

Dynamic performance improvement of wind farms equipped with three SCIG generators using STATCOM

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Abstract

The main causes of wind farms disconnection from the grid is the three-phase grid faults at the point common coupling (PCC) e.g. the voltage dip. The use of a Static Synchronous Compensator (STATCOM) which is from the family of Flexible AC Transmission System (FACTS) devices can be used effectively in a wind park based on FSIG to provide transient voltage and to improve wind system stability. Due to the asynchronous operation nature, system instability of wind farms based on FSIG (Fixed Speed Induction Generator) is largely caused by the reactive power absorption by FSIG because due to the large rotor slip during grid fault. STATCOM contributes to control the grid voltage at PCC and maintain wind farm connection to the grid during some severe conditions of grid faults and used for power flow control and for damping power system oscillations. The evaluation of this control strategy using (STATCOM) is investigated in terms of regulation reactive power and transient stability of the wind farm during grid disturbances.

Keywords: wind farm, grid code, STATCOM, voltage dips

1. Introduction

During the present energy crisis, renewable energy sources have emerged as the most preferable alternatives for generating electric power. Presently, wind energy is the most developed of the renewable technologies due to the massive number of wind turbines that are installed around the world, as well as many projects currently in progress. In the past, power production through wind turbines did not have any severe effects on the wind power system,

but now it actively involved in the grid because the wind power penetration level is increasing quickly with the different used technologies.

One of the important fields of investigation of wind energy systems is their stability issue when they are connected to the grid. In the past, wind turbines were disconnected during faults on the grids, but this led to dynamic instability and blackouts (Mukund, 2006) to maintain wind turbines connected to the grid, ride through the problems, without disconnection from the grid. Two of the strategies objectives are reactive power control in normal operation case and Low fault ride-through capability during grid fault case (Allagui *et al.*, 2014).

The primary role of normal operating requirements is to maintain the voltage between the two is qualified for security and energy quality limits. Given reactive power can be transmitted long distance, it must be provided locally (Jayam, 2009). So in grid specifications connection farms turbines are generally required to contribute to reactive power (and sometimes voltage) control (Kadam *et al.*, 2014). The opportunities for large-scale integration of wind appear, and the need of a contribution to the stability of the system was recognized in low voltage demands and most requirements for grid connection to the present-day (Review of Grid Codes, 2011). The majority of existing wind parks using the induction machine with fixed speed. These generators consume significant quantities of reactive power from the grid to magnetize their stator.

For the reason that this specified generator cannot supply adaptable reactive power (Tsili *et al.*, 2009) it needs the support of external loops 'FACTS' as that Static Synchronous Compensator 'STATCOM' to ameliorate the stability of the power system operation so as to stay connected during grid faults.

The connection of a largest wind farm will usually be a connection agreement between the proprietors of the wind park and the grid. The connection agreement sets specific technical requirements to be met by the wind park e.g. Fault ride through capability (Sedighzadeh *et al.*, 2010).

2. Wind turbine and electronic models

The mathematical relationship for the extracting of mechanical power from wind may be given by:

$$P_t = \frac{1}{2} \cdot \rho \cdot \pi \cdot R^2 \cdot V^3 \cdot C_p(\lambda, \beta) \quad (1)$$

Where P_t is the established power from the wind, ρ is the air density [kg/m³], R is the blade radius [m] and C_p is the power coefficient, which depends on both the tip transmission ratio λ and the blades angle of inclination, β [deg]. A general equation used to model $C_p(\lambda, \beta)$, based on the modelling turbine characteristics is given by:

$$\left(\chi_2 \left(\frac{1}{\lambda + 0.08\beta} - \frac{0.0035}{\beta^3 + 1} \right) - \chi_3\beta - \chi_4 \right) \varepsilon^{-\chi_5 \left(\frac{1}{\lambda + 0.08\beta} - \frac{0.0035}{\beta^3 + 1} \right) + \chi_6\lambda} \quad (2)$$

Where the coefficient C_1 to C_6 are constants:

$$\begin{aligned} \chi_1 &= 0.5176 & \chi_2 &= 116 & \chi_3 &= 0.4 \\ \chi_4 &= 5 & \chi_5 &= 21 & \chi_6 &= 0.0068 \end{aligned}$$

And

$$\frac{1}{\lambda_1} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{1 + \beta^3} \quad (3)$$

In this level, the pitch control is disabling and the pitch angle Beta (β) is set to 0°. When the wind speed exceeds its rated value, the rotor speed cannot be controlled within the limits by growing the generator or the converter. In this case, the pitch strategy is operated to raise the pitch angle to decrease the mechanical power output (Appala Narayana *et al.*, 2013).

The C_p - λ curves are shown in Figure 1 for different values of Beta.

In order to generate power, the induction speed must be slightly greater than the synchronous speed, but the speed variation is typically so low that WTIG is considered to be an affixed speed wind generator (Elsady *et al.*, 2010).

3. The stability of induction generators

The normal operation point is achieved when cutting the mechanical torque of the electric torque curve. Assuming condition of the generator, the generator will speed up during fault in the power

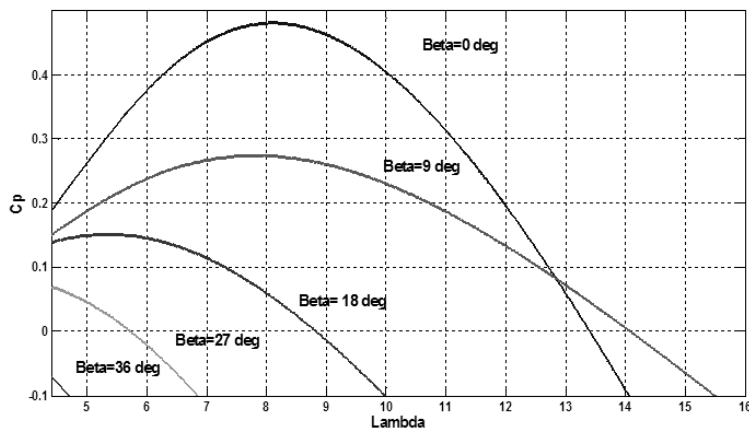


Figure 1: CP- λ curves for different pitch angles

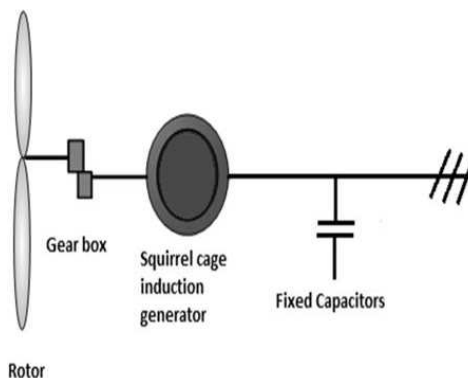


Figure 2: Wind turbine and induction generator

system in accordance with the next equation of movement:

$$\frac{d}{dt} \omega_m = \frac{1}{2H} \cdot (T_m - T_e) \quad (4)$$

A typical torque-speed static characteristic of an induction machine is presented in Figure 3.

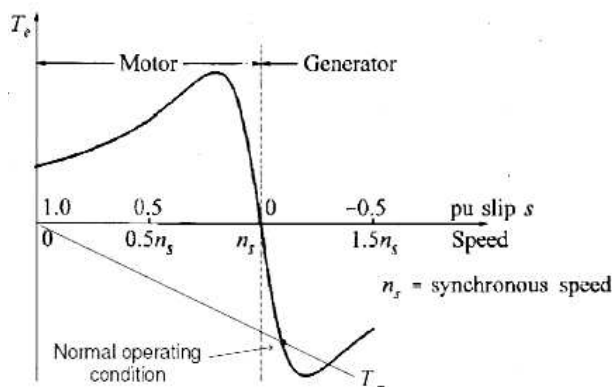


Figure 3: Typical torque-speed characteristic of an induction machine (Paulo Fischer *et al.*, 2005)

During the grid faults in the power system, T_m is the mechanical torque almost unchanged; in con-

trast, the electrical torque will drop because the electrical torque is proportional to the square of the voltage. This means that the speed allowed in depends on the inertia constant H of the generator, the fault duration and severity of the fault (Paulo Fischer *et al.*, 2005; Jahangir Hossain *et al.*, 2010).

To improve the transient voltage stability and therefore help the wind during grid faults, an alternative is to utilize dynamic reactive power compensation such as a STATCOM as considered in this study.

4. STATCOM

4.1 STATCOM operation

The STATCOM is a FACTS controller that can be treated as a solid-state synchronous condenser connected in shunt with the AC system. The output current of this controller is adjusted to control either the nodal voltage magnitude or reactive power injected at the bus. STATCOM is a new breed of reactive power compensators based on VSC as shown in Figure 4. It has a characteristic similar to a synchronous condenser, but because it is an electrical device it has inertia and it is superior to the synchronous condenser in several ways (Wei, 2007). Lower investment cost, lower operating and maintenance costs and better dynamics are big advantages of this technology (Zhang *et al.*, 2006).

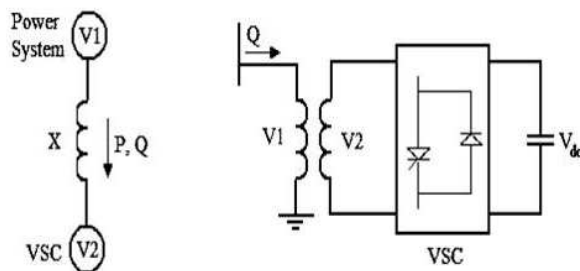


Figure 4: Schematic representation of working principle of STATCOM (Jernej, 2012)

With the VSC voltage and the bus voltage, the output of the VSC can be expressed as follows:

$$\begin{cases} P = \frac{V_1 V_2}{X} \sin \delta \\ Q = \frac{V_1 V_2}{X} \cos \delta - \frac{V_1^2}{X} \end{cases} \quad (5)$$

where P and Q are respectively the active and reactive power of the VSC. V1 and V2 are the bus voltage and VSC voltage respectively. X is the reactance of the coupling transformer and δ is the phase difference between the voltage V1 and V2 (Noureldeen, 2009). The assumption that no active power shall be traded between STATCOM and the gate (operation without loss) for the voltage the

controller is consistent with the voltage. If the amplitude of the compensation voltage is lower than the voltage at the connection node, the current flows from the gate of STATCOM (Ilyas *et al.*, 2014). In such cases, reactive power is consumed. If reverse is true for the reactive power, it is delivered to the gate.

4.2 STATCOM model

The following equations describe the STATCOM modelling, shown in Figure 5:

$$\vec{V}_{sh}^{(d,q)} = V_{shd} + jV_{shq} = v \cos \theta + jv \sin \theta \quad (6)$$

$$v = m * U_{dc} \quad (7)$$

With m: modulation index.

The model of STATCOM through a conversation on the axes d and q equations in the following voltages and currents are found:

$$V_d - mU_{dc} \cos \theta = R_{sh} I_{shd} + L_{sh} \frac{dI_{shd}}{dt} - L_{sh} \omega I_{shq} \quad (8)$$

$$V_q - mU_{dc} \sin \theta = R_{sh} I_{shq} + L_{sh} \frac{dI_{shq}}{dt} - L_{sh} \omega I_{shd} \quad (9)$$

In this case, when the harmonics and switching losses are neglected, Psh is given by the following equations:

$$P_{sh} = \frac{3}{2} (V_{shd} I_{shd} + V_{shq} I_{shq}) \quad (10)$$

$$U_{dc} I_{dc} = \frac{3}{2} (V_{shd} I_{shd} + V_{shq} I_{shq}) \quad (11)$$

The dynamic model of SATCOM is shaped in following matrices:

$$\frac{d}{dt} \begin{bmatrix} I_{shd} \\ I_{shq} \\ U_{dc} \end{bmatrix} = \begin{bmatrix} \frac{-R}{L_{sh}} & \omega & \frac{-m \cos \theta}{L_{sh}} \\ -\omega & \frac{-R}{L_{sh}} & \frac{m \sin \theta}{L_{sh}} \\ \frac{3m \cos \theta}{2C} & -\frac{3m \sin \theta}{2C} & -\frac{1}{R_c C} \end{bmatrix} \begin{bmatrix} I_{shd} \\ I_{shq} \\ U_{dc} \end{bmatrix} + \begin{bmatrix} \frac{1}{L_{sh}} & 0 \\ 0 & \frac{1}{L_{sh}} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} V_d \\ V_q \end{bmatrix} \quad (12)$$

When the resistor Rc represents the losses of the converter, which may be significant, according to the number of switches and the switching frequency (Campos, 2004).

For this study we will neglect the phase angle θ .

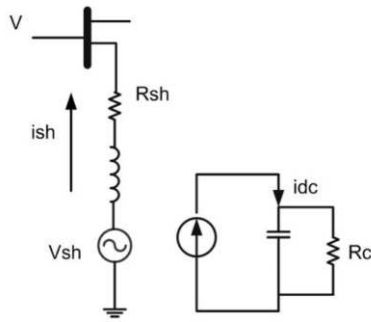


Figure 5: STATCOM model

4.3 Control scheme of the STATCOM

The reactive power exchange of STATCOM with the ac system is controlled by regulating the output voltage amplitude of VSC. The AC terminals of VSC are connected to the point of common coupling (PCC) through the leakage inductance of the coupling transformer (Allagui *et al.*, 2013).

Reference currents are obtained from the powers desired in Figure 6.

$$\begin{bmatrix} I_{shd}^* \\ I_{shq}^* \end{bmatrix} = \frac{2}{3} \frac{1}{V_d^2 + V_q^2} \begin{bmatrix} V_d & -V_q \\ V_q & V_d \end{bmatrix} \begin{bmatrix} P_{sh}^* \\ Q_{sh}^* \end{bmatrix} \quad (13)$$

The current reference on the axis d and q are obtained from a linear controller type Proportional integral (PI). The control of power is carried out by controllers that are set so to ensure proper servo line currents hand report their values. Indeed, the use of two PI controllers is required (Allagui *et al.*, 2014). Then the controllers inject a voltage (Vshd, Ishq) (Paulo Fischer *et al.*, 2005). The cross-coupling terms between the d and q axes whether (+ω Ishq, -ω Ishd) are detected. Those cross-coupling terms are as see in Figure 7 are subjoined to the PI controllers as feed-forward expression. To regulate the DC voltage of the outer control loop to its constant value a PI controller is used.

This method is investigated from equations (14) (15) (16).

$$\frac{d}{dt} \begin{bmatrix} I_{shd} \\ I_{shq} \end{bmatrix} = \begin{bmatrix} \frac{-R_{sh}}{L_{sh}} & \omega \\ -\omega & \frac{-R_{sh}}{L_{sh}} \end{bmatrix} \begin{bmatrix} I_{shd} \\ I_{shq} \end{bmatrix} + \frac{1}{L_{sh}} \begin{bmatrix} V_d - V_{shd} \\ V_q - V_{shq} \end{bmatrix} \quad (14)$$

$$\frac{1}{L_{sh}} \begin{bmatrix} V_d - V_{shd} \\ V_q - V_{shq} \end{bmatrix} = \begin{bmatrix} X_1 \\ X_2 \end{bmatrix} \quad (15)$$

$$\begin{cases} X_1 = (K_p + \frac{K_i}{s})(I_{shd}^* - I_{shd}) - \omega I_{shq} \\ X_2 = (K_p + \frac{K_i}{s})(I_{shq}^* - I_{shq}) + \omega I_{shd} \end{cases} \quad (16)$$

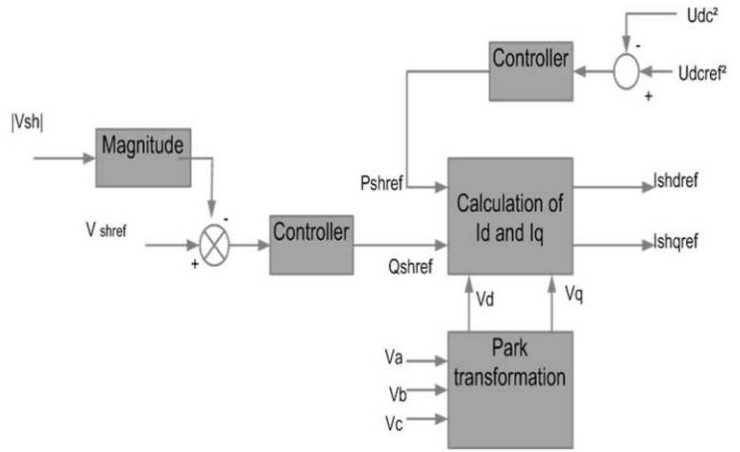


Figure 6: Block diagram of currents references controller

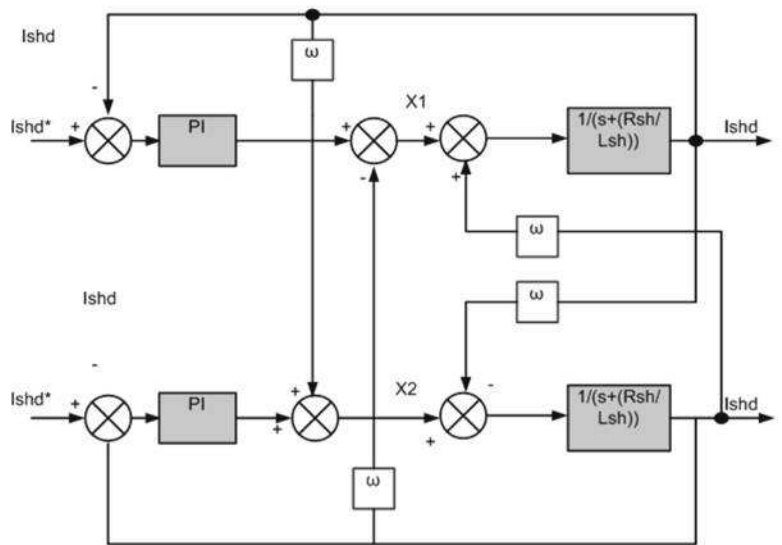


Figure 7: the Watt-Var decoupled control

The STATCOM control strategy used in this paper is shown in Figure 8.

For synchronizing the output of the full scale converter of wind turbine, a Phase Locked Loop

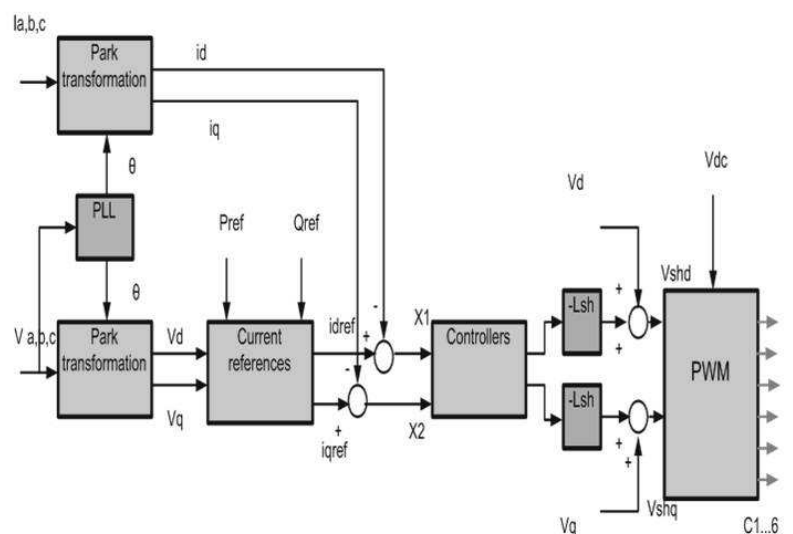


Figure 8: General control scheme of STATCOM

(PLL) algorithm is used. For Park transformation, the information about the angle of grid voltage is required. It is determined by a Phase Locked Loop (PLL) algorithm. This algorithm is very important because it makes synchronization with the grid possible. A change of the angle of grid voltage through time gives us the information about grid frequency f (Teodorescu *et al.*, 2006; Jernej, 2012).

5. Studied system and results

The wind farm is organized into a grid consisting of three units for the wind turbine as describe in Figure 9. Each of these wind turbine units is equipped with a rotor, gearbox, squirrel-cage induction generator, a 400 KVAR fixed capacitor banks; applied for the reactive power compensation; connected at each unit a low voltage bus (25-Kv) which presented the main bus of the investigated wind park. The wind farm is connected to the 120-kV transmission through a 25 km 25-kV grid voltage. The studied power system is simulated using Simulink Matlab software package.

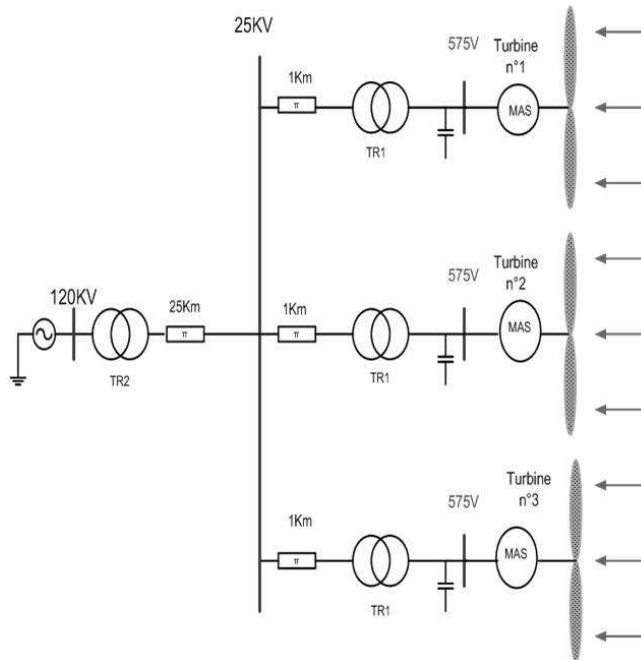


Figure 9: Test system

In this paper, the simulated disturbance is shown in Figure 10 starts at the seventh second, for 150 ms duration. According to the studied required grid code E.ON Netz, which clarifies the minimum voltage dip level and the profile of maximum duration of the occurrence, for which the production is obliged to remain 'online' are specified as described in Figure 11 (Margaris *et al.*, 2007; Nourelddeen, 2011; Hasnaoui *et al.*, 2008).

To study the effect of STATCOM, the operation of the wind farm is monitored twice. The one is without STATCOM and the other with STATCOM connection at the main bus 25 of the wind farm.

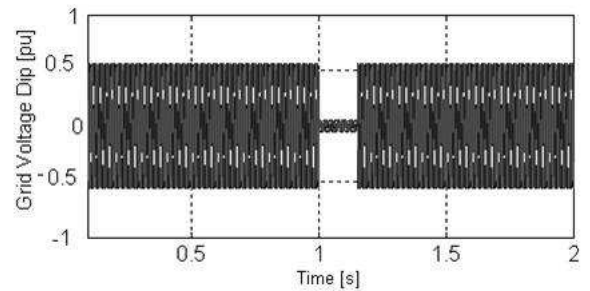


Figure 10: Behaviours of grid voltage dip

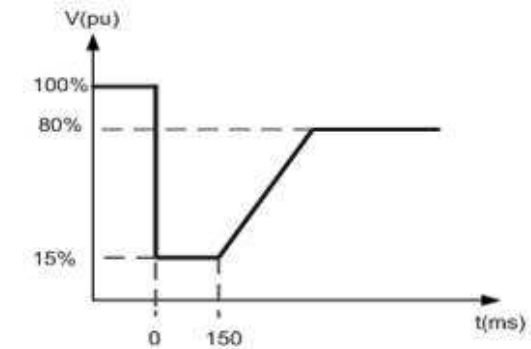


Figure 11: Voltage profile according to the requirements of LVRT capability of wind turbine according to E.ON Netz, 2006

5.1 Steady state results

When the generator is accelerated to the synchronous speed, 1200 rpm (1pu), the circuit breaker is closed and the generator is directly connected to the grid. The simulated waveforms for the generator are illustrated in Figure 12, where the system is simulated at the rated wind speed for the turbine which is 9 m/s. During the transitional system, a high inrush currents empties into the generator and a DC offset current appears in every of the stator currents i_{sa} , i_{sb} and i_{sc} , but the sum of these currents is zero compensated due to a balanced three-phase system. Such as a rotating magnetic range is designed and the core is magnetized by the generator stator current, an electromagnetic torque T_e is produced.

It can be noticed that after the direct connection to the grid, the active power will exceed its nominal value and reach its maximum value. The wind turbine generates active power at a steady state -2.915 MW, reactive power of 1.47 MVAR. It reached the steady state after 2.15 s from the time of direct connection to the grid.

5.2 Disturbance state results without STATCOM connection

In this case, the protection system uses the circuit breaker if this grid faults lasts longer than 150 ms.

It is obvious that the wind turbine (MW 3) is activated when it senses a failure of wind reactive power support. Due to the lack of reactive power and the electrical torque in a wind turbine starts to speed up induction as illustrated in Figure 14.

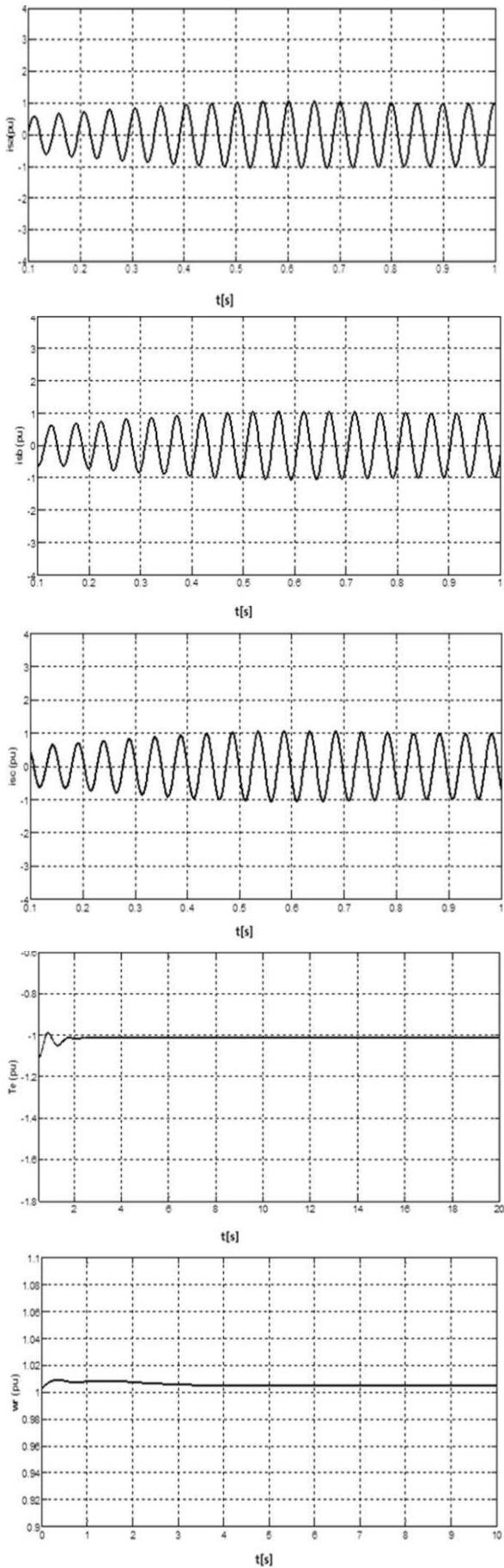


Figure 12: Dynamic behaviours of SCIG with direct grid connection

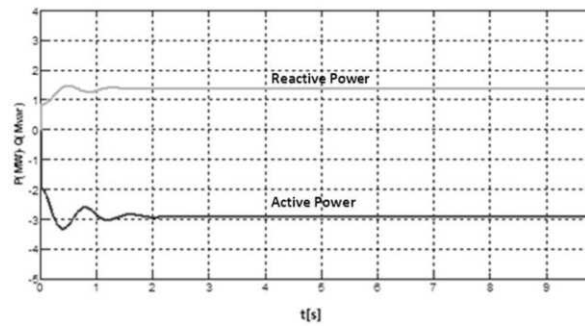


Figure 13: Response of active and reactive powers

Without STATCOM, the total produced active power during a grid fault decreased and drops to zero where the protection system trips the wind farm.

5.3 Results with STATCOM connection during grid fault

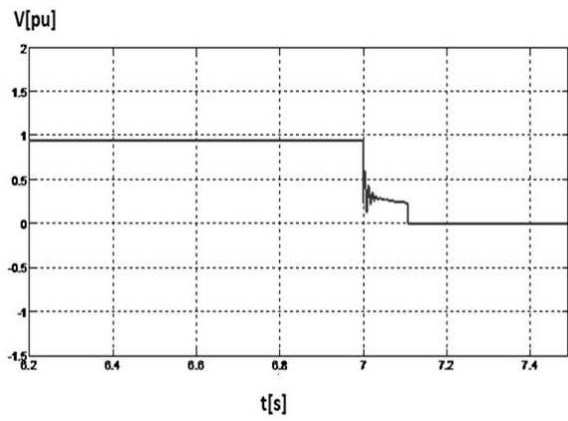
STATCOM delivers to the wind farm a reactive power and supports the grid voltage and providing the required power to the grid fault.

When connection of 30 MVAR STATCOM, the wind park remains in normal operation and the wind system restores back to initial state after duration of post-disturbance period. On the other side, in case of 3 MVAR STATCOM the delivered reactive power to the grid is still decreased to zero and the wind system is disconnected from the grid using the protection systems.

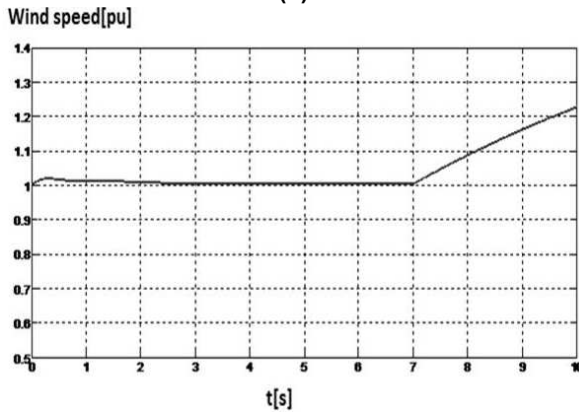
6. Conclusion

Flexible AC Transmission System (FACTS) is one aspect of the power electronics revolution that happened in all areas of electric energy.

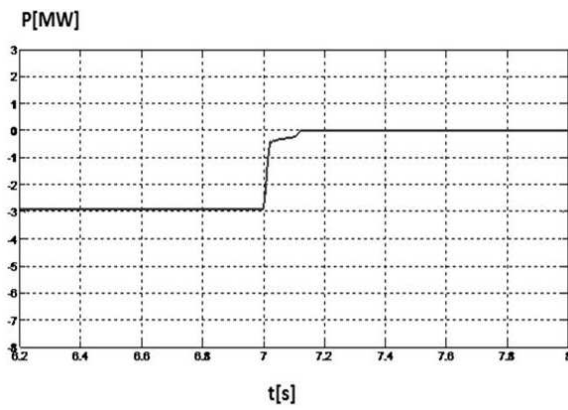
This paper investigates the using of the STATCOM which is one of the FACTS's family to support the fixed speed wind power plant in order to fulfill the required voltage-dip ride-through capability. An 85% Low Voltage Ride through LVRT for 150 ms on the grid side is studied based on E.ON grid code. It is applied to a 9 MW fixed speed wind farm connected grid. Simulation studies show that the studied SCIG wind farm cannot stay connected under the studied voltage dip without STATCOM connection to its terminal and, with low rating STATCOM, while through 30 MVAR STATCOM connection at the main bus of the studied wind farm, it can stay connected.



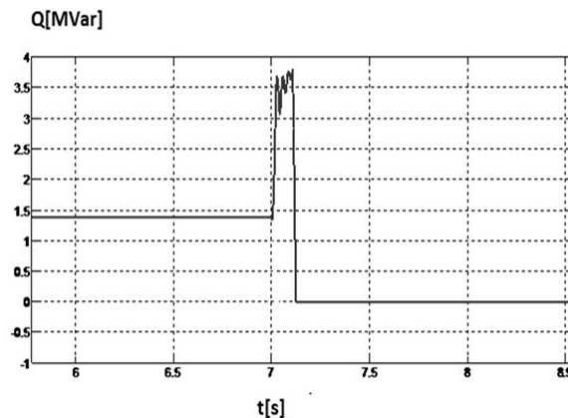
(a)



(b)

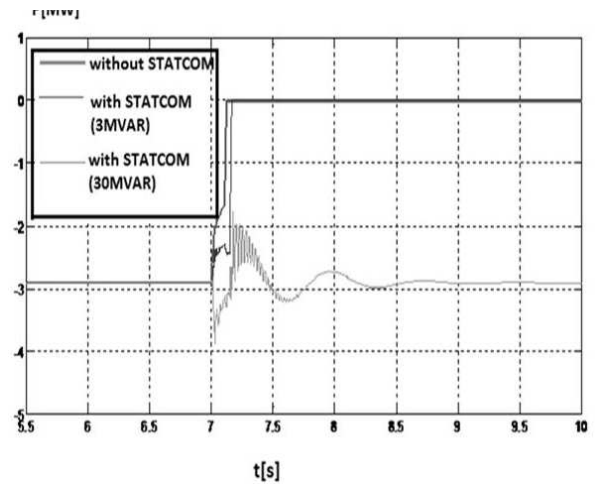


(c)

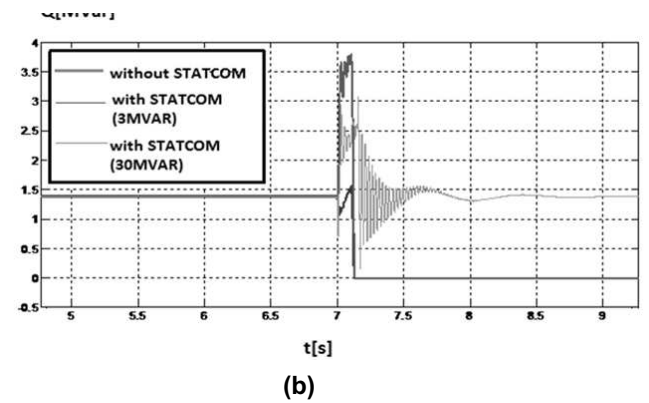


(d)

Figure 14: (a) Voltage at bus 25, (b) rotor speed, (c) Active power, (d) Reactive power



(a)



(b)

Figure 15: (a) Active power at B25 (b) reactive power at B25

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References

- Allagui, M., Hasnaoui, O.B.K., and Belhadj, J. (2013). Exploitation of pitch control to improve the integration of a direct drive wind turbine to the grid, *Journal of Electrical Systems*, 9(2), 179-190.
- Allagui, M., Hasnaoui, O.B.K., and Belhadj, J. (2014). A 2 MW Direct Drive Wind Turbine; Vector Control and Direct Torque Control Techniques Comparison, *Journal of Energy of Southern Africa*, 25(2), 117-126.
- Appala Narayana, C.H., Ananth, D.V.N., Syam, K.D., Prasad, CH., Saibabu, SaiKiran, S., and PapiNaidu, T. (2013). Application of STATCOM for Transient Stability Improvement and Performance Enhancement for a Wind Turbine Based Induction Generator, *International Journal of Soft Computing and Engineering (IJSCE) ISSN: 2231-2307, Volume-2, Issue-6*.
- Campos, F.G.R., and Penteado, A.A.Jr. (2004). Wind Energy generation Simulation with asynchronous generator connected to ENERSUL distribution System, *IEEE/PES Transmission and Distribution conference and Exposition, Latin America*, pp. 149-

- 154.
- Elsady, G., Mobarak, Y. A., and Youssef, A-R, (2010). STATCOM for Improved Dynamic Performance of Wind Farms in Power Grid, Proceedings of the 14th International Middle East Power Systems Conference (MEPCON'10), Cairo University, Egypt, Paper ID 207.
- E.ON Netz GmbH (2006). Netzanschlussregeln für Hoch- und Höchstspannung, Bayreuth.
- Hasnaoui, O. BK., Belhadj, J., and Elleuch, M. (2008). Direct Drive Permanent Magnet Synchronous Generator Wind Turbine investigation: Low Voltage Ride Through capability, -Dynamic behaviour in presence of grid disturbance, Journal of Electrical Systems, 4(3).
- Ilyas, M., and Ubaid Soherwardi, M., (2014). STATCOM for Improved Dynamic Performance of Wind Farms in Power Grid, published in International Journal of Modern Engineering Research, IJMER.
- Jahangir Hossain, M., Hemanshu, R. P., Valeri, A., Rodrigo, A. (2010). Simultaneous STATCOM and Pitch Angle Control for Improved LVRT Capability of Fixed-Speed Wind Turbines, IEEE TRANSACTIONS ON SUSTAINABLE ENERGY, Vol. 1, No. 3.
- Jayam, A.P. (2009). Improving the dynamic performance of wind farms with STATCOM, Bechtel Oil, Gas & Chem. Inc., Houston, TX Chowdhury, B.H. Published in, Power Systems Conference and Exposition.
- Jernej, C. (2012). Laboratory prototype of a Static VAR compensator, XIV International PhD Workshop OWD.
- Kadam, D.P., Kushare, B.E. (2014). LVRT Issue in Wind Farm System, International Research Journal of Sustainable Science & Engineering, IRJSSE / Volume: 2 / Issue: 1.
- Margaris, I., Tsochnikas, A., and Hatziaargyriou, N. (2007). Simulation of Doubly Fed Induction Generator Wind Turbines, School of Electrical and Computer Engineering, National Technical University of Athens, Athens, Zografou 15780, Greece.
- Mukund, R., (2006). Wind and Solar Power Systems Design, Analysis, and Operation, 2ND, New York: CRC Press Taylor & Francis Group.
- Noureldeen, O. (2009). Characteristics of Fixed Speed Wind Turbines Interconnected Grid during Wind Speed Variations, 13th Middle East power systems conference MEPCON, Assuit University, Egypt.
- Noureldeen, O. (2011). Low Voltage Ride through Strategies for SCIG Wind Turbines Interconnected Grid, International Journal of Electrical & Computer Sciences IJECS-IJENS Vol. 11 No: 02, Electrical Engineering Department, Faculty of Engineering, South Valley University, Qena, Egypte, 117502-6565 IJECS-IJENS.
- Paulo Fischer, T., Hailian, X. (2005). Topic 7: Wind Farm in Weak Grids Compensated with STATCOM, KTH, KunglTekniskaHögskolan, EME departmentTeknikringen, 33-35, Stockholm, Sweden.
- Review of Grid Codes, (October 2011). Wind Integration, International Experience, WP2.
- Sedighzadeh, M., and Hosseini, M. (2010). Investigation and comparison of using SVC STATCOM and DBR's Impact on wind farm integration, International Journal of Engineering and Applied Sciences (IJEAS), Vol. 2, Issue 4, 38-54.
- Teodorescu, R., Blaabjerg, F., Liserre, M., and Loh, P.C. (2006). Proportional-Resonant Controllers and Filters for Grid-Connected Voltage-Source Converters, Electric Power Applications, IEE Proceedings.
- Tsili, M., and Papathanassiou, S., (2009). A review of grid code technical requirements for wind farms, Renewable Power Generation, IET, Vol. 3, No. 3, pp. 308–332.
- Wei, Q. (2007). Power Quality and Dynamic Performance Improvement of Wind Farms Using a STATCOM, Georgia Inst. of Technol., Atlanta Harley, and R.G. Published in: Power Electronics Specialists Conference.
- Zhang, X.P., Rehtanz, C., and Pal, B., (2006). Flexible AC Transmission Systems: Modelling and Control, ISBN-13 978-3-540-30606-1, Springer-Verlag Berlin Heidelberg.

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