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Generation of Voltage Reference Signal in Closed-Loop Control of STATCOM

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***Abstract*—Power theories are used to develop reference signals for FACTS applications such as voltage regulation and/or power factor correction. These signals are generally generated in current waveforms that are either absorbed or injected to a power system. Current oriented modulations (e.g. hysteresis strategy) are basically fast and simple, but variable high switching frequencies lowers efficiency of the controllers. Since high power applications need very high efficiency, fixed low switching frequency is preferred. This can be achieved if reference voltages are available. Voltage references can be modulated using sinusoidal PWM or space vector modulation (SVM). This paper proposes a closed-loop control for voltage regulation using the average model of STATCOM. The whole system is simulated to verify the suggested method, including the average model along with the engaged control and modulation techniques.**

***Keywords*—PWM, closed-loop control, fixed switching frequency.**

I. INTRODUCTION

COMPENSATING references are used to be derived out in the form of current waveforms using power theory. Simple and fast current-controlled strategies can be employed to force the exact current waveforms trace the references. However, this is involved in high switching frequencies (i.e. high power losses), which is significantly undesirable in power system applications. At the same time, other issues are also emerged due to the variable high switching frequencies such as electromagnetic interference (EMI), leading to inappropriate operation of the compensator.

Modulating voltage references can be one solution to achieve fixed (and low) switching frequency. Various modulating techniques can be used such as sinusoidal PWM and space vector modulation (SVM). A fixed frequency enables many power applications to lower their switching losses. Nevertheless, unlike the current reference, the voltage reference cannot be generated easily from the current references. Different solutions have been proposed in [1]-[3] to tackle this issue in which certain problems, like long delays, will appear in practice.

This paper uses the average model of STATCOM introduced in [4]-[8] to generate reference voltages. Average model is a continuous model that is obtained from the discontinuous state space model of STATCOM. Inputs to the average model are the switching duty ratio information together with voltages of power system bus that is applied to STATCOM. The out-coming signals from the average model are the three-phase AC voltages of the AC/DC converter output. These reference voltages are then modulated using the carrier-based PWM technique to generate switching pulse train for the converter. Further, it is assumed that of the applied power system voltages are going to be regulated using STATCOM. Thus, a closed-loop control is arranged in which the model of the main plant provides the reference voltages. The whole system is simulated with SIMULINK, including the average model, the modulator and the controller. Simulations confirm the effectiveness of the average model in generation of reference voltages. Also, the closed-loop control can be simply designed, which provides fast and accurate voltage regulation for the power system bus.

II. THE PROPOSED CLOSED-LOOP CONTROL

Figure 1 shows the proposed closed-loop control of STATCOM in which three main parts contribute to the generation of switching pulse train for the AC/DC converter. These are the average model, the PI controller and the PWM modulator.

A. Average model of STATCOM

In brief, state-space model of STATCOM includes discontinuous switching functions. Figure 2 illustrates an AC/DC converter that is connected to a power system. State space equations of this equivalent system can be developed. Then, the average operator is applied to the obtained state space equation. The averaging integral is taken place during an averaging period which is smaller than the switching frequency in general. The averaging technique ignores high frequency ripples, and produces a continuous state-space model as below [4], [8]:

$$\dot{\mathbf{X}}_a(t) = [\mathbf{A}_0 + \sum_{k=a,b,c} \mathbf{A}_k (2D_k(t) - 1)]\mathbf{X}_a(t) + \mathbf{b}\mathbf{u}(t) \qquad (1)$$

Where $\mathbf{X}_a(t)$ is the average state vector, $D_a(t)$, $D_b(t)$ and $D_c(t)$ are three-phase duty ratios, $\mathbf{A}_0$, $\mathbf{A}_a$, $\mathbf{A}_b$, $\mathbf{A}_c$ and $\mathbf{b}$ are fixed matrices that include STATCOM's parameters and

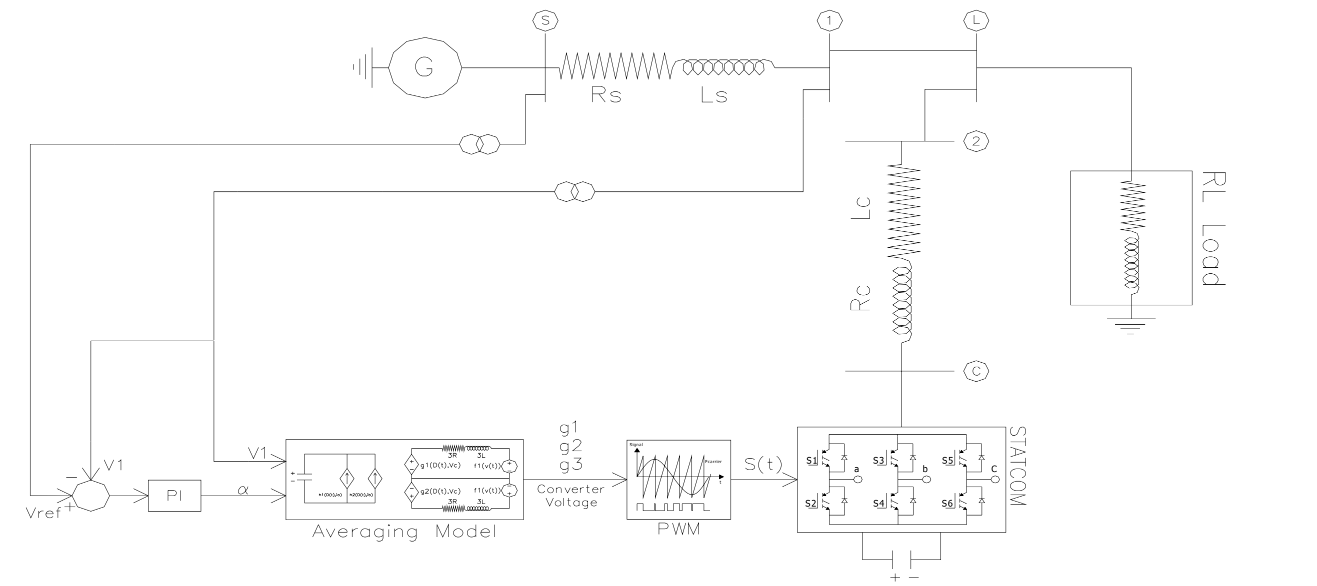

Figure 1: The proposed closed-loop control of STATCOM that contains three main blocks; average model, controller and modulator.

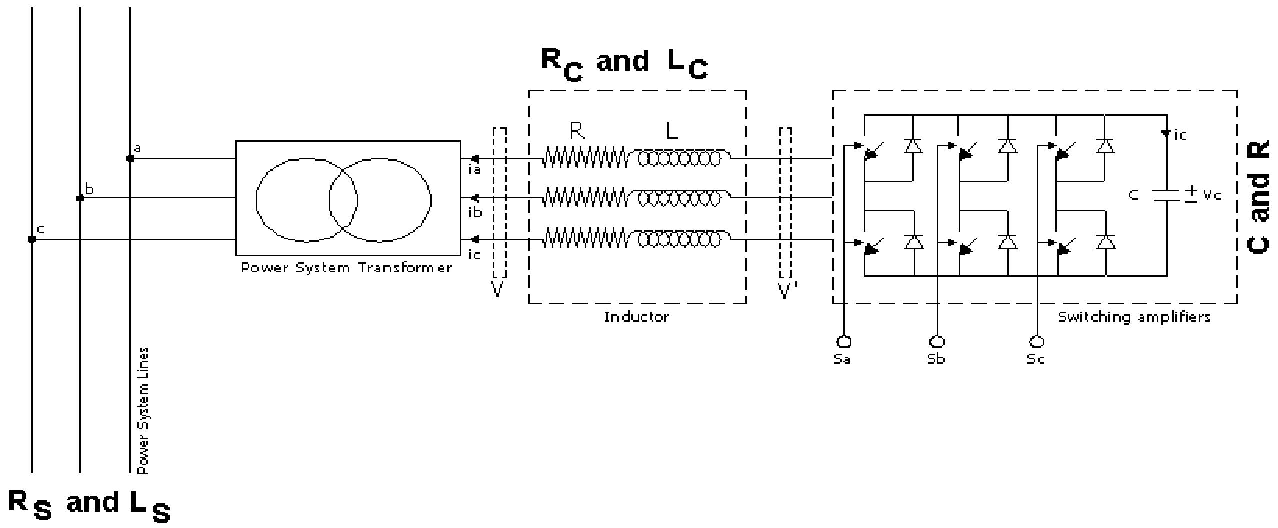

Figure 2: The AC/DC converter connected across a power system is used for deriving the state space equations.

$\mathbf{u}(t)$ is the three-phase applied voltages [4], [8]. State-space model (1) is described with block 1 in Fig. 1 in which inputs include duty ratios as well as the applied three-phase voltages. Also, the output shows three-phase converter AC voltages. Duty ratios depend on the phase difference between the converter AC voltages and the applied voltages.

B. The PI controller

Since voltage regulation is considered as the principal objective of STATCOM, the applied voltages are compared with the desirable reference for the power system. A PI controller is designed to provide the angle α that is basically represents the phase difference between the converter AC voltages and the system applied voltages. This process is shown in Fig. 1, which starts the closed-loop by monitoring the power system voltages.

This generated angle together with the voltage of the load-terminal is applied to the average model expressed by (1). The average model simulates the STATCOM behavior, and generates the three-phase output reference voltages that have to be modulated by the AC/DC converter. Conventionally, reference waveforms are the converter *currents* that flow into the power system. Since the average model makes three-phase output *voltages* of the converter available as the reference, a carrier-based PWM technique or space vector modulation (SVM) can be used in order to synthesize the references.

C. Modulator

Outcomes of the average model (g_1, g_2 and g_3 are the converter voltages) enter the modulation block in order to generate pulse train for the converter. Unlike current-controlled modulation techniques (e.g. hysteresis method), the converter voltages can now be modulated using a fixed switching frequency. This presents a crucial advantage of lower switching losses to the power system applications. Note that lower power losses is vital for high power

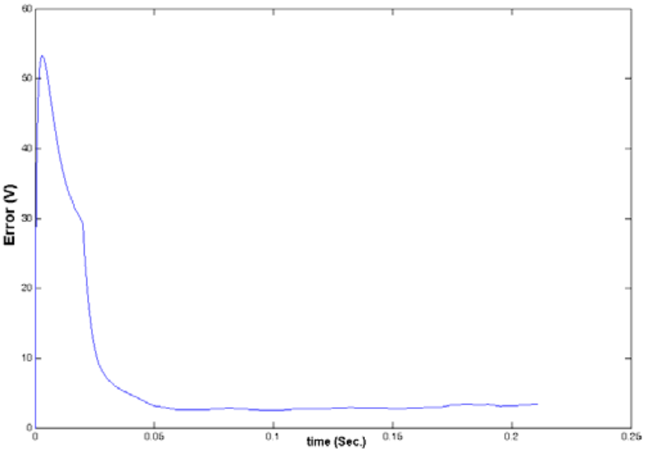

Figure 3: The input to the PI controller, which is the difference of the PCC voltage from the desirable value.

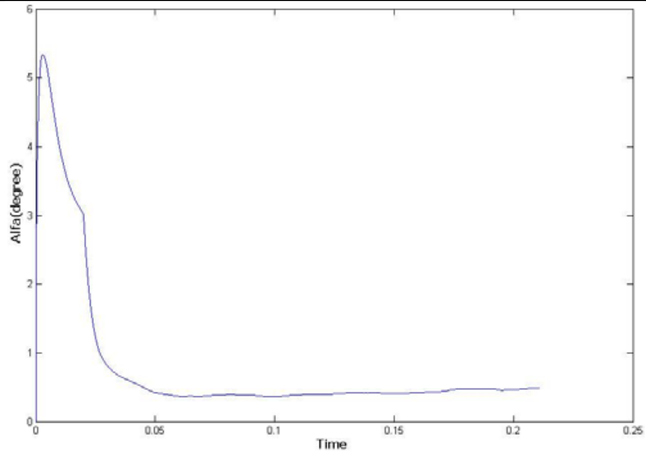

Figure 4: The output of the PI controller, which is the phase difference between the PCC voltage and the converter output voltage.

applications because even one percent power losses costs highly to the power systems.

The modulator is a carrier-based PWM that uses a 5 kHz ramp carrier that is compared with the generated voltage references out of the average model. The resultant switching pulse train is applied to the AC/DC converter. The converter is then connected to the power system through an equivalent inductance, completing the closed-loop of the whole suggested control technique. The modulator is shown by the third block in Fig. 1.

D. Closed-loop control

The switching pulse train for the three-phase converters is then applied to the STATCOM. Operation of the compensator will either inject or absorb reactive current to the point of common coupling (PCC). Hence, the PCC voltage will change, where the PI controller sense these variations. Thus, the described loop can be performed repeatedly until the PCC voltage approaches the desirable reference value.

III. Closed-loop simulation

To verify the suggested algorithms, a cascaded topology is simulated with MATLAB. The load is inductive, consisting of 1kVAr reactive power along with 1kW active power. The switching frequency is fixed at 5 kHz using a carrier-based PWM technique. To show the effectiveness of the engaged average model the outcomes of the closed-loop control is described. Table 1 describes the parameters related to the power system and STATCOM as shown in Fig. 2.

A. PI controller

Starting from the PI controller, the input to the controller is the voltage error. Figure 3 shows the difference between the PCC voltage and the desirable reference voltage. This picture shows that the absolute voltage difference is about 5V after about 0.25 Sec. Since the PI parameter is chosen such that the integral parameter is small, then the error will approach zero in longer terms.

The outcome of the PI controller is the phase difference between the PCC and the fundamental converter output voltage (α). Figure 4 presents the resultant angle α. It can be seen from this picture that α varies in a small region like the explained theory in [2]. This shows the operation of STATCOM in an inductive mode to regulate the voltage of the PCC.

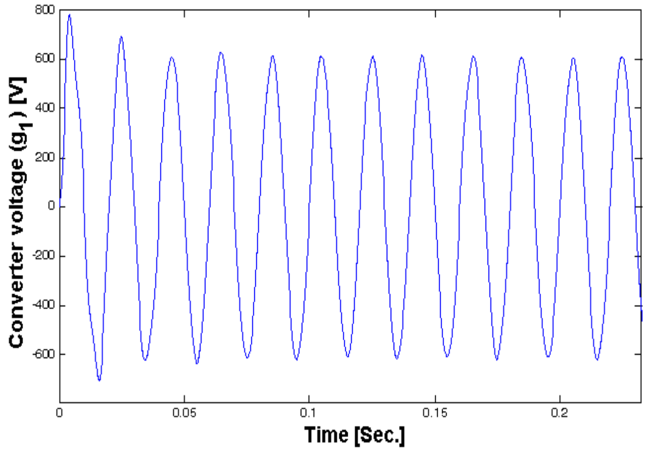

Figure 5: The output of the average model related to one phase (g_1), showing the output voltage of the converter.

TABLE 1: THE SIMULATION PARAMETERS THAT ARE USED IN SIMULINK ENVIRONMENT.

Parameters of the power system and STATCOM shown by Fig. 2.	
Rs	1 Ω
Ls	10^{-3} H
Rc	0.06 Ω
Lc	10^{-3} H
R	10^{6} Ω
C	10^{-3} F

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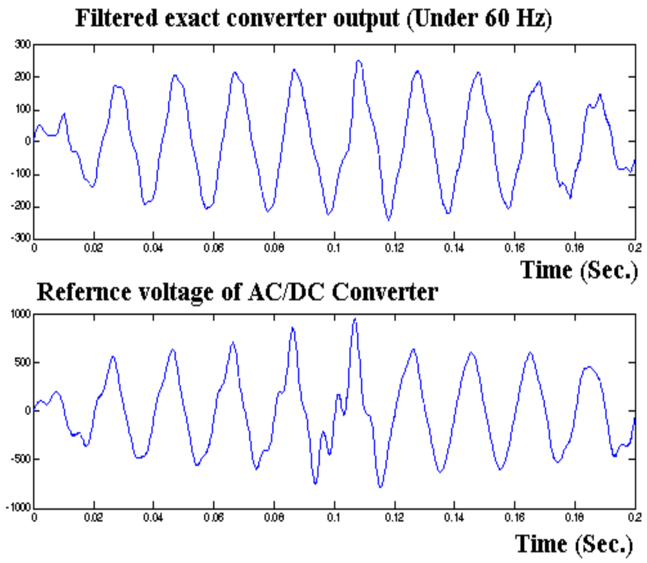

Figure 6: The filtered exact converter output together with the output of the average model.

B. *Average model*

The PCC voltage along with the angle α out of the PI controller is now being applied to the average model. The model performs required analysis based on (1) (the provided equivalent electrical circuit in Fig. 1), resulting in three output voltages of the AC/DC converter. These are the needed references, which the function g_1 is typically shown by Fig. 5 for one phase. The phase and magnitude of these references are varied by the average model when the two inputs to the model are changed.

Considering the discussed control algorithm, Fig. 6 shows the converter output reference and the exact modulated outcome of the AC/DC converter under the closed-loop operation. It can be seen that small differences appears between the two waveforms.

C. *Modulator*

While the reference voltage generated by the average model is distorted in some parts, the filtered exact output of the converter remains smooth as shown by Fig. 6. This is basically expected from the carrier-based PWM, which the switching signals are applied to the converters every 200 µs. In fact, all changes that occur faster than 200 µs cannot be seen by the PWM modulator. It should be noted that elimination of these variations helps the compensator to ignore high frequency oscillations, enhancing the harmonic performance of STATCOM.

D. *Closed-loop control*

Let us take a look into the performance of the closed-loop control by examining the resultant powers. Since the principal goal of the STATCOM is to regulate the load-terminal voltage, the compensator has to work on reactive power. Although power factor correction also works on reactive power control, it is different from voltage regulation applications. In fact, one can expect power factor improvement under voltage regulation closed-loop control, but the compensator is unable to adjust both objectives. Hence, the closed-loop control, shown by Fig. 1, is aimed

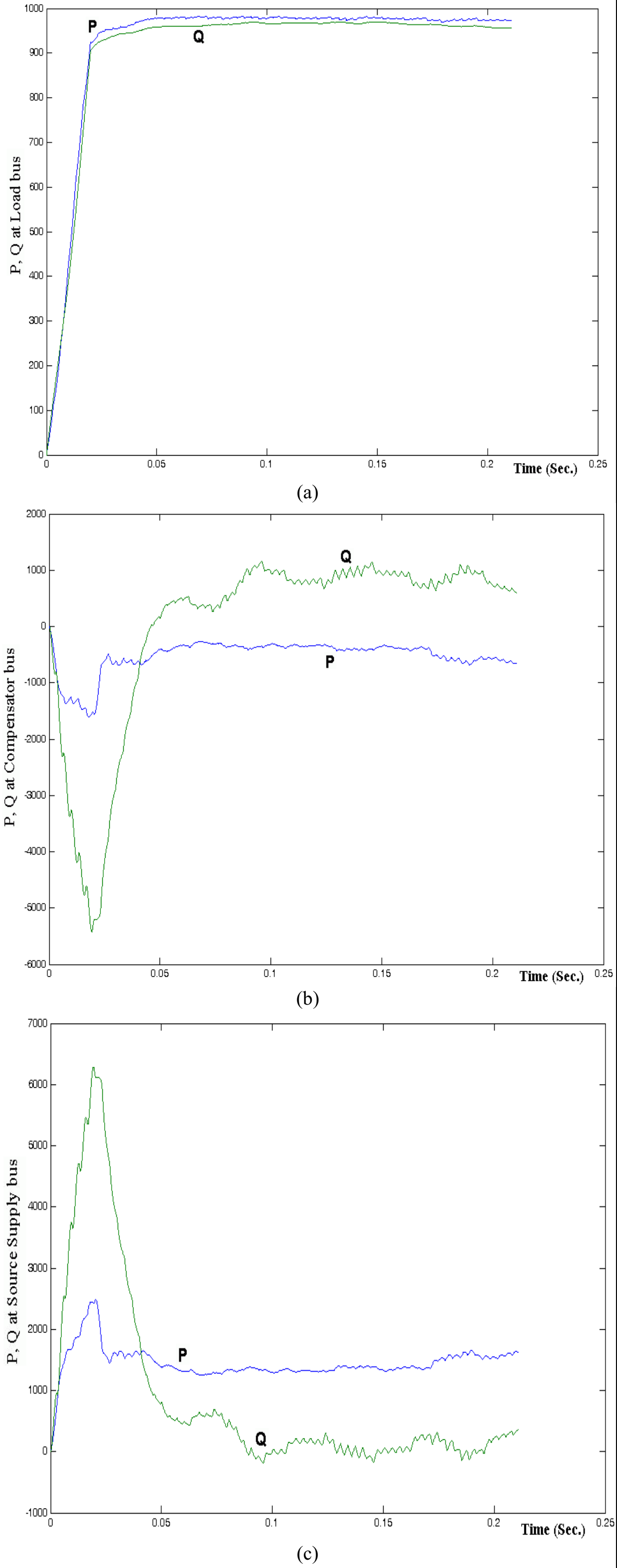

Figure 7: Active and reactive power of (a) the load, (b) the compensator (STATCOM), and (c) the source after compensation.

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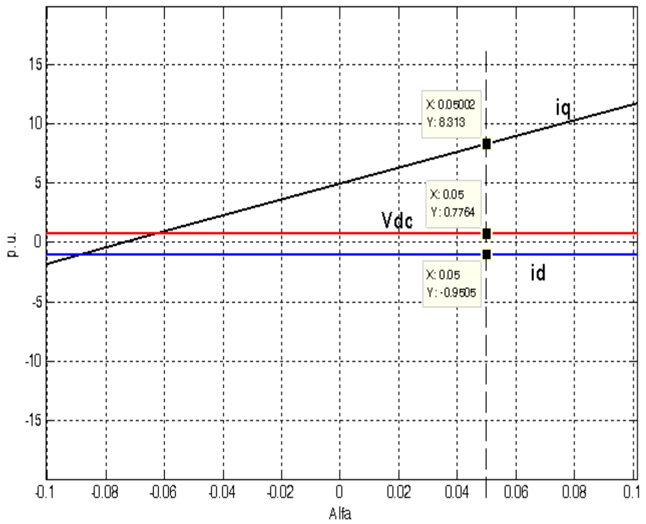

Figure 8: The steady state operating points of STATCOM that is obtained by varying α.

at finding a steady state operating point that keeps the load-terminal voltage close to a desirable value.

Considering above points and starting from the load powers shown in Fig. 7(a), both active power and reactive power are equal to about 1 kVA. Moving to Fig. 7(b), the active power supplied by the compensator is about zero. This is expected because the compensator is performing voltage regulation. Active power of STATCOM, however, has got a small value related to the power losses of the compensator. Reactive power of STATCOM is approaching about 1 kVAr.

Regarding the source powers, it supplies active power to the load as well as the compensator for its power losses. This can be observed from Fig. 7(c) that the source active power is slightly bigger than 1 kW. At the same time, the source reactive power is about 0 kVAr, which is equal to the sum of the load and the STATCOM reactive power. Thus, the regulation is taken place, while the source reactive power is small, but nonzero. This confirms the earlier discussion on power factor correction and voltage regulation relationship.

E. Discussion

To put the result of the closed-loop control on a firmer basis, the steady state operating points of STATCOM is obtained for a given angle α based on the model presented in [2]. Parameters of STATCOM are listed by Table 1. Then, the angle α is varied to find the state variables of the employed model, namely reactive current i_q, active current i_d and capacitor DC voltage V_{dc}. A program is developed using MATLAB, which plots i_q, i_d and V_{dc} in steady state versus α. The outcome of the software is shown in Fig. 8, and could be a basis for comparing the results of the closed-loop control based on the average model with those of the developed model in [2]. Both simulations are approaching to a certain steady state operating point that basically can be regarded as a confirmation of the correctness of the employed closed-loop control technique.

IV. Conclusion

This paper proposes a closed-loop control technique to generate three-phase reference voltages for the converter. Unlike the conventional methods, an average model together with a PWM modulating scheme is employed to trace the desirable reference currents that are normally available. The average model is programmed and simulated with MATLAB, and is applied to the closed-loop control in order to produce reference voltages. For a sinusoidal reference waveform, magnitude and phase of the reference voltage is required. This is principally done by the model state space representation. In fact, the state space model along with the averaging technique provides significantly fast approach in compensation technique. The aim of the closed-loop control is voltage regulation. This is managed by comparing the load-terminal voltage with a desirable reference, and applying to a PI controller. The outcome is then entered to the average model, which introduces reference voltage for the modulator. Then, the modulator produces a pulse train for the AC/DC converter of STATCOM. The whole loop is simulated with SIMULINK. Simulations confirm that the closed-loop control operate properly.

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