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Control of VSC-based STATCOM using conventional and direct-current vector control strategies

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ABSTRACT

A STATCOM is a device that can compensate reactive power and provide voltage support to an ac system. Due to the advance of power electronic technology, VSC-based IGBT or IGCT converters have been increasingly used in modern STATCOM systems. A traditional VSC-based STATCOM consists of a voltage source converter, connected to an energy storage device on one side and to the ac power system on the other, and a control system based on the conventional standard *d–q* vector control technology. This paper studies and compares the conventional and a direct-current vector control schemes for a VSC-based STATCOM. A limitation of the conventional control mechanism is analyzed. An optimal control strategy is developed based on a direct-current vector control design. Close-loop control evaluation demonstrates that a D-STATCOM system works well using the proposed control mechanism both within and beyond the converter linear modulation limit while the conventional standard control technique could result in over voltage and system oscillations when the converter operates beyond its linear modulation limit.

1. Introduction

The FACTS (flexible AC transmission system) devices have been widely used in today's power system [1]. One important function of FACTS devices is the reactive power compensation or the voltage support control of the power system [2]. Traditionally, reactive power compensation, within the FACTS devices, has been handled with the thyristor-based static VAR compensator (SVC) [3], which consists of thyristor-controlled reactors (TCR) or thyristor-switched capacitor banks to compensate reactive power or provides voltage support to a bus [4].

Nevertheless, due to the advance of power electronic technology, the replacement of the SVC by a new breed of static compensators, STATCOMs, based on the use of voltage source PWM converter is looming [4]. The STATCOM provides all the functions that the SVC can provide but has a faster speed and better dynamic characteristics that do not depend on the grid voltage [4,5]. This is particularly important when a rapid dynamic response is required or the electric grid voltage is low. In addition, a STATCOM device is more compact and requires only a fraction of the land required by an SVC installation. Modern STATCOM devices based on PWM power converter technology, such as IGBTs (Insulated Gate Bipolar Transistors) and IGCTs (Integrated Gate Commutated Thyristors), can rebuild output ac voltage waveform with rapidly controlled magnitude and phase angle [5,6].

But, the performance of a STATCOM depends not only on the converters but also on how it is controlled. Traditionally, control of a VSC-based STATCOM utilizes the standard decoupled *d–q* vector control approach [7–9]. The behavior of the controller is evaluated through either transient simulation or transient measurement techniques [5–9]. The performance of the controller has not been studied in detail when converter operates beyond the linear modulation limit. The evaluation of this paper shows that there is a limitation in the traditional standard STATCOM vector control strategy, which could result in large oscillations in the STATCOM and/or the grid systems, particularly when the converter operates over its linear modulation limit.

This paper presents an optimal and direct-current vector control mechanism for a VSC-based STATCOM. The proposed control approach employs a decoupled *d–q* vector control technique while the details of the control implementation, including the generation of control signals, are completely different from the conventional control method. The purpose of the proposed control scheme is to retain a constant dc capacitor voltage, improve reactive power compensation, and enhance system stability both within and beyond the converter linear modulation limit. In the sections that follow, the paper first presents the configuration and transient and steady-state models of a VSC-based STATCOM in Section 2. Section 3 presents the conventional standard STATCOM *d–q* vector control mechanism. Section 4 proposes an optimal control scheme based on a direct-current vector control configuration. Performance and comparison study of the conventional and proposed control strategies is given in Sections 5 and 6 for reactive power

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and bus voltage support controls of a power distribution network using a D-STATCOM. Finally, the paper concludes with the summary of the main points.

2. STATCOM transient and steady-state models in *d–q* reference frame

Fig. 1 depicts the basic configuration of a STATCOM connected with the grid, where a capacitor is shunt connected with a voltage source PWM converter. A transformer and a grid filter are connected between the converter and the grid [8,9]. The grid filter consists of a resistor and an inductor. The transformer can be modeled as a resistor plus an inductor too. Hence, the equivalent circuit between the converter and the grid is modeled as a resistor and an inductor in series for convenient analysis.

Fig. 2 shows the equivalent circuit of the integrated STATCOM and grid system, where V_{dc} represents the voltage over the capacitor *C*, the resistor R_p represents the power loss in the converter and the dc circuit. The voltages v_{a1}, v_{b1}, and v_{c1} represent the three-phase output voltage of the PWM converter, and the voltages v_a, v_b, and v_c represent the three-phase grid voltage at the point of common coupling (PCC). The transformer and grid filter in Fig. 1 are represented as a series combination of a resistor R_f and an inductor L_f.

In the *d–q* reference frame, the voltage balance equation across the *RL* of the ac system is

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = R_f \begin{bmatrix} i_d \\ i_q \end{bmatrix} + L_f \frac{d}{dt} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \omega_s L_f \begin{bmatrix} -i_q \\ i_d \end{bmatrix} + \begin{bmatrix} v_{d1} \\ v_{q1} \end{bmatrix} \tag{1}$$

where ω_s is the angular frequency of the grid voltage, v_d, v_q, v_{d1}, and v_{q1} represent the *d* and *q* components of the grid voltage and converter output voltage, respectively, and i_d and i_q represent the *d* and *q* components of the current flowing between the ac system and the STATCOM.

Eq. (1) can be expressed by a complex Eq. (2) using space vectors, in which v_{dq}, i_{dq}, and v_{dq1} are instantaneous space vectors of grid voltage, line current, and converter output voltage. In the steady-state condition, (2) becomes (3), where V_{dq}, V_{dq1}, and I_{dq} stand for the steady-state space vectors of the ac system and converter output voltages and line current.

$$v_{dq} = R_f \cdot i_{dq} + L_f \frac{d}{dt} i_{dq} + j\omega_s L_f \cdot i_{dq} + v_{dq1} \tag{2}$$

$$V_{dq} = R_f \cdot I_{dq} + j\omega_s L_f \cdot I_{dq} + V_{dq1} \tag{3}$$

In the PCC voltage orientation frame [7–9], the ac system *d*-axis voltage is constant and *q*-axis voltage is zero. Thus, the instantaneous active and reactive powers transferred from the ac system to the STATCOM are proportional to the *d*- and *q*-axis currents, respectively, as shown by

$$p_{ac}(t) = v_d i_d + v_q i_q = v_d i_d \tag{4}$$

$$q_{ac}(t) = v_q i_d - v_d i_q = -v_d i_q \tag{5}$$

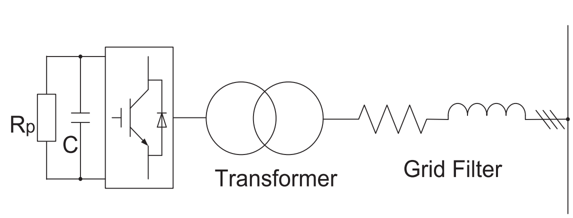


Fig. 1. Configuration of a STATCOM.

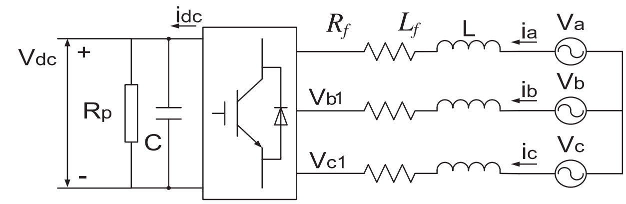


Fig. 2. Equivalent circuit the STATCOM and the grid

In terms of the steady state condition, $V_{dq} = V_d + j0$ if the *d*-axis of the reference frame is aligned along the PCC voltage position. Assuming $V_{dq1} = V_{d1} + jV_{q1}$ and neglecting the resistor R_f, then, the current flowing between the ac system and the STATCOM according to (3) is

$$I_{dq} = \frac{V_{dq1} - V_{dq}}{jX_f} = \frac{V_{d1} - V_d}{jX_f} + \frac{V_{q1}}{X_f} \tag{6}$$

where X_f stands for the reactance of the transformer and grid filter between the STATCOM and the ac system.

Supposing passive convention is applied, i.e., power flowing toward the STATCOM as positive, then, the power transferred between the STATCOM and the ac system can be achieved from the fundamental complex power equation, $P_{ac} + jQ_{ac} = V_{dq} I_{dq}^* = V_d I_{dq}^*$. By solving this power equation and Eq. (6), (7) is obtained. According to (7), the ac system active and reactive powers, P_{ac} and Q_{ac}, are controlled through *q* and *d* components V_{q1} and V_{d1} of the injected voltage by the converter to the ac system, respectively. If the resistor R_f is considered, the similar power control characteristics of the STATCOM still exist under both steady-state and transient open-loop control conditions as shown in [10].

$$P_{ac} = -\frac{V_d V_{q1}}{X_L}, \quad Q_{ac} = \frac{V_d}{X_L}(V_d - V_{d1}) \tag{7}$$

3. Conventional vector control mechanism of VSC-based STATCOM

The conventional standard vector control technology for a VSC-based STATCOM has a nested-loop structure consisting of a faster inner current loop and a slower outer loop that generates *d*- and *q*-axis current references i_d^* and i_q^* to the current loop controllers [7–9]. The outer loop consists of a capacitor voltage controller that adjusts the *d*-axis current reference i_d^* depending on the difference between the desired and actual capacitor voltages and a bus voltage or reactive power controller that regulates the *q*-axis current reference i_q^* according to an ac system bus voltage support or a reactive power compensation requirement. The inner current loop controllers assures that the *d*-axis component of the actual current reaches the *d*-axis current reference i_d^* and the *q*-axis component of the actual current reaches a *q*-axis current reference i_q^*. Note that the capacitor voltage control is actually implemented through the regulation of active power absorbed by the STATCOM.

Fig. 3 shows the overall traditional standard *d–q* vector control structure. The *d* and *q* reference voltages v_{d1}^* and v_{q1}^*, linearly proportional to the converter output voltages V_{d1} and V_{q1} [11], include the *d* and *q* voltages v'_d and v'_q from the current-loop controllers plus the compensation items as shown by (8) and (9). The two reference voltages are used to generate a three-phase sinusoidal reference voltage, v_{a1}^*, v_{b1}^*, and, v_{c1}^*, to control the PWM converter. Thus, this control configuration actually regulates i_d and i_q (i.e., the capacitor voltage and reactive power) using v'_d and v'_q, respectively [12]. But, according to Section 2 and (7), *d*-axis voltage is only effective for reactive power or i_q control, and *q*-axis voltage is only effective for active power or i_d control. Therefore, the

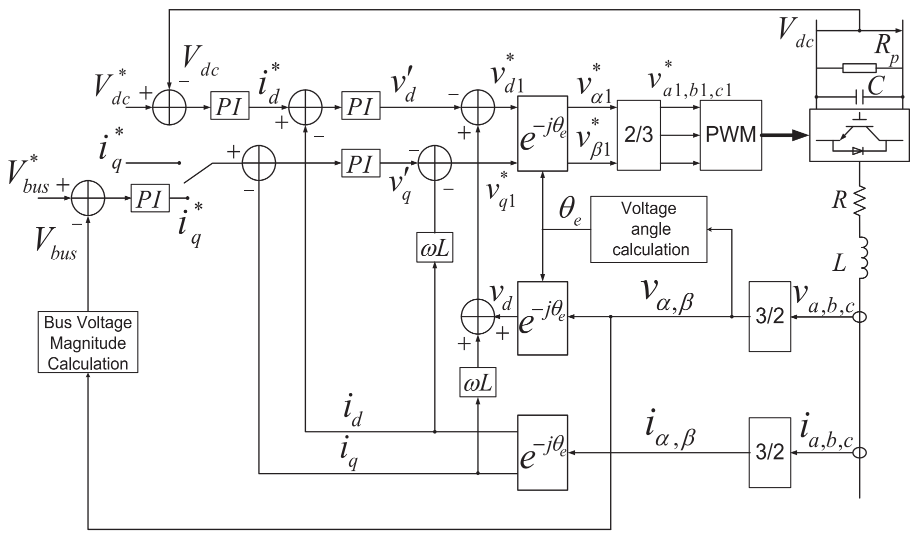


Fig. 3. Conventional decoupled *d–q* vector control structure for VSC-based STATCOM.

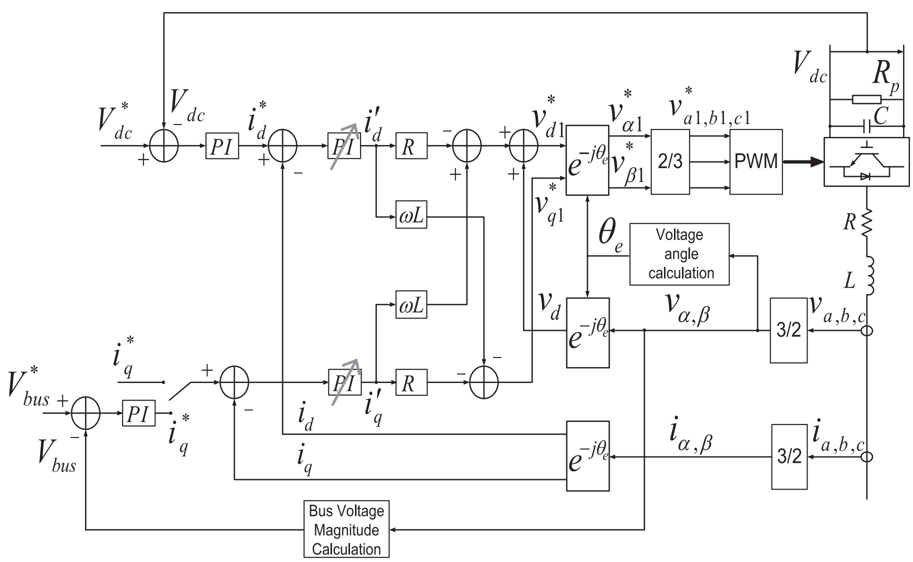


Fig. 4. Direct-current vector control of VSC-based STATCOM.

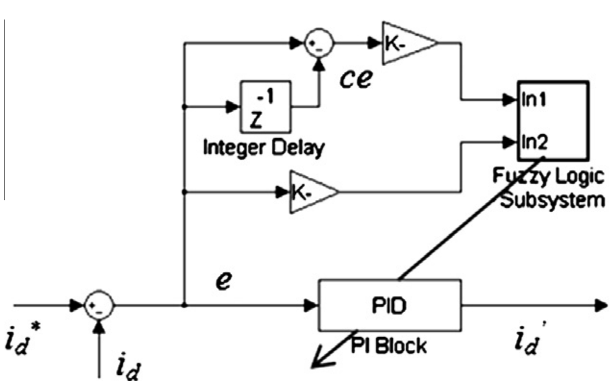


Fig. 5. Basic concept of fuzzy-PI based control mechanism.

conventional control method relies mainly on the compensation items rather than the PI loops to regulate the *d*- and *q*-axis currents. However, those compensation items are not contributed in a feedback control principle and concept.

$$v^*_{d1} = -v'_d + \omega_s L i_q + v_d \tag{8}$$

$$v^*_{q1} = -v'_q - \omega_s L i_d \tag{9}$$

The following issues are considered in the design of the nested-loop control system.

(1) To prevent the converter from getting into the nonlinear modulation mode, a saturation mechanism is applied to the output voltage of the controller if the amplitude of the reference voltage generated by the controller exceeds the converter linear modulation limit. The general strategy is to set a limitation on $|v^*_{dq1}|$ but keeps $\angle v^*_{dq1}$ unchanged as shown by (10) [13,14], where $v^*_{d1\_new}$ and $v^*_{q1_new}$ are the *d* and *q* components of the modified controller output voltage and V_{max} is the maximum allowable *dq* voltage. It is found that any other saturation mechanisms could cause more system oscillations and unbalances.

$$v^*_{d1\_new} = V_{max} \cdot \cos(\angle v^*_{dq1}) \;\; id^*, iq\_new^* = V_{max} \cdot \sin(\angle v^*_{dq1}) \tag{10}$$

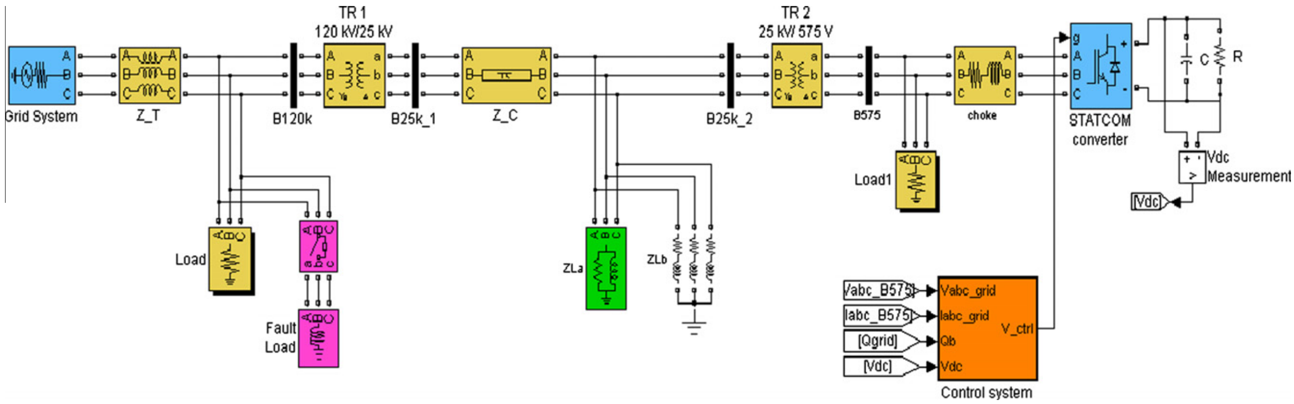


Fig. 6. A VSC-based D-STATCOM in a distribution network.

Table 1
Network data.

Component	Parameter	Value
The grid	Line voltage Frequency	120 kV 60 Hz
120 kV transmission line Z_T	Positive sequence *R*, *L* Zero sequence *R*, *L*	9.6 Ω, 0.255 H 28.8 Ω, 0.764 H
Transformer TR1 (Y–Δ connection)	Line voltage 120 kV winding *R*, *L* 25 kV winding *R*, *L*	120 kV/25 kV 0.817 Ω, 65 mH 0.106 Ω, 8.47 mH
25 kV cable connection Z_C	Length Positive sequence *R*, *L*, and *C* Zero sequence *R*, *L*, and *C*	30 km 0.1153 Ω/km, 1.05 mH/km, 11.33 nF/km 0.413 Ω/km, 3.32 mH/km, 5.01 nF/km
Load Z_{La}	Line *a*,*b*,*c*	500 kVA, 0.9 lagging
Unbalanced load Z_{Lb}	Line *a* Line *b* Line *c*	300 kVA, 0.8 lagging 400 kVA, 0.7 lagging 200 kVA, 0.8 lagging

Table 2
Parameters of individual D-STATCOM components.

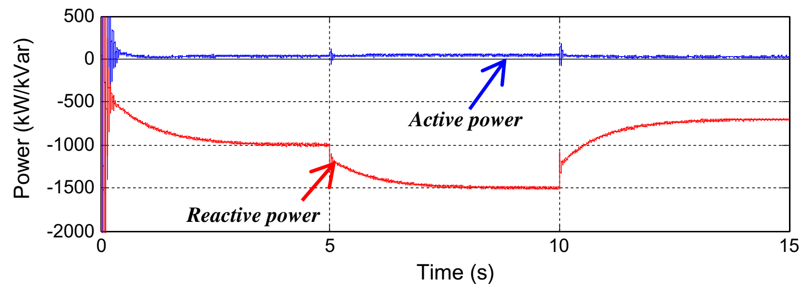
Component	Parameter	Value
Transformer TR2 (Y–Δ connection)	Line voltage 25 kV winding *R*, *L* 575 V winding *R*, *L*	25 kV/575 V 1.25 Ω, 18.7 mH 1.98 mΩ, 30 μH
Grid-filter	Resistance Inductance	0.00112 Ω 0.25 mH
Capacitor	Resistance R_p Capacitance Reference voltage	800 Ω 16,000 μF 1500 V

(2) To prevent the converter from exceeding the rated current, the q-axis current reference is adjusted if the amplitude of the reference current generated by the dc voltage and reactive power control loops exceeds the rated current limit. The general approach is keeping the d-axis current reference unchanged to maintain dc voltage control effectiveness while modifying the q-axis current reference to satisfy the reactive power control demand as much as possible as shown by [13,14]

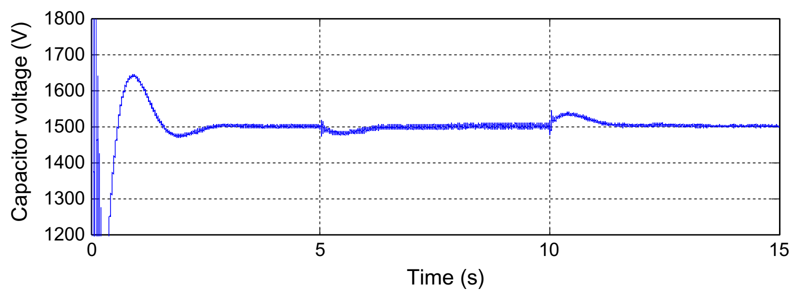
$$i^*_{d\_new} = i^*_d, i^*_{q\_new} = \text{sign}(i^*_q) \cdot \sqrt{(i^*_{dq\_\max})^2 - (i^*_d)^2} \quad (11)$$

4. Optimal and direct-current vector control of VSC-based STATCOM

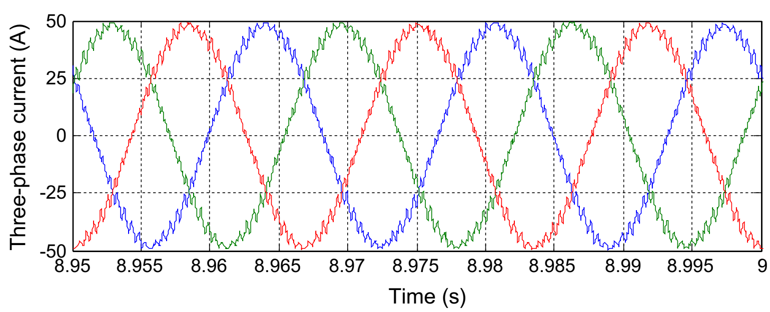
The theoretical foundation of the proposed direct-current vector control strategy is Eqs. (4) and (5), i.e., using d-axis current for active or dc capacitor voltage control and q-axis current for reactive power or grid voltage support control. But, instead of generating a d- or q-axis voltage based on a d- or q-axis current error signal as shown by the standard control structure (Fig. 3), the direct-current vector control mechanism outputs a current signal from the d or q current-loop controller. This control strategy is mainly based on typical intelligent control principles, i.e., a control goal of minimizing absolute or root-mean-square (RMS) error between the desired and actual d and q currents [15]. The output from the proposed current-loop controller is a d or q tuning current while the input error signal tells the controller how much the tuning current should be adjusted during the dynamic control process. This tuning current is different from the actual measured current. It is necessary to point out that a fast current-loop controller is critical to assure the highest power quality in terms of harmonics and unbalance. Thus, elimination of the current control loop [16,17] is not an option for the proposed control strategy.



(a) Active and reactive power at 25kV bus of TR2



(b) Capacitor voltage of the D-STATCOM



(c) Three-phase current at 25kV bus of TR2

Fig. 7. D-STATCOM performance using traditional standard control approach (within linear modulation limit).

However, due to the nature of the voltage source converter, the d and q tuning current signals i'_d and i'_q generated by the current-loop controllers must be transferred to d and q voltage signals v^*_{d1} and v^*_{q1} for the VSC control. This is implemented through (12) and (13), which is equivalent to the transient d–q Eq. (1) after being processed by a low pass filter for the purpose to reduce the high oscillation of d and q reference voltages applied directly to the converter.

$$v^*_{d1} = -Ri'_d + \omega_s L i'_q + v_d \tag{12}$$

$$v^*_{q1} = -Ri'_q - \omega_s L i'_d \tag{13}$$

Fig. 4 shows the overall direct-current vector control structure for the VSC-based STATCOM. The control system consists of a d-axis current loop for dc capacitor voltage control and a q-axis current loop for reactive power or grid voltage support control. Signal processing technology is applied to the measured dc voltage and d- and q-axis currents to prevent the high order harmonics from entering the controllers. The current-loop controller may operate on a mechanism that combines PID, fuzzy and adaptive control technologies [16]. The PID part operates on a direct target control principle while the fuzzy and adaptive parts adjust the PID parameters based on the error e, between the controlled variable and its target value, and the change in error ce as shown by Fig. 5. For instance, if the error e is small, both the proportional and integral gains of the PI system should be small; if the change of error ce is large, both the proportional and integral gains of the PI system keep almost unchanged [16]. However, it is found that the improvement obtained from the fuzzy and adaptive strategies is not significant. The simulation study shows that the performance of the controller is still mainly determined by the pre-tuned PI gains. This seems to be consistent with the results shown in [16].

In addition, a nonlinear programming formulation as shown below is employed to prevent the resultant d–q current from going over the STATCOM rated current and to prevent the converter from getting into a nonlinear modulation mode, where I_{rated} is the rated phase rms current, Q^*_{ac} is a reactive power reference, and V^*_{bus} is an ac system bus voltage reference. The basic principle of the nonlinear programming formulation is that under the converter rated power and linear modulation constraints, the STATCOM should be operated to achieve the dc voltage control goal as the first priority while minimizing the difference between reference and actual reactive powers or reference and actual ac system bus voltages.

$$\text{Minimize}: |Q_{ac} - Q^*_{ac}| \quad \text{or} \quad |V_{bus} - V^*_{bus}|$$

$$\text{Subject to}: V_{dc} = V^*_{dc}, \sqrt{\frac{I_d^2 + I_q^2}{3}} \leqslant I_{rated}, \quad \sqrt{\frac{V_{d1}^2 + V_{q1}^2}{3}} \leqslant \frac{V_{dc}}{2\sqrt{2}}$$

The nonlinear programming strategy is implemented in the following way. If $|i^*_{dq}|$ generated by the dc voltage and reactive power control loops exceeds the rated current limit, i^*_d and i^*_q are modified

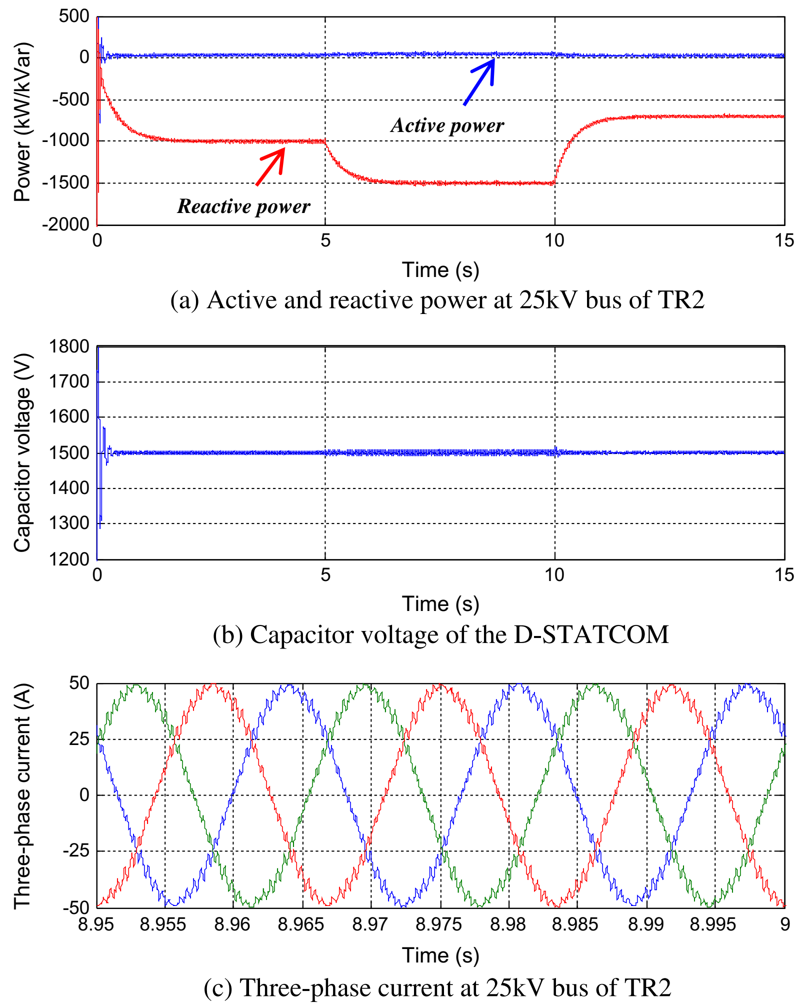


Fig. 8. D-STATCOM performance using proposed control approach (within linear modulation limit).

by (11). If $|v^*_{dq1}|$ generated by the current control loops exceeds the converter linear modulation limit, v^*_{d1} and v^*_{q1} are modified by (14). In fact, according to Section 2, (14) represents an optimal control strategy of keeping the q-axis voltage reference v^*_{q1} unchanged so as to maintain the capacitor dc voltage control effectiveness while modifying the d-axis voltage reference v^*_{d1} to meet the reactive power or the bus voltage support control demand as much as possible.

$$v^*_{d1\_new} = \mathrm{sign}(v^*_{d1}) \cdot \sqrt{(v^*_{dq1\_max})^2 - (v^*_{q1})^2},\ v^*_{q1\_new} = v^*_{q1} \qquad (14)$$

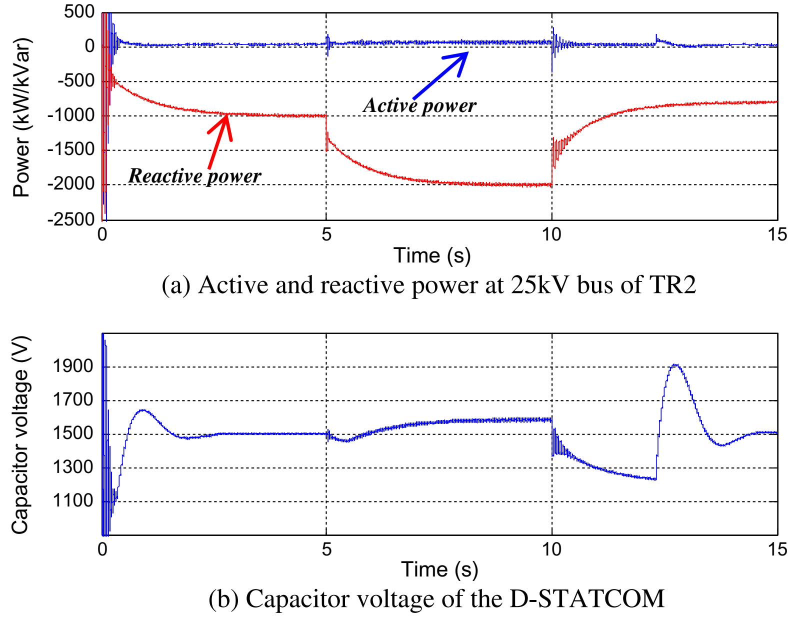
5. Evaluation and comparison of reactive power control using a D-STATCOM

The performance of the traditional and proposed control strategies is evaluated for the reactive power control of a power distribution network using a VSC-based D-STATCOM [18–20]. The modeled system, presented in Fig. 6, is built using MatLab SimPowerSystems. The grid is represented by a three-phase 120 kV ac voltage source. A Y–Δ 120 kV/25 kV transformer $TR1$ is connected to the grid through a transmission line Z_T. The transformer feeds a balanced and an unbalanced load, Z_{La} and Z_{Lb}, through a 30 km 25 kV cable connection Z_C [18]. The network data are given in Table 1.

A D-STATCOM is shunt connected to the distribution network at the grid connection point through a Y–Δ 25 kV/575 V transformer $TR2$. A grid-filter is employed between the D-STATCOM and the transformer. The values of individual D-STATCOM components are given in Table 2. The reference capacitor voltage is 1500 V. The reactive power measurement, obtained at 25 kV bus of transformer $TR2$, is compared with the reactive power reference to generate an error signal to the reactive power controller.

5.1. Within linear modulation limit

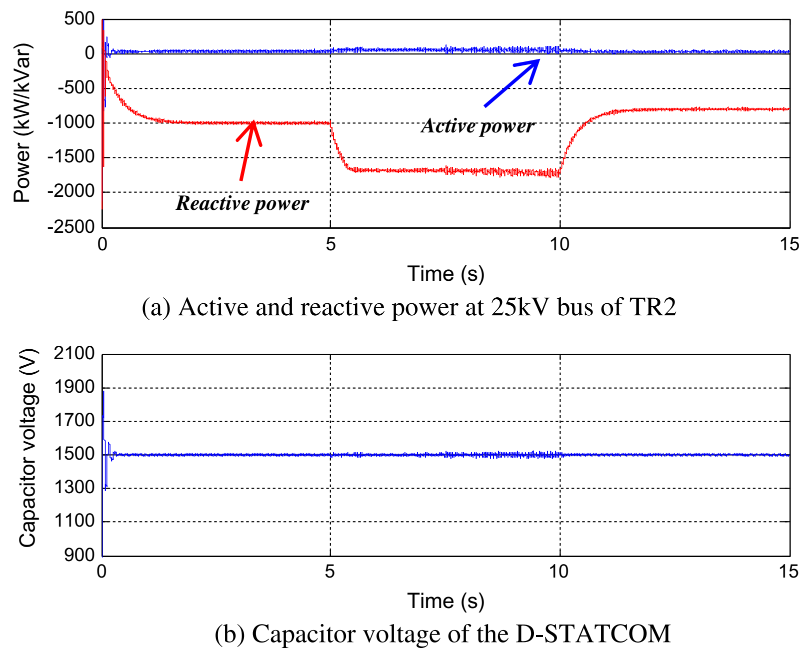
In the first case, the performance of the D-STATCOM is evaluated for balanced Z_{La} load under the condition that the controller output voltage does not exceed the converter linear modulation limit (Figs. 7 and 8). The initial reactive power reference of the STATCOM at 25 kV bus is −1 MVar, i.e., a demand of a generating reactive power. At t = 5 s, the reactive power reference changes to −1.5 MVar. At t = 10 s, the reactive power reference changes to −700 kVar. It can be seen from Figs. 7 and 8 that, when the converter operates in its linear modulation mode, both the conventional and the proposed control mechanisms, having similar performance, can effectively regulate the reactive power generated by the STATCOM to the grid according to the grid reactive power demands (Figs. 7 and 8a) and maintain the dc capacitor voltage around the reference value (Figs. 7 and 8b) while only a small amount of the real power is absorbed by the STATCOM (Figs. 7 and 8a). Both approaches have similar power quality (Figs. 7 and 8c). Note: in both Figs. 7 and 8 as well as the following figures, a ramp limitation is applied to the q-axis current reference



(a) Active and reactive power at 25kV bus of TR2

(b) Capacitor voltage of the D-STATCOM

Fig. 9. D-STATCOM performance using traditional standard control approach (over linear modulation limit).



(a) Active and reactive power at 25kV bus of TR2

(b) Capacitor voltage of the D-STATCOM

Fig. 10. D-STATCOM performance using proposed control approach (over linear modulation limit).

generated by the reactive power controller for the purpose to prevent the occurrence of a high overshoot. This is a general practice used in industry too but it would normally result in a longer settling time [21]. Therefore, depending on different applications, the tradeoff between overshoot and settling time could be different.

5.2. Beyond linear modulation limit

In the second case, the performance of the D-STATCOM is evaluated for balanced Z_{La} load under the condition that the controller output voltage may exceed the linear modulation limit (Figs. 9 and 10). This may happen for a high generating reactive power demand. The reactive power references of the STATCOM at 25 kV bus are −1 MVar before $t = 5$ s, −2 MVar from 5 s to 10 s, and −800 kVar between 10 s and 15 s.

For the conventional standard control strategy, the STATCOM works properly for dc capacitor voltage and reactive power controls if the controller output voltage does not exceed the converter linear modulation limit (before $t = 5$ s in Fig. 9). However, if at any instant, a reactive power demand makes the controller output voltage go over the linear modulation limit (after $t = 5$ s in Fig. 9), the dc voltage of the STATCOM becomes uncontrollable and floating with the reactive power references (Fig. 9b). The more the controller output voltage exceeds the linear modulation limit, the more the dc voltage deviates from the reference dc voltage. During the

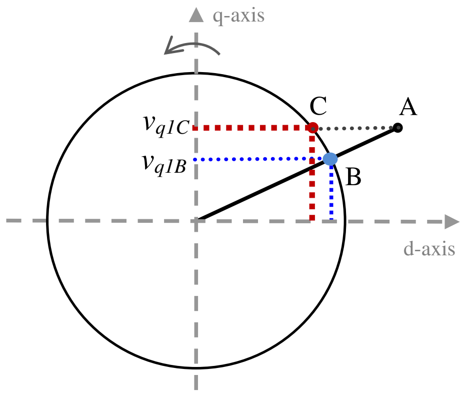


Fig. 11. Illustration of control voltage adjustment under over modulation condition.

improper function state of the conventional control mechanism, there are more oscillations in the dc capacitor voltage and the active and reactive powers absorbed by the STATCOM [22], and the current taken by the STATCOM from the grid becomes more unbalanced during each control transition.

Nevertheless, for the same condition, the proposed control strategy performs differently (Fig. 10). Shortly after the start of the system, the controllers regulate (i) the dc capacitor voltage at the target dc voltage value and (ii) reactive power at the reactive power reference. As the reactive power reference of the D-STATCOM change to −2 MVar at $t = 5$ s, a condition that the output voltage of the controller exceeds the converter linear modulation limit, the proposed control technique regulates the STATCOM reactive power according to the optimal control rule, i.e., maintaining the capacitor voltage constant as the first priority while generating reactive power as much as possible. As the controller output voltage drops below the converter linear modulation limit at $t = 10$ s due to a low reactive power demand, the proposed control mechanism returns quickly to its normal operation mode. For each reactive power demand changing from one condition to another, the proposed control technique can adjust the actual dc voltage to the reference value swiftly with much reduced oscillation (Figs. 9 and 10b).

The difference between Figs. 9 and 10 can be explained more clearly by Fig. 11. Assume that the output voltage of the current-loop controller of the STATCOM is at point A for an over modulation condition (i.e., outside the circle of 1 p.u. radius). Then, according to (10), the conventional standard approach adjusts the control voltage applied to the power converter to point B, which reduces both d and q components of the control voltage. The decline of the q-axis voltage increases the power transferred from ac to dc systems according to (7), causing the dc voltage to rise. However, the proposed approach, based on (14), changes the

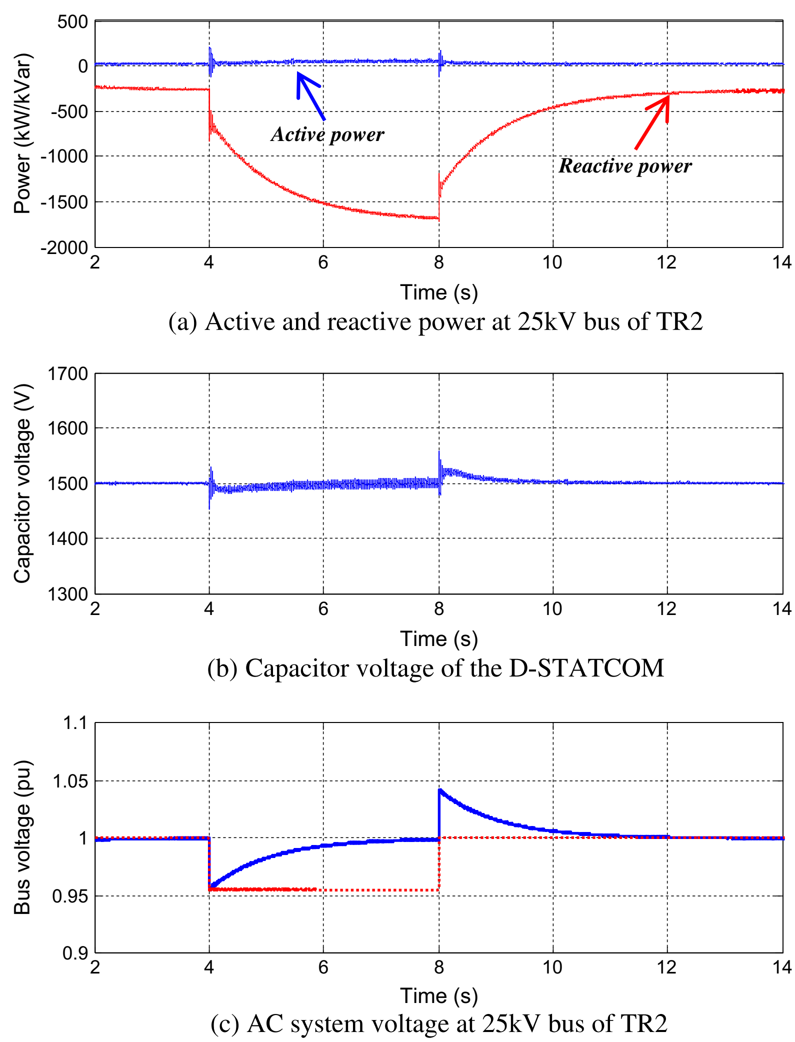
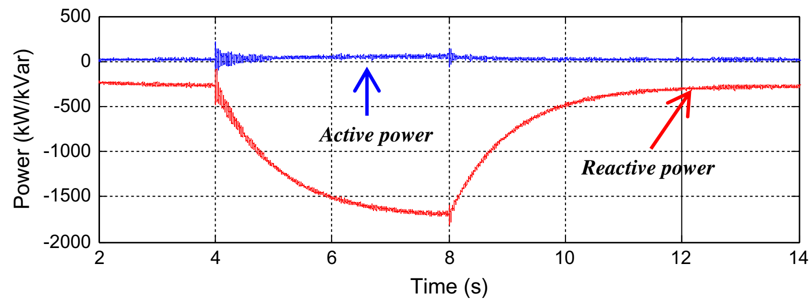
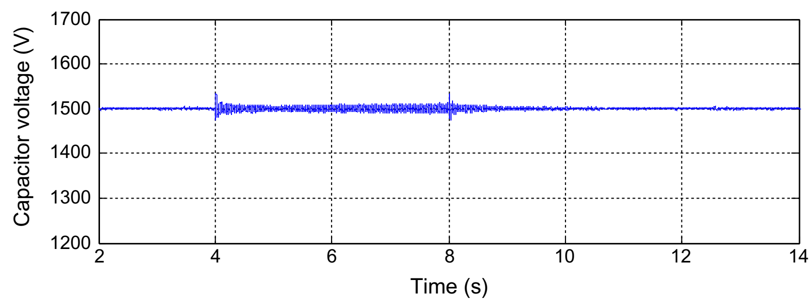


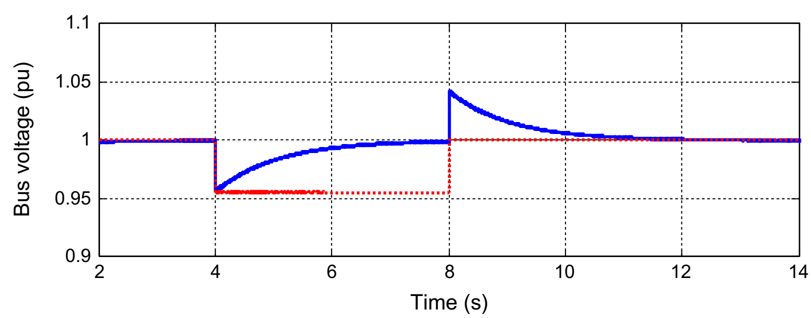
Fig. 12. Performance of voltage support control using traditional control approach (low voltage sag condition).



(a) Active and reactive power at 25kV bus of TR2



(b) Capacitor voltage of the D-STATCOM



(c) AC system voltage at 25kV bus of TR2

Fig. 13. Performance of voltage support control using proposed control approach (low voltage sag condition).

control voltage applied to the power converter to point C, which reduces *d*-axis voltage but keeps the q-axis voltage unchanged. Hence, the dc voltage control is not affected by the adjustment of the control voltage while the reactive power is regulated according to the optimal control rule. It is necessary to point out that this optimal control strategy cannot be applied to the conventional control structure (Fig. 3), which could result in high oscillations and unbalances of the system.

5.3. Unbalanced load condition

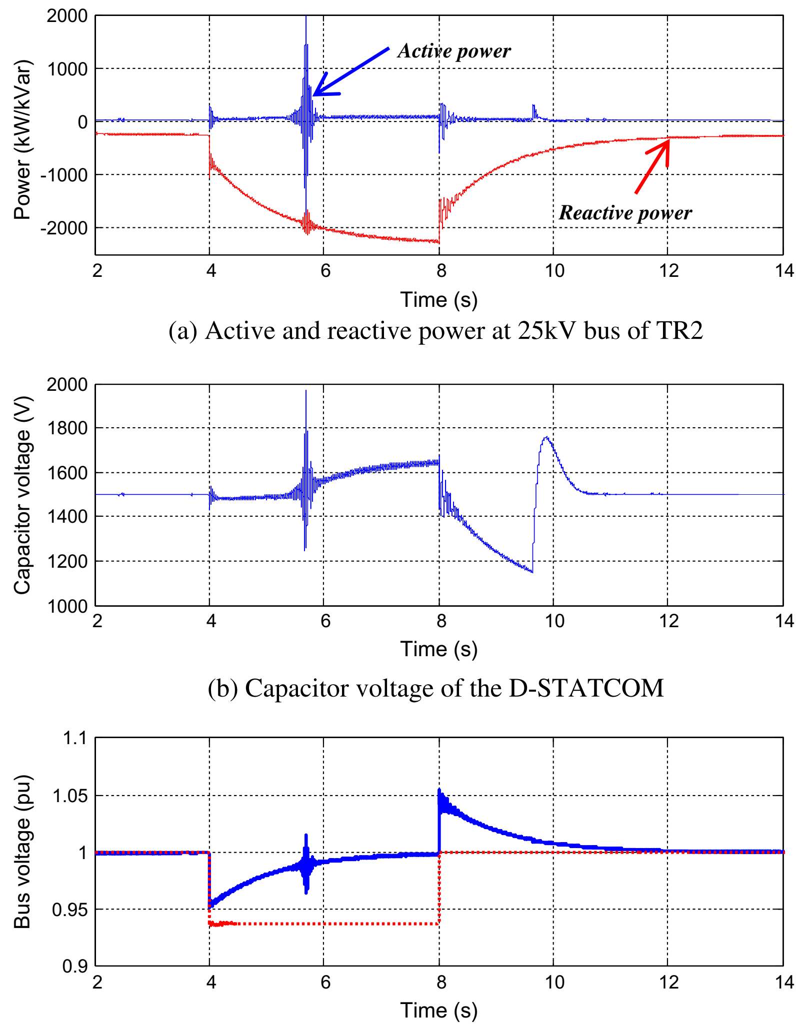
When the unbalanced Z_{Lb} load is added into the power network, the performance of the reactive power control using both the conventional and the proposed approaches does not change much. For the same condition used in Figs. 7 and 8, only a little bit more oscillation is found on the dc capacitor voltage and active and reactive power at the 25 kV bus. The extent of the oscillation depends on how much unbalanced the load is and the overall D-STATCOM system design.

6. Bus voltage support control using conventional and proposed control strategies

For grid voltage support control using the D-STATCOM, the control objective is to maintain a bus voltage at a desired value for any voltage fluctuation due to a load change or for any voltage sag due to a fault. Assume there is a fault in the 110 kV transmission system at a certain time (Fig. 6), which causes a voltage droop on the 25 kV bus to which the D-STATCOM is connected. The extent of the voltage sag depends on the location and type of the fault in the distribution network. Under the grid voltage support control condition, the q-axis current reference as shown in Figs. 3 and 4 is determined by a bus voltage controller based on the error signal between the desired and actual bus voltages to be controlled. Hence, the alteration of the *q*-axis current reference i_d^* may cause more instability problems to the overall system.

Figs. 12 and 13 compare the performance of the traditional and proposed approaches for grid voltage support control when there is a small voltage sag on the 25 kV bus, in which only the balanced load Z_{La} is considered. The voltage sag starts at $t = 4$ s and ends at $t = 8$ s. Under a low voltage sag condition, the reactive power needed for the voltage support control is small so that the converter operates within its linear modulation limit. As shown by Figs. 12 and 13, both the traditional and proposed control approaches are able to achieve the capacitor voltage and the grid voltage support control goals.

However, if a voltage sag makes the amplitude of the controller output voltage exceeding the converter linear modulation limit, the conventional control approach could cause critical problems to both the STATCOM and grid systems. As it is shown by Fig. 14,



(a) Active and reactive power at 25kV bus of TR2

(b) Capacitor voltage of the D-STATCOM

(c) AC system voltage at 25kV bus of TR2

Fig. 14. Performance of voltage support control using traditional control approach (moderate voltage sag condition).

the reactive power generation of the D-STATCOM starts to increase when the voltage sag appears at $t = 4$ s. Around $t = 5.5$ s, the amplitude of the control voltage generated by the STATCOM controller exceeds the converter linear modulation limit so that Eq. (10) is applied to modify the control voltage, which results in a high transient disturbance to the overall system (Fig. 14). The control strategy of Eq. (10) also makes the dc capacitor voltage uncontrollable and deviate away from the dc voltage reference. Although the voltage support control at the 25 kV bus is maintained due to the increased reactive power generation, the dc capacitor voltage could be much higher than the reference dc voltage depending on the extent of the voltage sag. As the voltage sag is cleared at $t = 10$ s, there is a high oscillation period in order for the STATCOM system to shift from the abnormal to the normal operating conditions. The more the voltage sag is, the more and the longer the oscillations are found in the STATCOM and grid systems after the voltage sag.

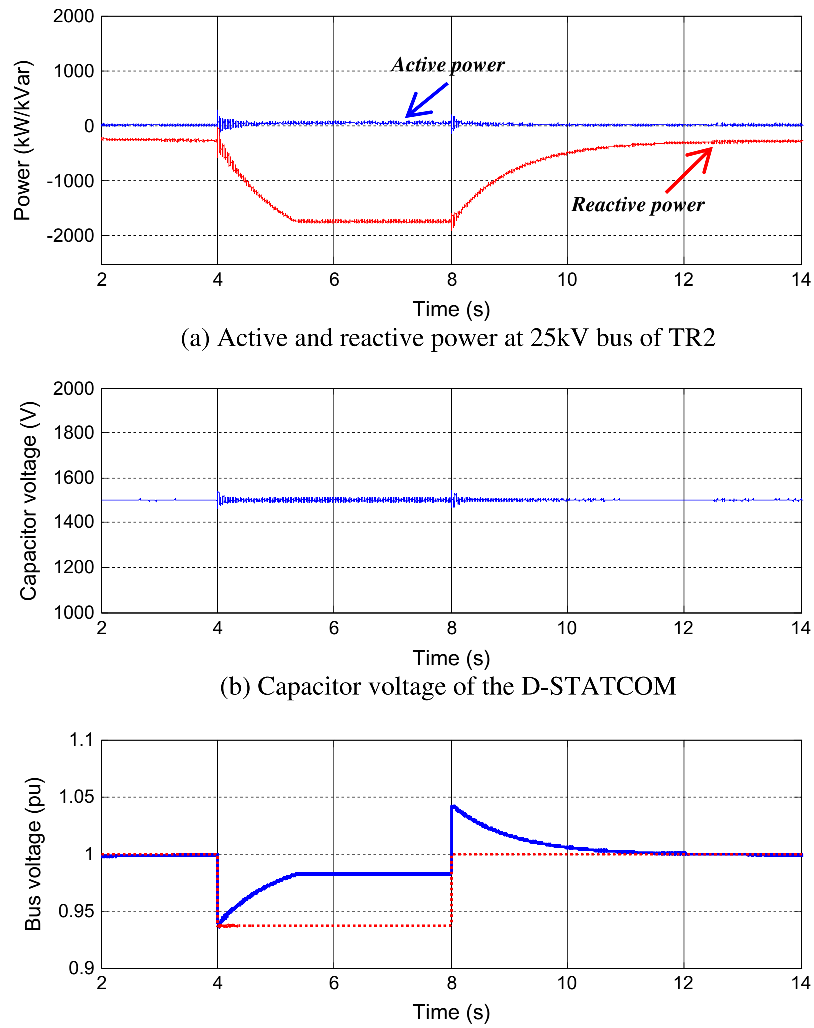
Compared to the traditional standard control approach, the proposed control mechanism has much more improved behavior under a moderate to high voltage sag condition. Fig. 15 shows the performance of the proposed STATCOM control approach for the same system condition used in Fig. 14. Unlike the conventional control strategy, the proposed control method regulates the STATCOM system according to the optimal control rule during the voltage sag period by retaining the dc capacitor voltage constant while supporting the grid voltage as much as possible. After the voltage sag, the proposed control strategy returns to normal system operation effectively and stably, and the system always responses to a control condition transition smoothly with much more reduced oscillations (Fig. 15).

7. Conclusions

This paper evaluates and compares the conventional standard and a direct-current vector control mechanisms for reactive power and grid voltage support controls using a VSC-based STATCOM. The proposed STATCOM control mechanism employs an optimal control strategy through a PI or an integration of PID, fuzzy and adaptive control mechanism while the conventional control strategy is found to perform weakly under extreme situations.

In the reactive power control mode using the VSC-based STATCOM, if the converter operates within its linear modulation mode, the conventional standard control scheme can properly regulate the reactive power and maintain the STATCOM dc capacitor voltage around a reference value; if the controller output voltage goes over the converter linear modulation limit, however, it will trigger the system into a malfunction state so that the dc capacitor voltage becomes uncontrollable.

In the grid voltage support control mode, if a voltage droop does not cause the converter operating beyond its linear modulation



(a) Active and reactive power at 25kV bus of TR2

(b) Capacitor voltage of the D-STATCOM

(c) AC system voltage at 25kV bus of TR2

Fig. 15. Performance of voltage support control using proposed control approach (moderate voltage sag condition).

limit, the STATCOM operates appropriately using the conventional control approach; if a voltage sag causes the output voltage from the controller exceeding the converter linear modulation limit, it could trigger the conventional control approach into a malfunction state and cause critical stability problems to both the STATCOM and grid systems.

For both reactive power and grid voltage support controls, the proposed control scheme operates according to an optimal control strategy and has much more improved performance than the conventional control approaches. Both within and beyond the converter linear modulation limit, the proposed control scheme is always stable, has better control characteristics, causes less oscillation to the STATCOM and the grid systems, and maintains a much more stable dc capacitor voltage.

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