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Research Article

STATCOM Application to Increase Voltage Stability of Wind Farms

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ABSTRACT

The integration ratio of wind farms to the grid is increased tremendously derived by the need for cleaner and renewable energy. However, the stability of the grid is a major concern due to large wind and other renewable resource-based power plants. Thus, wind turbine generators must adhere to the regulations of other conventional forms of generation. To boost stability, especially voltage-based, Flexible AC Transmission Systems such as Static Var Compensators (SVC) or Static Synchronous Compensator (STATCOM) are put in the vicinity of the wind farm's connection point to the grid. This study is intended to model and simulate dynamically a wind farm using the Doubly Fed Induction Generator (DFIG) turbine type and STATCOM under faulty conditions. The dynamic equation of turbine aerodynamics, drive train, pitch angle controller, frequency controller, and doubly-fed induction machine is provided in this study. Furthermore, STATCOM is also modeled. The aggregated modeling approach is used to model the wind farm. The models are implemented inside the DigSILENT Power Factory simulation tool. The results show that STATCOM can improve the voltage stability of wind farms at the point of connection to the grid.

1. INTRODUCTION

The wind is among the renewable energy sources that has matured technology. Wind turbines are used to convert the kinetic energy of the wind to electrical energy. Wind turbines are available in a variety of technologies and sizes. Both Fixed-speed and Variable-speed wind turbines have been used in large-scale wind farms. The variable speed type wind turbines are more efficient and common. Under variable speed category Doubly Fed Induction Generator (DFIG) and Permanent Magnet Synchronous Generator (PMSG) technologies of wind turbines are very common and usable in large-scale MW wind farms.

As wind is available almost everywhere and again derived by the renewable energy demand, the wind power plant ratio in the power system is steadily increasing. Due to variations in wind speed from time to time, its output is not like conventional power generation systems. In addition, it consumes reactive power when connected to the grid. The fault may cause wind turbine generators to trip due to grid voltage drop below the set limit, furthermore, large-scale wind farm tripping can result then severe system oscillation aggravating the transient instability. This will affect the power quality and stability of the grid if it is not compensated for and handled accordingly. In addition to mitigation of problems caused by wind farms, compensation of reactive power can improve the utilization of the equipment, efficiency of transmission line, and the power quality. After clearance of the fault, wind generators require large amounts of reactive power. If this is not available, the machine speeds out of control and the protection system disconnects it from the power system [1-2]. If the wind power plant is small, the capacity loss may be acceptable, but large wind farms are subject to Grid Code which requires them not to disconnect easily. The grid code requires them not to be disconnected for specified voltage and power conditions based on the strength or weakness of the system. It is now possible to meet the grid code and increase system stability by utilizing FACTS controllers like SVCs, STATCOMs, and Unified Power Flow Controllers (UPFCs) [3-4].

The majority of STATCOMS are voltage source converters with appropriate energy storage systems, such as batteries, fuel cells, flywheel storage, supercapacitors, etc., that have substantial capacity for power modulation.

This work discusses the compensation of the wind farm by using STATCOM. The STATCOM has the following advantageous:

- It can ensure minimal losses while transmitting the electrical energy generated to the main grid by maintaining the voltage profile of the wind farm at the proper level.
- It can assist the wind farm in meeting the reactive power-related grid connection needs.

In this work one of the most effective power system software programs with an integrated graphical one-line interface is DigSILENT, which stands for "Digital Simulation and Electrical Network Calculation Program." and it has fast simulation. Three phase short circuit is applied at the connection point of the wind farm to the grid.

2. DFIG WIND TURBINE MODELING

Modeling all systems involved in energy conversion system, rotor, pitch controller, frequency converter, generator etc. have been done in many studies [5] and in this work only brief discussion will be made and more focus will be made on STATCOM. Furthermore, the components that affect the system's dynamics are the primary objective of this study.

2.1 Wind Model

The simulation study is about the dynamics of the system under faults which will last for a very small time (Milli seconds). The wind speed can be assumed constant [5] in this period. Thus, wind speed modeling is not a concern of this work.

2.2 Aerodynamic Model

The rotor of the turbine converts the available aerodynamic power in the flowing wind stream into mechanical power. The associated wind energy that the rotor blades change into mechanical energy can be calculated using [6-7]:

$$P_{rot} = 0.5\rho\pi R^2 u^3 C_p(\theta,\lambda). \tag{1}$$

The following static relations are used to simulate the aerodynamic torque $\boldsymbol{\tau_{rot}}$ (in N.m.) developed on the main shaft of a wind turbine with radius R (in m) and air density $\boldsymbol{\rho}$ (in kg/m3) at a wind speed u (in m/s).

$$\tau_{rot} = 0.5\rho\pi R^3 u^2 C_q(\theta,\lambda). \tag{2}$$

Where $\boldsymbol{\lambda}$ is the tip speed ratio $\left(\frac{R\omega_{rot}}{u}\right)$, $\boldsymbol{C_p}$ is the aerodynamic power coefficient, $\boldsymbol{C_q}$ is the torque power coefficient and $\boldsymbol{\theta}$ is the pitch angle.

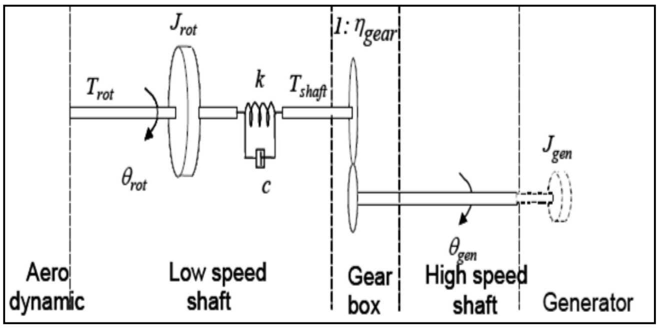

Figure 1. Two Mass Drive Train Model

2.3 Drive Train Model

Mostly for the simulation of dynamic response of wind turbines, a two-mass drive train model is used as shown in Figure 1. It improves the simulation efficiency and can give accurate results [8]. The following are the fundamental equations for the representation of the dynamics of a two-mass drive train: [8-9]:

$$\omega_k = \omega_{rot} - \frac{\omega_{gen}}{n_{gear}}. \tag{3}$$

$$\dot{\omega}_{rot} = \frac{\tau_{rot} - \tau_{shaft}}{J_{rot}}. \tag{4}$$

$$\tau_{shaft} = c\omega_k + k\theta_k. \tag{5}$$

Where: θ_k and ω_k are the angle and angular speed differences between the two ends of the flexible shaft, respectively; ω_{gen} and ω_{rot} are generator and rotor angular speeds respectively; J_{rot} is rotor inertia; τ_{rot} and τ_{shaft} are aerodynamic torques at low and high speed shafts respectively. The n_{gear} is the gear ratio; k and c are the low-speed shaft stiffness and a is damping coefficient respectively.

2.4 Pitch Angle Controller Model

When the wind speed exceeds the rated value, pitch angle control is used to limit power to the rated value. When the wind speed is lower than the rated wind speed, it is also employed to maximize the power extracted from the wind. Additionally, it aids in emergency stops and startup.

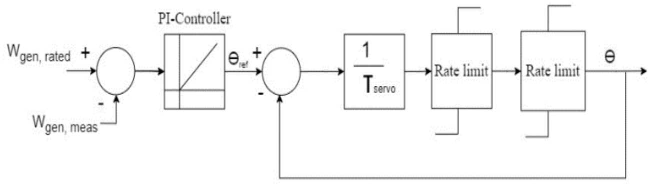

Figure 2. Pitch angle controller

Pitch angel controller model is described in references [7-8]. As in shown Figure 2 it contains the PI controller and servo controller.

2.5 Frequency Converter Model

In this work the fundamental frequency model of converter is used; thus, the AC and DC voltage relation is described as in equation 6 [9-12].

$$|U_{ac}| = K_o m U_{dc}. \tag{6}$$

Where m stands for the pulse-width-modulation index and is constrained to a value of 0-1 to prevent saturation effects. The modulation method, such as sinusoidal or rectangular modulation, is indicated by the factor $\boldsymbol{K_o}$. For frequency converter control as in the literature [9–12] primarily vector control method is used. The frequency converter model is available as an inbuilt module in the DigSILENT Power Factory simulation tool.

2.6 The Doubly Fed Induction Machine Model

The equation of the doubly fed machine is derived from single-fed induction machine equations (Figure 3).

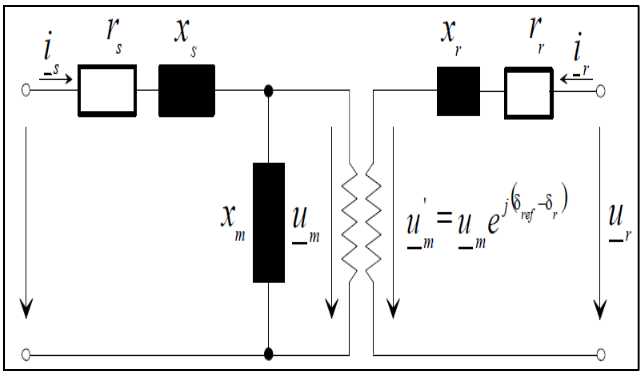

Figure 3: DFIG model [1]

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The rotating reference frame with $\boldsymbol{\omega_{ref}}$ is chosen and the dynamic equations described as follows [14]:

$$\underline{u}_s = r_s \underline{i}_s + \frac{d\underline{\Psi}_s}{\omega_n dt} + j\frac{\omega_{ref}}{\omega_n}\underline{\Psi}_s. \quad (7)$$

$$\underline{u}_r = r_r \underline{i}_r + \frac{d\underline{\Psi}_r}{\omega_n dt} + j\frac{\omega_{ref} - \omega_g}{\omega_n}\underline{\Psi}_r. \quad (8)$$

$$J\frac{d\omega_g}{dt} = t_m + t_{el}. \quad (9)$$

$$t_{el} = Im(\underline{\Psi}_s i_s^*). \quad (10)$$

Where: r_s and $\underline{i}_s$ are stator resistance and current respectively; $\underline{u}_s$ is stator voltage; $\underline{\Psi}_s$ is stator flux; ω_n and ω_{ref} nominal and reference speeds respectively; $\underline{u}_r$ is rotor voltage; r_r and $\underline{i}_r$ are rotor resistance and current respectively; J is moment of inertia; $\underline{\Psi}_r$ is the rotor flux; ω_g is generator speed; t_m and t_{el} are mechanical and electrical torques respectively.

The model of DFIG machine model is available in DigSILENT PowerFactory as an inbuilt model.

2.7 STATCOM Modeling

A voltage source converter (VSC) with rapidly controllable amplitude and phase angle serves as the building block of a STATCOM. On the grid side, a coupling transformer filter and the DC bus capacitor are also present. The VSC is used along with an appropriate energy storage system. (Figure 4). The difference between grid voltage and power converter voltage determines STATCOM reactive current. The reactive power supply in STATCOM is not impacted by the connection point's actual voltage [15–16].

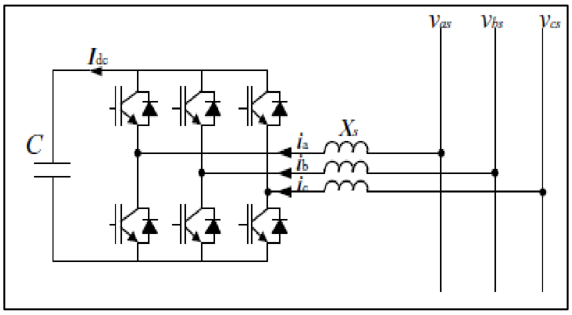

Figure 4. STATCOM model

It can be demonstrated that the output of the VSC can be expressed as follows if the bus voltage is denoted by V_1 and the VSC voltage is V_2 [17]:

$$P = \frac{V_1 V_2}{X}\sin\delta. \quad (11)$$

$$Q = \frac{V_1(V_2\cos\delta - V_1)}{X}. \quad (12)$$

If the phase shift between the bus voltage and the VSC voltage is zero, the VSC will act as a purely reactive element. The phase shift angle can determine the direction of active power while the magnitude of the voltage determines the direction of reactive power flow. The VSC will have a capacitive character if $V_2 > V_1$ and act as a generator of reactive power. If $V_1 > V_2$, the VSC will have an inductive character and act as a reactive power absorber.

The vector control technique can be used as a control strategy in STATCOM. The i_d and i_q currents on the d- and q-axes can be quickly controlled using the vector control technique. The real and reactive power output of the STATCOM is primarily determined by these currents, as shown in the equations 13-14.

$$P_s = \frac{3}{2}V_q i_q \quad (13)$$

$$Q_s = \frac{3}{2}V_q i_d \quad (14)$$

.

By controlling the DC voltage, we can indirectly control the real power ($P_S = V_{AC} i_{AC} = V_{DC} i_{DC}$). The DC voltage measured from the DC bus of the STATCOM is subtracted from the DC reference voltage. The error signal passes through PI controller and module limiter giving i_d_ref (Figure 5). In a similar way the AC voltage is measured from the point the STATCOM is connected to the network.

Then the error between reference and measured AC voltage passes through the PI controller to give i_q_ref (Figure 5). The interconnected DigSILENT frame model is shown in Figure 6. These signals are used in the internal current control loop of the converter inside the VSC model to generate the PWM signals P_{md} and P_{mq} as shown in Figure 7. It contains voltage measurement devices for AC and DC, the controller block whose detail is shown in Figure 5 and the VSC. In addition, it contains a phase locked loop for synchronization.

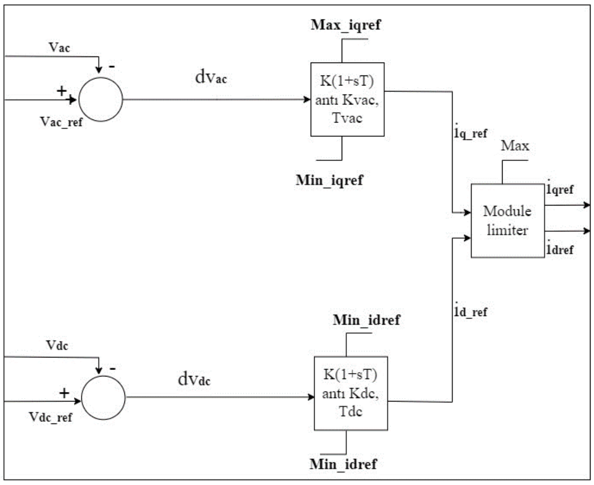

Figure 5. STATCOM Outer Controller loop DigSILENT model

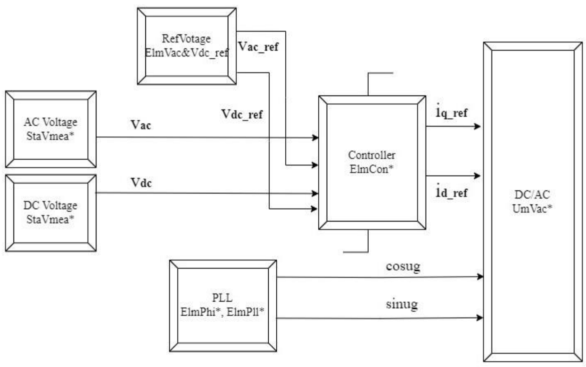

Figure 6. STATCOM frame DigSILENT model

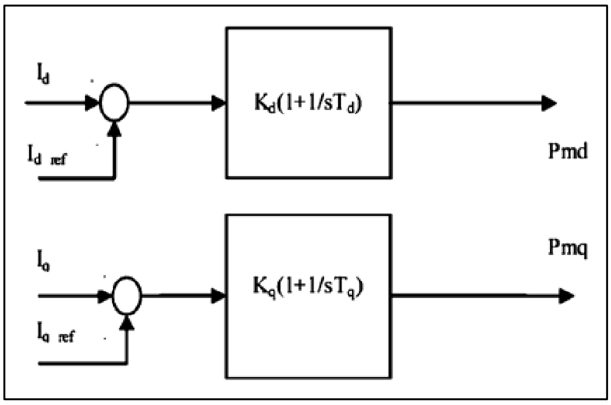

Figure 7. Internal current control loop

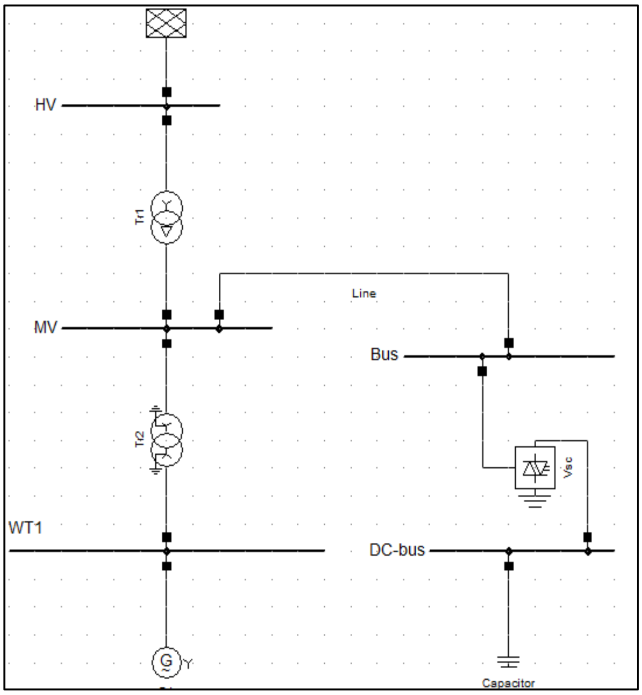

Figure 8. Wind farm, STATCOM and Network DigSILENT PowerFactory interconnection.

3. SIMULATION AND ANALYSIS

The modeling of DFIG wind turbines was discussed in the previous sections. To model wind farms for dynamic study, a mostly aggregated modeling approach is used. In the aggregated modulating approach, each component is rated to the capacity of the wind farm [17]. For example, in this study 30 DFIG with 2 MW capacity wind turbines are used with total wind farm installed capacity of 60 MW. Rather than putting 30 models of every equipment, the equivalent wind turbine, transformer, and other components rated to 60 MW is used. DigSILENT has an inbuilt aggregating facility and only specifying the number "n" of equipment to be aggregated is enough to model the equipment.

The wind farm is connected to a weak system with short circuit capacity of 952.6279 MVA. The STATCOM used in the simulation is 30 Mvar and connected to 33.6 kV voltage level (Figure 8). The voltage output of the wind turbine is 0.69 kV and then stepped up to 33.6 kV by unit transformers. In the main substation, the voltage is stepped up to 132 kV.

Three phase short circuit fault is applied on the high voltage (HV) side of the network when simulation time is 0.25 seconds. The fault is cleared when the time is 0.4 seconds (the fault duration is 1.5 s). The AC voltage and reactive power variations are observed when the STATCOM is connected to the medium voltage (MV) side of the network and by also disconnecting the STATCOM.

Figure 9(a) shows that the voltage on high voltage side is reduced to about to 4.8% because of three phase short circuit fault. In this case STATCOM is out of service. The voltage returned to almost pre fault of value about 1.022 pu with 17 ms. This shows that the DFIG wind turbines have fault ride through capability. When STATCOM is connected to the system even though the same short circuit is applied, the voltage is reduced to about 20.4%. (Figure 9(b)). In 17 ms after the clearance of the fault, the voltage returned to about 0.987 pu (Figure 9(b)) showing good performance as summarized in Table 1. Figure 9 (a) shows the voltage under a similar condition of fault, but on the MV side. In this case voltage returns to pre fault value after reduced to very low voltage when the STATCOM is not connected. The STATCOM is connected on MV bus and voltage profile is shown in Figure 10(b). In this case voltage reduction is not an issue; rather the voltage increased and returned to almost pre fault values of 0.971 pu within 17 ms.

Figures 11 - 12 show the reactive power on the HV and MV sides of the network. On the MV without STATCOM, Figure 12(a) the reactive power only varied at the beginning and end of the short-circuit fault. But in Figure 12(b) it is varied by MV side to support the voltage.

TABLE 1
COMPARISON OF VOLTAGE REDUCTION

STATCOM	VOLTAGE REDUCTION (PU)	POST FAULT VOLTAGE (PU)	Difference from nominal value (%)
Out of service	4.8	1.022	2.2
In service	20.4	0.987	1.3

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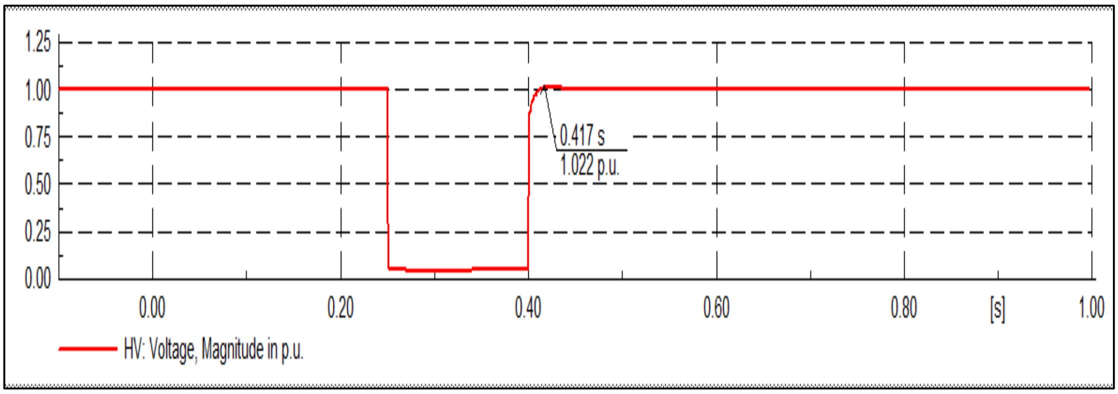
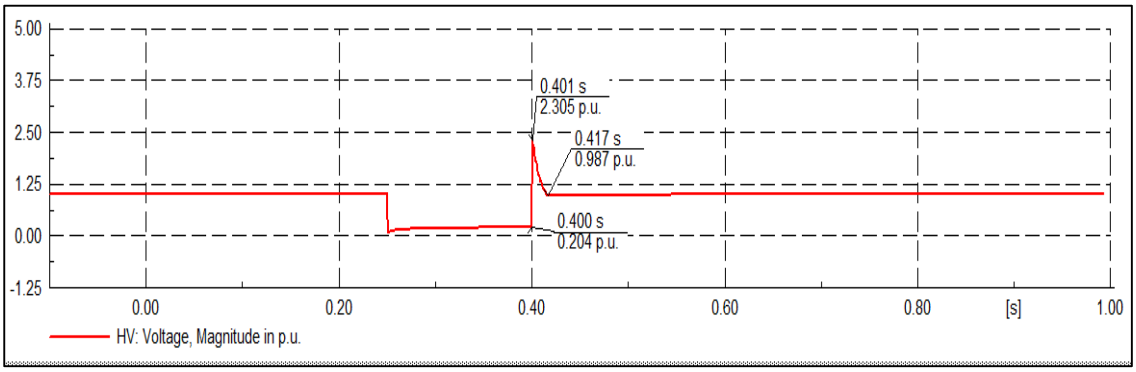
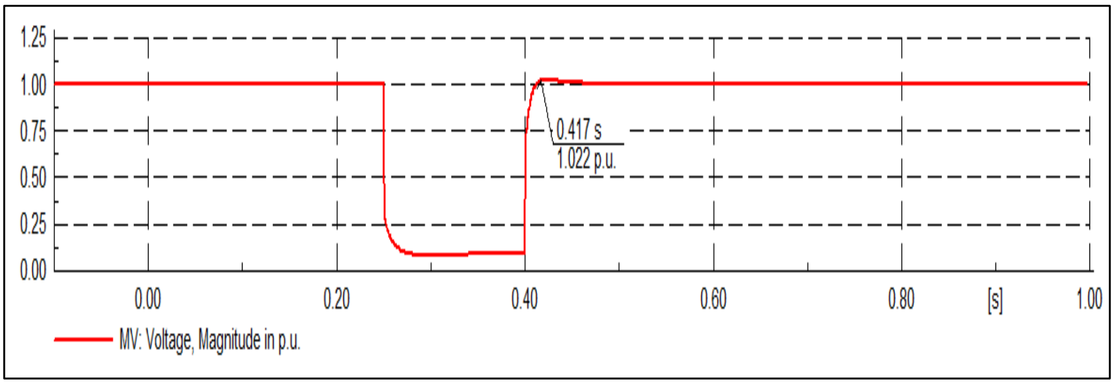


(a)

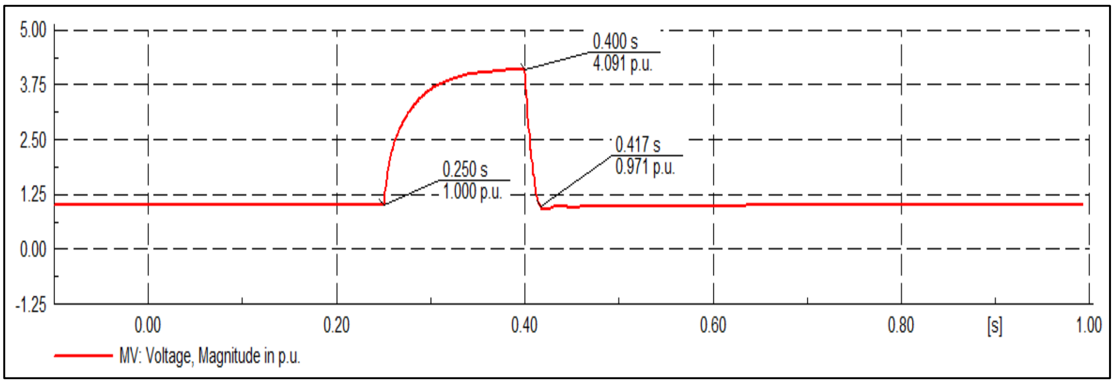


(b)

Figure 9. HV AC voltage (a) without STATCOM (b) with STATCOM

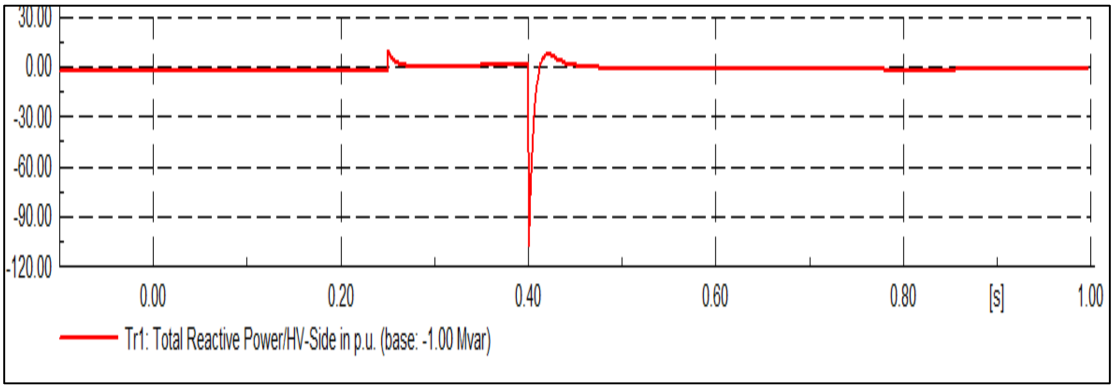


(a)

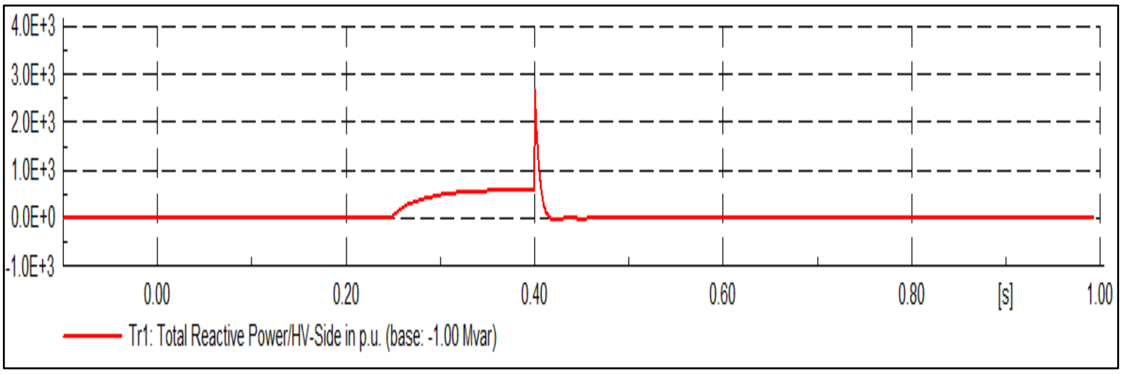


(b)

Figure 10:MV AC voltage (a) without STATCOM (b) with STATCOM

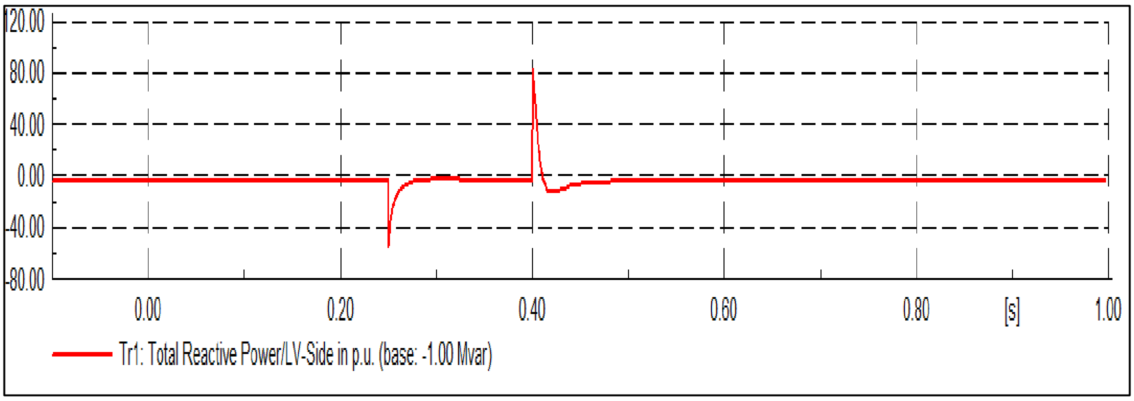


(a)

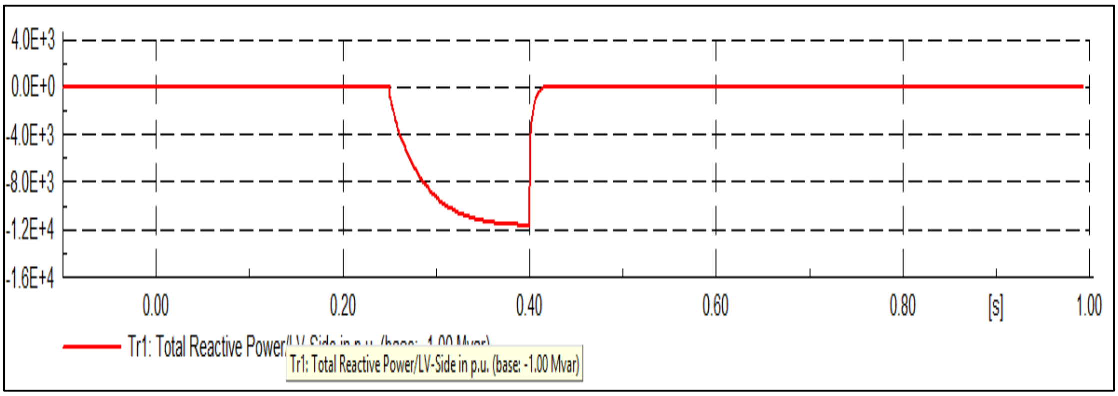


(b)

Figure 11. HV reactive power (a) without STATCOM (b) with STATCOM



(a)



(b)

Figure 12. MV reactive power (a) without STATCOM (b) with STATCOM

4. CONCLUSION

In this work wind farm with 30 DFIG wind turbines are dynamically modeled. In addition, STATCOM is also modeled and connected to the wind farm at medium voltage level. The case when this wind farm is connected to a weak system is considered in simulation by applying three phase short circuit at high voltage point of common coupling to the grid. Since wind turbines have inherent fault ride through capability, it was observed that the wind farm voltage on high voltage performed well even though the STATCOM is not connected. When the STATCOM is connected to the system, the voltage on HV did not drop to zero which could be considered as an advantage. In the medium voltage level where the STATCOM is connected, the voltage is observed to increase during fault on high voltage level which can be considered as another advantage. But when the STATCOM is not connected the voltage is decreased. In addition, when the STATCOM is connected, the reactive power is observed to increase in negative direction increasing the voltage on medium voltage side. Generally, the STATCOM can increase the system stability when connected to the wind farm terminal. But the influence is more significant in the area near to the connection point.

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