling (PCC) for reactive power compensation. The parameters of all components are presented in Tables I, II, III, IV.

TABLE II. Transmission Line Parameters

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

TABLE III. 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 IV. LOAD DATA PARAMETERS

	P (MW)	QL (KVAR)	Qc (KVAR)
Load 1 (L1)	1.4	25	80
Load 2 (L2)	1.4	25	80
Load 3, 4, 5 (L3, L4, L5)	1.2	20	0
Load 6, 7, 8 (L6, L7, L8)	1.2	20	0
Load 9, 10, 11 (L9, L10, L11)	1.2	20	0

VI. SIMULATION RESULTS DISCUSSION

A. Normal Case

The test model is simulated firstly without taking into account any occurrence of short circuits. The generated power is transferred to the high voltage grid with rated voltage of 132 KV through a 20 Km overhead line. The stator winding of the SCIG is directly connected to the 60 Hz 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 1 per unit at no load and 1.005 per unit at full load.

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 induction generators. Consequently, In order to support the voltage and provide reactive power compensation at PCC, STATCOOM and SVC of equal converter ratings (30 MVA) are attached at PCC.

Fig. 3 shows the various wind speeds of the proposed wind farms which is connected to the medium voltage grid. As shown from the figure, the first wind farm has a speed of 9 m/s which is the base wind speed, the second wind farm has a speed of 7 m/s which is low wind speed, and the third one has a speed of 11 m/s which is high wind speed.

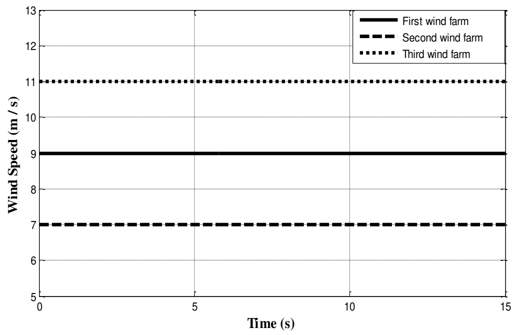

Figure 3. Wind speed of wind farms turbines

Fig. 4 depicts the voltage magnitudes at each WTIG bus for the proposed wind farms. The voltage magnitudes approach 0.57 per unit at first and third wind farm buses and 0.64 per unit for the second wind farm buses. Since the shunt capacitor banks can’t provide the needed reactive power in order to support the voltage at these buses and because of a weak grid support, the voltage magnitude at buses of the WTIGs is not accepted and will likely be disconnected from the grid by the protection system operation.

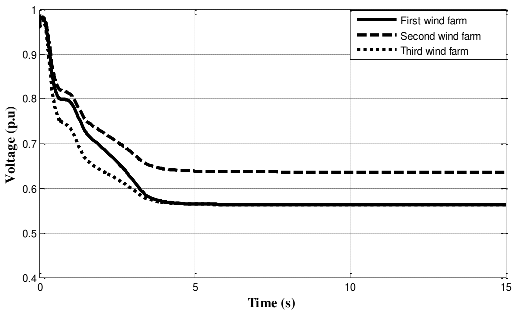

Figure 4. Voltage magnitude at wind farms buses

Fig. 5 depicts the voltage magnitudes of each WTIG bus for the abovementioned wind farms with the support of FACTs devices (STATCOM, SVC). It can be noticed from this figure that the voltage magnitude approaches approximately to 0.984 per unit for the first and third wind farm buses and 0.995 per unit for the second wind farm buses. This improvement of voltage magnitude is due to reactive power support of the FACTs devices connected in shunt with the transmission line.

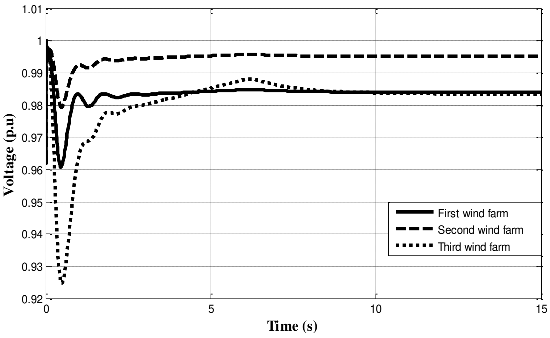

Figure 5. Voltage magnitude at wind farm buses with FACTs

The rotor speed of the WTIGs without FACTs devices can be shown from Fig. 6. It is clearly shown from this figure that the rotor speed of the first and third wind farms generators are rapidly increasing due to the lack of reactive power and low voltage condition at wind farms buses. However, the second wind farm is approximately within rotor speed limits (1 – 1.005 per unit) due to the low running speed of this wind farm which is approximately compensated by the shunt capacitor banks.

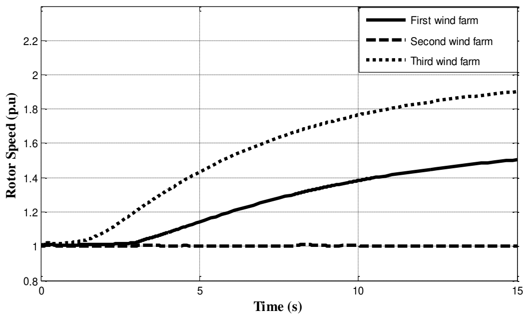

Figure 6. Rotor speed of the wind farms generators without FACTs

Fig. 7 depicts the rotor speed of the WTIGs with the support of FACTs devices. It can be shown from this figure that the rotor speed of the wind farms generator have been stabilized and get back to the rotor speed limits due to the support of reactive power from the dynamic var compensators.

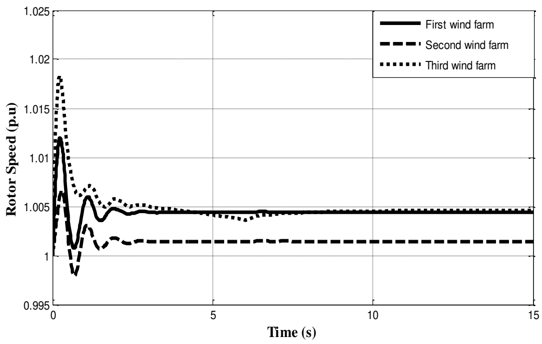

Figure 7. Rotor speed of the wind farms generators with FACTs

The voltage magnitude at point of common coupling (PCC) with and without the support of FACTs devices is shown in Fig. 8. It can be noticed that the voltage magnitude at PCC is about 0.65 per unit without the support of FACTs devices and 0.99 per unit with the support of FACTs devices. The excessive drop in voltage magnitude at PCC in the case of FACTs being not connected to the network can be attributed to the massive reactive power absorption by the wind turbines for compensation which affects the voltage magnitude at PCC. With the support of FACTs (STATCOM, SVC), it can be shown that the voltage magnitude is improved due to the dynamic injection or absorption of reactive power at PCC. It is also shown from figure 8 that STATCOM and SVC have the same performance in maintaining voltage stability at PCC.

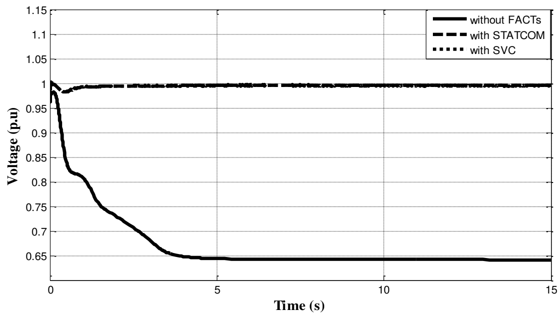

Figure 8. Voltage magnitude at PCC with and without FACTs

The reactive power with and without FACTs at PCC can be seen from Fig. 9. It can be observed from this figure that the reactive power was approximately 2.4 MVAR without FACTs support. But, when FACTs are attached to the network this value reduced to approximately 0.7 MVAR due to increased active power production and reliance of WTIGs on the dynamic var compensators (FACTs) attached at the transmission system. It is also worth noting that STATCOM and SVC have approximately the same performance in active and reactive power support.

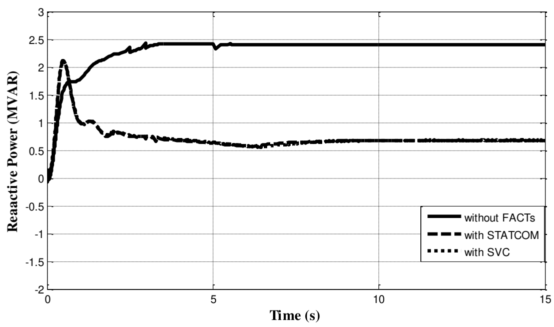

Figure 9. Reactive power at PCC with and without FACTs

B. *Abnormal Case*

Two successive faults (line to line fault followed by three phase to ground fault) was simulated at PCC in this study. Improving the transient stability margin of PCC can be obtained by the integration of the given two FACT devices (STATCOM, SVC) at the transmission network which represents the PCC. In order to investigate as well as compare the performance of these two FACT devices, three parameters were monitored during this transient condition. These parameters are voltage, reactive power at PCC and rotor speed of the wind farms generators. The first line to line fault occurs at t=3s and stills to t=3.2s and the second three phase to ground fault occurs at t=8s and stills to t=8.2s.

Fig. 10 depicts the voltage recovery performance of SVC and STATCOM due to a transient condition at PCC. It is clearly shown that after the faults recovery, the voltage at PCC gets back to the pre-fault value. In maintaining voltage stability point of view or the voltage recovery time, It’s also worth noting that the performance of SVC is approximately the same as of STATCOM performance for the first fault (L-L) fault, while the performance of STATCOM is better than SVC action for the second fault (3 phase- ground) fault.

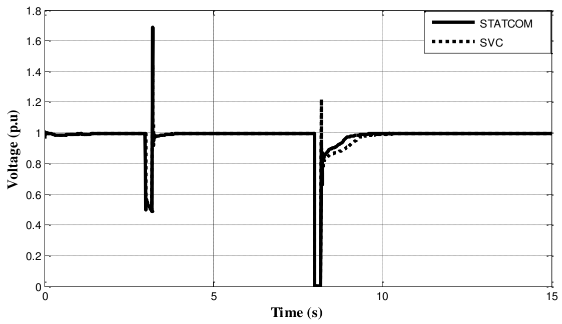

Figure 10. Voltage at PCC during and after transient

The reactive power at PCC during and after the transient condition with the support of FACTs is shown in Fig. 11. It is clearly shown that the reactive power gets back to the steady state condition after the faults recovery. But, it should be noted that STATCOM is better and faster than SVC in recovering the reactive power to its pre-fault value for the second fault (3 phase to ground). However, SVC and STATCOM have approximately the same performance in recovering the reactive power to its pre-fault value for the first fault (L-L). Wind farm generators rotor speed is also monitored so as to investigate its stability and its behavior with and without the integration of FACTS devices to the power system.

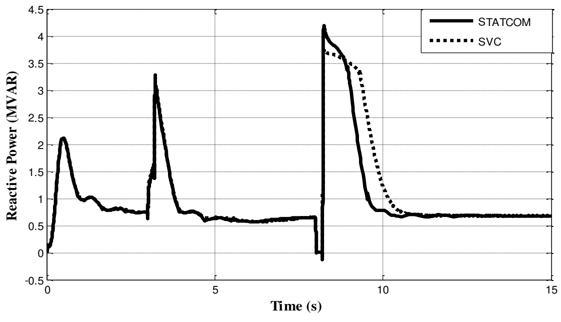

Figure 11. Reactive Power at PCC during and after transient

The rotor speed of the proposed wind farms induction generators with the support of FACTs during and after the transient condition is depicted in Fig. 12. This figure indicates that the rotor speed was increased rapidly due to the transient condition in order to support the network and consequently the possibility of the generators to remain connected to the grid is almost impossible. However, FACTs devices (STATCOM, SVC) have reduced the rapid increase of the rotor speed by means of their reactive power support. It is also worth noting that STATOM and SVC have approximately the same performance in stabilizing the rotor speed of the proposed wind farms induction generators.

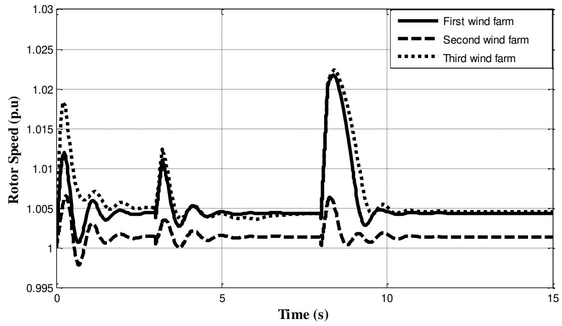

Figure 12. Rotor Speed of wind generators during and after fault

VII. CONCLUSION

Grid connected to three wind farms of different wind speed which are operated together have been proposed and simulated with the absence and presence of FACTs devices (STATCOM, SVC) under healthy and faulty conditions. It can be observed from the simulation results that STATCOM and SVC could be an essential condition in improving weak networks as well as for large scale wind farms connection requirements to the grid. . In healthy conditions (without short circuits), STATCOM and SVC have the same performance in improving the voltage stability of the system and they provide successfully the reactive power support to the network to compensate the large amount of reactive power absorbed by the WTIGs. In faulty conditions, STATCOM has better capability in voltage recovery and reactive power support than SVC for the second fault while it is approximately the same for the first fault. Concerning the wind farms induction generators rotor speed, STATCOM and SVC have approximately the same performance in rotor speed rapid increase stabilization. It can also be observed from the results in the abnormal case that if the converter ratings of STATCOM & SVC are equal, STATCOM is mostly faster and more effective than SVC in system stability improvement.

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