Symmetrical Optimum Design of Compensating Current and DC Voltage Controllers for D-STATCOM

Kittaya Somsai[1], Nitus Voraphonpiput[2] and Thanatchai Kulworawanichpong[1*]

[1]*School of Electrical Engineering, Suranaree University of Technology, Nakhon Ratchasima, Thailand*

[2]*Power Purchase Division, Electric Generating Authority of Thailand, Bangkok, Thailand*

** Corresponding author, e-mail: thanatchai@gmail.com*

Abstract

Distribution static compensator (D-STATCOM) is used for load voltage regulation in distribution system. This paper presents the system modeling and controller design based on symmetrical optimal method for D-STATCOM. The modeling strategy similar to that used for the field-oriented control of three-phase AC machines is employed. In this work, the current and DC voltage decoupling control based on the dq reference frame are determined. The symmetrical optimum method is applied to obtain the parameters of PI controllers. The response of the D-STATCOM current and DC voltage controllers with and without the decoupling are compared and discussed.

Keywords: *D-STATCOM; decoupling control; power distribution system; symmetrical optimum design*

1. Introduction

In a power distribution system, fast load voltage regulation is required to compensate for time varying loads. Controlled reactive power sources are commonly used for load voltage regulation in presence of disturbances. Due to their high control bandwidth, D-STATCOM and STATCOM, based on three-phase pulse width modulation voltage source converters, has been proposed for this application [1-6]. For a fast control, D-STATCOM is usually modeled using the dq frame theory for balanced three-phase systems, which allows definition of instantaneous reactive current and instantaneous magnitude of phase voltages [7]. In addition, the current controller design is developed using a rotating dq frame of reference that offers higher accuracy than the stationary frame of reference [8].

Several literatures on D-STATCOM and STATCOM control concentrate in control of the output current and DC voltage regulation for a given reactive compensating current reference. The current decoupling control based on dq reference frame received considerable attention in [9-11]. A remarkable advance was presented. That is, the d-axis was letting to be coincident with the supply voltage and first prototypal control where active and reactive powers are decoupled was realized. However, since the DC voltage is not always maintained at constant, the idea that the divisible control of the reactive and active current was found to be unattainable. To mitigate the interaction between the active and reactive currents, a feed-forward control loop with reactive current deviations as the input was introduced to compensate for the DC voltage drop [12]. In addition, an alternative approach using a linearized state space model in the D-STATCOM and STATCOM control design was proposed in [13-14].

In this paper, a modeling strategy similar to that used for the field oriented control of three-phase AC machines is exploited. This gives a clear representation of instantaneous load voltage magnitude and D-STATCOM reactive current without any restriction on the dynamics. The D-STATCOM current and DC voltage decoupling control based on the dq reference frame are designed. The symmetrical optimum design is applied to obtain the proportional gain and integral time of PI controllers. The response of the D-STATCOM current and DC voltage controllers with and without the decoupling are compared and discussed. Performance of the propose model and the controller design were verified using computer simulation performed in SIMULINK/MATLAB.

2. Power distribution modeling

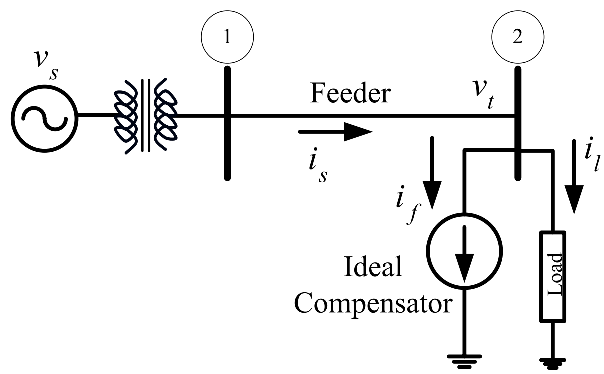


Figure 1. The distribution system with the installed D-STATCOM

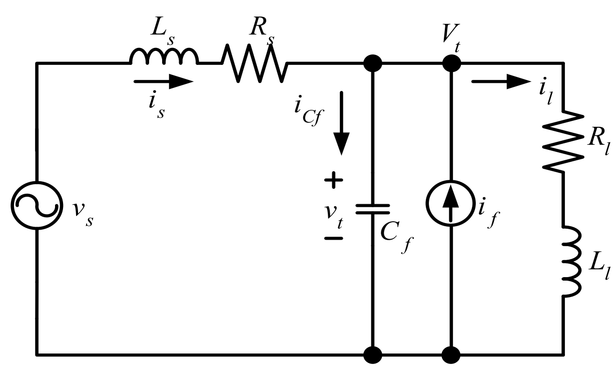


Figure 2. Per-phase equivalent circuit

The system considered here is a simplified model of a load supplied in a power distribution system. D-STATCOM is connected in parallel with a load. The distribution system with an installed D-STATCOM and its per-phase equivalent circuit are shown in Figure 1 and Figure 2, respectively. This system consists of the source modeled as an infinite bus with an inductive source impedance, the load modeled by a series of resistance and inductance, the D-STATCOM modeled as a controllable current source with a coupling capacitor. The coupling capacitor is used as a harmonic filter or a fixed compensation capacitor connected in parallel with the load. In Figure 2, it is assumed that the source, load and D-STATCOM are balanced three-phase systems. The system dynamics are described as:

$$L_s \frac{di_{s,abc}}{dt} = -R_s i_{s,abc} - v_{t,abc} + v_{s,abc} \tag{1}$$

$$C_f \dot{v}_{t,abc} = -i_{l,abc} + i_{s,abc} + i_{f,abc} \tag{2}$$

$$L_l \dot{i}_{l,abc} = -R_l i_{l,abc} + v_{t,abc} \tag{3}$$

Here, $i_{s,abc}$, $i_{f,abc}$, $i_{l,abc}$, $v_{s,abc}$ and $v_{t,abc}$ are vectors consisting of the individual phase quantities denoted in Figure 2, L_l and R_l are the load inductance and resistance, L_s and R_s are the source inductance and resistance, and C_f is the coupling capacitor. Under the assumption that zero sequence components are not presented, (1) – (3) can be transformed to an equivalent two phase system by applying the following transformation:

$$v_{s,xy} = v_{sa} e^{j0} + v_{sb} e^{\frac{j2\pi}{3}} + v_{sc} e^{\frac{j4\pi}{3}} \tag{4}$$

Where the complex $v_{s,xy} \triangleq v_{sx} + jv_{sy}$. This is followed by a rotational transformation:

$$v_{s,dq} \triangleq v_{sd} + jv_{sq} = e^{-j\theta} v_{s,xy} \tag{5}$$

Applying the transformations, (1) – (3) can be rewritten as:

$$L_s \dot{i}_{sd} = -R_s i_{sd} + \omega L_s i_{sq} - v_{td} + v_{sd} \tag{6}$$

$$L_s \dot{i}_{sq} = -R_s i_{sq} - \omega L_s i_{sd} - v_{tq} + v_{sq} \tag{7}$$

$$C_f \dot{v}_{td} = -i_{ld} + \omega C_f v_{tq} + i_{sd} + i_{fd} \tag{8}$$

$$C_f \dot{v}_{tq} = -i_{lq} - \omega C_f v_{td} + i_{sq} + i_{fq} \tag{9}$$

$$L_l \dot{i}_{ld} = -R_l i_{ld} + \omega L_l i_{lq} + v_{td} \tag{10}$$

$$L_l \dot{i}_{lq} = -R_l i_{lq} - \omega L_l i_{ld} + v_{tq} \tag{11}$$

Where $\omega \triangleq d\theta / dt$ and it is a function of time. We choose the *dq* reference frame which is similar to that used for the field-oriented control of three-phase AC machines. Thus, the angle θ used in (5) is defined by $\theta = \tan^{-1}\left(v_{ty} / v_{tx}\right)$. This implies

$$v_{tq} \equiv 0 \rightarrow \dot{v}_{tq} = 0 \tag{12}$$

Defining $\alpha = \theta - \omega_s t$, where ω_s is the system frequency, that is $v_{s,dq} = V_s . e^{-j\alpha}$, where V_s is the magnitude of the supply source voltage. The relative orientation of the vectors $v_{t,dq}$, $v_{s,dq}$ and the reference frame are shown in Fig. 3. The system equations can now be rewritten as:

$$L_s \dot{i}_{sd} = -R_s i_{sd} + \omega L_s i_{sq} - v_{td} + V_s \cos\alpha \quad (13)$$

$$L_s \dot{i}_{sq} = -R_s i_{sq} - \omega L_s i_{sd} - V_s \sin\alpha \quad (14)$$

$$C_f \dot{v}_{td} = -i_{ld} + i_{sd} + i_{fd} \quad (15)$$

$$L_l \dot{i}_{ld} = -R_l i_{ld} + \omega L_l i_{lq} + v_{td} \quad (16)$$

$$L_l \dot{i}_{lq} = -R_l i_{lq} - \omega L_l i_{ld} \quad (17)$$

$$\dot{\alpha} = \omega - \omega_s \quad (18)$$

$$\omega = \frac{-i_{lq} + i_{sq} + i_{fq}}{C_f v_{td}} \quad (19)$$

Where (19) is derived using (12). These should be noted that ω varies with time and is different from ω_s. Since $v_{tq} = 0$, v_{td} represents the instantaneous magnitude of the phase voltages $v_{t,abc}$, while i_{fq} denotes the instantaneous reactive current supplied by the D-STATCOM.

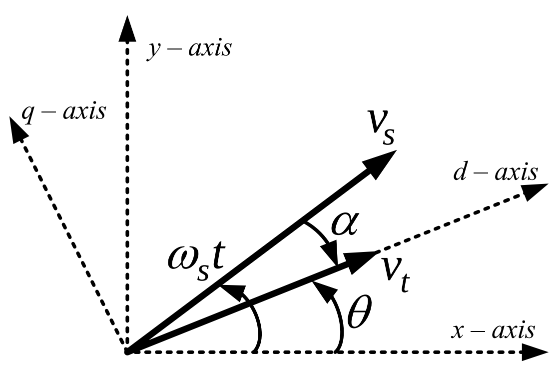


Figure 3. Orientation of reference frames

3. D-STATCOM modeling and control

The circuit diagram and control of the D-STATCOM system are shown in Figure 4. It consists of a three-phase voltage source converter (VSC), interfacing inductors, DC link capacitor, and its control system. The VSC is connected to the network through the transformer and the interfacing inductors which are used to filter high-frequency components of compensating currents. The inductance L_f describes the leakage inductance of the transformer and the interfacing inductors. The switching losses of a converter and the copper loss of the transformer can be represented by R_f. In this paper, the primary control objective is to rapidly regulate the currents to the reference value. A secondary control objective is to keep the DC voltage around a desired value. It is assumed that the dynamics of the D-STATCOM are slower when compared to the switching frequency of the converter [15], therefore the D-STATCOM dynamics can be described as:

$$L_f \dot{i}_{f,abc} = -R_f i_{f,abc} - v_{t,abc} + v_{st,abc} \tag{20}$$

$$C_{dc}\dot{v}_{dc} = -\frac{v_{dc}}{R_d} - v_{st,abc}^T i_{f,abc} \tag{21}$$

Here, v_{dc} is the D-STATCOM DC voltage, v_{st} is the D-STATCOM output ac voltage, i_f is the D-STATCOM output current, v_t is the load voltage, while the subscript "*abc*" implies vectors consisting of individual phase quantities. Parameters in these equations are- C_{dc} DC link capacitance and R_d capacitor leakage resistance. After applying the three-phase to two phase transformation given by (4) followed by the rotational transformation of (5), the D-STATCOM dynamics can be rewritten as:

$$L_f \dot{i}_{fd} = -R_f i_{fd} + \omega L_f i_{fq} - v_{td} + k_p u_d v_{dc} \tag{22}$$

$$L_f \dot{i}_{fq} = -R_f i_{fq} - \omega L_f i_{fd} + k_p u_d v_{dc} \tag{23}$$

$$C_{dc}\dot{v}_{dc} = -\frac{v_{dc}}{R_d} - \frac{3}{2} k_p u_d i_{fd} - \frac{3}{2} k_p u_q i_{fq} \tag{24}$$

Where ω has been previously defined in (19), v_{dc}, i_{fd} and i_{fq} represent the state variables of the D-STATCOM, k_p is a constant value depending on the type of converter and transformer ratio [16], while u_d and u_q are the control inputs.

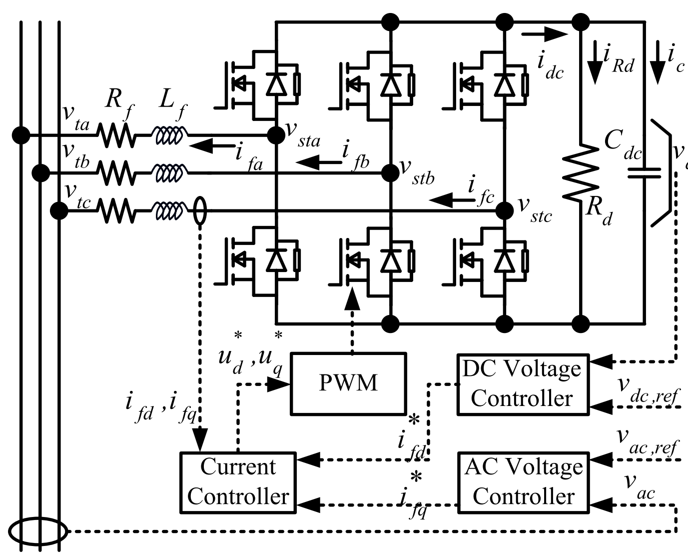


Figure 4. Circuit diagram and control of the D-STATCOM system.

4. Design for compensating current and DC voltage controllers

4.1. Symmetrical optimum design

The PI controllers' parameters depend on the parameters of the open loop transfer function (*i.e.*, natural frequency (ω_0), damping coefficient (ζ), and pole value (p)). In general, ω_0 and ζ characterize the desired system behavior and they are arbitrarily constant, while the location of poles can be chosen. The specific pole locations can be imposed by using supplementary conditions. The conditions for choosing the pole locations refer to the symmetrical optimum method, which simplifies the expressions of the PI parameters. The goal of this scheme is to find the pole locations of the closed-loop transfer function, which satisfy the assumptions given by the symmetrical optimum design around ω_0, for the transfer function of open-loop system.

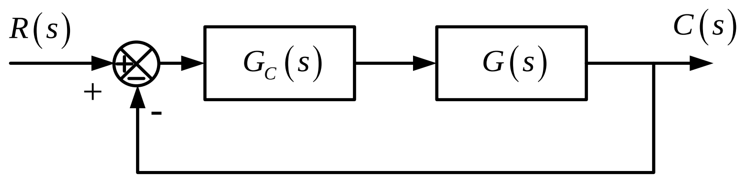


Figure 5. Classical control system.

The symmetric optimum method is suitable for an open-loop transfer function of a third-order polynomial in the denominator. Consider the classical control loop, as shown in Figure 5. The controller is of PI type as described in (25). If the plant includes a delay whose time constant is more than four time as large as the sum of the time constants of the remaining delays ($T_1 > 4T_e$) as described in (26), then the large delay acts, as a first approximation, like an integrator.

$$G_c(s) = k_p \left(\frac{1 + sT_I}{sT_I} \right) \quad (25)$$

$$G(s) = \frac{k_1}{(sT_1 + 1)(sT_e + 1)} \quad (26)$$

The proportional gain and integral time constant of the PI controller can be calculated in the following forms [17, 18]:

$$k_p = \frac{T_1}{2k_1 T_e} \quad (27)$$

$$T_I = 4T_e \quad (28)$$

4.2. Current control strategy

The equations in (22) and (23) are used for designing the D-STATCOM current controller. These equations clearly show that the D-STATCOM output currents are induced by its output voltage modulation. However, the current control of the converter on the synchronously rotating reference frame (*dq*-axis) is a two-input two-output system with cross coupling between the active and reactive currents. To obtain a decouple-like control for the i_{fd} and i_{fq}, (22) and (23) can be modified as:

$$\frac{L_f}{R_f}\dot{i}_{fd} = -i_{fd} + x_d \tag{29}$$

$$\frac{L_f}{R_f}\dot{i}_{fq} = -i_{fq} + x_q \tag{30}$$

Where the cross coupling terms $\omega\frac{L_f}{R_f}i_{fq}$ and $\omega\frac{L_f}{R_f}i_{fd}$ are collected by the actions x_d and x_q, respectively

$$x_d = \omega\frac{L_f}{R_f}i_{fq} - \frac{1}{R_f}v_{td} + \frac{1}{R_f}k_p u_d v_{dc} \tag{31}$$

$$x_d = -\omega\frac{L_f}{R_f}i_{fd} + \frac{1}{R_f}k_p u_q v_{dc} \tag{32}$$

Equation (29) shows that the active current is increasingly induced following the transient in x_d. This is also true for the reactive current in (30). Based on these principles, the control actions x_d and x_q can be expressed as:

$$x_d = k_{p,i}\left(\frac{1+sT_{I,i}}{sT_{I,i}}\right)\left(i^*_{fd} - i_{fd}\right) \tag{33}$$

$$x_q = k_{p,i}\left(\frac{1+sT_{I,i}}{sT_{I,i}}\right)\left(i^*_{fq} - i_{fq}\right) \tag{34}$$

Where the proportional-plus-integral (PI) regulators are used to control the D-STATCOM currents in the present work. Once the control actions x_d and x_q are determined, the D-STATCOM output voltage commands u^*_d and u^*_q in (33) and (34) can be rearranged as:

$$u^*_d = \frac{-\omega L_f i_{fq} + v_{td} + R_f x_d}{k_p v_{dc}} = \frac{v^*_{std}}{k_p v_{dc}} \tag{35}$$

$$u^*_q = \frac{\omega L_f i_{fd} + R_f x_q}{k_p v_{dc}} = \frac{v^*_{stq}}{k_p v_{dc}} \tag{36}$$

The current control structure for the D-STATCOM and the D-STATCOM output current are detailed in Figure 6. Since the D-STATCOM control is based on the VSC scheme, the D-STATCOM output voltage commands can be adjusted by using (35) and (36). In addition, the v_{st} is generated by the VSC with pulse width modulation (PWM) and the u_d^* and u_q^* are the input.

The VSC with PWM can be modeled as $\dfrac{k_p v_{dc}}{sT_d + 1}$, where T_d represents a dead time.

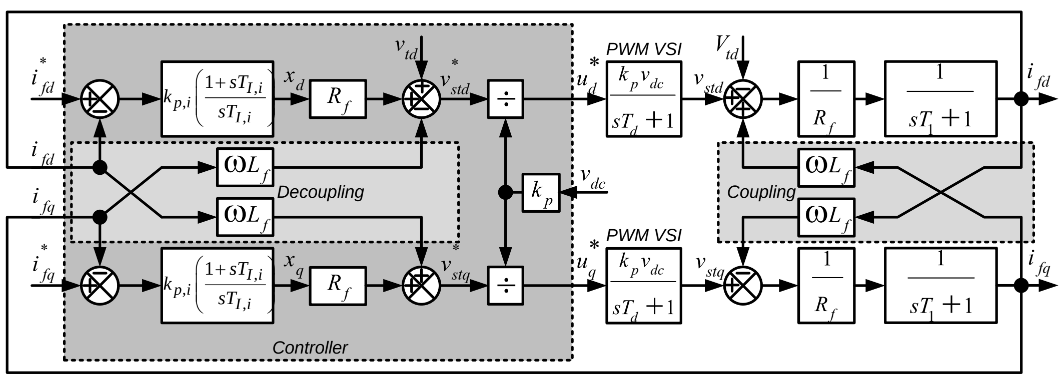


Figure 6. Control structure for the D-STATCOM output current

4.3. PI controller design for the current control

To simplify the design, the power converter dead time (T_d), the time delay of the feedback filter and the sampling period (T_f), and the digital signal processing delay ($T_{\mu p}$) are combined as:

$$T_e = T_d + T_f + T_{\mu p} \tag{37}$$

However, with the switching frequency, f_{sw}, the statistical delay of the PWM converter is $0.25/f_{sw}$, the feedback delay (average) is $0.25/f_{sw}$ and the delay of the discrete-time signal processing is $0.5/f_{sw}$. The sum of the small time constant, T_e, is in the range of $0.75/f_{sw}$ to $1/f_{sw}$ [16]. Therefore, the open-loop transfer function (Figure 6) is given as:

$$G_{o,i}(s) = G_c(s)G(s) \tag{38}$$

$$G_{o,i}(s) = k_{p,i}\left(\frac{1+sT_{I,i}}{sT_{I,i}}\right)\left(\frac{1}{sT_1+1}\right)\left(\frac{1}{sT_e+1}\right) \tag{39}$$

Where the proportional gain, $k_{p,i}$, and integral time, $T_{I,i}$, of PI controllers can be obtained by the symmetric optimum method in (27) and (28).

4.4. DC link voltage control

The secondary control objective is to keep v_{dc} around its reference. This objective cannot be achieved directly by u_d through (24) as there might be possibility of i_{fd} going to zero during a transient. However, the v_{dc} can be regulated indirectly by controlling i_{fd}. For designing the DC voltage controller, (24) is used. Although, the v_{dc} can be controlled by i_{fd}, i_{fq} still affects v_{dc} as there exists the term of $u_q i_{fq}$ in (24). To eliminate this effect, the decouple control like those of the current control is also applied. To obtain the decouple control for v_{dc}, (24) can be modified as:

$$R_d C_{dc} \dot{v}_{dc} + v_{dc} = -x_{dc} \tag{40}$$

Where the coupling term $u_q i_{fq}$ is included in x_{dc} as

$$x_{dc} = \frac{3}{2} k_p R_d \left(u_d i_{fd} + u_q i_{fq} \right) \tag{41}$$

Equation (40) shows that v_{dc} is increased following the transient with negative x_{dc}. Based on this principle, the control action x_{dc} can be expressed as:

$$x_{dc} = -k_{p,v} \left(\frac{1 + sT_{I,v}}{sT_{I,v}} \right) \left(v_{dc}^* - v_{dc} \right) \tag{42}$$

Where the proportional-plus-integral (PI) regulators are used to control the DC voltage in the present work. Since the control action x_{dc} is determined, the D-STATCOM active current command i_{fd}^* in (41) can be rearranged as:

$$\left(\frac{x_{dc}}{\frac{3}{2} k_p R_d} - u_q i_{fq} \right) \left(\frac{1}{u_d} \right) = i_{fd}^* \tag{43}$$

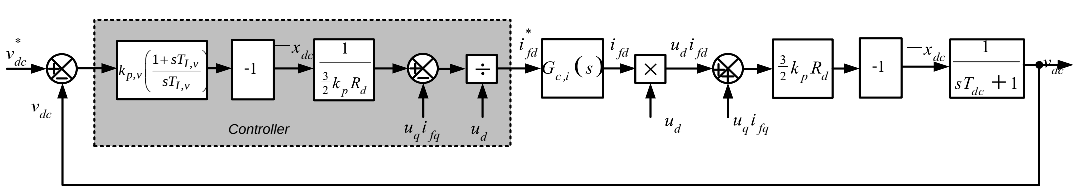


Figure 7. DC voltage control structure and the D-STATCOM DC voltage

The DC voltage control structure and the D-STATCOM's DC voltage are demonstrated in Figure 7. The i_{fd}^{*}, accounting for the DC voltage regulation, can be generated by the DC voltage controller with the DC voltage deviation as the input. The i_{fd}^{*} is used as the input of the current control, $G_{cl,i}(s)$, then, the controlled active current results in the DC voltage which enables the DC voltage control.

4.5. PI controller design for the DC link voltage control

In Figure 7, the control loop is a cascade control in which the DC voltage control is a main control loop and the current control is an auxiliary control loop. The main control loop is superimposed on the auxiliary control loop. This means that the current control is substantially faster than the DC voltage control. The current control is adjusted in conformity with the symmetrical optimum and then its action is a third-order delay. However, to simplify the overall behavior of the controlled system relevant to the superimposed loop, the current control loop can be replaced by a first-order delay [17]. Therefore, the transfer function of the current control loop can be simplified as:

$$G_{cl,i}(s) = \frac{1}{sT_{ei} + 1} \tag{44}$$

Where T_{ei} is an equivalent time constant of the current control loop. The equivalent time constant for the symmetrical optimum control loop is defined by $T_{ei} = 4T_e$ [17] where T_e is defined in (37). To simplify this design, T_d, T_f, $T_{\mu p}$ and T_{ei} must be combined as:

$$T_v = T_d + T_f + T_{\mu p} + T_{ei} \tag{45}$$

Hence, the open-loop transfer function as shown in Fig. 7 is given as:

$$G_{o,v_{dc}}(s) = G_c(s)G(s) \tag{46}$$

$$G_{o,vdc}(s) = k_{p,v}\left(\frac{1 + sT_{I,v}}{sT_{I,v}}\right)\left(\frac{1}{sT_{dc} + 1}\right)\left(\frac{1}{sT_v + 1}\right) \tag{47}$$

Where the proportional gain, $k_{p,v}$, and integral time, $T_{I,v}$, of the PI controllers can be obtained by the symmetric optimum method in (27) and (28).

Table 1. Parameters of the power distribution system and the D-STATCOM

The distribution power system parameters	
The nominal source voltage (V_s)	12.81 *kV*
The desired load voltage magnitude (v_{td}^*)	11.00 *kV*
The source resistance and inductance (R_s and L_s)	1 Ω and 10 *mH*
The load resistance and inductance (R_l and L_l)	10 Ω and 10 *mH*
The system frequency (f_s)	50 *Hz*
The D-STATCOM parameters	
The interfacing resistance and inductance (R_f and L_f)	0.1 Ω and 10 *mH*
The coupling capacitor (C_f)	50 μF
The constant value of converter (k_p)	0.55
The DC link voltage (v_{dc})	30 *kV*
The DC link capacitance (C_{dc})	200 μF
The capacitor leakage resistance (R_d)	61.273 $k\Omega$
The switching frequency (f_{sw})	10 *kHz*

5. Simulation results and discussion

The parameters of the power distribution system and the D-STATCOM used to validate the proposed models and control approaches are shown in Table 1. Given that $T_e = 0.0001$, the PI controller's parameters of the current control can be obtained as $k_{p,i} = 500$ and $T_{I,i} = 0.0004$. Similarly, when $T_v = 0.0005$, the PI controller's parameters of the DC voltage control as in Figure 7 can be calculated as $k_{p,v} = 12,247.4$ and $T_{I,v} = 0.002$.

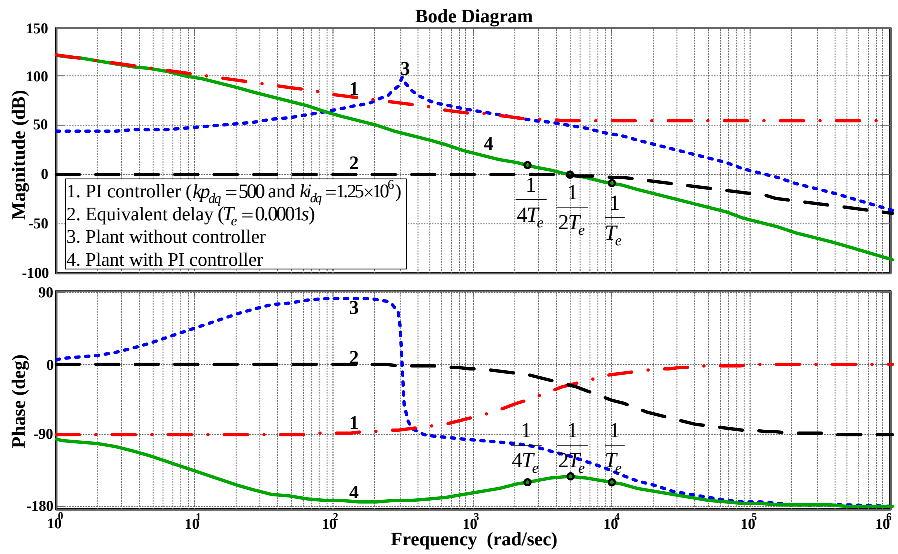


Figure 8. Bode diagram of compensating current control loop

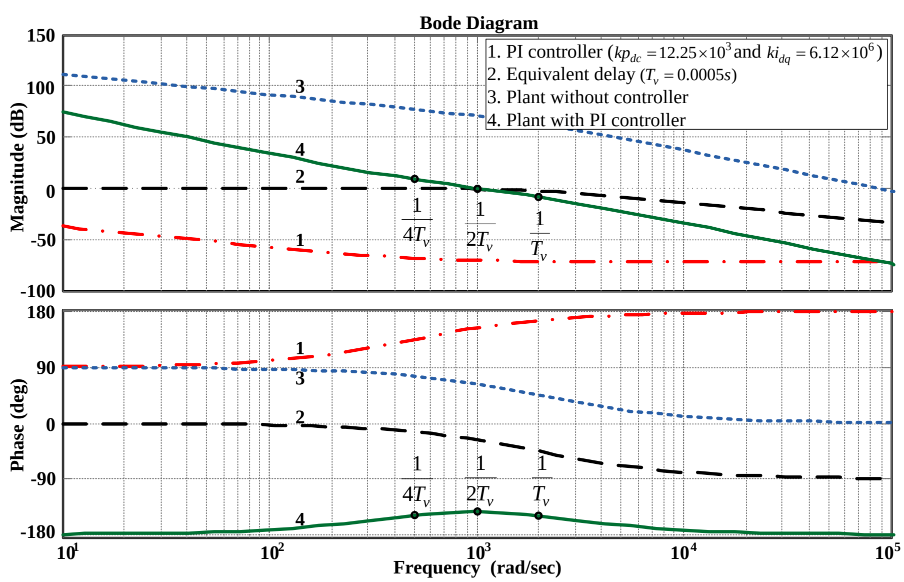
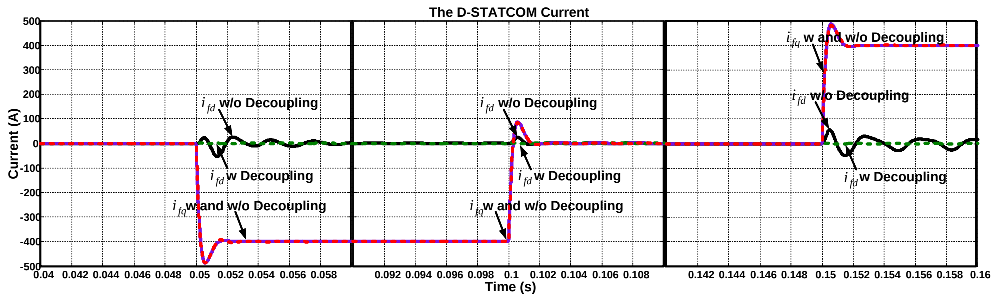
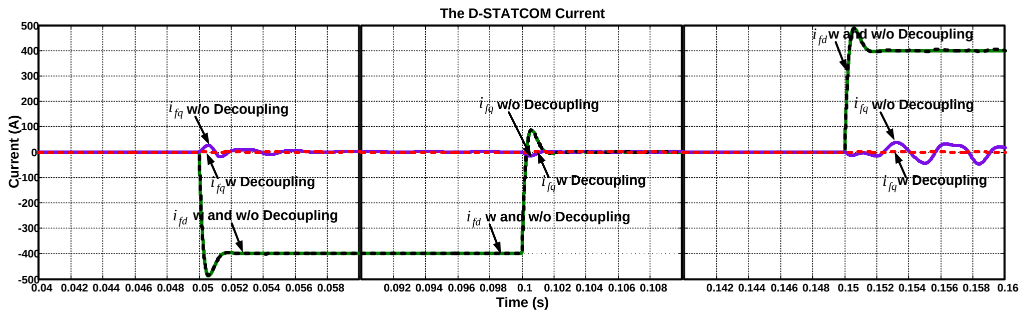


Figure 9. Bode diagram of DC voltage control loop

It is to clarify the concept of symmetrical optimum. Figure 8 and 9 shows the frequency characteristics (bode diagram) of the individual system elements in the compensating current and the DC voltage control loop, respectively. Line 4 in Figure 8 trace for the modulus of the open-loop transfer function of the current control which shows symmetry of the corner points $0.25/T_e$ and $1/T_e$ with respect to the gain crossover frequency $0.5/T_e$ on the 0 dB line. Meanwhile, line 4 in Figure 9 trace for the modulus of the open-loop transfer function of the DC voltage control which shows symmetry of the corner points $0.25/T_v$ and $1/T_v$ with respect to the gain crossover frequency $0.5/T_v$ on the 0 dB line. If the control loop is adjusted in accordance with the symmetrical optimum, the behavior is dependent on the sum of the time constants of the small delays in the control loop.



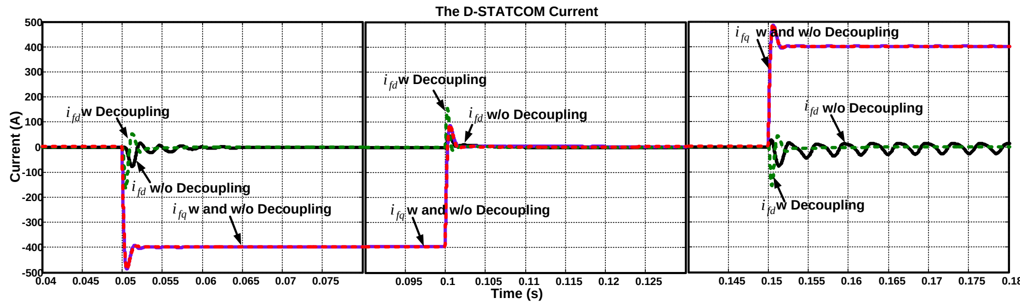
(a) Step changes in the reference reactive current.



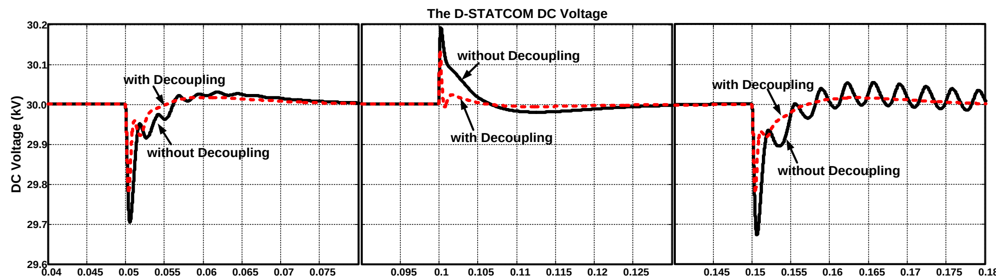
(b) Step changes in the reference active current.

Figure 10. Response of the current controller with and without the decoupling to step changes in the reference D-STATCOM currents

Effectiveness of the D-STATCOM model and the controllers designed above were verified through computer simulation performed by using SIMULINK/MATLAB. The current and DC voltage controllers with and without the decoupling are compared. To study the current control, it is noted that the v_{dc} is kept constant. Figure 10 compares the response of the current controller with and without the decoupling to step changes in the reference D-STATCOM currents, i.e. i_{fd}^* and i_{fq}^* from 0 (A) to -400 (A), -400 (A) to 0 (A) and 0 (A) to 400 (A). As can be seen in the figure, the current controller with the decoupling gives the best dynamic response. The decoupled current controller also gives smaller oscillation in the i_{fd} when step changes in the i_{fq}^* occur as shown in Figure 10(a). Similarly, with the step changes in the i_{fd}^*, the current controller with the decoupling gives smaller oscillation in the i_{fq} as shown in Figure 10(b). However, the responses of the i_{fd} and i_{fq} to the step change in its reference have the same response for with and without the decoupling.



(a) D-STATCOM currents to step changes in the reference reactive current.



(b) DC voltage to step changes in the reference reactive current.

Figure 11. D-STATCOM currents and the DC voltage to step changes in the reference reactive current

For the DC voltage control, the DC voltage regulation during to step changes in the i_{fq}^* is investigated. Figure 11(a) compares the response of the D-STATCOM's currents for both current and DC voltage controllers with and without the decoupling to the step changes in the i_{fq}^* from 0 (A) to -400 (A), -400 to 0 (A) and 0 (A) to 400 (A). Although, the response of the i_{fq} for the controller with and without the decoupling is the same, the controller with the decoupling gives smaller oscillation and higher overshoot in the i_{fd}. The response of the v_{dc} to step changes in the i_{fq}^* for the controllers with and without the decoupling are shown in Figure 11(b). Using the controllers with the decoupling effect, the response of the v_{dc} gives smaller settling time and also smaller overshoot. In addition, the controllers without the decoupling gives oscillation in the v_{dc} for these step changes in the i_{fq}^* from 0 (A) to -400 (A) and 0 (A) to 400 (A). In comparison, the results show that the controller, i.e. the compensating current and DC voltage controllers with the decoupling gives a better performance in the transient states.

6. Conclusion

This paper proposed the system modeling and controller design of compensating current and DC voltage control of D-STATCOM. The modeling strategy similar to that used for the field oriented control of three-phase AC machines is used. The D-STATCOM currents and DC voltage decoupling control based on the *dq* reference frame are used. The symmetrical optimum method is applied to obtain the proportional and integral gains of the PI controllers. The compensating current controller with and without the decoupling and the DC voltage controller with and without decoupling term $u_q i_{fq}$ are compared. In comparison, the simulation results showed that the controllers, *i.e.*, current controller and DC voltage control with the decoupling gives a better performance in transient states.

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Authors

Kittaya Somsai

Kittaya Somsai received the B.Eng degree in Electrical Engineering from Rajamangala University of Technology Thanyaburi (RMUTT) and the M.Eng degree in Electrical Engineering from King Mongkut's Institute of Technology North Bangkok (KMITNB), THAILAND in 2003 and 2005 respectively. He is currently working toward the Ph.D. degree. He is currently researching on Power System Control, Custom Power Device (CPD) and Flexible AC Transmission Systems (FACTS).

Nitus Voraphonpiput

Nitus Voraphonpiput received his B.Eng, M.Eng and Ph.D.Eng in Electrical Engineering from King Mongkut's Institute of Technology North Bangkok (KMITNB), THAILAND in 1993, 1998 and 2007 respectively. He is an engineer in charge of Power Purchase Agreement Division, Electricity Generating Authority of Thailand (EGAT). His current research interests on Power System Control and Flexible AC Transmission Systems (FACTS).

Thanatchai Kulworawanichpong

Thanatchai Kulworawanichpong is an associate professor of the School of Electrical Engineering, Institute of Engineering, Suranaree University of Technology, Nakhon Ratchasima, THAILAND. He received B.Eng. with first-class honour in Electrical Engineering from Suranaree University of Technology, Thailand (1997), M.Eng. in Electrical Engineering from Chulalongkorn University, Thailand (1999), and Ph.D. in Electronic and Electrical Engineering from the University of Birmingham, United Kingdom (2003). His fields of research interest include a broad range of power systems, power electronic, electrical drives and control, optimization and artificial intelligent techniques. He has joined the school since June 1998 and is currently a leader in Power System Research, Suranaree University of Technology, to supervise and co-supervise over 15 postgraduate students.