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Comparative Study of SVC and STATCOM Reactive Power Compensation for Prosumer Microgrids With DFIG-Based Wind Farm Integration

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ABSTRACT Uncertainties of renewable energy sources like wind power are one of the considerable challenges of prosumer microgrids. To meet the grid codes requirements regarding the voltage stability of wind farm integration, finding the balance between providing the demanding dynamic performance of the voltage and reactive power, and at the same time decreasing the investment on centralized reactive power compensation device, becomes an important research topic. This article compares the effects of the static synchronous compensator (STATCOM) and static VAR compensator (SVC) on transient voltage stability at the point of common coupling (PCC) of a doubly fed induction generator (DFIG)–based wind farm. And a new fast coordinated control scheme of STATCOM and DFIG is proposed for minimizing the capacity of centralized reactive power compensation device and making the best use of the reactive power control capability of DFIG. The simulation results based on test system show that STATCOM, even with less capacity, can contribute more reactive power than SVC for voltage stability, especially during the serious voltage drop transient stage, and perform a faster voltage recovery time after fault than SVC, proved to be a more economic choice; The proposed coordinated control scheme can not only improve the transient voltage stability, but also help reducing the capacity of STATCOM, so that the cost of investments in wind farms would be reduced.

INDEX TERMS DFIG, STATCOM, SVC, coordinated control.

I. INTRODUCTION

Recently, renewable wind energy has been developed rapidly and it becomes the third electricity source of China. However, a lot of large-scale wind farms integrate to power grid brings great influence on voltage stability of main network [1], [2]. To reduce this negative influence, the grid codes always require that wind farm provides the capability of dynamic voltage control by continuously adjusting reactive power supplied to the power system. Consequently, the dynamic reactive power compensation capability becomes an essential requirement for wind farm. How to achieve the goal with the most efficient manner becomes an important research topic.

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Currently, installing dynamic compensation devices at the point of common coupling (PCC) is an important way for wind farms to achieve dynamic reactive power compensation [3]–[5]. Centralized dynamic compensation devices mainly include static VAR compensator (SVC) and static synchronous compensator (STATCOM) [3]–[11]. The performance of these two devices has its own pros and cons, and a number of research has been conducted in the past few years. The comparison study of SVC and STATCOM at the performance and the contribution to the stability of the wind farm has been shown in [10]–[12], in which, SVC and STATCOM with same rating are applied to wind farm based on fixed-speed induction generators (FSIG). Literatures [7]–[9] show that STATCOM providing dynamic reactive power support, the system voltage can be established shortly after grid fault, and the transient voltage stability will be improved.

Literatures [13], [14] show that the rotor-side converter (RSC) of DFIG possesses obvious superiority in improving transient voltage stability of wind power system with voltage control mode than unity power factor control operation during a slight voltage drop.

Considering the cost of centralized reactive power compensation device, making the best use of the reactive power control capability of DFIG is a feasible solution to minimize the capacity of these expensive devices. To eliminate the deterioration and to make best use of both STATCOM and DFIG reactive power ability, the coordination method between them is desirable. Very few researchers presents coordinated control strategy for DFIG and STATCOM. Researches [15] and [16] only consider the coordination between the RSC and GSC of DFIG for voltage regulation and reactive power support. However, in case of serious grid faults, the RSC is blocked, the DFIG starts to absorb reactive power from the system, and GSC cannot guarantee the grid reactive power demand. For solving above problems, [17], [18] utilizes STATCOM to provide dynamic voltage support, the transient voltage stability is improved. Unfortunately, the GSC contribution is not taken into account, which would result in a higher capacity of STATCOM installed, so does the investment still high.

In this article, the performance of SVC and STATCOM is compared by simulation test firstly. Then a new coordination method is proposed for reactive power control of DFIG and STATCOM, the RSC, the GSC and STATCOM supplying reactive power to the grid coordinately, and the DFIG is fully utilized and prior to activating the STATCOM. To verify the effectiveness of the proposed control method, it is also applied to different working conditions for simulation testing.

This article is structured as follows. The model of wind farm turbine is described in Section II. The comparison of SVC and STATCOM is described in Section III, which consists of the models of SVC, STATCOM and the studied case. Section IV presents a new coordination control scheme and case study. The advantage of the proposed coordination control has been analysed and verified based on several scenarios of system short circuit faults. The conclusions are stated in Section V.

II. MODELING OF WIND GENERATOR

The topology of DFIG system is shown in Figure 1. The wind turbine is connected to the DFIG through a drive train composed of a low-speed shaft and a high-speed shaft. The stator windings of the DFIG are directly connected to the low-voltage side of the step-up transformer. The rotor windings of the DFIG are connected to the grid via a back-to-back converter which controls the rotor frequency and speed. The back-to-back PWM converter consists of two pulse-width modulated voltage source converters, the RSC and the GSC, linked by a DC bus. The Crow-Bar is used to protect DFIG and RSC, including voltage limitation and over current protection. If the rotor current exceeds the maximum allowed value, a bypass single is immediately inserted to RSC and then the RSC will be blocked.

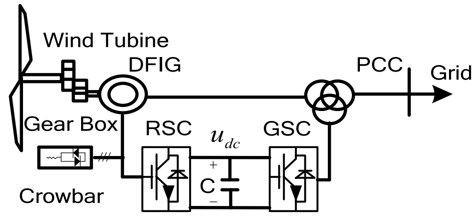

FIGURE 1. DFIG wind power system.

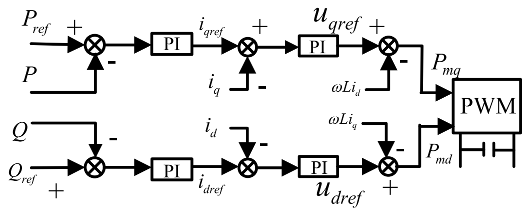

FIGURE 2. Control block diagram of RSC.

A. WIND POWER MODEL

A wind turbine is a device which extracts energy from the wind and then the energy is transformed into mechanical energy driving the generator. According to Betz, the theoretical power extracted from the wind is calculated by:

$$P_{\rm m} = \frac{1}{2}\rho C_p(\lambda, \beta)AV^3 \tag{1}$$

where, ρ $(kg{\cdot}m^{-3})$ is the density of air, $A(m^2)$ is the area covered by the wind turbine rotor blades, $V(m/s)$ is the wind speed, C_p is the power efficiency of a wind turbine, which is a nonlinear function of the tip speed ratio λ and the blade pitch angle β. λ is the ratio between blade tip speed, v_t(m/s), and wind speed at hub height upstream of the rotor, v_w(m/s).

B. CONTROL MODEL OF DFIG

The DFIG control system mainly consists of two parts, i.e, the control of RSC and GSC. Using vector control can realize decoupling control of active power and reactive power of DFIG wind power system.

The RSC controller is used to regulate the stator reactive power and reactive power. Figure 2 illustrates the vector control scheme of the RSC. A double-loop control method has been used, which consists of outer power loop and inner current loop. The power control loops generate the reference values of the d- and q-axes rotor currents for the current control loops. Here, the optimal active power reference P_{ref} is obtained from specific maximum power point tracking (MPPT) control. When the DFIG feeds into a weak power system, the Q_{ref} can set to a non-zero value so that RSC can

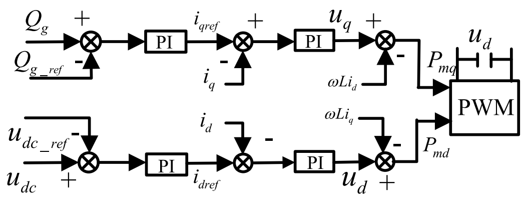

FIGURE 3. Control block diagram of GSC.

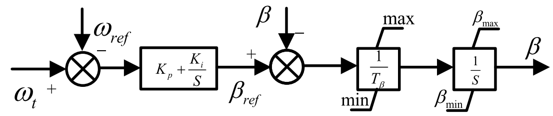

FIGURE 4. Control block diagram of pitch angle.

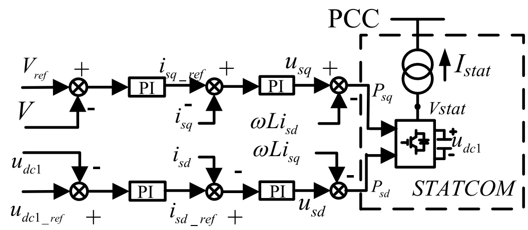

FIGURE 5. STATCOM control model.

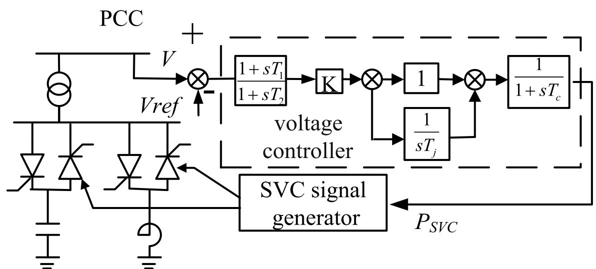

FIGURE 6. SVC control structure diagram.

provide reactive power to support the voltage. i_{dref} and i_{qref} can be used to obtain u_{dref} and u_{qref}, respectively.

Grid side converter control diagram is shown in Figure 3. The main purpose of GSC is used to regulate the dc-link voltage. The GSC control system can independently control the active power (DC voltage) and reactive power by controlling the q-axis and d-axis currents, respectively. In order to decrease the current and losses in DFIG, the reactive reference Q_{ref} is usually set at zero. However, the GSC control can also be designed to rapidly respond to the reactive power required by the grid for voltage supporting. Even if the fault becomes so heavy that the RSC has been blocked, the GSC can also supply reactive power.

C. PITCH ANGLE CONTROLLER

The pitch angle control is triggered to limit the increase of rotor speed when the wind speed exceeds its rated value, the control block diagram of which is shown in Figure 4. The pitch controller is employed in the system using a PI controller. When wind speed is below the rated speed, $\beta = 0°$. When the wind speed is higher than the rated wind speed, the actual rotor speed signal is compared with the reference signal to form the error signal, which is passed through a PI controller. Then the pitch angle will increase to prevent the rotor from overspeeding.

III. COMPARISON OF SVC AND STATCOM

A. MODELING AND CONTROL OF STATCOM

STATCOM is a fast-compensating reactive power source that can provide real-time voltage control, and improve both power factor and system voltage stability, which can also assist in quick recovery after contingency events. A STATCOM is built with a type of voltage-source converter (VSC), a dc capacitor, and a coupling transformer which connects the VSC in shunt to the power network. The structure and control model is shown in Figure 5. The STATCOM is used for controlling the voltage at the PCC in the desired range, to which the STATCOM is connected. The reactive power supplied to the power grid can be controlled, by controlling the ac output voltage magnitude of the STATCOM, V_{stat}.

B. MODELING AND CONTROL OF SVC

A thruster controlled reactor (TCR) and thruster switched capacitors (TSC) configuration of the SVC is used in this analysis. The SVC works in voltage control mode, and an SVC control structure is shown in Figure 6, where K, T_1, T_2, T_c, T_j, T_j are the gain and time constants of the voltage controller, respectively. After comparison of the PCC voltage and reference voltage, the error signal is the input of the voltage controller to generate the trigger signal of the signal generator, i.e., P_{SVC}. According to the trigger signal, the SVC signal generator decides to switch TSC and calculate firing angle to adjust the SVC output reactive power. Thus the PCC bus voltage can be controlled by SVC in the desired range.

C. TEST SYSTEM SIMULATION AND DISCUSSION

1) SYSTEM SIMULATION

The test power system is the IEEE 3-machine 9-bus system, as shown in Figure 7. In these simulation, the synchronous generator (SG) G3 is replaced by a large wind farm. It consists of ten individual wind turbine generators (WTGs). Each individual wind turbine is equipped with a 5 MW DFIG whose parameters are shown in Table 1. For each WTG, the capacity of GSC is 2MVA. The rated voltage of the three-winding transformers is 30kV, 3.3kV, 0.69kV, respectively. The STATCOM or SVC would be separately connected to PCC point through step-up transformer for voltage regulation and reactive power support during wind speed variation and grid

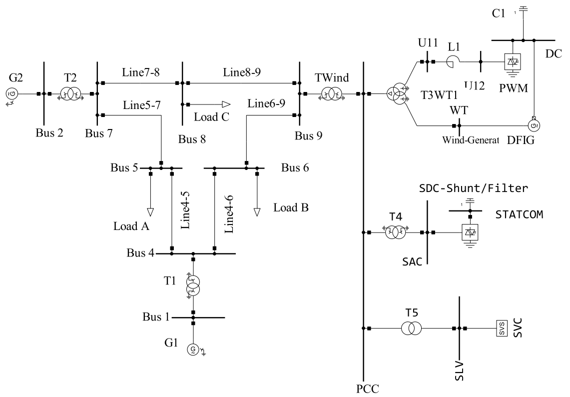

FIGURE 7. Configuration of the test power system.

TABLE 1. DFIG parameters.

Parameters	Values	Parameters	Values
Stator Voltage	3.3 kV	Stator resistance	0.003 pu
DC voltage	1.15 kV	Stator reactance	0.125 pu
DC Capacitor	4.81 uF	Rotor resistance	0.004 pu
Inductance	0.24 mH	Rotor reactance	0.050 pu

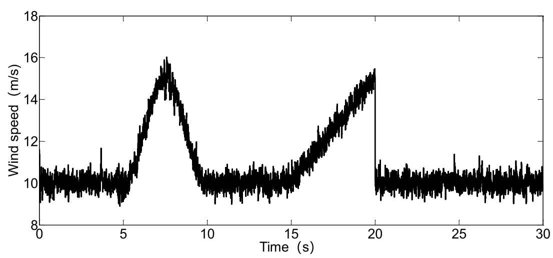

FIGURE 8. Combined wind speed.

fault. The DFIGs are assumed to be operated at unity power factor (UPF) control mode.

2) CASE ONE: WIND SPEED VARIATION

As shown in Figure 8, the combination of constant wind, gradient wind, gust wind and dry wind are used to evaluate the performance of SVC and STATCOM. The constant wind is set as 10m/s. The gust wind starts at the time of 5s and lasts for 5 seconds, with the wind peak at 16m/s. The gradient wind at the speed of 1m/s begins to rise at the time of 15s for 5 seconds, then the wind speed drops to 10m/s suddenly. A STATCOM and SVC rated at 15Mvar are respectively installed on PCC bus for comparison. For simplicity, the DFIG operates at almost unity power factor.

With the prescribed wind speed variation, the dynamic performance of the voltage at PCC is shown in Figure 9(a). Without any reactive current injection by reactive power compensation devises, the voltage at the PCC voltage fluctuates when wind speed varies. Though both FACTS devices can improve the stability condition of the grid voltage,

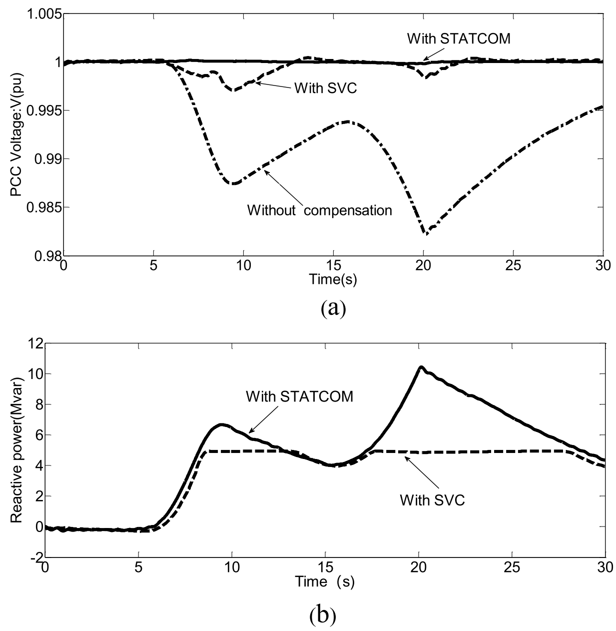

FIGURE 9. Performance of the wind: (a) PCC bus voltage; (b) Reactive power of compensations.

STATCOM performs better. This is because STATCOM responses faster and can provide more reactive power than SVC at the same capacity, as shown in Figure 9(b). Although it does not cause any system transient instability in this case study, system can becomes the scale of wind farms.

3) CASE TWO: GRID FAULT

In this study, a momentary three-phase fault happens at the bus 8 in Figure7 at the time of 1s for 0.15s. In order to prevent the rotor protection Crowbar device from repeated movements for the rotor winding current, the Crowbar will be set out of operation 0.5s later.

(1) Three distinctive reactive power control strategies are simulate; namely, system voltage control with SVC, with STATCOM and without any compensation. A STATCOM and SVC rated at 10Mvar are separately installed at PCC. As shown in Figure 10(a), STATCOM performs the better compensation to bring the system voltage back to normal. And the STATCOM can provide approximately 26Mvar of reactive power after the fault is cleared while SVC can only provide 9Mvar reactive power and fail to reestablish the system voltage recovery. It is because STATCOM can provide up to 264% of the rated output for 2 seconds-rapidly restoring transmission system voltage [11]. In this case, the installed capacity of SVC is not enough for voltage recovery.

(2) In this case, A STATCOM rated 10Mvar and SVC rated 20Mvar are separately installed on PCC bus. Figure 11 shows that, with the increased rating for the SVC capacity, the voltage sags do not change significantly during the fault, but the voltage recovery process is considerably shortened. The volt-

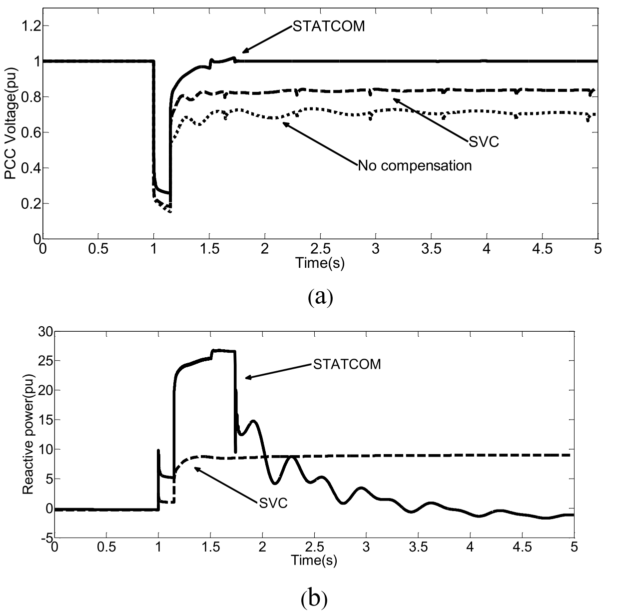

FIGURE 10. **Dynamic performance of SVC and STATCOM with same capacity: (a). PCC bus voltage; (b). Reactive power provided by SVC and STATCOM.**

age recovery time and reactive power generation for both the 20MVar SVC and 10MVar STATCOM are comparable. This indicates that, for the same transient stability, the capacity of STATCOM is generally smaller than SVC. In this case, the percentage of installed capacity of STATCOM and SVC is 1:2.

IV. COORDINATED CONTROL APPROACH OF STATCOM AND DFIG

The main purpose of coordinated control of DFIG and STATCOM is to give full play of the DFIG's reactive ability, and to reduce the reactive power compensation devices equipped. The reactive power coordinated control model is shown in Figure 12. Measurement model measure the PCC bus voltage in real-time, and the voltage controller which is formulated based on a proportional and integral (PI) controller generates the reference of the reactive power, Q. If the capacity of the GSCs is insufficient for the command of the reactive power, $Q\text{-}Q_{g\_max} > 0$, the reactive power reference value of GSC, $Q_{g\_ref} = Q$, reactive power distribution will be sto; If $Q\text{-} Q_{g\_max} < 0$, $Q_{g\_ref} = Q_{g\_max}$, then start the second layer assignment. First, determine whether the crowbar is act or not, if failure is very serious, leading to crowbar act, RSC will be blocked, DFIG will be lost reactive power regulation capabilities, the reactive power reference of STATCOM, $Q_{s\_max} = Q\text{-}Q_{g\_max}$; If the crowbar is not act, judge the difference between $\Delta Q = Q\text{-}Q_{g\_max}$ and stator side capacity of reactive powe Q_{r_max}, if it is greater than zero, $Q_{r\_ref} = Q_{r\_max}$, STATCOM bear the remaining of reactive powe; If the difference is less than zero, that is mean, the stator side can bear all the remaining reactive power, so $Q_{r\_ref} = Q\text{-}Q_{g\_max}$.

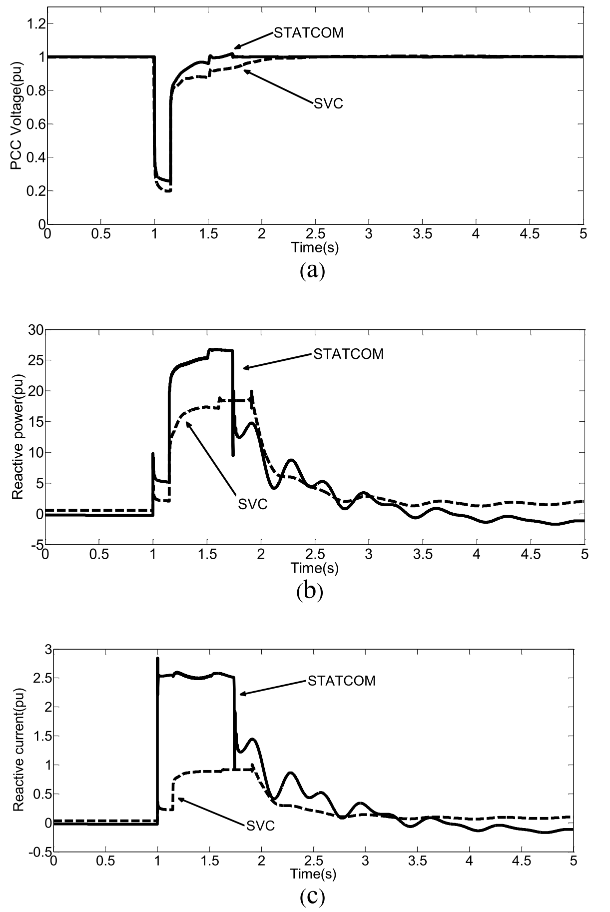

FIGURE 11. **Performance of different compensation capacity: (a) PCC bus voltage; (b) Reactive power of compensations; (c) Reactive current of compensations.**

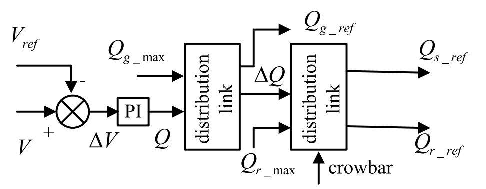

FIGURE 12. **Coordinated control mode.**

A. COORDINATION CONTROL SIMULATION RESULTS

In this study, simulation results for the operation of the induction generators and the stabilization by the coordinated control under different degrees of voltage drop and voltage rise are presented and discussed. STATCOM rated 7.5Mvar is installed on PCC bus.

For comparisons, the wind farm has been simulated with 3 different control strategies considering possible scenarios with different voltage dips swells. Strategy A: the DFIG operate in unity power factor; Strategy B: the DFIG operate in unity power factor, and a 15 MVA STATCOM is installed at the PCC bus to support the grid voltage; Strategy C: the wind farm adopts the proposed coordinated control strategy which

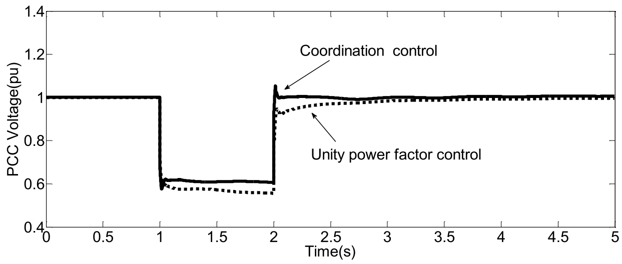

FIGURE 13. **PCC bus voltage.**

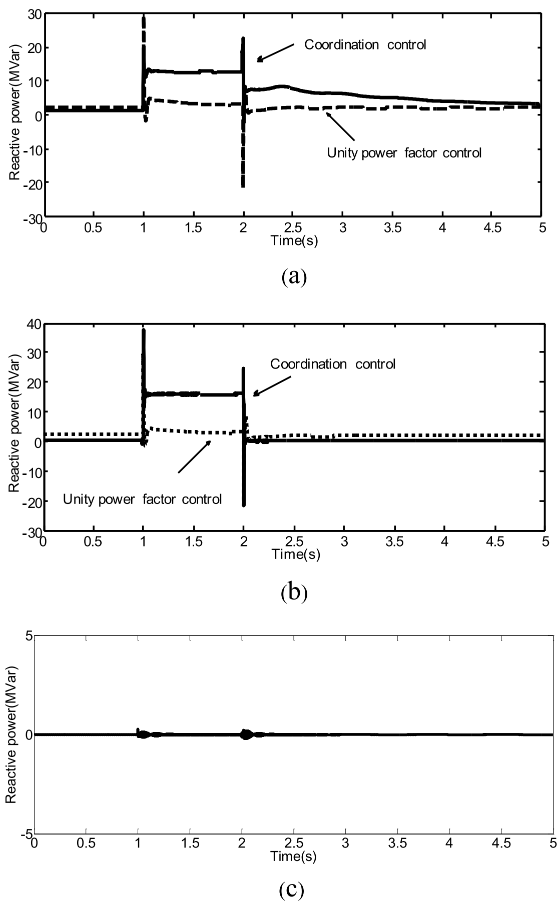

FIGURE 14. **Reactive power of reactive resources:(a) Reactive power of GS;(b) Reactive power of DFIG stato;(c)Reactive power of STATCOM.**

is described in Section 5, with 7.5Mvar STATCOM installed on PCC bus.

B. SCENARIOS WITH 40%∼1s VOLTAGE DIPS

In this study, the symmetrical voltage sagging of 40 % is created by a temporary three-phase circuit fault at t=1 second, and the fault is cleared after 1 second. Figure13 plots transient time-response curves of the PCC voltage with Strategies A and C. By adopting coordinated control strategy, the converters are assumed to be sufficiently robust to provide all the reactive power demands of the grid, as shown in Figure 14. As a result, the voltage is increased from 0.58pu to 0.65pu, an increase of 11.21% during the grid fault, compared to unity power factor operation. What is more, when the fault is cleared, and the PCC voltage can be reestablished more shorten. During this grid fault, the crowbar does not act, but reactive power demands are relatively large. Figure 14 can be illustrated that GSC provide 13MVar and the DFIG stator side issued about 18MVar reactive power; STATCOM does not provide any reactive.

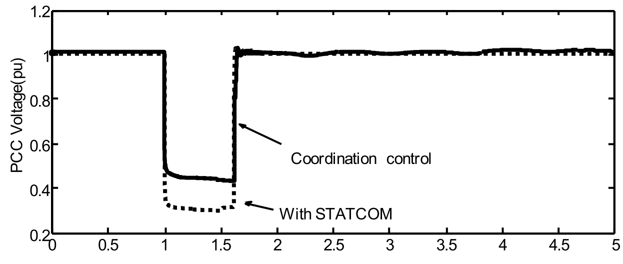

FIGURE 15. **PCC bus voltage.**

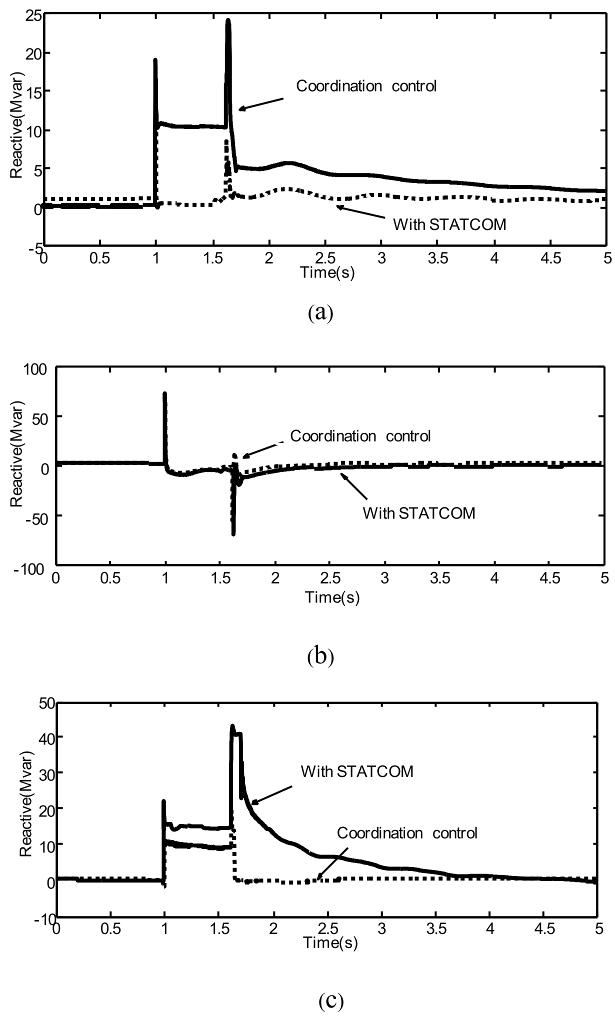

FIGURE 16. **Reactive power of reactive resources: (a) Reactive power of GS; (b) Reactive power of DFIG stator;(c) Reactive power of STATCOM.**

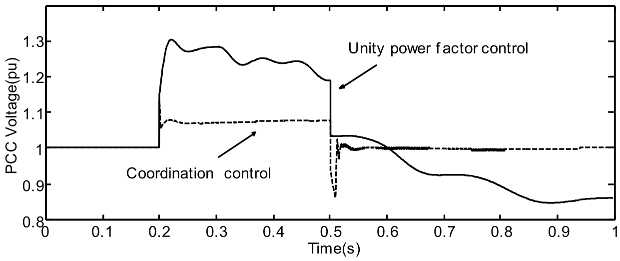

FIGURE 17. PCC bus voltage.

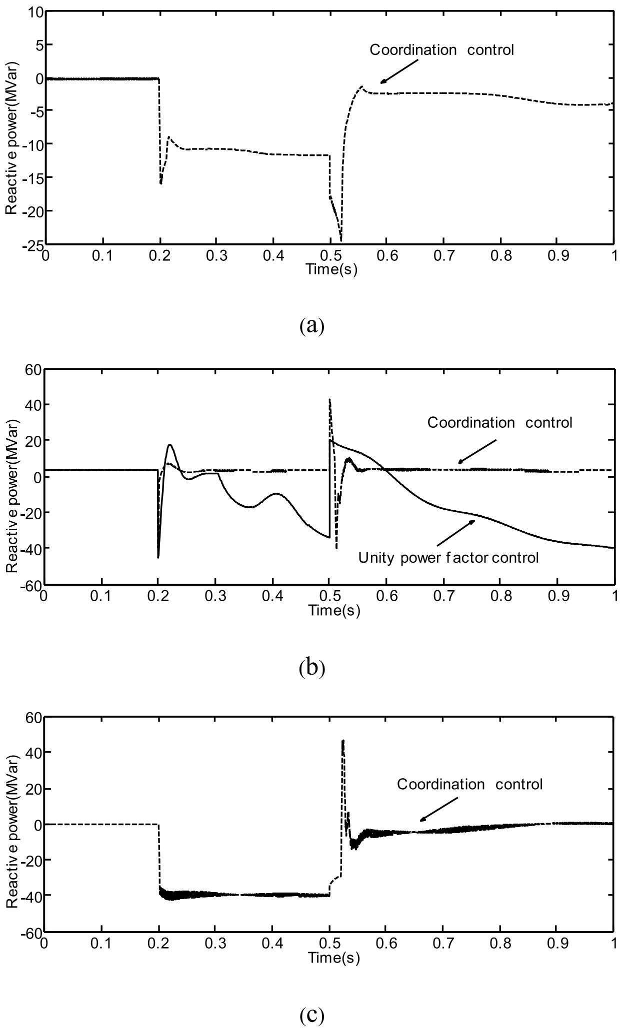

FIGURE 18. Reactive power of reactive resources: (a) Reactive power of GSC; (b) Reactive power of DFIG stator;(c) Reactive power of STATCOM.

C. SCENARIOS WITH 70%∼0.625s VOLTAGE DIPS

This scenario has a 70% voltage drop, fault duration of 0.625ms. As comparison, a 15 MVA STATCOM is connected to the wind farm bus in this test system. Figure 15 shows the PCC voltage with Strategies B and C. With the coordinated reactive power control, the PCC bus voltage drops lighter, which is increased from 0.3pu to 0.41pu, an increase of 11.21%. That is because the coordination can provide about 22Mvar reactive power, but STATCOM only provide about 15Mvar, as shown in Figure 16. What is more, with the coordination, the installation capacity of STATCOM is reduced to 10Mvar. From our simulation analyses, we can conclude that the proposed controller not only can reduce voltage sag and assist voltage in quick recovery, but also can reduce the installed capacity of dynamic compensation devices. In this case, the RSC is blocked; DFIG has the same behavior as a typical induction generator at this moment.

D. SCENARIOS WITH 30%∼0.3s VOLTAGE SWELLS

This scenario has a 30% voltage rise, fault duration of 0.3s. Figure17 plots transient time-response curves of the PCC voltage with Strategies A and C. As shown in Figure17, the GSC loses stability when adopting Strategy A during normal operation, which causes the DC bus voltage to rise. Then the wind turbine is disconnected from the grid. While adopting Strategies C, nearly 40MVar of inductive reactive power is sent out by STATCOM, as shown in Figure 18. Besides, GSC sends 11MVar of inductive reactive power to the grid to support the fast recovery of grid voltage due to excessive grid reactive power surplus.

V. CONCLUSION

This article has investigated different reactive compensation equipment to enhance the PCC voltage regulation in both steady state conditions and grid faults. Then a novel coordinated control model about reactive power is presented. The conclusions are drawn as follows:

Compared to the SVC, the STATCOM can provide more reactive power under the same compensation position and capacity, as well as faster voltage recovery. In order to achieve the same effect, SVC is required to install with much larger capacity than STATCOM. STATCOM is perhaps a more economic choice.

The reactive power coordinated control strategy can provide enough reactive power effectively to ensure system transient voltage stability for different degrees of voltage dips. Moreover, the capacity of STATCOM will be reduced which saves the cost of investment significantly.

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