State-Feedback Current Control of VSI-Based D-STATCOM for Load Compensation

Peyman Jafarian
School of Electrical and Computer Engineering,
University of Tehran,
Tehran, Iran
p.jafarian@ece.ut.ac.ir

Mohamad Tavakoli Bina
Electrical Engineering Faculty,
K. N. Toosi University of Technology,
Tehran, Iran
tavakoli@ieee.org

***Abstract*— This paper presents a closed-loop control technique for the D-STATCOM, aiming at load balancing as well as load power factor correction. Compensation for the oscillatory components of the active and reactive powers of an unbalanced load requires the D-STATCOM to inject unbalanced three-phase currents to the power network. For this purpose, the compensator current references would contain an ac component on top of the dc value in the rotating-reference-frame. As a result, the closed-loop current control of the device would become different from that under balanced condition. In this paper, a state-feedback-based current controller is proposed and the engaged pulse width modulation is enhanced by dynamically modification of the switching duty ratios to tackle the dc-side voltage oscillations effects. The whole method, including the control technique and the modulation compensation, is simulated by using PSCAD/EMTDC software to demonstrate the validity of the proposed approach.**

Keywords- current controller, state feedback, distribution synchronous compensator (D-STATCOM), load balancing

I. INTRODUCTION

The D-STATCOM is a shunt device suggested for different purposes such as supplying load reactive power either for voltage regulation or load power factor correction. A D-STATCOM is connected to a power system bus, which is forced to work under unbalanced applied voltages particularly at the distribution substation feeders. This situation would affect the operation of the inverter, deteriorating its harmonic performance. Operations of dc/ac inverters have been studied under such a condition [1]–[2], introducing various practical issues. Energy oscillation between the inverter dc and ac sides results in dc-side voltage oscillations at twice the mains frequency as a consequence of unbalanced supplying condition, injecting current harmonics to the grid system [1]. This will force the utility to react by feeding unwanted current components, distorting the sinusoidal waveform of the source currents. In brief, the operation of D-STATCOM may cause malfunction not only for the device itself but also for the utility network as well.

Referring to Fig. 1, the closed-loop control of a D-STATCOM consists of two main control loops (i.e., outer- and inner-loops). The outer-loop controller generates the appropriate current references in accordance with the compensation objectives. The inner-loop controller is responsible for changing the switching status such that the compensator output currents track the generated references. Since the internal controller is placed within the path of the outer-loop controller, the dynamic performance of the whole system would be affected by the response time of the inner-loop controller. Therefore, fast response of the inner-loop controller is essential for transient and dynamic stability of the closed-loop system.

Most of the suggested current control techniques employ the Park transformation to convert the three-phase signals to constant values (i.e., d and q modal components) [3]-[7]. This simplifies the controller design of the compensator for the balanced condition, in which a simple PI-controller is capable of managing zero steady-state error. Nevertheless, under unbalanced condition, the current references would contain an ac-component on top of the dc value in the orthogonal-rotating-coordinates (d-q). A decoupling method is introduced in [8] which uses separate PI-controllers for the positive- and negative-sequences of the compensator reference currents. This technique can improve the steady-state operation of the D-STATCOM. Nevertheless, extraction of the currents positive- and negative-sequences imposes a delay time within the control loop, which adversely affects the transient response and stability of the system.

This paper proposes a closed-loop control technique to remedy the stated issues under the unbalanced condition, in which the inverter output ac-voltage is intentionally combined with negative-sequence component. Consequently, the inverter would be capable of supplying unbalanced currents to the power network. This way, the oscillating component of the load active power as well as its total reactive power is locally compensated by the D-STATCOM. As a result, the three-phase currents drawn from the power network would become balanced and in phase with their respective positive-sequence bus voltages. Unlike conventional control strategies, this paper designs a controller in the stationary-coordinates (α-β) to track the reference signals. Meanwhile, the feedforward path within the suggested controller structure enables the D-STATCOM to track the current references accurately, regardless of uncertainties of the system model. The proposed technique provides faster dynamic response compared to the conventional approaches under unbalanced condition because the suggested controller does not require extracting the signals positive- and negative-sequences within the feedback loop.

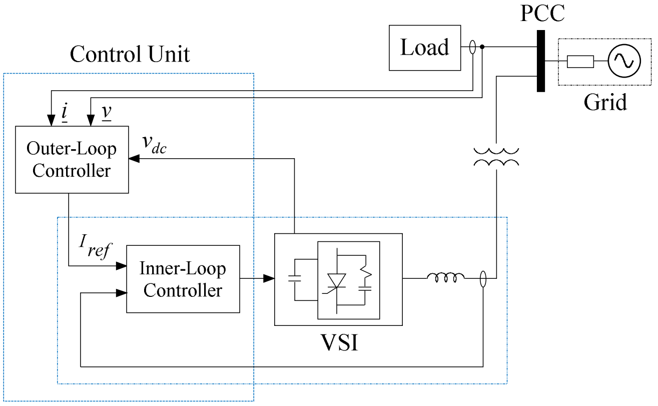

Fig. 1. General block diagram of a closed-loop control for the D-STATCOM

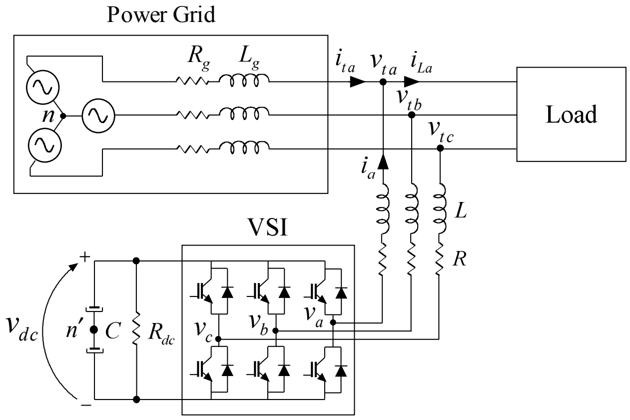

Fig. 2. Circuit diagram of the D-STATCOM

II. SYSTEM DESCRIPTION

Fig. 2 depicts the equivalent circuit of a D-STATCOM. In this figure, v_n and $v_{n'}$ denote the neutral point voltages at the power network and the D-STATCOM sides, respectively. The compensator losses are modeled by a shunt resistance (R_{dc}). The produced high-frequency harmonics due to the PWM operation of the inverter are usually filtered out by using a passive low-pass filter. A well designed low-pass filter presents a high impedance at the fundamental-frequency but a very low impedance at the switching frequency and higher frequencies. Therefore, the low-pass filter is excluded from the equivalent circuit of the D-STATCOM at the fundamental-frequency.

Assuming the three-phase coupling impedances of the D-STATCOM are identical, it can be concluded that the neutral point voltages at both sides are equal (v_n=$v_{n'}$). The system state-space equations in the α-β coordinates can be rearranged by transferring three KVLs of the three-phases along with description of the dc-side capacitor voltage as [3]:

$$\begin{cases} \dfrac{di_\alpha}{dt} = -\dfrac{R}{L}\cdot i_\alpha + \dfrac{1}{L}\cdot(v_\alpha - v_{t\alpha}) \\ \dfrac{di_\beta}{dt} = -\dfrac{R}{L}\cdot i_\beta + \dfrac{1}{L}\cdot(v_\beta - v_{t\beta}) \\ \dfrac{dv_{dc}}{dt} = -\dfrac{1}{C\cdot v_{dc}}\cdot(i_\alpha\cdot v_\alpha + i_\beta\cdot v_\beta) - \dfrac{v_{dc}}{C\cdot R_{dc}} \end{cases} \quad (1)$$

where v_{dc} denotes the dc-side voltage, i_α, i_β, v_α and v_β are the inverter currents and voltages transferred to the α-β coordinates, $v_{t\alpha}$ and $v_{t\beta}$ and the modal components of the load bus voltages. Meanwhile, both v_α and v_β depend on the dc-side voltage as:

$$\begin{cases} v_\alpha(t) = k_m \cdot v_{dc}(t)\cdot m_\alpha(t) \\ v_\beta(t) = k_m \cdot v_{dc}(t)\cdot m_\beta(t) \end{cases} \quad (2)$$

where $m_\alpha(t)$ and $m_\beta(t)$ are modulation functions defined by:

$$\begin{cases} m_\alpha(t) = M_\alpha \sin(\omega_0 t + \delta_\alpha) \\ m_\beta(t) = M_\beta \cos(\omega_0 t + \delta_\beta) \end{cases} \quad (3)$$

in which M_α and M_β are the amplitudes of the modulation functions, and δ_α and δ_β denote the phase differences between the inverter output and the load bus voltages. Furthermore, ω_0 is the angular frequency, and k_m is a constant parameter which depends upon the employed modulation technique.

It should be considered that since the amplitudes and the phase differences of the α and β modal components could be different, the inverter would be able to generate three unbalanced voltages. This way, the compensator could locally supply the oscillatory parts of the load instantaneous active and reactive powers.

III. THE PROPOSED CLOSED LOOP CONTROLLER

A. Dynamically Modification of the Switching Duty Ratios

It is well known that the compensation for the oscillatory component of the load active power by the D-STATCOM would lead to inevitable second-order oscillations on the inverter dc-side voltage [1]. These oscillations would be modulated by the inverter to its ac-side, and consequently, the compensator would inject unwanted third-order harmonic current to the power network. One solution can be raised in which appropriate modification of duty ratios of the switching status is managed to reduce the unwanted generated harmonics. This suggestion can be accomplished by the pulse width modulator. For this purpose, the modified modulation function (MDF) $m'_\alpha(t)$ is defined as:

$$m'_\alpha(t) = [\bar{v}_{dc}/v_{dc}(t)]\cdot m_\alpha(t) \quad (4)$$

in which $\bar{v}_{dc}$ denotes the average value of the dc-side voltage. Replacing $m_\alpha(t)$ in (2) with the MDF defined by (4), the VSI output voltage can be rewritten as:

$$\begin{aligned} v_\alpha(t) &= k_m v_{dc}(t) m'_\alpha(t) = k_m \bar{v}_{dc} M_\alpha \sin(\omega_0 t + \delta_\alpha) \\ &= k_m \bar{v}_{dc}\, m_\alpha(t) \end{aligned} \quad (5)$$

In other words, as long as the dynamically modified duty ratios vary within the range of [0-1], the VSI output voltages would be generated independent of the dc-side voltage oscillations. Similar modification can be made for the β-axis component.

In order to ensure that the modified duty ratios do not exceed the maximum value, the dc-side voltage should always be kept above a certain level. The appropriate level for the dc-side voltage could be calculated according to the rated power

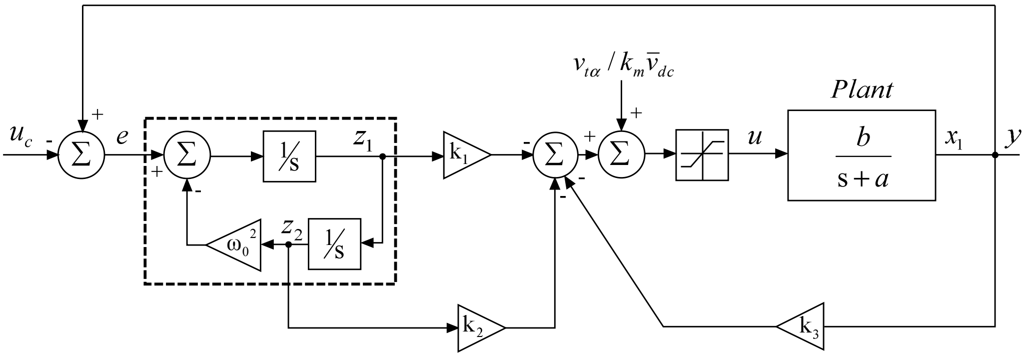

Fig. 3. Block diagram of the proposed state-feedback-based current controller

of the compensator, the employed modulation technique and the coupling inductance value.

B. Current Controller Design

The proposed state-feedback-based current controller is depicted in Fig. 3. The proposed controller consists of two identical units for the α and β axes, which are decoupled according to the first two state-equations given in (1). For the sake of simplicity, the controller design is only illustrated for the α-axis. Referring to the system equations given in (1)-(4), u_c, u, a, b and x_1 denote the input reference (i_α^*), the control input (m_α), the ratio of R/L, the ratio of $k_m \bar{v}_{dc}/L$, and the state-variable (i_α), respectively.

The key point of the proposed structure is the block which is shown within a bold rectangle. This block is based on the internal modal principle [9], and ensures the zero steady-state tracking error to a sinusoidal reference signal. To use the internal modal principle, four extra state-variables (two state-variables per axis, i.e. z_1, z_2 for i_α and z_3, z_4 for i_β) are added to the existing state-variables. The transfer function for the error signal to the reference signal is given by (6), which yields zero steady-state error to a sinusoidal input at the frequency of ω_0.

$$\frac{e}{u_c} = -\frac{k_3 b + (s+a)}{[k_3 b + (s+a)]\cdot(s^2+\omega_0{}^2) + k_1 b s + k_2 b}\cdot(s^2+\omega_0{}^2) \quad (6)$$

The dc-side voltage is controlled by the outer-loop controller using a Fuzzy-based non-linear technique, which is excluded from the Fig. 3. It is also necessary to seek the best locations for the poles of the closed-loop system. This will help to stabilize the system and get the desired dynamic response, reducing consequences of disturbances. In this paper, a linear quadratic regulator (LQR) is used to locate the optimal palaces for the closed-loop system poles by defining a performance function.

C. Extraction of the Compensator Current References

In a three-phase three-wire system, the active and reactive powers of an unbalanced load include both ac ($\tilde{p},\tilde{q}$) and dc ($\bar{p},\bar{q}$) components, where the D-STATCOM can locally supply $\bar{q},\tilde{q}$ and $\tilde{p}$ to the load. Since $\tilde{p}$ is constantly exchanging between the dc-side capacitor and the ac-side of the compensator, the D-STATCOM requires theoretically no external energy source but a small amount of active power is absorbed to keep the dc voltage above a certain level.

In order to extract the appropriate current references, the modified equal current strategy is employed [10]. This way, the compensator reference currents are derived such that the three-phase currents drawn from the power network become balanced, and, lag by φ radian in phase with the respective positive-sequence bus voltages. Aiming at totally compensation for the load reactive power, the phase lag is considered to be zero (φ=0).

IV. CASE STUDY AND SIMULATIONS

Let us consider parameters of a 250-kVAR D-STATCOM, which is experimented in [11]. This case is studied here by simulating both power circuit and the above proposed control technique using PSCAD/EMTDC software. Assume the notations of Fig. 2 are used for the power circuit. The coupling inductance of D-STATCOM (L) is 0.457 mH, and the dc capacitance is equal to 3.4 mF. The power system is a 380-V three-phase system, which has an internal inductance (L_g) of 0.147 mH. An unbalanced load affects the load bus voltage that is applied to the D-STATCOM. The source currents are expected to become balanced by the compensator.

Regarding the control and modulation strategy, the switching frequency was fixed at 3200 Hz. Thus, developing the state-space equations of the D-STATCOM, like those in (1), prepares the system to apply the state gain matrix obtained by the LQR. This forms the closed-loop format that placement of the closed-loop poles are determined as below (delay was also considered):

$$\begin{aligned} \text{poles:}\ \{&\mathrm{z_1,z_2:-729\pm j302,\ \ x_1:-274,} \\ &\mathrm{z_3,z_4:-729\pm j302,\ \ x_2:-274}\} \end{aligned} \quad (7)$$

Initially, the simulated system is operating in a steady-state condition, where the source is supplying unbalanced active and reactive powers to the load as shown in Figs. 4(a)-(b). The mains frequency is 50 Hz. It can be seen that at t=0.04 sec., the proposed state-feedback-based controller comes into effect. The D-STATCOM is aimed at compensating two issues; first, the effects of the load unbalance on the source, and second, supplying the load reactive power. The control technique becomes active using a sudden stepwise change. Figs. 4(a)-(b) show that when the compensator starts balancing

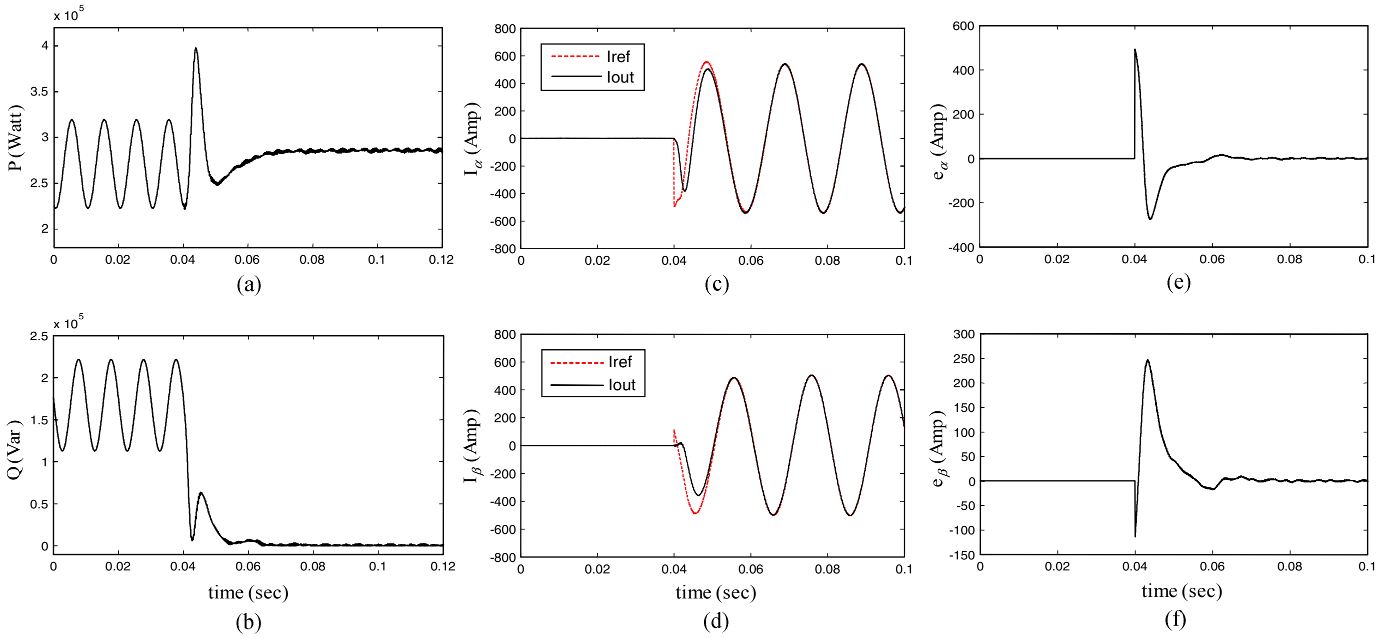

Fig. 4. Simulation results of the proposed state-feedback-based controller operating at $t = 0.4$ sec., (a) reactive power control, (b) active power oscillations control, (c)-(d) tracking the compensator reference currents, (e) (f) the tracking errors.

the source currents, the instantaneous active power drawn from the power network becomes nearly fixed. Also, reactive power approaches zero.

Similarly, Figs. 4(c)–(d) present the transient of the output current waveforms of the D-STATCOM for the α and β axes, respectively. These currents track their respective references, which takes less than one cycle to approach the zero tracking error. Also, Figs. 4(e)–(f) depict tracking errors of the α-β axes currents. Simulation results show that the D-STATCOM remains stable when a transient stepwise change in reactive power is arranged. This confirms that the proposed control technique provides an efficient method to compensate for the load dynamic changes.

V. CONCLUSION

This paper introduces an extended state-feedback-based control technique for the D-STATCOM to compensate for both of the load unbalance and reactive power. The proposed controller performs accurately with a desirable dynamic response to track the reference signals, even if, the employed model has got uncertainties. Since the unbalanced condition imposes the inverter dc-side voltage a dominant oscillation at twice the mains frequency, the inverter duty ratios are dynamically modified appropriately to avoid injection of third-order harmonic current to the power network. The proposed current control technique provides faster response compared to the conventional approaches under unbalanced condition, because there is no need to extract the signals positive- and negative-sequences within the feedback loops. The performed simulation studies by using PSCAD/EMTDC software, confirmed a stable system under transient conditions along with fast tracking response of the reference signals.

REFERENCES

[1] M. T. Bina, M. D. Eskandari, “Consequence of unbalance supplying condition on a distribution static compensator,” IEEE Annual Power Electronics Specialists Conference, PESC, vol. 5, pp. 3900-3904, Jun. 2004.

[2] H. Lassseter, C. Hochgraf, “STATCOM control for operation with unbalanced voltages,” IEEE Transactions on Power Delivery, vol. 13, no.2, pp. 538-544, Apr. 1998.

[3] P. W. Lehn, M. R. Iravani, “Experimental evaluation of STATCOM closed-loop dynamics,” IEEE Transactions on Power Delivery, vol. 13, no. 4, pp. 1378-1384, Oct. 1998.

[4] P. C. Gonzalez, and A. G. Cerrada, “Control system for a PWM-based STATCOM,” IEEE Trans. Power Delivery, vol. 15, no. 4, pp. 1252-1257, Oct. 2000.

[5] C. K. Sao, P. W. Lehn, M. R. Iravani, and J. A. Martinez, “A benchmark system for digital time-domain simulation of a pulse-width-modulated D-STATCOM,” IEEE Trans. Power Delivery, vol. 17, no. 4, pp. 1113-1120, Oct. 2002.

[6] E. Song, A. F. Lynch, and V. Dianavahi, “Experimental validation of nonlinear control for a voltage source converter,” IEEE Trans. Control System Technology, vol. 17, no. 5, pp. 1135-1144, Sep. 2009.

[7] M. Saeedifard, H. Nikkhajoei, and M. R. Iravani, “A space vector modulated STATCOM based on a three-level neutral point clamped converter,” IEEE Trans. Power Delivery, vol. 22, no. 2, pp. 1029-1039, Apr. 2007.

[8] B. Blazic, A. I. Papic, “Improved D-STATCOM control for operation with unbalanced currents and voltages,” IEEE Trans. Power Delivery, vol. 21, no. 1, pp. 225-233, Jan. 2006.

[9] B. A. Francis, and W. M. Wonham, “The internal modal principle of control theory,” Automatica, vol. 12, pp. 457-465, 1976.

[10] R. S. Herrera, P. Salmeron, and H. Kim, “Instantaneous reactive power theory applied to active power filter compensation: different approaches, assessments, and experimental results,” IEEE Trans. Industrial Electronics, vol. 55, no. 1, pp. 184-194, Jan. 2008.

[11] M. Tavakoli Bina, M. D. Eskandari, and M. Panahlou, “Design and installation of a ±250kVAr D-STATCOM for a distribution substation,” Electric Power Systems Research, vol. 73, pp. 383-391, Mar. 2005.