Voltage Control of the SVM-Modulated STATCOM Using the Average Model

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***Abstract*—Reference signals are generally generated for various applications in current waveforms, including active and reactive power control, voltage regulation and unbalance compensation. Current modulators (e.g. hysteresis method) are dynamically fast and simple to implement. However, variable high switching frequencies result in lower efficiency compared to other modulators. In the mean time, if references are available in voltage waveforms, then higher efficiencies are achievable through much lower fixed switching frequencies. This paper initially uses the average model of STATCOM, coupling it with the space vector modulation (SVM). Then, a control method is suggested in order to derive the converter three-phase reference voltages using the complemented average model. The proposed control algorithm was simulated with MATLAB that provides high efficiency outcomes. Simulations are also compared with those of another method to confirm the performance of the suggested control system.**

Keywords- reference Voltage, Average model, SVM modulation, STATCOM.

I. INTRODUCTION

THE use of static compensators can improve some problems in control and utilization of power systems. While STATCOM is used in both transmission and distribution systems to control reactive power, it can eliminate unwanted harmonics and unbalance of power systems [1], [2]. To reach these aims, having a compensating reference signal is necessary. This reference signal is generally generated in current waveforms using the well-known power theory. Simple and fast current controlled strategies (e.g. hysteresis current control) can be employed to force the exact current waveforms to 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. Unlike the current reference, the voltage reference cannot be generated easily from the current references [3]. Different approaches have been presented in [4]-[7] to solve this problem.

This paper uses the average model of STATCOM introduced in [8] to generate reference voltages. Switching duty ratio information and the applied voltages to STATCOM are the inputs of the average model. In [8], switching duty ratios are calculated for a PWM-modulated STATCOM as three functions depending on the phase angle between the PCC and STATCOM outputs voltages (α). In [3], this relation is implemented to control the PWM-modulated STATCOM. First, STATCOM output voltages are derived as three voltage dependent sources, presenting the SVM-modulated STATCOM related to α. Then, a control system is proposed based on the average model that produces a proper α for STATCOM in order to regulate voltage of the PCC by injecting/absorbing reactive power.

II. AVERAGE MODEL OF SVM-MODULATED STATCOM

State space model of STATCOM includes discontinuous switching functions. Figure 1 illustrates a STATCOM that is connected to a power system.

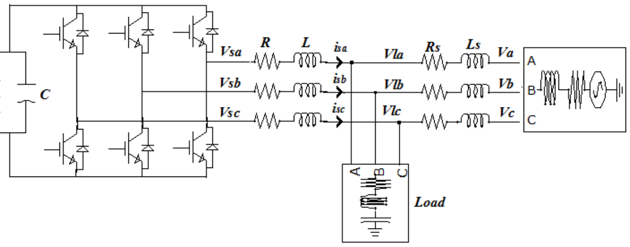

Figure 1. Schematic representation of STATCOM connected to a utility system at the load terminal.

State space equations of this equivalent system can be developed. Then, the average operator is applied to the obtained state space equations. The averaging integral is taken place during an averaging period which is equal or smaller than the switching frequency in general. The averaging technique ignores high frequency ripples, and produces a continuous state space model as below [8]:

$$\frac{di_{sa}}{dt} = -\frac{R}{L}i_{sa} + \frac{1}{3L}(2D_a - D_b - D_c)v_{dc} - \frac{1}{3L}(2v_{la} - v_{lb} - v_{lc}) \quad (1)$$

$$\frac{di_{sb}}{dt} = -\frac{R}{L}i_{sb} + \frac{1}{3L}(2D_b - D_a - D_c)v_{dc} - \frac{1}{3L}(2v_{lb} - v_{la} - v_{lc}) \quad (2)$$

$$\frac{dv_{dc}}{dt} = \frac{1}{c}(D_c - D_a)i_{sa} + \frac{1}{c}(D_c - D_b)i_{sb} \tag{3}$$

In recent years SVM technique has been frequently used for switching voltage source inverters (VSI). In this method, all switching states along with the reference voltage are transferred to the d-q plane using Park transformation. Considering Fig. 2, the reference voltage (V_{ref}) is always located between two switching states, V_1 and V_2, can be synthesized during a fixed switching period T_s and two subintervals T_1 and T_2 as below:

$$T_s V_{ref} = T_1 V_1 + T_2 V_2 + T_0 V_0 \tag{4}$$

$$T_s = T_1 + T_2 + T_0 \tag{5}$$

This implies the volt-second balance for V_1 in T_1 seconds, V_2 in T_2 seconds, V_0 in T_0 seconds and V_{ref} in T_s seconds. Meanwhile, two zero switching states ((0,0,0)′ and (1,1,1)′) are used here equally in $T_0/2$.

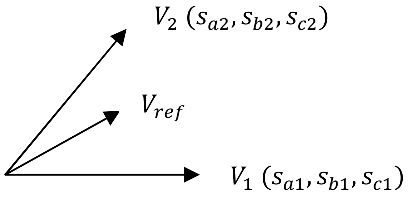

Figure 2. Reference voltage located between two switching states in the first sextant of the SVM diagram.

In two level three-phase VSI, the relationship between output voltages and switching functions is as below:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \frac{v_{dc}}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}\begin{bmatrix} s_a \\ s_b \\ s_c \end{bmatrix} \tag{6}$$

Equation (6) in d-q coordinates is:

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \sqrt{\frac{2}{3}} v_{dc}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} s_a \\ s_b \\ s_c \end{bmatrix} \tag{7}$$

So, the switching state vectors are:

$$v_k = \sqrt{\frac{2}{3}} v_{dc}\left[\left(\frac{2s_{ak} - s_{bk} - s_{ck}}{2}\right) + j\frac{\sqrt{3}}{2}(s_{bk} - s_{ck})\right] \ (k = 1,2) \tag{8}$$

Thus, (4) can be developed as follow:

$$T_s V(\cos\theta + j\sin\theta) = \sqrt{\frac{2}{3}} v_{dc}\left[\frac{2(T_1 s_{a1} + T_2 s_{a2}) - (T_1 s_{b1} + T_2 s_{b2}) - (T_1 s_{c1} + T_2 s_{c2})}{2} + j\frac{\sqrt{3}}{2}[(T_1 s_{b1} + T_2 s_{b2}) - (T_1 s_{c1} + T_2 s_{c2})]\right] \tag{9}$$

Then, duty ratios can be worked out:

$$D_k = \frac{T_1 S_{k1} + T_2 S_{k2} + \frac{T_0}{2}}{T_s} \quad (k = a, b, c) \tag{10}$$

Defining $A_m = \frac{V}{\sqrt{\frac{2}{3}} v_{dc}}$ and substituting D_k from (10) into (9) and simplifying the relationships result in:

$$2D_a - D_b - D_c = 2A_m \cos\theta \tag{11}$$

and

$$D_c - D_b = -\frac{2}{\sqrt{3}} A_m \sin\theta \tag{12}$$

Using (11) and (12), it can be obtained:

$$2D_b - D_a - D_c = 2A_m \cos\left(\theta - \frac{2\pi}{3}\right) \tag{13}$$

$$D_c - D_a = -\frac{2}{\sqrt{3}} A_m \sin\left(\theta + \frac{\pi}{3}\right) \tag{14}$$

Equations (11)-(14) suggest an average model that is based on the SVM-modulation technique. The next section shows the performance of this average model.

III. CONTROL METHOD

Real power and reactive power exchange between the STATCOM and the power system are controlled using the dq-current components (i.e. i_{ds} *and* i_{qs}), respectively [9]. Transferring the three KVL in AC-side of Fig. 1 to the dq-plane will lead to the dq-voltages of the STATCOM as below:

$$v_{ds} = V_{ml} + Ri_{ds} + L\frac{di_{ds}}{dt} - L\omega i_{qs} \tag{15}$$

$$v_{qs} = Ri_{qs} + L\frac{di_{qs}}{dt} + L\omega i_{ds} \tag{16}$$

Where v_{ds} and v_{qs} are the dq-voltages of STATCOM, V_{ml} is the d-axis voltage component of the PCC, R and L are resistance and inductance of the commutation inductor (see Fig. 1) and ω is the radian frequency of the power system. Then, i_{ds} and i_{qs} are decoupled in [9] by rearranging (15) and (16) as follows:

$$\left(\frac{R}{L} + \frac{d}{dt}\right)i_{ds} = dv_{ds} \tag{17}$$

$$\left(\frac{R}{L} + \frac{d}{dt}\right)i_{qs} = dv_{qs} \tag{18}$$

$$dv_{ds} = \omega i_{qs} + \frac{v_{ds} - V_{ml}}{L} \tag{19}$$

$$dv_{qs} = -\omega i_{ds} + \frac{v_{qs}}{L} \tag{20}$$

Then, independent control diagrams of Fig. 3 were proposed according to (17)-(20).

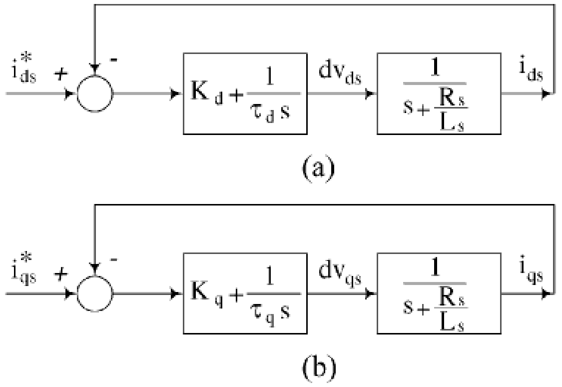

Figure 3. (a) The d-axis current component controller, and (b) the q-axis current component controller

Where i_{ds}^* *and* i_{qs}^* are the references for i_{ds} *and* i_{qs} that are calculated from the well-known power theory equations as bellow:

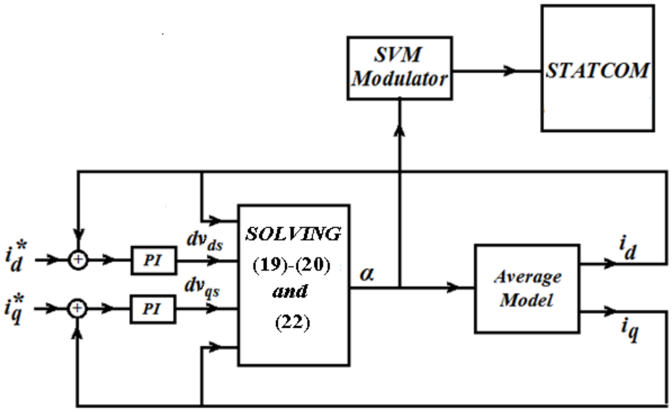

Figure 4. STATCOM control system based on the average model

TABLE I. PARAMETERS OF STATCOM AND THE POWER SYSTEM

Parameters of the power system and STATCOM	
R_s	1Ω
L_s	1mH
R	0.01Ω
L	0.5mH
R_c	$10^5\Omega$
C	1mF
$f_{switching}$	2000HZ
A_m	0.9

$$\begin{bmatrix} i^*_{ds} \\ i^*_{qs} \end{bmatrix} = \frac{1}{v_{dl}^2+v_{ql}^2}\begin{bmatrix} v_{dl} & -v_{ql} \\ v_{ql} & v_{dl} \end{bmatrix}\begin{bmatrix} P_{ref} \\ Q_{ref} \end{bmatrix} \qquad (21)$$

Where $P_{ref}\ and\ Q_{ref}$ can be either obtained from the planned active and reactive power control or the PCC voltage regulation.

From (19) and (20), α can be calculated as below:

$$\alpha = \tan^{-1}\frac{v_{qs}}{v_{ds}} \qquad (22)$$

A. Control of SVM-modulated average model of STATCOM

Using the control algorithm given in [9], here the control of the SVM-modulated STATCOM is suggested. The resultant control method is examined based on the average model described in (5)-(10). Figure 4 shows this control technique in which the first part uses the suggested method in [9] to generate α. Then, this is applied to the average model of STATCOM; three duty cycles are calculated according to (10)-(14). Further, these duty ratios are applied to (1)-(3) in order to estimate the dq-currents of STATCOM. These are then correspondingly compared with their references.

IV. SIMULATIONS

Here it is examined the performance of the SVM-modulated STATCOM average model and the suggested control method using MATLAB SIMULINK. Table I describes related parameters of the power system and STATCOM according to the variables named in Fig. 1. It should be noted that using an SVM-modulator causes a delay in STATCOM output voltages that a compensation lookup table was prepared to be utilized in simulations.

A. Average model of SVM-modulated STATCOM

In section II, duty ratio functions of the average model were obtained to simulate the SVM-modulated STATCOM. First, the behavior of both exact and average model are simulated for a certain steady state operation with a given α. Figure five compares these simulations for $\alpha = 1^\circ$. It can be seen that the average model approximates the exact model properly excluding switching frequency ripples. Then, dynamic response of the averaged SVM-modulated STATCOM is examined, which Fig. 6 shows the dynamic state of the average model when α changes from -0.8º (capacitive mode) to 0.9º (inductive mode) at $t = 1\,sec$. Simulations illustrate the full trace of the exact STATCOM by the average model

B. Reactive-power control

Here the proposed control algorithm using the average model is examined. To assess the control algorithm, the load reactive-power is varied from -150 kVAr to 150 kVAr, moving

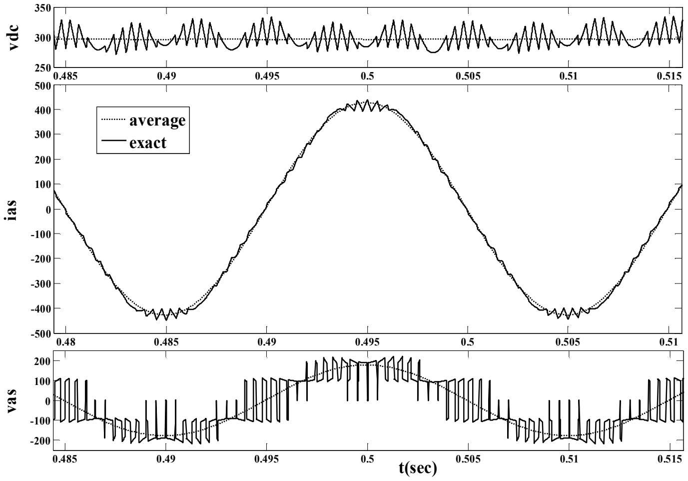

Figure 5. Comparison of average model and Exact model for $\alpha = 1^\circ$

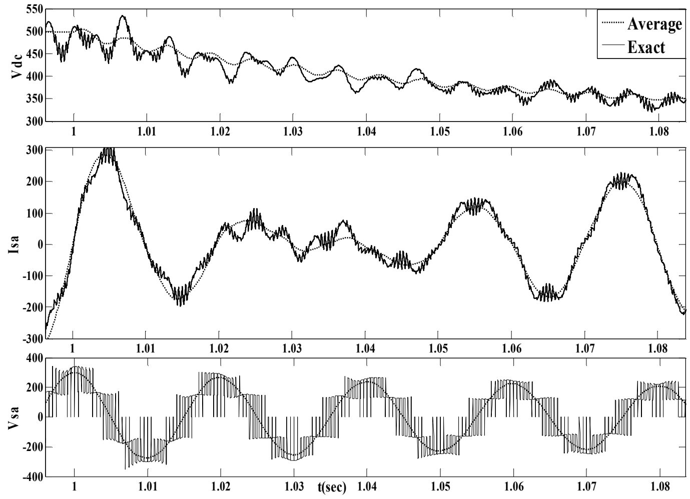

Figure 6. Comparison of dynamic response of Average model and Exact model for change α, from $\alpha = -0.8^\circ$ into $\alpha = 0.9^\circ$

from one steady state condition to another at $t = 1\,sec$. Variations of α and reactive power are demonstrated in Figs. 7 and 8, respectively. To evaluate the performance of the controlled average model, simulations related to the dq-model used in [7] is also demonstrated in Figs. 9 and 10. Comparing Fig. 7 with that of 9 shows that while average model controller limits variations of α to a narrow region, this is quite large for the dq-model controller. At the same time, reactive power is moving from one operating to another with the average model smoother compared to that of the dq-model.

Further, the source current i_{sa} is illustrated in Fig. 11 for the average model controller, and is repeated for the dq-model controller of [7] in Fig. 12. It can be seen that the harmonic performance achieved by the average model is higher than that of the dq-model. Moreover, the converter voltages v_{sa} of the average model controller and the dq-model controller are illustrated in Figs. 13 and 14, respectively. Once again the harmonic performance is better for the average model than that of the dq-model. In brief, the average model controller provides smoother transition along with higher harmonic performance as well as higher efficiency compared to those of the dq-model.

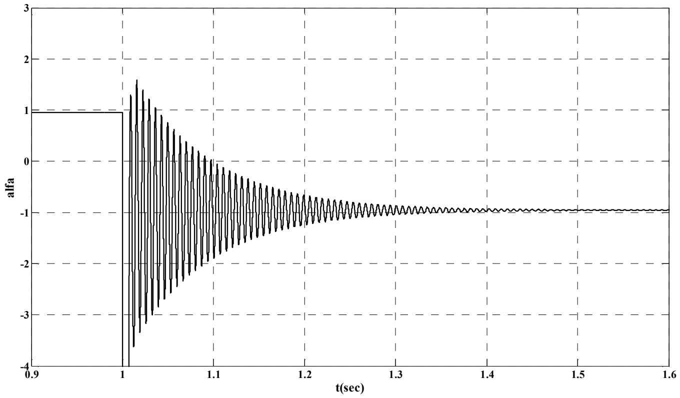

Figure 7. Variations of α for changing reactive power of STATCOM from -150 kVAr to 150 kVAr at t = 1sec using average model controller.

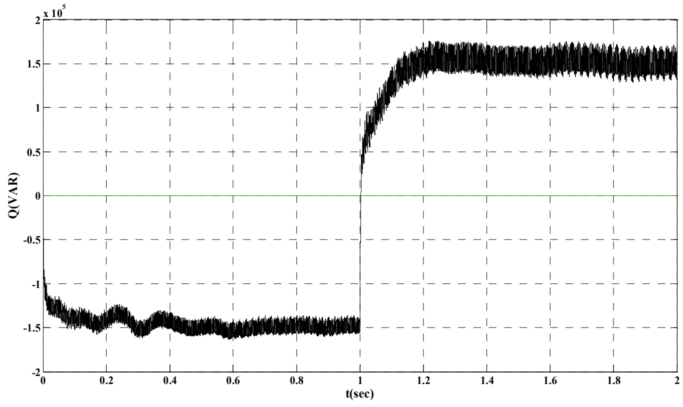

Figure 8. Reactive-power change from-150 kVAr to 150 kVAr at t = 1sec using average model controller.

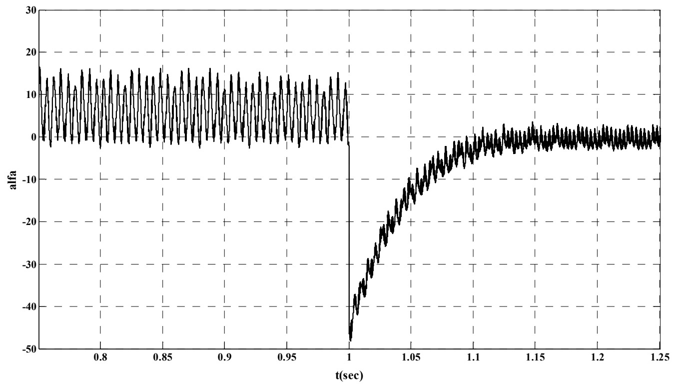

Figure 9. Variations of α for changing reactive power of STATCOM from -150 kVAr to 150 kVAr at t = 1sec using the dq-model controller.

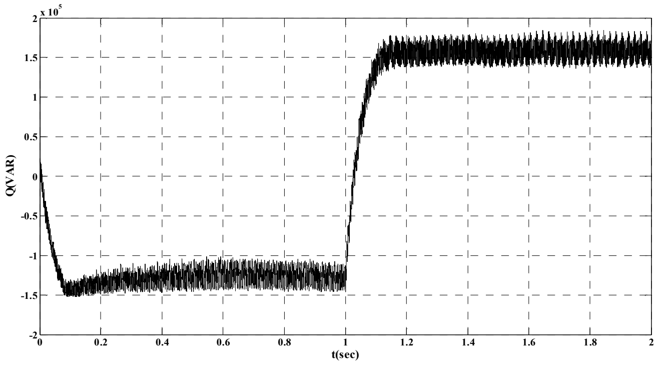

Figure 10. Reactive-power change from-150 kVAr to 150 kVAr at t = 1sec using the dq-model controller.

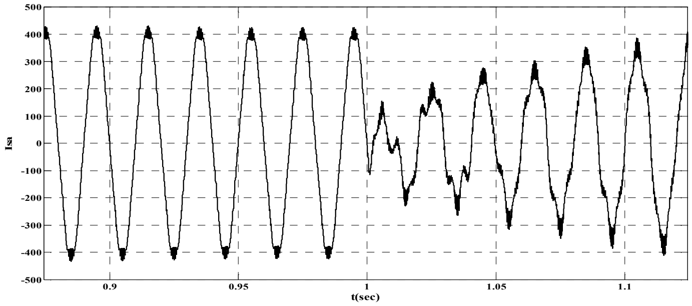

Figure 11. Variations of the source current for changing reactive power of STATCOM from -150 kVAr to 150 kVAr at t = 1sec using the average model controller.

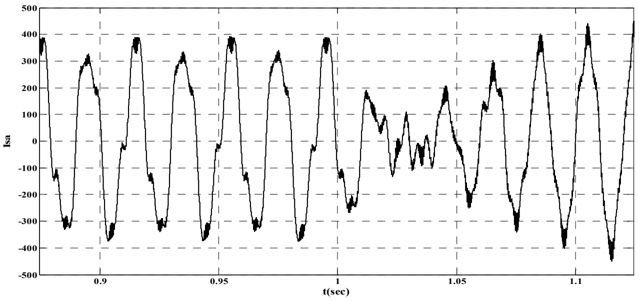

Figure 12. Variations of the source current for changing reactive power of STATCOM from -150 kVAr to 150 kVAr at t = 1sec using the dq-model controller.

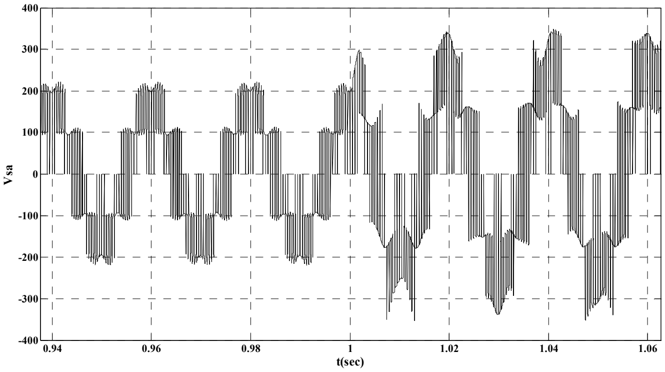

Figure 13. Variations of the converter voltage v_{sa} for changing reactive power of STATCOM from -150 kVAr to 150 kVAr at $\mathrm{t} = 1\mathrm{sec}$ using the average model controller.

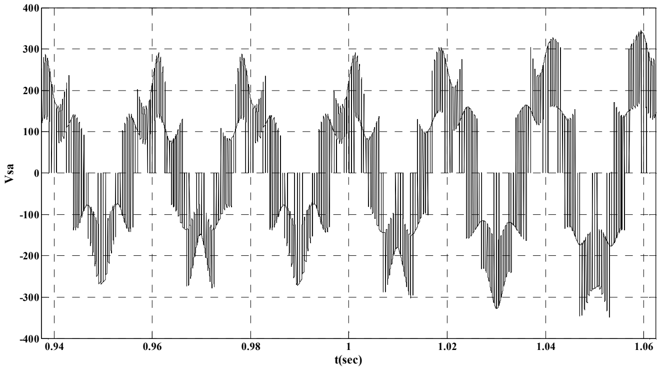

Figure 14. Variations of the converter voltage v_{sa} for changing reactive power of STATCOM from -150 kVAr to 150 kVAr at $\mathrm{t} = 1\mathrm{sec}$ using the dq-model controller.

V. CONCLUSION

This paper suggests a way to modulate three-phase output voltages for the converter of STATCOM rather than tracking three-phase currents. This would avoid variable high switching frequency modulations that cause certain issues in high power applications such as low efficiency and EMI. In this context, first average model of STATCOM is modified in a way to be capable of dealing with the SVM. A lookup table eventually describes the tuning of the average model against a small phase shift that modifies it for the SVM purposes. Hence, duty ratio functions of SVM-modulated are derived that are control inputs of the average model. Simulations show that this SVM-modulated average model traces the exact model properly. Then, a new control method for the developed model of STATCOM is suggested. The performance of both the model and the controller are verified by SIMULINK. Further, a classic dq-model is also simulated, where simulations related to the average model are compared with those of the dq-model. Simulations confirm that the average model controller introduces higher performance than the dq-model controller, lowering variations and distortions of the control parameters as well as the power system three-phase source-end currents and voltages.

VI. ACKNOWLEDGMENT

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