

Determination of STATCOM Rating for Grid Integration of a 6 MW Squirrel-Cage Induction Generator Wind Farm

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Abstract—The increasing integration of fixed-speed squirrel-cage induction generator (SCIG) wind farms is leading to a greater need for reactive power compensation to ensure stable grid integration and proper voltage regulation. In this paper, the impact of a Static Synchronous Compensator (STATCOM) rating on the steady-state and transient operation of a 6 MW SCIG wind farm is analyzed. As opposed to traditional installations where the compensator is placed at the point of common coupling (PCC), in this study, the STATCOM is connected directly to the low-voltage terminal of the wind farm to provide local reactive power compensation to the induction generators. The model is developed to analyze the impact of four STATCOM ratings (1, 2, 3, and 4 MVA) on the system's behavior at a constant wind speed of 10 m/s and consequently to determine the proper STATCOM rating. The system performance is evaluated based on the following parameters: PCC voltage and current, wind farm active and reactive powers, PCC active and reactive powers, and STATCOM reactive power. The simulation results demonstrate that increasing the STATCOM rating leads to better voltage regulation, lower power demand at the PCC, and improved active power transfer from the wind farm. However, performance improvements become marginal when the STATCOM rating exceeds 3 MVA. The results show that a 3 MVA STATCOM system delivers adequate local reactive power support to operate the 6 MW SCIG wind farm, achieving system performance similar to the 4 MVA configuration without oversizing the converter.

Keywords—SCIG wind farm, reactive power compensation, voltage regulation, STATCOM, PCC, STATCOM rating.

I. INTRODUCTION

The increasing use of renewable energy sources has led to a major transformation in modern energy systems. Among renewable energy sources, wind energy is considered one of the fast-developing sources because of its benefits and lower costs of installing new wind turbines [1].

Although variable-speed wind turbines with doubly-fed induction generators (DFIGs) or permanent magnet synchronous generators (PMSGs) dominate modern wind-energy systems, fixed-speed squirrel-cage induction generator (SCIG) based turbines remain deployed in some wind power plants because of their mechanical robustness, lower maintenance requirements, and lower initial investment cost [2, 3]. However, SCIGs inherently consume reactive power from the electric grid to create the magnetic field in their operation [4-6]. Therefore, phenomena such as voltage drop, high consumption of reactive power, low power factor, and poor transient stability can occur during operation [7,8].

Thus, reactive power compensation has become a necessity to ensure required voltage profiles and enhance the dynamic performance of SCIG-based wind energy generation systems. Traditional compensation techniques like capacitor banks and switched capacitors are inexpensive but have disadvantages of slow dynamic response, discontinuous operation, and poor performance during transient disturbances [9-11]. On the other hand, Flexible AC Transmission System (FACTS) devices offer fast and continuous control of reactive power and thus are very useful in modern wind energy systems [7], [12-14].

Among FACTS devices, the Static Synchronous Compensator (STATCOM) has received considerable attention due to its fast dynamic response, excellent voltage regulation, and capability to generate or absorb reactive power independently of the grid voltage [15-17]. Many research papers have established that the STATCOM increases voltage stability, improves transient performance, reduces voltage fluctuation, and increases fault ride-through capability for the

wind power plants [7, 18]. The research in [5] highlighted the need for reactive power in SCIGs and the benefits of using STATCOM for dynamic compensation. [19] showed that STATCOM can control the PCC voltage of SCIG-based wind turbines effectively under normal and fault conditions. The study in [20] compared STATCOM and capacitor bank compensation, demonstrating the superiority of STATCOM in voltage regulation during disturbances. However, these studies focus primarily on STATCOM control, compensation technology, or system stability, rather than a systematic quantitative assessment of the impact of STATCOM rating on the electrical performance of a specific wind farm using SCIGs.

From an engineering perspective, there is another solution where the installation of a STATCOM at the low-voltage terminal of the wind farm would act as an alternative approach. In this scheme, the converter delivers the reactive power needed by the SCIG locally before the power flows through the step-up transformer. Therefore, in this way, the imported reactive power from the grid is decreased, leading to lower transformer loads and minimizing the current flow as well as improving the voltage regulation at the PCC.

Another problem is related to the proper sizing of STATCOM. If oversized, the converter cost will be higher, while under-sizing would restrict the available reactive power support and degrade voltage regulation. Although several STATCOM sizing methodologies have been proposed, much of the literature relies on optimization-based or simplified analytical approaches [21], and fewer studies provide a detailed dynamic comparison of different STATCOM ratings for SCIG wind farms under identical network conditions. To address these gaps, this study compares four STATCOM ratings (1, 2, 3, and 4 MVA) for a 6 MW SCIG wind farm, with the STATCOM connected at the generator terminal, and evaluates several electrical performance indices.

In this paper, a 6 MW SCIG-based wind farm connected to the utility grid through a medium-voltage feeder and a high-voltage transmission network is modeled in MATLAB/Simulink. As opposed to typical scenarios, the STATCOM is placed at the terminal point of the 575 V wind farm to provide local reactive power compensation. Four STATCOM ratings of 1, 2, 3, and 4 MVA are analyzed under a constant wind speed of 10 m/s. System performance is evaluated based on PCC voltage and current, wind farm active and reactive powers, PCC active and reactive powers, and STATCOM reactive power. The objective is to determine the minimum STATCOM rating that can provide satisfactory dynamic and steady-state performance while avoiding unnecessary converter oversizing.

The simulation results show that the increase in the STATCOM rating significantly improves voltage regulation, reduces the amount of reactive power import from the grid, improves the active power transfer, and reduces the current flowing through the PCC. Additionally, the results show that the increase in the STATCOM rating to higher than 3 MVA does not significantly improve the system performance, and therefore, 3 MVA represents the suitable rating for the 6 MW SCIG wind farm.

The main contributions of this paper are summarized as follows:

- ✓ A detailed dynamic comparison of four STATCOM ratings (1, 2, 3, and 4 MVA) for a 6 MW SCIG wind farm connected to the utility grid.
- ✓ Placement of the STATCOM at the bus 575 V wind farm terminal to provide local reactive power compensation instead of the conventional PCC placement.
- ✓ Comprehensive evaluation of seven electrical performance indices:
 - PCC voltage,
 - PCC current,
 - Wind farm active power,
 - Wind farm reactive power,
 - PCC active power,
 - PCC reactive power,
 - STATCOM reactive power.

Identification of the minimum effective STATCOM rating, showing that a 3 MVA STATCOM provides almost identical performance to a 4 MVA capacity.

II. SYSTEM MODELING

The studied system consists of a two 3 MW (6 MW) SCIG-based wind farm operating under a constant, fixed wind speed profile of 10 m/s, connected to a 120 kV utility grid through a 575 V/25 kV step-up transformer; a 30 km transmission line connects the PCC 25 kV feeder that is designated as bus B25, and a 25/120 kV grid transformer. As shown in Figure 1, the STATCOM is connected in shunt at the B575 wind farm terminal to supply the reactive power required by the SCIG units locally, and indirectly enhances the voltage profile and power quality at the PCC. The system parameters used in the simulation are provided in Table I.

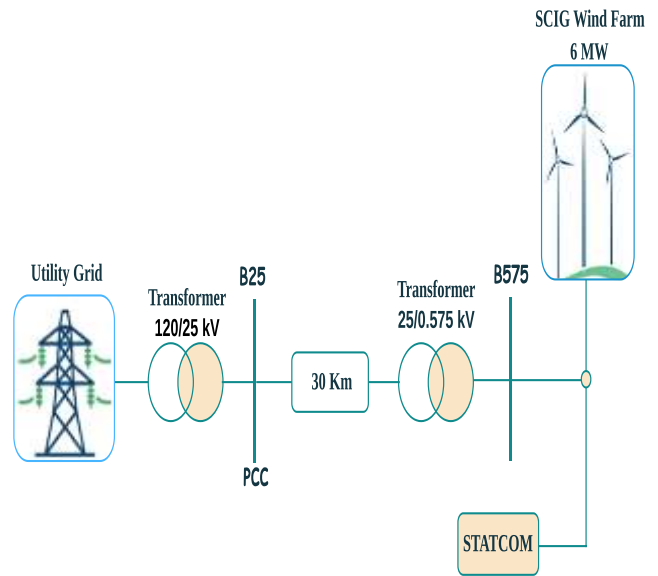


Fig. 1. Single-line diagram of the studied power system.

TABLE I. SYSTEM PARAMETERS

Category	Parameter	Value
Wind farm	Total capacity	6 MW
	Number of turbines	$2 \times 3\text{MW}$
	Rated voltage	575 V
	Wind speed	10 m/s
Grid & Network	Grid voltage	120 kV
	Feeder voltage	25 kV
	Feeder length	30 km
Transmission line	Positive sequence resistance	0.1153 Ω/km
	Positive sequence inductance	1.05 mH/km
	Positive sequence capacitance	11.33 nF/km
	Zero sequence resistance	0.413 Ω/km
	Zero sequence inductance	3.32 mH/km
	Zero sequence capacitance	5.01 nF/km
Transformer (25/0.575 kV)	Resistance	0.0008 pu
	Reactance	0.025 pu
Transformer (120/25 kV)	Resistance	0.002 pu
	Reactance	0.08 pu
STATCOM	Location	B575 bus
	Tested ratings	1, 2, 3, 4 MVA

A. Wind Turbine Model

The wind turbine model represents a fixed-speed wind turbine using a squirrel-cage induction generator directly connected to the electrical network. The maximum power output obtained by the wind power turbine is characterized by:

$$P_{mech} = \frac{1}{2} \rho A_r V_w^3 C_p(\lambda, \beta) \quad (1)$$

Where: ρ is the air density (1.225 kg/m³), V_w is the wind speed, A_r is the rotor swept area, C_p is the rotor power coefficient, β represents the blade pitch angle and λ represents the tip speed ratio (TSR).

B. SCIG Model

Each wind turbine uses a squirrel-cage induction generator directly connected to its shaft. In contrast to synchronous generators, SCIG requires reactive power to generate the air-gap flux required for electromagnetic energy conversion. The mathematical equations of the dynamic SCIG wind turbine type are detailed in [22]. The electrical behavior of the induction generator is described in the reference frame that rotates in synchronism with the rotor, whereas the electromagnetic torque is given by:

$$T_e = \frac{3P}{4} (\psi_d i_q - \psi_q i_d) \quad (2)$$

Where:

P is the total number of poles;

i_d, i_q are the stator currents;

ψ_d, ψ_q are the stator flux linkages.

C. STATCOM Model

The Static Synchronous Compensator (STATCOM) is connected in shunt at the B575 wind farm terminal via a coupling transformer.

The STATCOM employs a cascaded dq vector control structure that consists of outer AC voltage and DC link voltage regulation loops and an inner d-q current control loop. The AC voltage regulator generates the q-axis current reference to maintain terminal voltage stability, while the DC link voltage regulator generates the d-axis current reference to preserve capacitor energy. These references are tracked by the inner proportional-integral (PI) current controllers to generate the converter voltage references. Reactive power exchange between the STATCOM and the grid terminal bus (B575) is expressed as:

$$Q = \frac{V_{B575}(V_{st} - V_{B575})}{X_{cp}} \quad (3)$$

Where: V_{B575} : AC voltage at B575, V_{st} : STATCOM converter voltage, X_{cp} : coupling transformer reactance.

Unlike conventional compensation devices, the STATCOM provide continuous and instantaneous of reactive power, enabling effective voltage regulation during both steady and transient state operations. In order to determine the proper size of the converter, four STATCOM ratings (1 MVA, 2 MVA, 3 MVA, and 4 MVA) are analyzed.

III. SIMULATION RESULTS AND DISCUSSION

To evaluate the dynamic performance and establish the appropriate capacity threshold of the STATCOM, a comprehensive power system model was developed in the MATLAB/Simulink environment at a fundamental frequency of 50 Hz. This section presents a comparative analysis that considers the voltage and current at the PCC, active and reactive power exchanged at the PCC, wind farm active and reactive power, and STATCOM reactive power output under four STATCOM power ratings: 1 MVA, 2 MVA, 3 MVA, and 4 MVA to determine the proper rating for the investigated 6 MW SCIG wind farm and evaluate the system's performance. Figure 2 and Figure 3 present the voltage and current responses at the PCC of the 6 MW SCIG wind farm for different STATCOM ratings, with a constant wind speed of 10 m/s.

As illustrated in Figure 2, the PCC voltage responses for the four STATCOM ratings show that voltage regulation improves with increasing STATCOM capacity. In the initial transient state, in all cases, the PCC voltage oscillates during start-up due to the SCIG electromagnetic dynamics and the STATCOM control response. Although the STATCOM is connected at the B575 wind farm terminal, increasing its rating enhances the local reactive power compensation, which improves the wind farm terminal voltage at the PCC (B25) through the step-up transformer. The 1 MVA STATCOM has the lowest capability to enhance the PCC voltage because the steady-state PCC voltage has reached approximately 0.97 pu, indicating that the STATCOM rating provides insufficient reactive power support to compensate for the reactive power demand of the 6 MW SCIG wind farm. Increasing the STATCOM rating to 2 MVA significantly improves the PCC voltage regulation, reaching a steady-state value of about

0.996 pu. Further increasing the STATCOM to 3 MVA and 4 MVA has only marginal effect on improving the PCC voltage regulation, with almost identical steady-state voltage values and transient recovery times. This shows that the reactive power demand of the wind farm is largely satisfied by the STATCOM rating of 3 MVA, while additional capacity provides only limited improvement in PCC voltage performance.

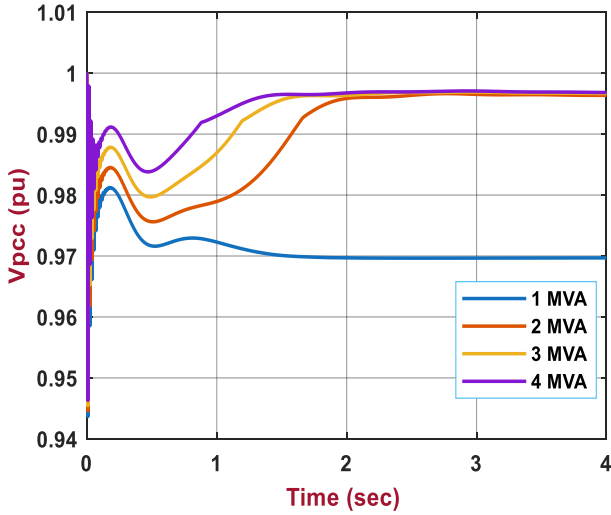


Fig. 2. PCC voltage responses for different STATCOM ratings.

The PCC current responses match the voltage results as seen in Figure 3. In all cases, a transient current peak is observed associated with the induction generator startup and STATCOM response. With the 1 MVA capacity, the STATCOM shows a maximum steady-state value of the current, which is about 0.80 pu, due to insufficient reactive power support for the 6 MW SCIG wind farm. When increasing the capacity of the STATCOM to 2 MVA, the PCC current is reduced to approximately 0.30 pu. Current responses at 3 and 4 MVA capacities show almost similar results to the 2 MVA case, demonstrating that additional converter capacity provides little further reduction in the current flowing through the PCC.

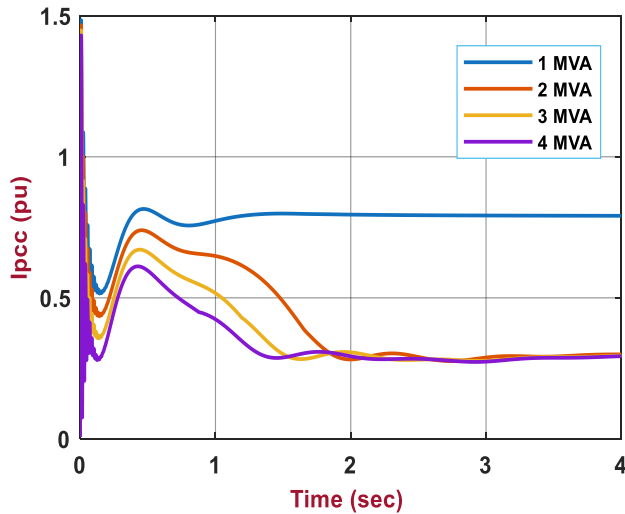


Fig. 3. PCC current responses for different STATCOM ratings.

The active and reactive power of the wind farm responses for different STATCOM ratings are shown in Figure 4 and

Figure 5, respectively. All cases exhibit an initial transient related to induction generator electromagnetic dynamics and control unit initialization, as shown in Figure 4. However, the steady-state responses vary greatly with the STATCOM rating. The 1 MVA STATCOM does not supply enough reactive power and, thus, the wind farm active power gradually decreases to about zero value. On the other hand, the 2, 3, and 4 MVA capacities improve and restore the active power to approximately 0.9 pu. Furthermore, the higher-rated capacities of STATCOM reduce oscillations and accelerate the recovery process. Also, there is no significant difference between the 3 and 4 MVA ratings, demonstrating that additional increases of the converter rating are ineffective.

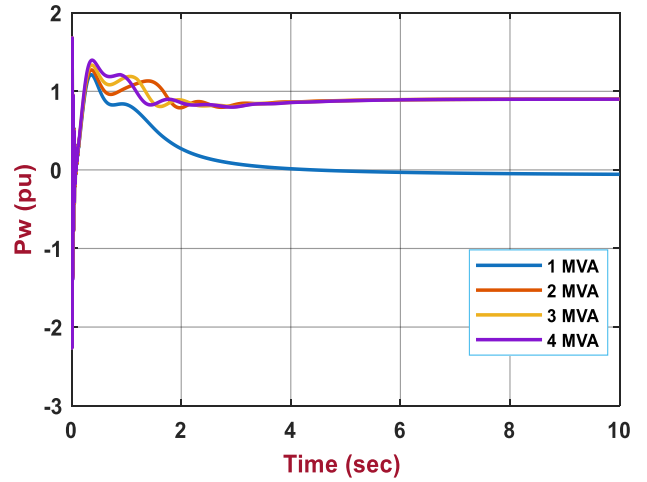


Fig. 4. Wind farm active power responses for different STATCOM ratings.

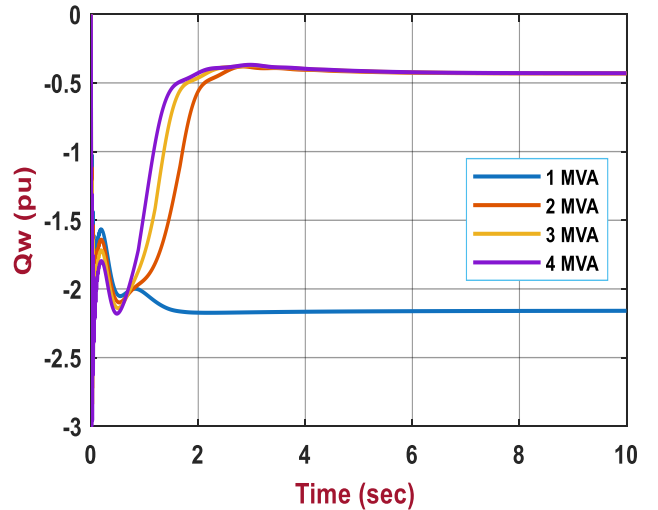


Fig. 5. Wind farm reactive power responses for different STATCOM ratings.

In Figure 5, all scenarios experience large reactive power absorption at start-up due to induction generator magnetization. Once the STATCOM controller operates at the stable state, the reactive power consumption is reduced based on the size of the converter. For instance, when the converter rating is 1 MVA, the wind farm keeps absorbing about 2.2 pu of reactive power, implying inadequate reactive power compensation. An increase in the size of the STATCOM to 2 MVA considerably reduces the amount of reactive power

absorbed from the network. For both 3 MVA and 4 MVA, the amount of reactive power demand is reduced to -0.43 pu, indicating that a converter rating of 3 MVA is sufficient to meet reactive power compensation requirements for the 6 MW SCIG wind farm, whereas extra capacity offers insignificant benefits.

Figure 6 presents the active power exchanged at the PCC for different STATCOM ratings under a constant wind speed of 10 m/s. All cases show a short transient oscillation caused by the interaction between the electromagnetics of the SCIG and STATCOM controller before it reaches its steady-state value. In the case of 1 MVA STATCOM, the active power injected at the PCC remains very low and close to zero in the steady-state, suggesting that the wind farm does not have enough reactive power supply to transfer considerable active power to the grid. Increasing the STATCOM rating to 2 MVA significantly improves the power transfer, where the 3 MVA and 4 MVA show almost the same response with less oscillations.

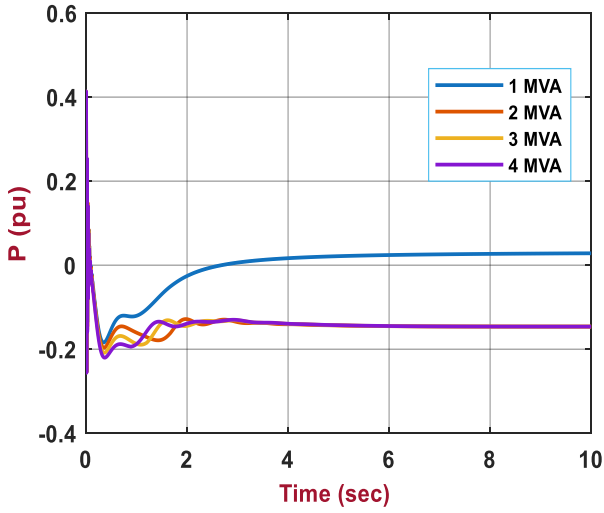


Fig. 6. PCC active power responses for different STATCOM ratings.

Figure 7 shows the reactive power exchanged at the PCC for different STATCOM ratings. All cases exhibit a transient increase in reactive power related to induction generator magnetization and converter control unit.

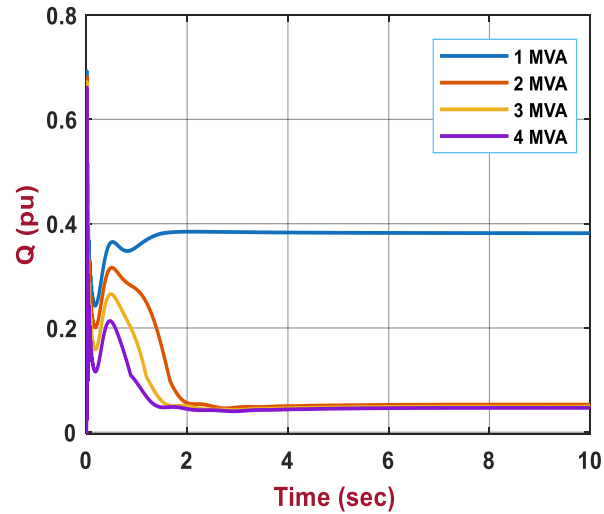


Fig. 7. PCC reactive power responses for different STATCOM ratings.

The 1 MVA STATCOM is still unable to provide enough reactive power support for SCIG magnetization, resulting in a steady-state reactive power import of approximately 0.38 pu from the grid. On the other hand, the 2 MVA, 3 MVA, and 4 MVA capacities decrease the PCC reactive power to around 0.05 pu, indicating that most of the generator reactive demand is being supported locally by the STATCOM connected at the B575 wind farm terminal rather than being drawn through the transmission system.

The reactive power delivered by the STATCOM with different converter ratings is shown in Figure 8.

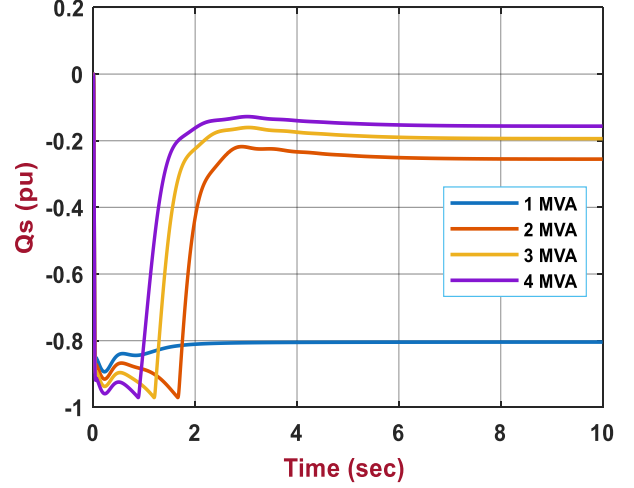


Fig. 8. STATCOM reactive power responses for different STATCOM ratings.

At the initial state, all STATCOM configurations inject a higher quantity of reactive power to maintain the required voltage profile at the wind farm terminal. With the 1 MVA STATCOM, the reactive power level quickly approaches its maximum value (-0.8 pu), implying a continuous operation near saturation caused by its limited compensative ability to support the SCIG. Increasing the STATCOM rating to 2 MVA reduces the loading of the converter while improving voltage regulation. The 3 MVA and 4 MVA capacities rapidly stabilize at approximately -0.20 pu and -0.15 pu, respectively, demonstrating that larger converter capacity require only a fraction of their available reactive power capability to maintain satisfactory voltage regulation. Based on the small difference between the 3 MVA and 4 MVA responses, a proper converter rating can be considered to be 3 MVA for a 6 MW SCIG wind farm.

These results are consistent with previous studies [5, 19, 20], which demonstrated that STATCOM-based reactive power compensation can improve voltage regulation in wind farms. However, these studies have generally focused on demonstrating the effectiveness of STATCOM compensation rather than examining the effect of STATCOM capacity under identical network conditions. In contrast, the present results demonstrate that increasing the rating from 1 to 3 MVA provides substantial voltage regulation benefits, whereas the increase from 3 to 4 MVA produces only a marginal improvement. This behavior supports the selection of 3 MVA as the preferred rating among the investigated cases for the 6 MW wind-farm configuration.

As summarized in Table II, increasing the STATCOM capacity from 1 MVA to 3 MVA yields a substantial 2.68% increase in PCC terminal voltage (restoring it to 0.996 pu) and

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reduces the excess PCC current demand from 0.800 pu to 0.280 pu, representing a 65.0% reduction in grid line current stress during the recovery phase. While 2 MVA restores steady-state voltage, its dynamic recovery requires 2.0 s compared to 1.6 s for 3 MVA. Increasing the rating further to

4 MVA provides a negligible voltage gain (+0.001 pu) and a minor 0.2 s speed improvement, which does not justify the higher converter equipment cost. Thus, 3 MVA is quantitatively established as the most effective capacity for the 6 MW SCIG wind farm.

TABLE II. QUANTITATIVE PERFORMANCE COMPARISON OF STATCOM RATINGS

Parameter	1 MVA	2 MVA	3 MVA	4 MVA	3 MVA vs 1 MVA
PCC voltage (pu)	0.970	0.996	0.996	0.997	+0.026 (2.68%)
PCC current (pu)	0.800	0.290	0.280	0.275	-0.520 (-65.0%)
STATCOM reactive power (pu)	-0.806	-0.250	-0.190	-0.150	Less grid reactive power demand
Voltage settling time (s)	Unsettled	2.0	1.6	1.4	Fast recovery

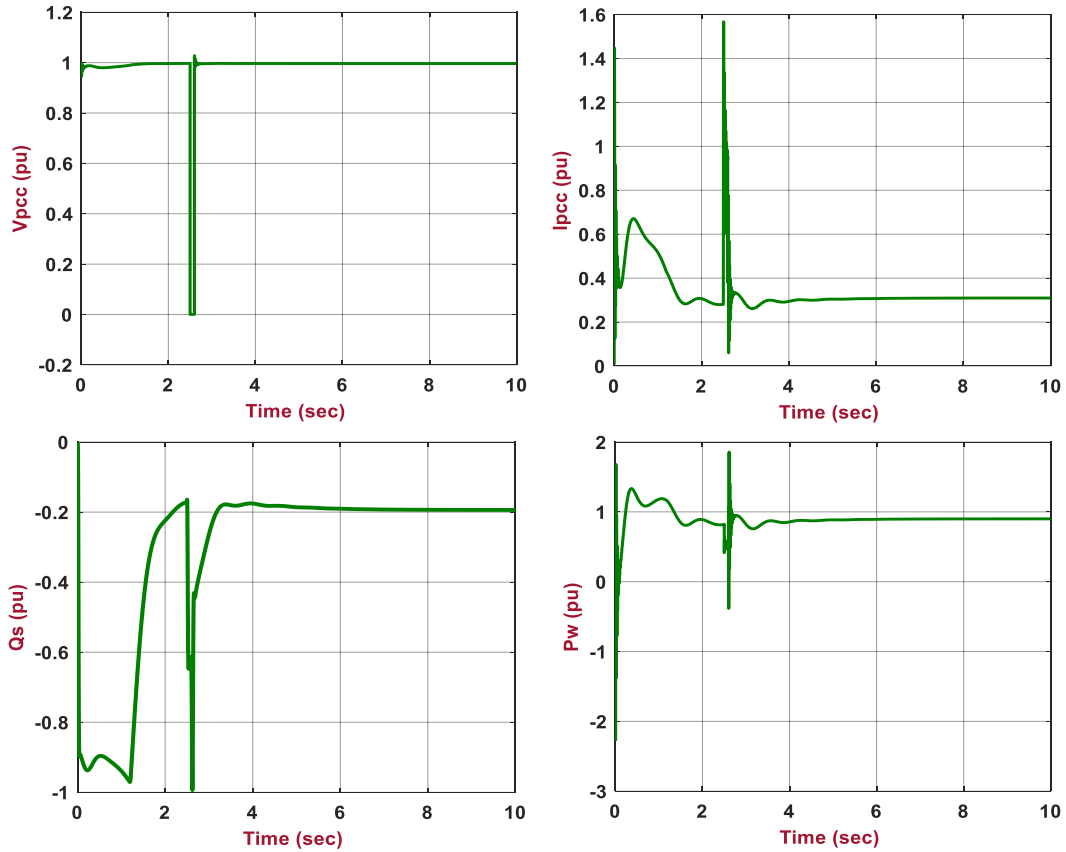


Fig. 9. Dynamic response of the system under an asymmetrical LLG fault at $t = 2.5$ s with the 3 MVA STATCOM: (a) PCC voltage (V_{pcc}), (b) PCC current (I_{pcc}), (c) STATCOM reactive power (Q_s), and (d) wind farm active power (P_w).

To further validate the robustness of the selected rating during severe dynamic disturbances, the system performance was evaluated under a transient asymmetrical grid fault condition (double line-to-ground: LLG fault) at $t = 2.5$ s for the 3 MVA STATCOM rating and it cleared after 100 ms. As shown in Figure 9, despite the PCC voltage dropping temporarily to 0 pu during the fault, the 3 MVA unit dynamically increases its reactive support to full capacity (approximately -1.0 pu). Upon fault clearance, the V_{pcc} recovers to nominal 1.0 pu in approximately 0.1 s, while PCC current and wind farm active power output re-stabilize smoothly at 0.3 pu and 0.9 pu, respectively. These results confirm that the selected 3 MVA rating guarantees full Fault Ride-Through (FRT) capability and rapid dynamic recovery without converter overload.

IV. CONCLUSION

This paper presented a comparative assessment of different STATCOM ratings for reactive power compensation and voltage support of a 6 MW SCIG-based wind farm connected to the utility grid. Four STATCOM power ratings, namely 1, 2, 3, and 4 MVA, were investigated under identical operating conditions to determine the suitable rating for the investigated 6 MW SCIG wind farm and evaluate their influence on the system. The STATCOM was installed at the low-voltage wind farm terminal (575 V) to provide local reactive power compensation before power is transferred through the step-up transformer to the PCC.

The simulation results indicated that a higher rating of the STATCOM is able to improve the transient and steady-state

system performance. The increased STATCOM rating improves the voltage profile at the PCC, improves the rate of voltage recovery, and also reduces the current flowing through the transformer and the transmission line. In addition, the reactive power supplied locally by the STATCOM reduces the reactive power imported from the grid, hence improving the operating condition of the SCIG wind farm, thus allowing for a stable generation and transfer of active power.

Of all the studied configurations, it is evident that the 1 MVA STATCOM was not adequate enough to meet the reactive power requirement of the 6 MW SCIG wind farm, resulting in poor voltage regulation (settles about 0.970 pu), higher PPC currents, high reactive power demand from the grid, and reduced active power transfer. The STATCOM rating with 2 MVA provided a significant improvement in performance parameters, with the PCC voltage increasing to approximately 0.996 pu, while the PCC current and reactive power decrease to about 0.30 pu and 0.055 pu, respectively. But there was no significant difference between the 3 MVA and 4 MVA. Both configurations basically showed almost identical values for PCC voltage (settles at approximately 0.996–0.997 pu), PCC current, wind farm active and reactive powers, PCC active and reactive powers, and STATCOM characteristics. So overall, these findings indicate that the wind farm reactive power requirements can be effectively covered using a 3 MVA STATCOM.

According to the simulation results, the suitable rating for the studied network configuration and operating condition is 3 MVA because a STATCOM unit connected to the 575 V wind farm terminal provides an ideal balance between its dynamic performance and converter capacity. The selected 3 MVA rating also guaranteed full fault ride through capability and rapid dynamic recovery under transient asymmetrical grid fault condition (LLG fault) at $t = 2.5$ s. A higher 4 MVA capacity will improve the dynamic response marginally along with the increase in the converter rating and installation cost.

Future work on this research may be expanded through the assessment of the rating of the proposed STATCOM under various wind speed profiles (e.g., 8 to 14 m/s ramp-up and stochastic wind speed conditions) or through the comparison of the effectiveness of alternative STATCOM controllers like adaptive proportional-integral (PI), fuzzy logic, or MPC controllers to optimize voltage control and transient response.

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