Power System Stabilization of a Grid Highly Penetrated from a Variable-Speed Wind Based Farm Through Robust Means of STATCOM and SSSC

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Pierre O. Dorile, Daniel R. Jagessar, Lizbeth Guardado, Sarah S. Jagessar, Roy A. McCann
Department of Electrical Engineering
University of Arkansas
Fayetteville, AR 72701, U.S.A.
podorile@uark.edu, drjagess@uark.edu

***Abstract*—There has been significant strides to integrate renewable energy sources into our current power system. In this work, we focus on wind farm integration into a weak grid. To ensure that this proposed idea is suitable, we perform tests to ensure that the power system remains stable under some potential scenarios. To facilitate integration and suitable steady state conditions are maintained, the use of Flexible AC Transmission System (FACTS) devices are employed. In this work, we focus on the transient stability characteristic for power system stability. Specifically, we present how the use of Static Synchronous Compensators (STATCOM) in the first portion of this work, used alongside Static Synchronous Series Compensators (SSSC) to improve voltage stability, also improved transient stability of the wind dominated power system.**

***Index Terms*—power system stability, transient stability, wind generation, High-Inverter Based Resource Penetration, Compensation devices**

I. Introduction

The electric power system is one of the most important infrastructure to the world today [1]. As time continues, the demand on the grid increases in an attempt to supply the needs of power provision. However, there are many challenges seen by system engineers. Any power system must maintain a specific level of performance on top of meeting load demands. Thus, in expanding, there is also the concern on impacts in this regard. It is also imperative to note that power systems are large, highly non linear systems which also have varying time characteristics [2]. As a result, there are various influences and responses that any power engineer must study to truly conclude a power system is reliable.

For most power systems, there exists synchronized devices for generating power and receiving that spans over large geographical areas and are connected with other networks to form one mesh that exchanges power. Power systems with high power output transmitting over long distance are those that suffer from more stability problems. Large disturbances and small disturbances limit transmission capability which even poses a stronger threat as distance increase. The power flow of many systems can reach over thousand of Megawatts of power [3]. Each device in the power system is intertwined with each other to form the network. However, as already mentioned, each device provides its own dynamic which are non-linear in nature. Thus, affecting the performance of the system as a whole. Even though components of the system are never in isolation, the stability as a result of the non-linear characteristics can mostly be studied through isolation [1,2,3]. That is, at various parts of equilibrium. This shows, that planning is a very tedious process in power system generation, distribution and transmission. Per IEEE guidelines [4], power system stability refers to the ability of an electrical power system to return to its equilibrium operation state after being under a physical disturbance withing its given operating conditions and system variable bounds. Furthermore, the entire system should remain intact and services should not be interrupted.

However, with the increasing emission of green house gases, there becomes an increasing demand to reduce the aforementioned. As such, renewable sources such as wind energy has become more developed recently worldwide. The problem that arises is that these components provides its own unique dynamics, and, thus, its own challenges. As such, we need to employ compensating devices which can stabilize, prevent voltage collapses and mitigate/alleviate faults in a certain area of power system (or node) that consists of wind turbines, thus preventing the issue propagating throughout the entire network. There has been extensive studies which suggests various means to enhance grid resiliency, maintain code compliance, and compensate reactive power in the system. The STATCOM has been suggested to provide the best means to enhance the dynamic stability in a wind dominated system which is then displayed on the transient stability and overall stabilization of the power system. In this work, the STATCOM will be operating as a voltage source converter (VSC) device that can then support the grid through the provision of reactive power into it. This paper therefore studies the impact of the STATCOM and SSSC in its response to unforeseen circumstances on a DFIG based wind farm and is a continuation of [5].

II. STATCOM Applications

The STATCOM is one of the most sophisticated power electronics-based member of the family devices called FACTS. Static Synchronous Compensator is a power electronic-based device that uses forced commutated devices like IGBT, GTO for reactive power flow control in a transmission grid. They can either assist in absorbing or generating reactive power into a transmission grid to ameliorate the voltage stability [6,7].

A. Working principles of STATCOM

The working principle of STATCOM, is shown through the transfer equation of reactive power. To show, two voltage sources, V_1 and V_2, are considered and is connected together through an impedance $Z = R + jX$.

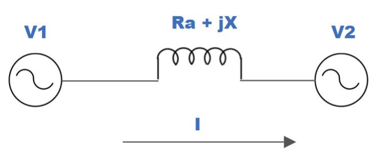

Fig. 1. Two voltage sources connected via an impedance

For a transmission line, the resistance can be neglected in comparison to the reactance of the line. The reactive power flow of the reactive power is:

$$Q = \frac{V_2}{X}(V_1 \cos\delta - V_2) \tag{1}$$

δ is the angle between V_1 and V_2. if $\delta = 0$ we have

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

It is evident that if $\delta = 0$, there is a zero flow of active power and the reactive power flow becomes a function of the difference between the two sources indicated as follows, $V_1 - V_2$ For reactive power flow, there are two cases.

1) if $V_1 > V_2$, reactive power will flow from V_1 to V_2
2) if $V_1 < V_2$, reactive power will flow from V_2 to V_1

The STATCOM uses this principle to control reactive power flow through the transmission line. FACTS devices are widely used to ameliorate the dynamics and transient stability of a wind-dominated power system.

The STATCOM has the following components as outlined in [8].

1) To convert a DC input to AC, a Voltage Source Converter (VSC) is employed. There are two types: square wave inverters and pulse width modulation (PWM) inverters.
2) To provide a constant DC voltage to the VSC, we use a DC capacitor.
3) Between the VSC and the transmission grid, inductive reactance, from the transformer, is inserted.
4) The harmonics alongside other high-frequency resultants from the VSC is filtered through harmonic filtering.

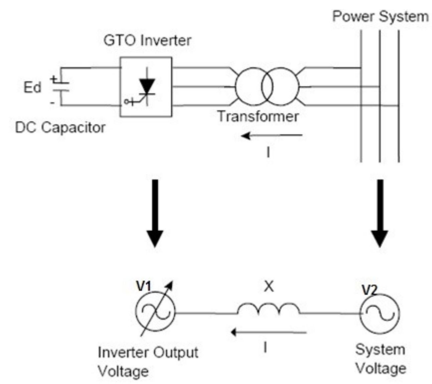

Fig. 2. Electrical diagram of STATCOM [8]

The STATCOM can operate in two modes namely:

1) Voltage regulation mode
2) Var control mode

The following figure shows the two-mode of operations of the STATCOM

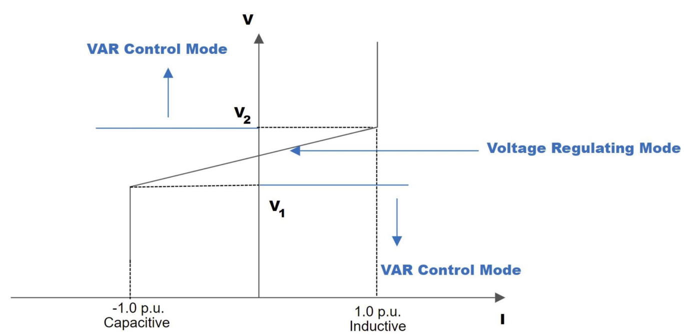

Fig. 3. Operation modes of a STATCOM

It can be seen that the voltage regulation of the STATCOM is between $V_1$and V_2 if the transmission grid voltage is lower than V_1 or higher than V_2. In this case, the STATCOM operates in Var control mode.

B. Motivations for STATCOM

Voltage stability is a major concern for power system operations. Engineers and researchers are busy trying to find the best techniques to mitigate this phenomenon. Now-a-day, the power system is being increasingly stressed due to the greater demand for electrical energy. It is burdensome to acquire new Right of Way of transmission lines. Huge demand on the transmission grid and absence of long-term planning has caused resulted in less security, thus reducing the power quality of supply. To alleviate this problem, reactive power compensation is essential. It is well established, that series and shunt compensation can increase the maximum transfer capabilities of the transmission line. Compensation aims to keep the voltage magnitude at the buses close to nominal values by injecting reactive power.

The output power of the wind farm and the total demand load demand fluctuates constantly. STATCOM is installed to keep the voltage magnitudes in the permissible ranges. The STATCOM can participate in the Low Voltage Ride Trough requirements since it can operate at full capacity and extremely low voltage. In this work, a VSC PWM technique is used to improve the voltage stability of the wind farm.

C. STATCOM Modeling

As outlined earlier, a STATCOM consists of a coupling transformer, a VSC, and a DC energy storage device. The highest compensating current of the STATCOM is not a function of the voltage of the grid. It is a very sophisticated FACTS device that can provide ease of voltage control, quick dynamic response, voltage support for changing loads conditions in a grid. A functional model of a STACOM is shown in Fig 4.

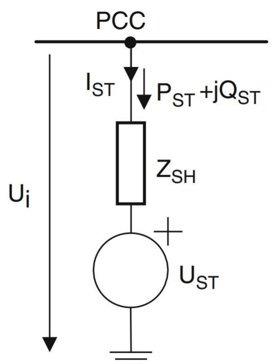

Fig. 4. Equivalent circuit diagram of the STATCOM [9]

The Voltage Source Converter (VSC) produces a voltage at the fundamental frequency of the transmission grid to which it is connected with a controllable voltage amplitude and phase. As one can depicted in Fig. 4, the VSC is connected to the AC grid via an inductive impedance Z_{SH} which represents the coupling transformer and the connection filter. To keep the voltage magnitude of the busbar constant, the STATCOM, via its controller, controls the magnitude and or the phase shift of the voltage output of the converter.

To achieve the reactive power exchange the STATCOM properly control its reactive current. While the DC voltage has a constant DC voltage to it, the error voltage is served as command signal to dictate the amount of active power to be injected by the converter [10]. The following figure shows the block diagram control of the STATCOM in DIgSILENT PowerFactory.

The STATCOM can provide reactive power support by continuously changing its susceptance whilst providing a fast voltage support response at a local node. In the d_q frame, the

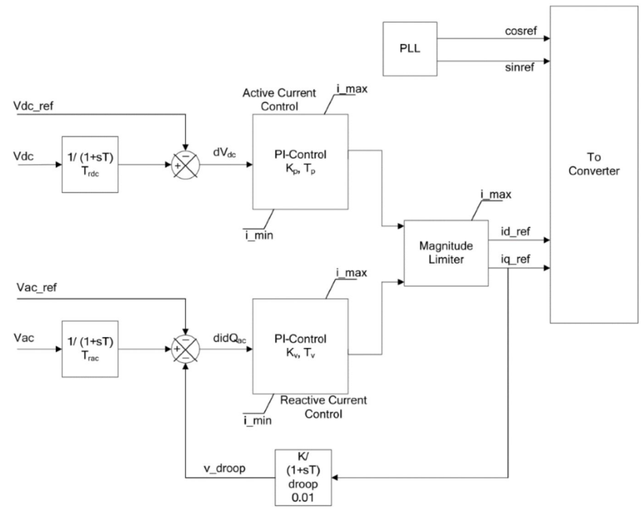

Fig. 5. Operation modes of a STATCOM [11]

outputs of the controller are i_{dref} , i_{qref} which are required to compute the power that can be injected by the STATCOM through the use of the following equations.

$$\begin{cases} P_{inj} = V_i(i_d \cos\theta_i + i_q \sin\theta_i) = v_d i_d + v_q i_q \\ Q_{inj} = V_i(i_d \sin\theta_i - i_q \cos\theta_i) = v_q i_q + v_q i \end{cases} \tag{3}$$

The power and the current injected by the STATCOM are the controlled variables. The rating of the STATCOM is done by considering several parameters such as the amount of reactive power needed to recover and survive during major disturbances. Also, the cost is a major factor to be considered. The type of fault of the external transmission grid plays a significant role in the size of the STATCOM. The lower the impedance of a three phase fault, the greater the size of STATCOM is needed.

D. Location of the STATCOM

Research has shown that the STATCOM can improve the voltage at the bus to which it is connected. For effective voltage support, the STATCOM should be positioned closely to the load bus. In doing so, the STATCOM can reduce the loss of the system and increase the transfer capability of the power system. Transmission System Operators place the STATCOM based on some quantitative benefits evaluation. The amount of reactive power injected into the grid by the STATCOM is a function of the voltage drop at the bus and its capabilities. It is also influenced by the wind turbine and the synchronous generator.

III. Static Synchronous Series Compensator (SSSC)

The SSSC is one of the key FACTS devices which is consisted of a Voltage Source Converter (VSC) and a transformer connected in series with a transmission line. They are used to control power flow and to oscillations in transmission grid following a large disturbance such a three-phase fault. The

SSSC can inject a voltage of variable magnitude in quadrature with the line current. As a result, they can easily emulate an inductive or capacitive reactance. This emulated reactance can influence the power flow in the transmission line.

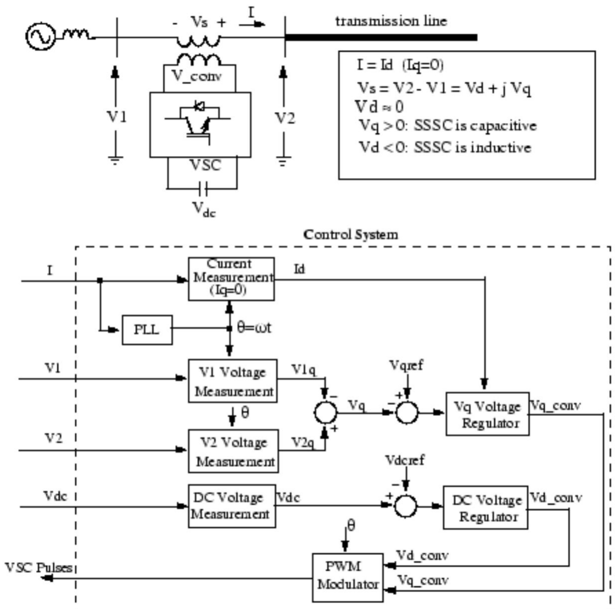

Fig. 6. Block diagram of a SSSC [12]

A. Sizing of the SSSC

The SSSC, as a reactive power, can inject compensation voltage in quadrature the line current. The voltage can either be positive or negative and the SSSC rating can computed as follow:

$$SSSC_{Rating} = (\sqrt{3})(I_{Max})(V_{SSSCMax}) \tag{4}$$

In this work, the optimal rating capacity of the SSSC is not computed. So, the SSSC might be oversized in the testing which deals with simulation to keep the injected voltage 10 percent of the voltage nominal of the power system. The test bed system is the modified IEEE-14 bus system. The use of series and shunt FACTS devices is the most sophisticated mean used by electric utilities to improve the voltage stability of the system. Stellar works done by scholars and researchers in the realm of power system engineering have led to the use of FACTS controllers for voltage stability amelioration and operating flexibility. As one of the key FACTS controllers, the SSSC can improve the dynamic performance of the power system and mitigate the damping power oscillation of the power system after being subjected to a three-phase fault. A three–phase fault is applied in the middle of the line 1 to 2 to show the amelioration of the steady-state voltage stability of a wind-dominated power system using SSSC.

IV. Doubly - Fed Induction Generator (DFIG) Wind Turbine Dynamics

The DFIG topology uses a wound rotor induction machine where the stator is connected to the grid and the rotor is connected to the grid via a back-to-back power electronics converter. The rated capacity of this power converter is between $30\% - 50\%$ of the nominal capacity Wind Turbine Generator. Through the state, reactive power can be provided to the grid.

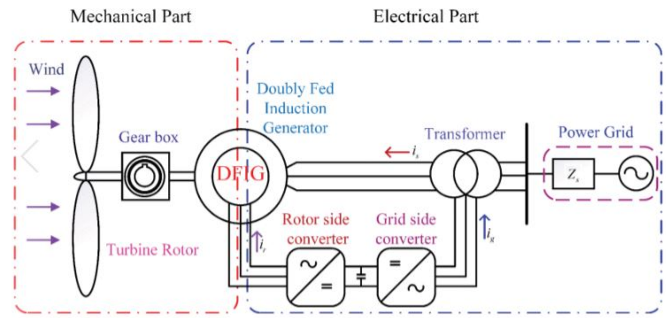

Fig. 7. Schematic diagram of the DFIG based Wind Turbine [13]

In the d-q reference frame, the stator and rotor of the DFIG can be expressed as the following equations [13],

$$v_{sdq} = R_s i_{sdq} + j\omega_s \lambda_{sdq} + \frac{d}{dt}\lambda_{sdq} \tag{5}$$

$$v_{rdq} = R_r i_{rdq} + j\omega_{slip} \lambda_{rdq} + \frac{d}{dt}\lambda_{rdq} \tag{6}$$

$$\lambda_s = L_s i_s + L_m i_r \tag{7}$$

$$\lambda_r = L_m i_s + L_r i_r \tag{8}$$

Furthermore, the torque, real and reactive power are represented as follows,

$$T_e = \frac{3}{2} p \left(\psi_{qs} i_{ds} - \psi_{ds} i_{qs}\right) \tag{9}$$

$$P_s = v_{ds} i_{ds} + v_{qs} i_{qs} \tag{10}$$

$$Q_s = v_{ds} i_{qs} - v_{qs} i_{ds} \tag{11}$$

$$T_{\text{mech}} - T_e = J \frac{d}{dt}\psi_r + B\psi_r \tag{12}$$

V. Test System

Using the IEEE 14 Bus Test System, a DFIG based wind farm was placed instead at Bus 14. A SSSC with rating of 150 MVA was inserted between lines 1 and 2 where the voltage is variable in terms of magnitude and is in quadrature with the line current. The voltage varies from $-0.20 p.u.$ to $0.042 p.u.$ by an imitation of a capacitive and reactive reactance respectively as follows. To begin, the voltage $V_{ref} = 0 p.u$ at $t = 2s$. Then after, $V_{ref} = -0.2 p.u$ and at $t = 6s$ $V_{ref} = 0.042 p.u$ The second step was to place a STATCOM rated at 150 MVA at Bus 2 in Var control mode. In capacitive mode, the STATCOM supplies reactive power to the system and absorbs reactive power in inductive mode. In the beginning $I_{ref} = 0$ at $t = 2s$ and STATCOM set $I_{ref} = -1 p.u$ in capacitive mode. After $t = 6s$, $I_{ref} = -1p.u$ inductive mode to control the compensation of the STATCOM controller. Fig. 8 provides the modified IEEE 14 Bus Test System.

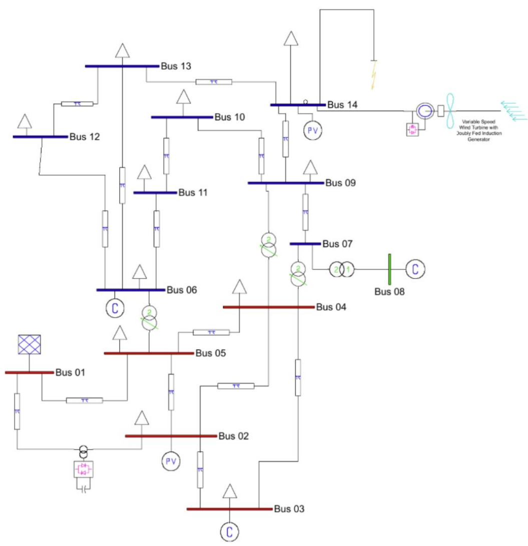

Fig. 8. Modified IEEE 14 bus system simulation diagram with SSSC & STATCOM

A three-phase fault was applied at different busbars of the test system and the effect of the SSSC and the STATCOM is appreciated. Table 1 provides the critical clearing time of several buses amid the performance of the system at Bus 14. Following this, to appreciate the effect of the STATCOM amid a short-circuit at the PCC, a three-phase fault was applied at Bus 14, the weakest bus. Most grid code worldwide considers the aforementioned fault as part of their FRT. The fault is applied at t = 1 sec and cleared at t = 1.083 sec. The system is studied with and without STATCOM. Furthermore, the voltage at bus 14 during the fault, the voltage recovery time, and the settling time are analyzed and compared. The results are depicted in Figs. 9 - 11. After the fault has been cleared, the active power oscillates for a long period before reaching its steady-state value.The same scenario is also valid for the reactive as one can see in Fig. 12.

VI. Results and Discussion

TABLE I
CRITICAL CLEARING TIME (CCT)

Faulted Bus	No FACTS	With STATCOM	With SSSC
Bus 2	0.378 s	0.427 s	0.456 s
Bus 4	0.425 s	0.489 s	0.539 s
Bus 6	0.695 s	0.749 s	0.778 s
Bus 8	0.787 s	0.845 s	0.788 s

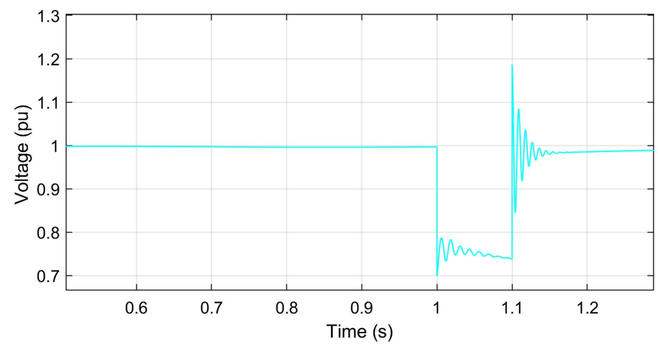

Fig. 9. Voltage at the point of interconnection without STATCOM

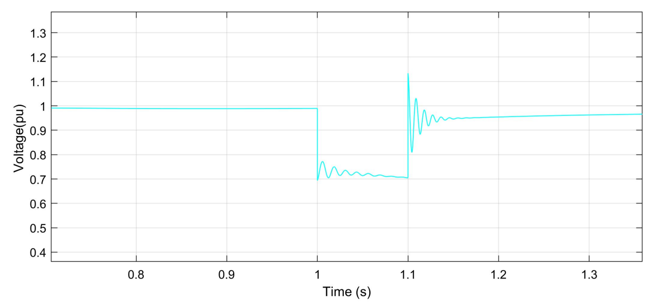

Fig. 10. Voltage at the point of interconnection with STATCOM

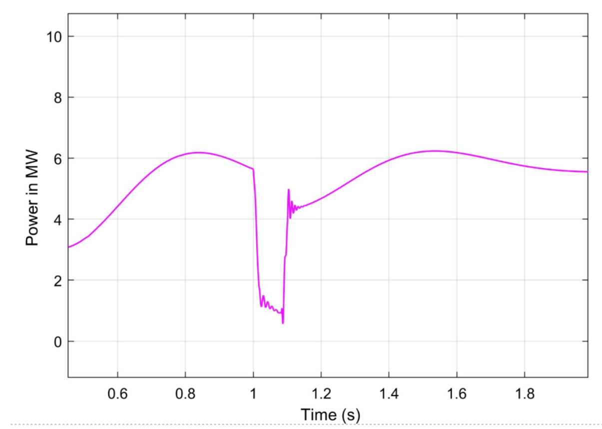

Fig. 11. Wind Farm active power output at PCC without STATCOM

From Fig 8, with the STATCOM the wind farm exhibits a better performance in the presence of a three-phase fault at the PCC.

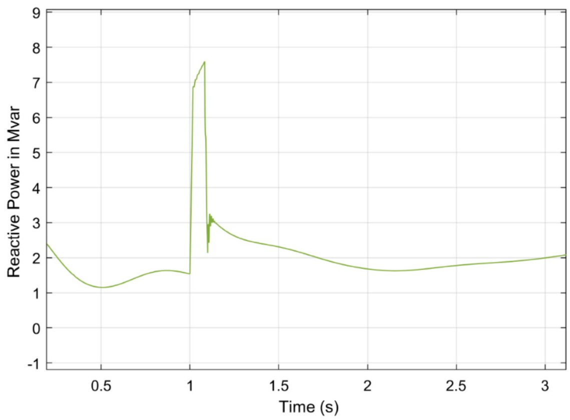

Fig. 12. Wind Farm reactive power output at PCC without STATCOM

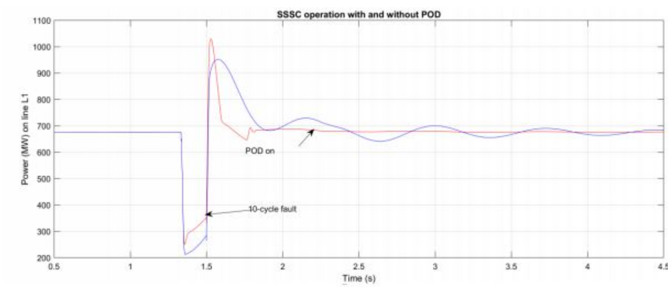

Fig. 13. Power oscillation in line 1 with and without the SSSC

VII. Conclusions

As it can be seen, in the absence of the STATCOM, when the fault has initiated the voltage at the PCC drop to almost zero. This leads to the electromagnetic torque reducing as well as the electric power output of the induction generator to reduce. Once the fault is cleared, the rotor speed increases amid the fault period, and the induction generator absorbs a huge amount of reactive from the grid. Consequently, the induction generator is incapable to satisfy the reactive power injection requirements along the fault. Hence, aggravating the voltage stability problems. Without any proper control actions, it might be burdensome to bring back voltage to the acceptable interval. Clearly, the wind farm, alone, does not meet the FRT requirements which stipulates the wind farm should be kept online for voltage lows as 5% of the nominal value for up to 250 ms. This type of behavior of the wind farm amid a short circuit is undesirable from a transmission system operator's point of view since it drives the entire grid into instability. Additionally, it was observed that the SSSC improves the damping as a result of a typical three-phase fault when it is expected to be a surplus of mechanical power to electrical output from the wind turbine.

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