Hybrid Reactive Power Compensation through Reactive Current Controlled SVC and Active Filter

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Abstract- A hybrid reactive power compensation through a static VAr compensator (SVC) and an active filter, with new technique for controlling SVCs (Fixed Capacitor–Thyristor Controlled Reactor) is presented in this paper. SVC controlled by the reactive current controller acts an excellent reactive power compensator for power factor correction. The active filter connected in parallel with SVC is used to filter out the harmonics generated in the system. The control signals are derived from the calculation of instantaneous active and reactive powers of the distribution feeder. Simulation results performed by the PSCAD program show that the proposed hybrid reactive power compensation configuration can effectively balance reactive currents, correct power factor and eliminate harmonic currents.

Keywords – SVC; Reactive power compensation; Control design; Active filter

I. INTRODUCTION

Reactive power consumption has a significant effect on the operation of a power system. FACTS controllers nowadays are able to achieve reliable, economic and stable compensation of reactive power to improve power factor at all conditions of loading. To achieve this requirement, FACTS have basically branched out into two main application levels, i.e. transmission systems (e.g., control the power transmitted through a line), and distribution networks (e.g., power factor correction). The latter is commonly concerned with load behavior, and hence load voltage regulation [1]-[2]. Thus, the design of FACTS controllers in distribution systems should include the control of the reactive power injected by the SVC to attain unity power factor [2]-[4]. FACTS controllers for distribution systems are typically defined by the type of feedback signal, i.e., load voltage or reactive current signal to either improve power factor or load voltage profile [5]-[8].

Generally, there is a wide range of daily demand for reactive powers in a distribution feeder. The reactive currents produced by unbalanced and balanced loads in a three-phase distribution feeder are often dynamic in nature. The fast response, low operating cost, and high reliability of a static VAr compensator (SVC) make it a good load balancer and reactive power generator. Usually a SVC is composed of a thyristor-controlled reactor (TCR) and fixed capacitors (FC). The SVC can give different amount of reactive power to each phase to reduce the reactive currents and adjust the power factor to unity so that the power source provides only in-phase balanced currents [2]-[4].

However, a TCR introduces harmonic currents. Some schemes have been employed to reduce the harmonic currents of a TCR, such as twelve-pulse arrangement by wye - wye and wye-delta connected transformers and the revised structure of the TCR [5],[6]. The revision of TCR structure, with limited harmonic reduction ability, complicates the control and design. The 5th and 7th harmonics could not be eliminated completely by the twelve pulse arrangement when the TCR is under unbalanced operation. To overcome this, the fixed capacitors, tuned with small reactors to act as passive filters in the characteristic harmonic frequencies of the TCR [2], [7], [8] are installed in parallel with SVC. However, the passive filter could introduce possible series and parallel resonance with source impedance.

The main objective of this paper is to present a hybrid reactive power compensation method of a static VAr compensator (SVC) in parallel with an active filter. SVC (Fixed Capacitor–Thyristor Controlled Reactor) is controlled by a new reactive current controlled technique for the three-phase distribution feeders. Control signal for the active filter is derived from the instantaneous active and reactive powers. To demonstrate the capability of the proposed hybrid compensator, simulations on a 415V distribution feeder with variable loads are performed by the PSCAD program. The simulation results show that the reactive power compensation and the harmonic elimination of the hybrid compensator with dynamic loads are better than that of the classic SVC’s controlled by standard PI based voltage controller.

This paper is organized as follows: Section II introduces some basic concepts in SVC. Section III presents the reactive current controller design of SVC. Section IV presents the basic concepts of active filter, its control. System configuration is given in section V. The PSCAD simulation results on the basic system, system with SVC, the system with reactive current controlled SVC and active filter are discussed in sections VI, VII, VIII respectively. The system with PI-Controlled SVC and active filter is simulated in section IX. And conclusions are drawn in section X.

II. STATIC VAR COMPENSATOR

Static VAR Compensator (SVC) is a first generation FACTS device that can control voltage at the required bus thereby improving the voltage profile of the system. SVCs are used for high performance steady state and transient voltage control compared with classical shunt compensation. SVCs are also used to dampen power swings, improve transient stability, and reduce system losses by optimized reactive power control [9], [10].

This paper deals with the fixed capacitor-thyristor controlled reactor SVC (FC–TCR SVC).

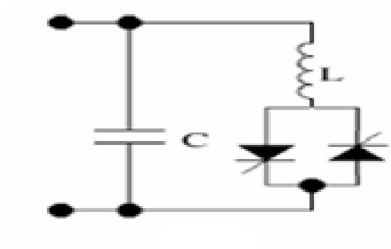

Figure 1: FC–TCR SVC

The performance and operating characteristics of this type of SVC is determined by the TCR performance. The main concept behind controlling TCR is the control of the firing time of the thyristor to control the current in the reactor, thus controlling the reactive power absorbed by the TCR. The amplitude I_{Lf} of the fundamental reactor current can be expressed as a function of the delay angle α as follows:

$$I_{Lf}(\alpha)=\frac{V}{\omega L}\left(1-\frac{2}{\pi}\alpha-\frac{1}{\pi}\sin(2\alpha)\right) \qquad (1)$$

where V is the amplitude of the applied voltage, L is the inductance of the thyristor controlled reactor and ω is the angular frequency of the applied voltage.

The delay angle control results in a non-sinusoidal current waveform in the reactor, i.e., the TCR generate harmonics. For identical positive and negative current half cycles, only odd harmonics are generated. The most significant harmonic components in this case are the 3rd , 5th , 7th and 13th harmonics.

III. DESIGN OF REACTIVE CURRENT CONTROLLER FOR SVC

For the FC–TCR SVC, at maximum capacitive reactive output, the TCR is off (α=90◦). To decrease the capacitive output, the current in the reactor is increased by decreasing the delay angle α. At zero reactive output, the capacitive and inductive currents become equal, and thus the capacitive and inductive reactive powers cancel out each other. With a further decrease of α, assuming that the rating of the reactor is grater than that of the capacitor, the inductive current becomes larger than the capacitive current, thus resulting in a net inductive reactive power output.

The control of the TCR in the FC–TCR SVC has four basic functions, as shown in Figure 2.

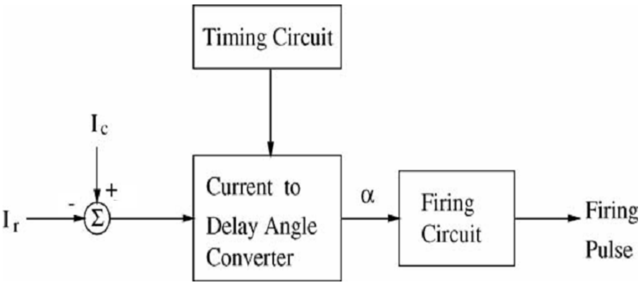

Figure 2: Control scheme for FC-TCR SVC

1. A timing circuit function that is provided by a phase-locked loop circuit that runs in synchronism with the system voltage and generates timing pulses with respect to the peak of that voltage.

2. A reactive current to firing angle conversion that can be implemented from the mathematical relationship between the amplitude of the fundamental TCR current and the delay angle (equation 1).

3. The third function is the transformation of the required fundamental reactor current I_{Lf} to a reference signal for the SVC control. This is simply done by subtracting the reactive current of the load I_r from the capacitor current I_c.

4. The fourth function is the thyristor firing pulse generation.

Thus, the control circuit is designed using these four main functions.

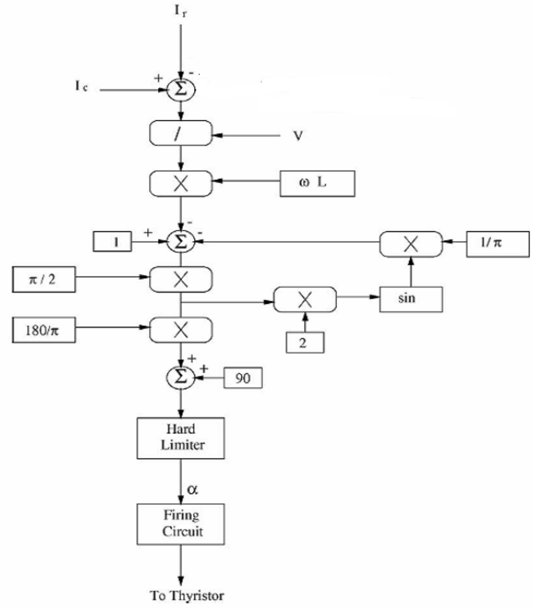

Figure 3: Modeling of reactive current controller in PSCAD

The PSCAD model of the control circuit used here is depicted in Figure 3. The reactive current I_r absorbed by the system is used as the reference signal. The reactive signal I_r is subtracted from the capacitive signal I_c to obtain the required reactor current. The net value of the reactor current is converted, as shown in figure 3, to the delay angle α through the use of equation (1). The delay angle α is then fed to the SVC firing circuit module.

The main advantage of this control is its flexibility. By using the reactive current of the load and any other reactive component connected to it, the required SVC compensation current can be automatically generated.

IV. ACTIVE FILTER

The active filter uses power electronic switching to generate anti harmonic currents that cancel the harmonic currents from a nonlinear load. The active filter configuration investigated in this paper is based on a pulse-width modulated (PWM) voltage source inverter (VSI) that interfaces to the system through a system interface filter as shown in Figure 4. In this configuration, the filter is connected in parallel with the load being compensated. Therefore, the configuration is often referred to as an active parallel filter. Figure 4 illustrates the concept of the harmonic current cancellation so that the current being supplied from the source is sinusoidal.

Active filter is installed in parallel with the SVC. The main circuit of the active filter is a three-phase voltage-source PWM inverter using six MOSFET's. The PWM inverter has a dc source. The purpose of a small-rated LC filter (L_R, C_R) is to suppress switching ripples generated by the active filter.

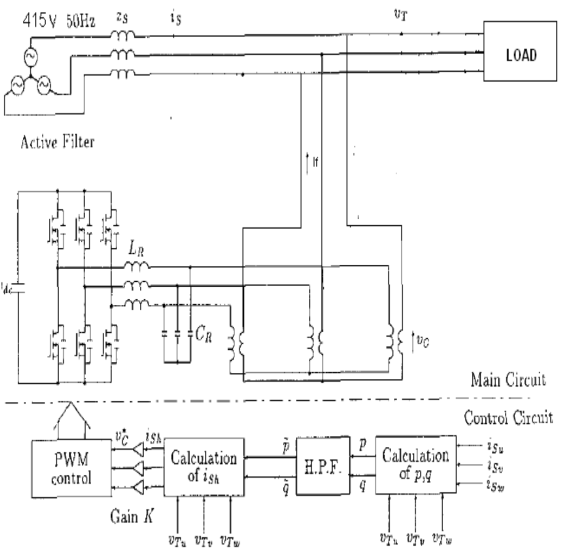

Figure 4: Control configuration of active filter

A control circuit of an active filter is also shown in Figure 4. Three-phase source currents, i_{su}, i_{sv} and i_{sw} are detected and a source harmonic current in each phase i_{sh} is calculated by applying the p-q theory. Terminal voltages and the source currents are transformed from three- to two-phase quantities as follows

$$\begin{bmatrix} e_\alpha \\ e_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} e_u \\ e_v \\ e_w \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{su} \\ i_{sv} \\ i_{sw} \end{bmatrix} \quad (3)$$

Here e_u, e_v and e_w are the fundamentals of the terminal voltages. Hence, the instantaneous real power p and the instantaneous imaginary power q are given by

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} e_\alpha & e_\beta \\ -e_\beta & e_\alpha \end{bmatrix} \begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} \quad (4)$$

From the equation (4), The high frequency components are p and q are extracted using a high-pass-filters, and the harmonics of the three-phase source currents, i_{shu}, i_{shv} and i_{shw} are obtained by the following calculation.

$$\begin{bmatrix} i_{shu} \\ i_{shv} \\ i_{shw} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{1}{2} \end{bmatrix} \begin{bmatrix} e_\alpha & e_\beta \\ -e_\beta & e_\alpha \end{bmatrix}^{-1} \begin{bmatrix} \tilde{p} \\ \tilde{q} \end{bmatrix} \quad (5)$$

The calculated harmonic current in each phase is, is amplified by the gain K and input to a PWM controller as a voltage reference

$$V = Ki_{sh} \quad (6)$$

To produce PWM switching patterns, the PWM controller compares V with a triangle-wave carrier whose frequency is 20 kHz.

V. SYSTEM CONFIGURATION

A simplified power system is simulated using PSCAD. As shown in figure 5, the test system consists of the following components.

1. Generation at 415V rated voltage at 50 Hz. This is simply modeled as a voltage source with an internal resistance of 0.01Ω.

2. The transmission network, modeled as a three-phase series inductive impedance with 0.1Ω resistance and 1mH inductance.

3. The load, modeled as a three phase inductive RL load with two levels of loading. The first level is given by R=10 Ω and L = 0.05 H. The second level is given by R=10 Ω and L = 0.1 H, and is switched on at 1 s and turned off at 2 s during the total simulation time of 3 s.

VI. SIMULATION RESULTS

A. Simulation on basic system

The simulation results are shown in Figures 6, 7, 8. The active power varies from 15kW to 30kW, and reactive power of the load varies from 10 to 15 kVAr, for the first and second levels of loading respectively. The phase voltage is 201V for the first loading level and drops to 196V, when the second load is connected to the system. In order to bring the reactive power drawn from the system to zero and to improve system voltage level, Static VAr compensator is to be introduced in to the system.

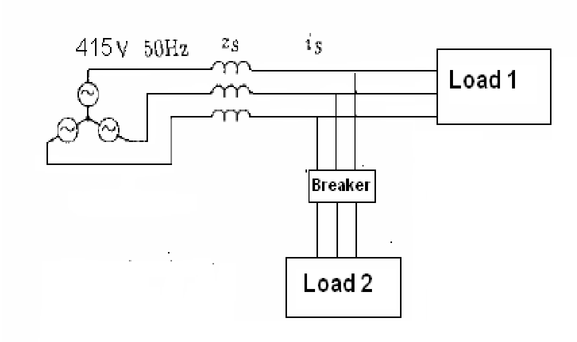

Figure 5: The basic test system

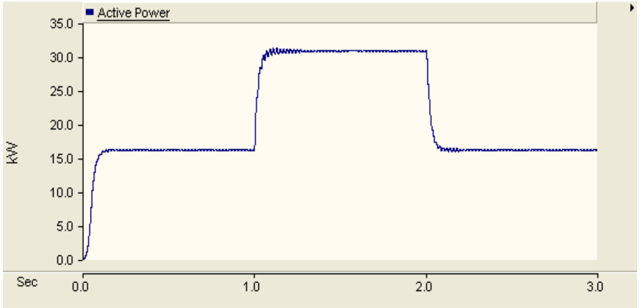

Figure 6: Active power absorbed by the load in the test system

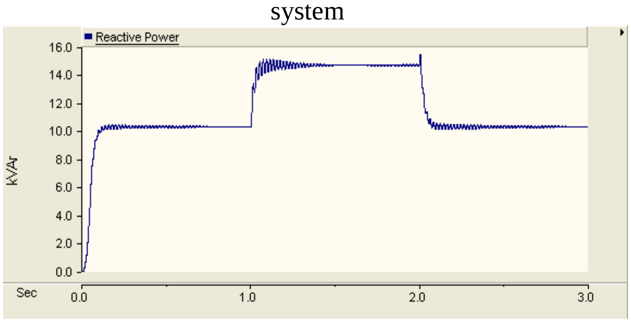

Figure 7: Reactive power absorbed by the load in the test system

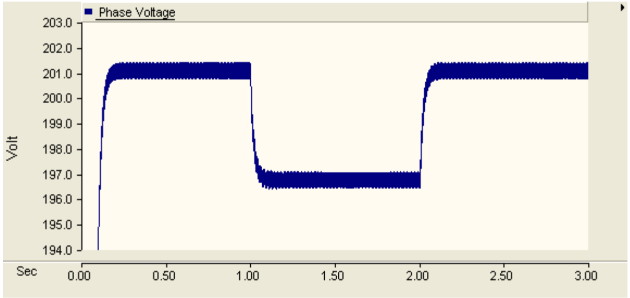

Figure 8: Load phase voltage in the test system

VII. SVC DESIGN AND SIMULATION

To design the FC–TCR SVC for the proposed reactive current control, the following steps should be taken:

1. The maximum consumed reactive power of the load is 15kVAr; hence, the fixed capacitor has to inject the same value to the system, i.e.

$$C = \frac{Q_c}{3V_{ph}^2\omega} \approx 300\ \mu\text{F} \qquad (7)$$

2. The value of the reactor to be connected in parallel with the capacitor has to be tuned with the capacitance at α=90°, i.e.

$$L = \frac{1}{\omega^2 C} = 0.035\text{H} \qquad (8)$$

The schematic diagram of the SVC PSCAD module added to the test system is shown in Figure 9, the corresponding simulation results are shown in Figures10, 11 and 12.

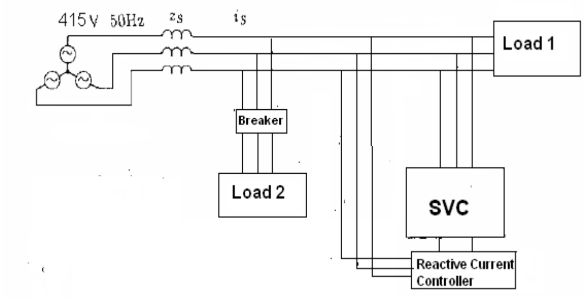

Figure 9: The test system with reactive current controlled SVC

A significant reduction in total reactive power consumption (1 kVAr for the first load level, 3 kVAr for the second level), as well as improved voltage profile (205V for the first level, 201V for the second level) is observed here. The reactive power drawn from the system is 1 kVAr for the first level of loading and 1.5 kVAr for the second level of loading. Even after the installation of SVC the reactive power drawn is not zero and it is due to the harmonics injected to the system. The harmonic analysis of the system shows that the 3rd, 5th, and 7th order harmonics are prominent in the test system. The figure13 shows the harmonic histogram of the test system.

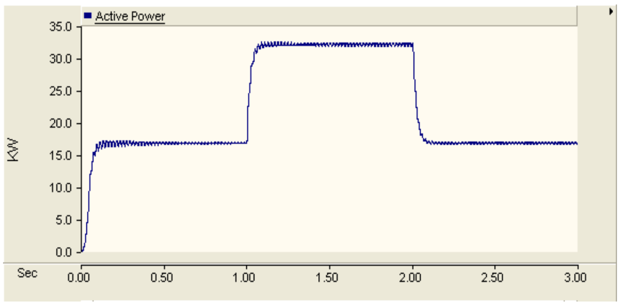

Figure 10: Active power absorbed by the load in the test system with reactive current controlled SVC

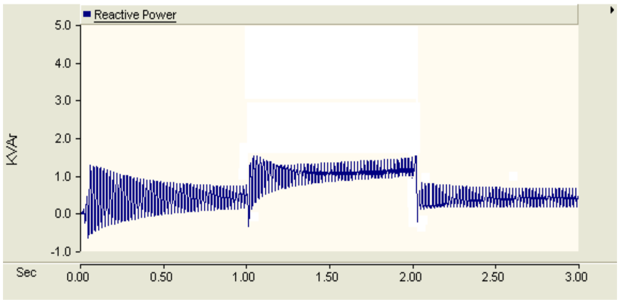

Figure 11: Reactive power drawn from the test system with reactive current controlled SVC

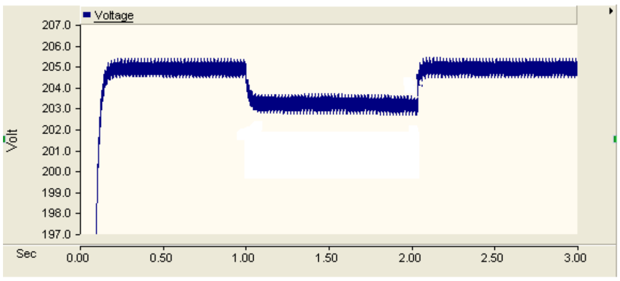

Figure 12: Load phase voltage in the test system with reactive current controlled SVC

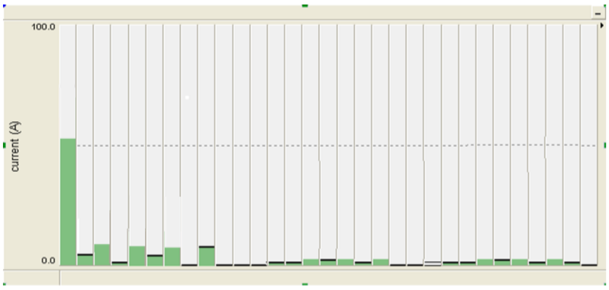

Figure 13: Harmonic histogram of the test system with SVC

In order to bring the reactive power drawn from the system to zero, the harmonics injected to the system is to be eliminated.

VIII. SIMULATION RESULTS WITH HYBRID COMPENSATOR

The proposed final system configuration is shown in the Figure14.

The active filter is designed and installed in the system in parallel with SVC. Now the harmonics generated by the thyristors of the SVC are cancels out by the active filter. Working principle of active filter is based on instantaneous power theory or p-q theory.

The simulation results show that, now the reactive power drawn from the system drops to zero since the reactive power requirement of the loads are locally satisfied by the reactive current controlled SVC. Since the reactive power drawn from the system becomes zero (Figure 15) the power factor achieves unity.

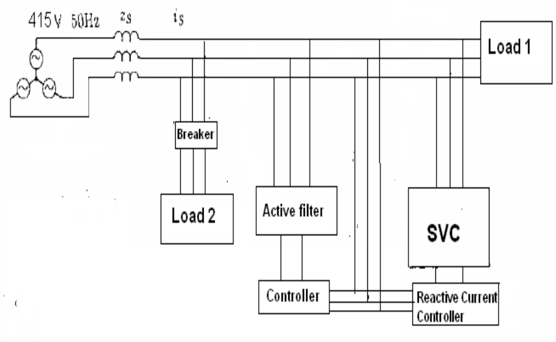

Figure 14: The test system with reactive current controlled SVC and active filter

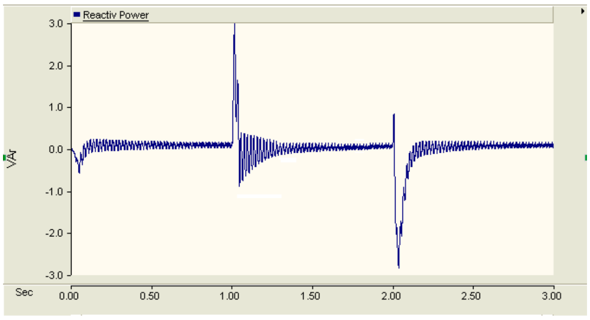

Figure 15: Reactive power drawn from the test system with reactive current controlled SVC and active filter

The results obtained with the SVC and active filter in the test system are shown in Figures 15 and 16. Figure 17 shows the harmonic histogram of the test system. Notice the zero reactive power observed at the two loading conditions, and the slight increase in load voltage.

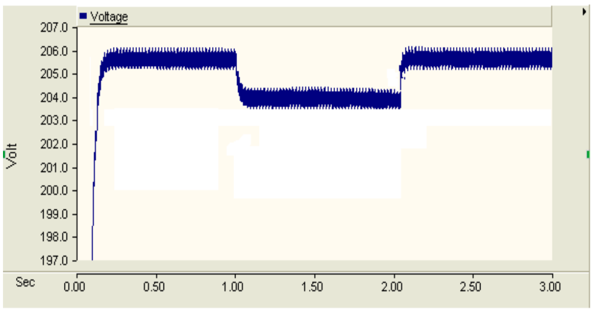

Figure 16: Load phase voltage in the test system with reactive current controlled SVC and active filter

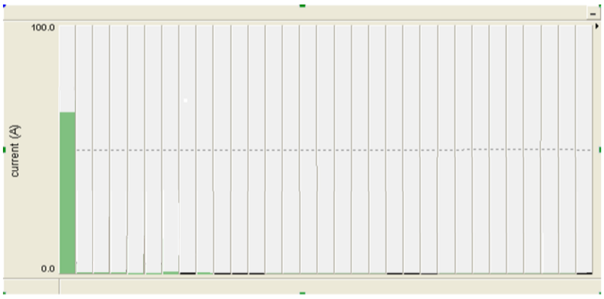

Figure 17: Harmonic histogram of the test system with SVC and active filter

IX. SVC WITH CONVENTIONAL PI-CONTROLLER

In order to evaluate the performance of the proposed reactive current controller of SVC, conventional standard PI-based voltage controller for the SVC is designed and tested. In this case the main concern here is voltage control, as opposed to current control in the previous case.

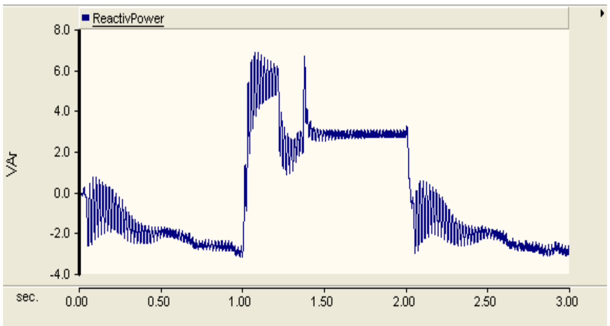

Figure 18: Reactive power drawn from the test system with PI controlled SVC and active filter

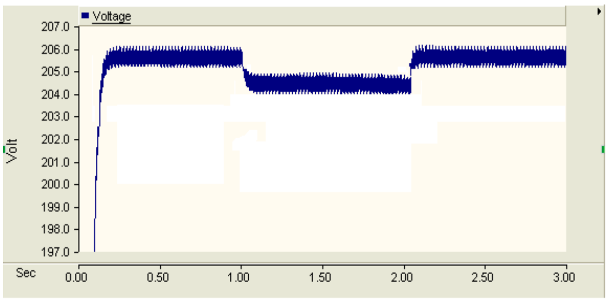

Figure 19: Load phase voltage in the test system with PI controlled SVC and active filter

The corresponding results are shown in Figs. 18 and 19, where it is clear that the system reactive power is not zero, even though the load voltage profiles are somewhat similar for both the controllers. Although a direct comparison of the two controllers is not possible, since different control strategies are used in each case, these results give a reasonably good idea of the improved performance of the proposed controller.

X. CONCLUSIONS

In this paper, a hybrid reactive power compensation method using a reactive current controlled SVC and an active filter is proposed for reactive power compensation. The reactive current controller gives the SVC an excellent performance in dynamic load conditions. Finally, a comparison between the proposed SVC controller and a standard PI-based voltage controller is presented. The results obtained show the excellent performance of the proposed SVC controller. The active filter can greatly improve the harmonics filtering ability. The PSCAD simulations show that the proposed hybrid reactive power compensation configuration can achieve unity power factor on the test system.

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