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THE ROLE OF FACTS CONTROLLERS IN ENHANCING VOLTAGE STABILITY OF GRID-CONNECTED WIND FARMS DURING BALANCED THREE PHASE FAULT

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Abstract : To solve voltage stability difficulties in grid-connected wind power systems, this research provides a collaborative control technique that employs Thyristor Controlled Series Compensator (TCSC) and Static Synchronous Compensator (STATCOM). The suggested strategy, which incorporates a dual closed-loop feedback control approach of STATCOM and TCSC, ensures that the wind power grid-connected system maintains sufficient reactive power for consistent and reliable operation. MATLAB/Simulink is used to create the simulation model of the wind power grid-connected system. The results of waveform analysis and comparison with TCSC-only, STATCOM-only, and TCSC-STATCOM situations show that cooperative control of TCSC and STATCOM allows for quick and efficient restoration of bus voltage at the network connection point. Wind farms function admirably after a fault, improving the voltage stability of grid-connected equipment and increasing low-voltage throughput capacity. When compared to separate implementations of TCSC or STATCOM, synergistic control of TCSC and STATCOM produces superior outcomes.

***Keywords* - Grid, wind farm, voltage stability, TCSC, STATCOM , MATLAB/Simulink.**

I. INTRODUCTION

The increasing scarcity of conventional energy sources has fueled a boom in interest in alternative energy sources. Wind power generation has been a driving force in improving renewable energy solutions because to its cutting-edge technology, extraordinary economic viability, and global demand [1-3]. Nonetheless, because wind energy is intermittent and uncertain, grid-connected wind turbines pose issues to the grid's smooth and stable operation. Currently, doubly fed induction generators (DFIG) are the most common model used in wind farms. DFIG requires a substantial amount of reactive power from the grid to maintain terminal voltage during system failures, resulting in an increased demand for reactive power on the electrical grid. Inadequate reactive power not only disturbs the generator set's normal operation but also jeopardizes grid voltage stability, worsening the situation [4, 5]. Hence, a key challenge in wind power grid integration is enhancing the voltage stability of the interconnected system.

Normal functioning requires the wind farm to draw reactive electricity from the grid, resulting in diminished voltage stability. Furthermore, when a problem develops in the system, additional reactive power is necessary to return the voltage to normal. FACTS device placement is typical practice to assure secure and dependable operations. To solve voltage stability concerns in wind power grid-connected systems, this work introduces an effective control method utilizing Thyristor Controlled Series Compensator (TCSC) and Static Synchronous Compensator (STATCOM).

II. RELATED WORK

The topic of voltage stability necessitates deeper investigation as it holds crucial significance for wind power grid-connected systems. This section includes a variety of research projects. [6–8] investigate the use of STATCOM in wind energy applications in conjunction with asynchronous generators. [14] and [19] investigate the FACT device's advancement and research opportunities in the field, as well as its application in stability analysis. [11] and [13] examine the stability of wind farms with an energy storage unit linked to STATCOM. [10] investigates STATCOM capability during symmetrical faults. [9] and [21] involve a thorough examination of STATCOM's uses in various contexts. [15–17] concentrate on the use of TCSC in power systems to reduce oscillations and sub-synchronous reactance. [3] and [20] investigate the improved power quality gained by combining TCSC and STATCOM. 23] explores wind power grid-connected systems using asynchronous wind turbines and series controllable compensation equipment (TCSC), efficiently preventing anomalous grid-connected system operation. [5] focuses on improving power system stability by combining Fixed Series Compensator (FSC) and TCSC. [31] shown how the dynamic continuous power flow approach, along with the combined effect of Static Var Compensator (SVC) and TCSC, is utilized to calculate the static voltage stability margin of a power system. This novel solution considerably enhances the static voltage stability of the power supply. [15] used the power system simulation toolkit PSAT to create a simulation model of SVC and TCSC in their investigation. The results show that implementing SVC and TCSC improves the stability of the power system significantly. The simultaneous use of SVC and TCSC to power system lines is illustrated in both [15] and [31], and the research findings support their successful contribution to boosting power system stability. Nonetheless, the practical application of STATCOM in grid-connected wind turbines has received little attention. The distinct advantage of STATCOM over SVC is its unaffected reactive power management capabilities, which is independent of system voltage, as well as its higher transient voltage support power. These characteristics make STATCOM more suitable for meeting the reactive power compensation requirements of wind farms.

This work proposes a unique method for improving voltage stability in wind power grid-connected systems during reactive power compensation for three-phase short-circuit failures by utilizing cooperative control of TCSC and STATCOM. A wind farm and power grid Matlab/Simulink model confirms the efficiency of this cooperative control technique in stabilizing system voltage.

III. PROBLEM STATEMENT

Grid-connected wind farms have demonstrated improved performance in recent years, but they also pose various issues in terms of power transfer, reactive power management, and voltage control. in the grid. Moreover, when a fault occurs in such a system, questions concerning frequency range, power/frequency characteristics, frequency control, reactive range capacity, and voltage control come into play. Voltage stability and reactive power management are difficult tasks. Each wind farm must be capable of managing voltage at the point of connection to the public power system. The fundamental goal of this research is to improve the voltage stability of grid-connected wind farms by implementing TCSC-STATCOM FACTS controllers.

IV. PROPOSED WORK

Figure 1 shows a grid-connected wind energy system. The wind farm comprises six 1.5 MW wind turbines, resulting in a total installed capacity of 9 MW. Before being fed into the grid, the wind farm's 575 V output voltage is step-up transformed to 25 kV. The STATCOM device proposed in this paper is installed on this step-up transformer's high voltage bus B2. The electrical energy is then supplied to the substation through the transmission line before being put into the grid. The TCSC is placed on the B2 bus. At t = 2 s, a three-phase short-circuit ground fault occurs on the system's bus B5 120 kV output line and is cleared in 100 ms. A consistent wind speed of 12 m/s is maintained throughout the experiment. Figure 1 depicts the Matlab/Simulink model for the grid-connected wind farm, which uses DFIG sets with TCSC and STATCOM control.

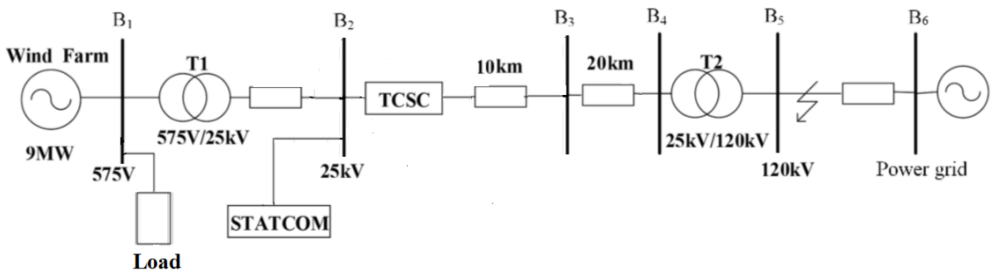

Figure 1 Single line diagram of proposed system

V. RESEARCH METHODOLOGY

FACTS solutions:

The standard procedures fall short of resolving the aforementioned issue precisely. FACTS systems reveal to be a superior technology option for addressing the issues associated with wind farm integration in today's context. The proposed method uses the FACTS model and the distributed resource model from the MatLab Simpower system to analyze the steady-state and dynamic performance of a distribution-connected wind farm. The research presented here is organized as follows.

Incorporating FACT devices TCSC and STATCOM in a grid-connected wind power system

Fundamentals and Modeling of FACTS Controllers

(i) Principles and Modeling of Thyristor Controlled Series Compensator (TCSC):

The TCSC module is built by connecting in series an inductor and an anti-parallel controlled thyristor, with the capacitor connected in parallel [2-10]. Parallel branch circuit breakers CB and variable resistors MOV are used to protect against voltage spikes and ensure appropriate connection of the capacitor to the line. The basic idea behind TCSC is to use a thyristor-controlled reactance (TCR) to cancel the capacitive reactance of particular series-connected capacitors, resulting in a constantly regulated inductive and capacitive impedance. The structural layout of the TCSC module is illustrated in Figure 2

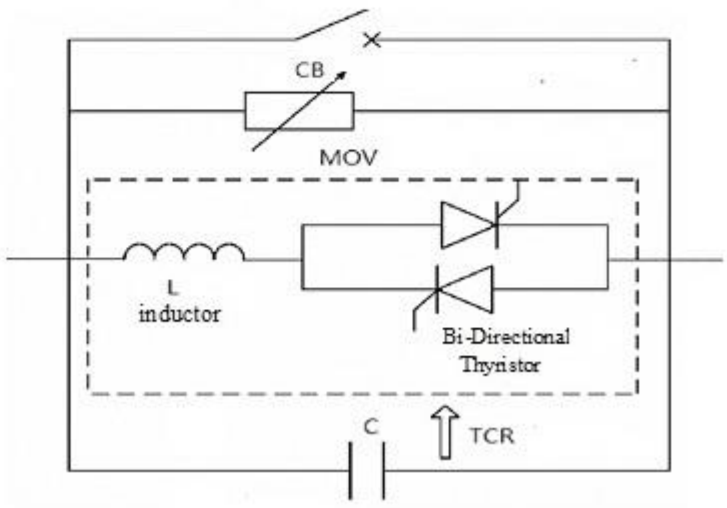

Figure 2: TCSC Module Structural Layout

The TCSC can vary the current flowing through the thyristor branch by adjusting the firing angle of the thyristor, hence changing the TCSC arm's corresponding reactance value. The LC circuit's inherent reactance in the TCSC module

$$X_{\text{TCSC}} = K_\beta X_\text{C}$$
$$= \left[1 + \frac{\omega_0^2}{\pi(\omega_0^2 - \omega^2)}\left(\frac{4\omega\cos^2\beta\tan\beta}{\omega_0 + \omega} - 2\beta - \sin\beta\right)\right] \times \left(-\frac{1}{\omega C}\right)$$
$$= -\frac{1}{\omega C} - \frac{\omega_0^2}{\pi C(\omega_0^2 - \omega^2)}\frac{4\cos^2\beta\tan\beta}{\omega_0 + \omega} + \frac{(2\beta + \sin\beta)\omega_0^2}{\pi\omega C(\omega_0^2 - \omega^2)} \quad (1)$$

The standard reactance value of TCSC is defined by equation (1) as K_β, where $\beta = \pi - \alpha$; X_C represents capacitive impedance; ω designates fundamental angular frequency; and ω_0 represents resonance angular frequency. Figure 3 depicts the power injection model associated with the TCSC access system.

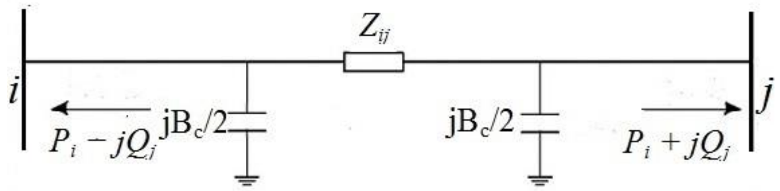

Figure 3 The power injection model of TCSC

The effect of the TCSC FACTS device on the system is relayed and overlaid on the nodes *i* and *j* placed at the branch's endpoints. The TCSC can be thought of as an adjustable reactance that acts in series with the power system as a variable reactance. The TCSC adds virtual equivalent injection power to the virtual equivalent, resulting in an access matrix that is always symmetric to the original network nodes. The TCSC provides active and reactive power to system nodes *i* and *j*, accordingly.

$$P_i = \frac{V_i V_j}{X_{\text{TCSC}}}\sin(\delta_i - \delta_j) \quad (2)$$

$$Q_i = -\frac{V_i}{X_{\text{TCSC}}}[V_i - V_j\cos(\delta_i - \delta_j)] \quad (3)$$

$$P_j = \frac{V_i V_j}{X_{\text{TCSC}}}\sin(\delta_j - \delta_i) \quad (4)$$

$$Q_j = -\frac{V_j}{X_{\text{TCSC}}}[V_j - V_i\cos(\delta_j - \delta_i)] \quad (5)$$

In this equation, V_i and V_j signify the voltages of bus nodes *i* and *j*, respectively, whereas δ_i and δ_j denote the voltage phases of bus nodes *i* and *j*, respectively.

As shown in (1) to (5), the TCSC's equivalent reactance fluctuates continually dependent on the trigger angle α, altering the distribution of active and reactive power along the line and optimizing the controlled line's current distribution.

(ii) Principles and Modeling of static synchronous compensator (STATCOM):

The voltage type STATCOM coupled to the wind system can efficiently function as reactive power compensation, improving system voltage stability. STATCOM's basic idea includes its parallel connection to the system via a choke or transformer, allowing the conversion of DC input voltage to AC output voltage. STATCOM efficiently adjusts for the reactive power requested by the system by making rapid and exact adjustments to the magnitude and phase of the output voltage. The corresponding circuit diagram of the STATCOM connected to the system is shown in Figure 4[20-21].

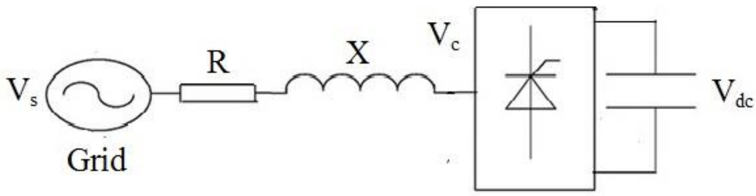

Figure 4 Equivalent circuit diagram of STATCOM

STATCOM's active and reactive power outputs are

$$P = -YV_cV_s \sin\delta \qquad (6)$$

$$Q = Y(V_cV_s\cos\delta - V_s^2) \qquad (7)$$

Y, which represents the reciprocal of a transformer's leakage reactance, can be written as 1/X, δ signifies the angle created by the mains voltage V_s and the STATCOM output voltage V_c. As δ approaches zero, sinδ is approaching zero. According to (6), STATCOM's active power is approximately negligible, making it ignorable. Nonetheless, (7) can be represented as follows

$$Q = Y(V_c - V_s)V_s \qquad (8)$$

Given equation (8), in circumstances when STATCOM's output voltage is smaller than the grid voltage, The STATCOM device consumes grid reactive power. When the output voltage of the STATCOM exceeds the grid voltage, The STATCOM device provides reactive power to the grid. When the STATCOM device's output voltage equals the grid voltage, The STATCOM device makes no reactive power exchange with the grid. The STATCOM's ability to rapidly and continuously modulate its output voltage enables rapid and continuous alteration of the reactive power exchanged between the STATCOM and the grid.

For STATCOM control, the controlling device employs a voltage-current double closed-loop control mode. The outer loop of the controller employs both DC and AC voltage regulators, which offer feedback for STATCOM's DC side Capacitor Voltage V_{dc} and grid side voltage V_s, respectively. The proportional control with static error is implemented by comparing it to the appropriate reference value [1 4]. A current regulator is used in the controller's inner loop to govern the inverter's output current, allowing for independent control of active and reactive currents.

TCSC and STATCOM Cooperative Control Strategy:

Asynchronous wind turbines, unlike synchronous generators, lack an excitation circuit and must be excited by an external power source. The electromagnetic torque of an asynchronous generator at constant speed is directly proportional to the square of the terminal voltage. When connected to the grid, the asynchronous wind turbine acquires the necessary excitation and reactive power from the grid, increasing the grid's reactive power burden. Under constant mechanical torque, a grid failure causes a drop in voltage across the wind farm, which reduces the generator's electromagnetic torque and causes the rotor to accelerate.

After the grid fault is cleared, the generator must absorb a large amount of reactive power from the grid during system voltage recovery to restore the generator's internal electromagnetic field. This causes a significant drop in the bus voltage of the grid-connected wind farms and further reduces the voltage at the wind farm terminals. Under normal conditions, the terminal voltage of the wind farm must be changed on a regular basis in order to maintain the rated voltage value. To ensure the necessary reactive power for the wind turbines, the installation of the STATCOM device in the system eliminates the need for frequent voltage adjustments at the wind farm terminals, maintaining the desired value consistently. Asynchronous wind turbines contribute to greater damping effects by introducing fluctuating output currents into the grid. The system's constant operation necessitates not only the STATCOM device, but also an excitation controller linked to the wind power grid-connected system. As a result, the wind power grid-connected system will use the collaborative control of both TCSC (Figure 2) and STATCOM (Figure 4). The STATCOM is linked to the wind energy access point in parallel, while the TCSC is linked to the grid transmission line in series.

A STATCOM device may dynamically supply the reactive power required by the asynchronous generator during its transient process as well as the reactive power required by the wind farms when it is connected into the system. By doing so, the terminal voltage is increased and the likelihood of asynchronous generators losing sync is decreased. By using TCSC, the line reactance may be adjusted, which reduces fault current, increases the low voltage ride-through capability of wind farms, and enhances system damping. The wind grid-connected system benefits from the simultaneous integration of STATCOM and TCSC because TCSC increases system dampening to improve vibration stability and STATCOM accounts for the reactive power requirement to promote voltage stability.

This work provides a DFIG-based wind power grid connection technology, as shown in Figure 1. A reference circuit (Figure 5) is built using the Matlab/Simulink platform, with STATCOM and TCSC placed strategically in relation to the B2 bus. A reference circuit (Figure 5) is built using the Matlab/Simulink platform, with STATCOM and TCSC placed strategically in relation to the B2 bus.

Case A: Grid connected wind farm without TCSC and STATCOM.

Case B: Grid connected wind farm with TCSC

Case C: Grid connected wind farm with STATCOM.

Case D: Grid connected wind farm with TCSC and STATCOM.

Comparing Case A against Cases B, C, and D to discover which case produces the best outcomes.

Figure 5 depicts a simulation of a 9 MW wind farm driven by a Doubly-Fed Induction Generator (DFIG). A 9-MW wind farm with six 1.5-MW wind turbines is linked to a 25-kV distribution system and supplies power to a 120-kV grid via a 30-kilometer 25-kV feeder. A 500-kW resistive load is linked to bus B575. The wind turbine phasor model simplifies the study of transient stability across long simulation durations.

VI. Simulations and Analysis

In this research, a DFIG-based wind power grid-connected system is simulated using the Matlab/Simulink platform, as shown in Fig. 5. The specifications of a single wind turbine are listed in Table 1, and the TCSC inductance parameter is set to 0.5 H in the simulation.

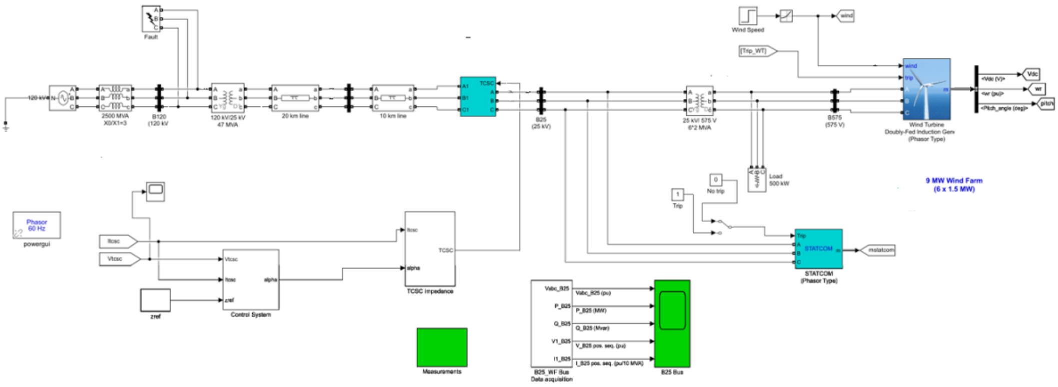

Figure 5, Wind power grid-connected system simulation model

Table 1. Parameters of single DFIG in the wind power system

Parameters	Value
Unit capacity /VA	$1.5x10^6$
Stator voltage /V	575
Stator and rotor resistance /p.u	0.00706, 0.005
Stator and rotor inductance /p.u	0.171, 0.156
Mutual inductance /p.u	2.9
Pairs of Poles	3
Frequency / Hz	60

Analysis of Simulations results:

VI. Results and Discussions

Fault Scenario: At t = 2 seconds, a three-phase short-circuit ground fault develops in the grid-connected system's 120 kV transmission line. After 0.1 seconds, the fault is cleared and corrected. Throughout the simulation, the wind speed remains constant at 12 m/s. Four simulation scenarios are created to test the system's behavior under severe disturbances in order to examine the combined effects of TCSC and STATCOM on improving the transient voltage stability of wind power grid-connected systems.

Working *Condition 1*: TCSC-STATCOM is not included in the simulation; just the base configuration is analyzed.

Working *Condition 2*: The simulation only includes TCSC and no STATCOM.

Working *Condition 3*: The simulation only includes STATCOM and no TCSC.

Working *Condition 4*: The simulation combines TCSC and STATCOM for improved control.

The relevant simulation model is created in Matlab/Simulink, and the simulation waveform comparison diagrams are shown in Figures 6–8.

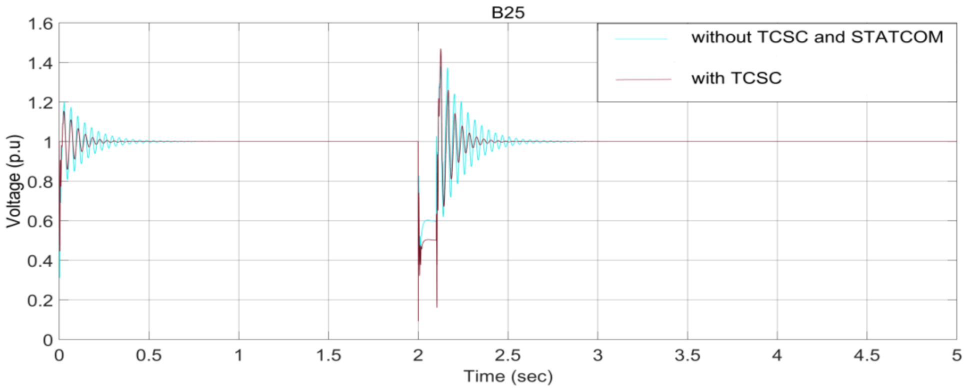

Figure 6, Bus B25 voltage comparison under *condition 1* and *condition 2*

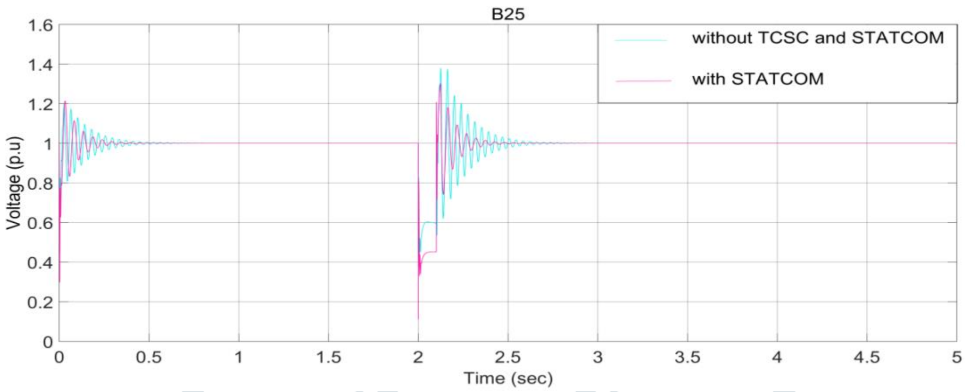

Figure 7, Bus B25 voltage comparison under *condition 1* and *condition 3*

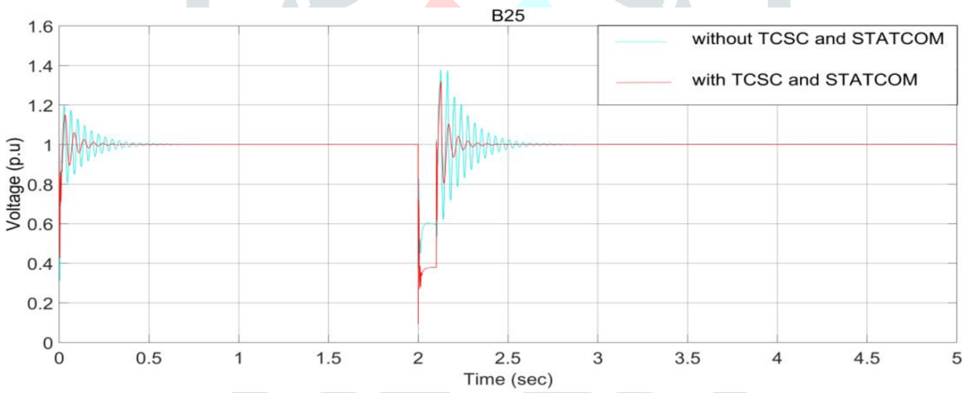

Figure 8, Bus B25 voltage comparison under *condition 1* and *condition 4*

Table 2. Comparison of different models

Parameter	Without TCSC and STATCOM		With TCSC		With STATCOM		With TCSC and STATCOM	
	after t = 0 s sec	after t = 2.1 sec	after t = 0 sec	after t = 2.1 sec	after t = 0 sec	after t = 2.1 sec	after t = 0 sec	after t = 2.1 sec
V_m	1.199 p.u	1.379 p.u	1.155 p.u	1.470 p.u	1.214 p.u	1.303 p.u	1.152 p.u	1.320 p.u
T_s	0.821 sec	2.995 sec	0.416 sec	2.552 sec	0.488 sec	2.619 sec	0.359 sec	2.471 sec

V_m: Maximum value of bus voltage amplitude oscillation
T_s: Time (after which bus voltage is stable)

Analyzing the operating *condition* 1, *condition* 2, *condition* 3, and *condition* 4, a full comparison is made to evaluate their respective performances:

Figure 6 and Table 2 provide a detailed comparison of the voltage curves at bus B25 of the grid-connected wind farm under operating conditions 1 and 2. The results demonstrate the importance of TCSC correction in increasing system voltage stability. Under operating condition 1, the bus voltage amplitude of the grid-connected wind farm exhibits significant swings upon switching at t = 0, resulting to sluggish stabilization. The bus voltage oscillation reached a high value of 1.199 p.u. and stabilized in approximately 0.821 seconds. A three-phase short circuit fault occurs on bus B120 kV at t = 2 seconds, causing an sudden drop in voltage at the grid-connected wind farm to 0.1101 p.u. The peak value of bus voltage oscillation reached 1.379 p.u. after the fault was removed at 2.1 seconds, and the bus voltage stabilized after 2.995 seconds.

When the system is only equipped with TCSC compensation, the highest bus voltage fluctuation after switching is 1.155 p.u., and the bus voltage stabilizes in 0.416 seconds. A three-phase short-circuit fault occurs at 2 seconds, causing the bus voltage to drop to 0.0925 p.u. The peak value of bus voltage oscillation reached 1.470 p.u. after the fault was cleared at 2.1 seconds, and the bus voltage stabilized after 2.552 seconds.

When operating *condition 1* and *condition 2* are compared, it is clear that TCSC improves system voltage stability, decreases oscillation time during disturbances, and reduces oscillation amplitude. TCSC has the capacity to considerably shorten oscillation subsidence time and minimize amplitude value, allowing for the rapid restoration of stable bus voltage to 1.0 p.u.

Figure 7 and Table 2 show the contrasting voltage curves at the grid-connected wind farm's bus B25 under operating *condition 1* and *condition 3*. Under condition 3, with only STATCOM compensation, the bus voltage oscillates to a maximum of 1.214 p.u after switching at t = 0 sec and stabilizes after 0.488 sec. A three-phase short-circuit fault occurs at 2 seconds, causing the bus voltage to decrease to 0.1101 p.u. The peak value of bus voltage oscillation was 1.303 p.u. after the fault was cleared at 2.1 seconds, and the bus voltage stabilized after 2.619 seconds.

Figures 6 and 7 show that the system with simply TCSC compensation improves voltage stability more effectively. When the system just includes STATCOM compensation, on the other hand, it has a greater impact on reducing the maximum value of the bus voltage amplitude after the fault is removed at 2.1 seconds.

Figure 8 and Table 5 show a comparison of voltage curves at the grid-connected wind farm's bus B25 under operating *condition1* and *condition4*. When the system is equipped with both TCSC and STATCOM correction, the bus voltage amplitude oscillation at the grid-connected point decreases more quickly under operating condition 4 than it does under operating *conditions* 1, 2, and 3 after switching at t = 0 sec and after the fault removal at 2.1 sec. Furthermore, the bus voltage stabilizes faster than in operating *conditions* 1, 2, and 3 after switching and after fault removal at 2.1 sec.

VII. Conclusions and Future Scope

The simulation model of a grid-connected wind system with TCSC and STATCOM is built using Matlab/Simulink simulation tools. The simulation contains a variety of operating conditions with a special emphasis on the system's response to a three-phase short-circuit faults. The simulation findings show that the cooperative control technique using TCSC and STATCOM is effective in overcoming the voltage stability concerns encountered by grid-connected wind systems. The integration of TCSC-STATCOM control in a grid-connected wind system ensures uninterrupted power transmission while quickly and efficiently restoring and maintaining system voltage stability during short circuit events. The cooperative control of TCSC and STATCOM proves superior to individual TCSC or STATCOM control, ensuring enhanced system performance and stability. The basis of this research is based on DFIG's accomplishments, with the possibility to apply its findings to various wind turbine configurations. The scope of this research can be expanded to include a broader test system, testing the effectiveness of TCSC and STATCOM support. This study, which looked at the three-phase short circuit problem, can be broadened to look at the system's response to different sorts of faults.

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