Electric Power Systems Research 58 (2001) 63–70
www.elsevier.com/locate/epsr

A compact control algorithm for reactive power compensation and load balancing with static Var compensator

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Received 2 February 1999; accepted 4 April 2000

Abstract

A compact control algorithm for reactive power compensation and load balancing with the static Var compensator (SVC) in three-phase three-wire systems is developed in this paper. The required compensation susceptance of each SVC phase can be obtained from a very simple function of voltage and power signals which are measured by a three-phase voltage transducer and two single-phase active and reactive power (P–Q) transducers at the load bus. The calculation of compensation susceptances is based on the criterion of a unity power factor and zero negative-sequence currents after compensation. A simulation is made, as the first stage, to show the validity of the proposed compensation algorithm. Then, a laboratory size microcomputer-based SVC, which consists of thyristor-controlled reactors (TCRs) and fixed capacitors (FCs), is designed and implemented. Simulation and experiment results show that the algorithm is very suitable for on-line control of the SVC which is designed for phase balancing and power factor correction. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Reactive power; Unbalanced power system; Static Var compensator; Electric power quality

1. Introduction

An unbalanced load in a three-phase three-wire system produces undesired negative-sequence currents. This negative-sequence component will cause additional generator, transmission line, and transformer losses. The negative-sequence voltage caused by negative-sequence current, which is one of poor power quality phenomena, will induce extra motor losses and ripple in rectifiers [1,2].

The reactive power requirements of loads in a distribution system could vary in a wide range within a short period of time when the feeder supplies electric power to fluctuating loads, such as arc furnaces, steel rolling mills and electric trains. The reactive power not only reduce efficiency and reliability of the power system but also make voltage regulation more difficult. Hence it is better to compensate the reactive power at the load bus [2–4].

The load balancing and power factor correction capability of an static Var compensator (SVC) is well known. A SVC adjusts the susceptance in each phase by controlling the conducting angles of the thyristor-controlled reactor (TCR). In practical application, the formula for the desired compensation susceptances must be in terms of measurable electrical signals at the load bus. Some computation algorithms have been proposed in the past. The feedback electrical signals that have been used in the literature include (a) phase reactive powers, (b) real part and imaginary part of symmetrical components of line currents, (c) amplitudes and angles of line currents, and (d) instantaneous power quantities [5–12]. The measurements of those electrical signals need special analog circuits or digital computation algorithms.

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PII: S0378-7796(01)00127-4

To simplify the measurement of electrical signals and the computation formula in determining the compensation susceptances, a compact algorithm is derived based on the symmetrical components method. Only two single-phase P–Q transducers and a three-phase voltage transducers are needed for the measurement of feedback signals. Each phase susceptance of the SVC can then be obtained from a very simple function of voltage and power signals measured by the transducers. The algorithm is a further improvement of a former algorithm proposed by the authors [12]. To demonstrate the validity of the proposed algorithm, at first, a simulation is performed. Then, a laboratory size microcomputer-based SVC, which belongs to the type of TCR/fixed capacitor (FC), is designed and implemented. The simulation and experiment results show that the SVC with the proposed compact compensation algorithm can greatly reduce the negative-sequence currents and improve the power factor.

2. Compensation susceptance

The diagram of the studied system is shown in Fig. 1, where a substation feeds electric power to an unbalanced load through a three-phase three-wire distribution system. It is assumed that both the substation bus voltages and transmission line impedances are balanced. The superscripts S, T, C, and L, used in this paper, represent the substation, transmission line, compensator and load, respectively. For the purpose of the SVC is to reduce the negative-sequence currents and imaginary part of positive-sequence currents, hence, the well known transformation matrix $[T]$ is defined at first to relate the phase and sequence quantities as shown in Eq. (1):

$$\begin{bmatrix} \bar{V}^{L}_{ab} \\ \bar{V}^{L}_{bc} \\ \bar{V}^{L}_{ca} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} \bar{V}^{L}_{0} \\ \bar{V}^{L}_{1} \\ \bar{V}^{L}_{2} \end{bmatrix} = [T] \begin{bmatrix} \bar{V}^{L}_{0} \\ \bar{V}^{L}_{1} \\ \bar{V}^{L}_{2} \end{bmatrix} \tag{1}$$

where $\alpha = e^{j(2/3)\pi}$.

In Fig. 1, it is assumed that the load is linear, and then the load current can be expressed as:

$$\begin{bmatrix} \bar{I}^{L}_{a} \\ \bar{I}^{L}_{b} \\ \bar{I}^{L}_{c} \end{bmatrix} = \begin{bmatrix} Y^{L}_{ab} & 0 & -Y^{L}_{ca} \\ -Y^{L}_{ab} & Y^{L}_{bc} & 0 \\ 0 & -Y^{L}_{bc} & Y^{L}_{ca} \end{bmatrix} \begin{bmatrix} \bar{V}^{L}_{ab} \\ \bar{V}^{L}_{bc} \\ \bar{V}^{L}_{ca} \end{bmatrix} \tag{2}$$

Applying the symmetrical component transform in Eq. (1) to both side of Eq. (2), we have

$$\begin{aligned} \bar{I}^{L}_{1} &= (1-\alpha)(Y^{L}_{0}\bar{V}^{L}_{1} + Y^{L}_{2}\bar{V}^{L}_{2}) \\ \bar{I}^{L}_{2} &= (1-\alpha^2)(Y^{L}_{1}\bar{V}^{L}_{1} + Y^{L}_{0}\bar{V}^{L}_{2}) \end{aligned} \tag{3}$$

where

$$\begin{bmatrix} Y^{L}_{0} \\ Y^{L}_{1} \\ Y^{L}_{2} \end{bmatrix} = [T]^{-1} \begin{bmatrix} Y^{L}_{ab} \\ Y^{L}_{bc} \\ Y^{L}_{ca} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix} \begin{bmatrix} Y^{L}_{ab} \\ Y^{L}_{bc} \\ Y^{L}_{ca} \end{bmatrix} \tag{4}$$

The negative-sequence voltage $\bar{V}^{L}_{2}$ is introduced by unequal voltage drops on the transmission lines with unbalanced currents flowing. In general, the negative-sequence voltage is smaller than its positive-sequence counterpart. To simplify the analysis procedure, the

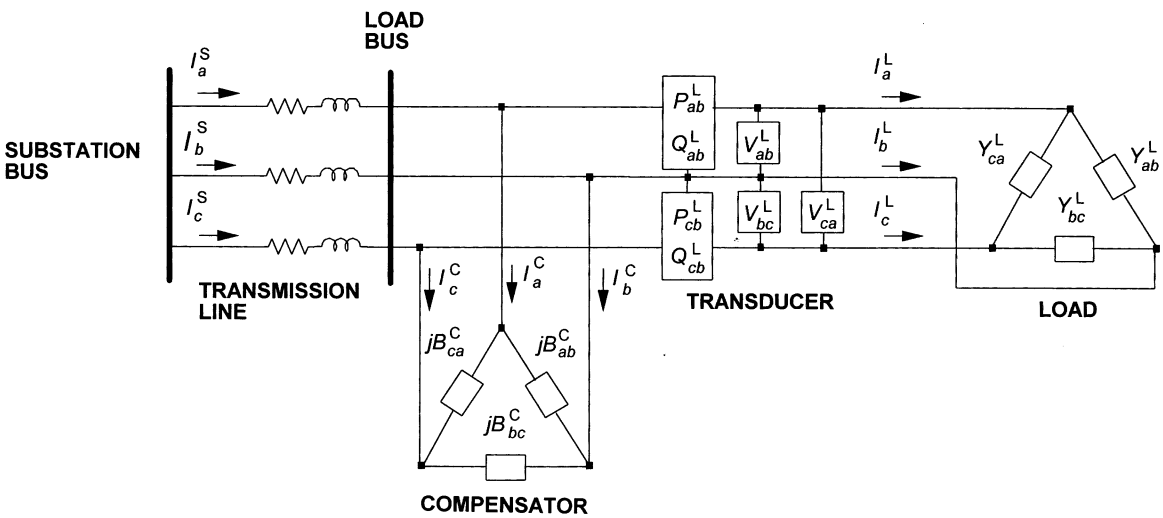

Fig. 1. A three-phase three-wire system with an SVC at the load bus.

negative-sequence voltage is neglected, that is $\bar{V}_2^L = 0$, $\bar{V}_1^L = V^L \angle 30°$. (The line-to-neutral voltage of phase a is selected as reference.) Eq. (3) then can be reduced to

$$\bar{I}_1^L = Y_0^L(\sqrt{3}V^L \angle 0°)$$
$$\bar{I}_2^L = Y_1^L(\sqrt{3}V^L \angle 60°) \quad (5)$$

In order to reduce the negative-sequence currents and imaginary part of the positive-sequence currents, the compensation susceptances of the SVC should meet the following constrains:

$$\mathrm{Im}(Y_0^C) = -\mathrm{Im}(Y_0^L) = \frac{-\mathrm{Im}(\bar{I}_1^L)}{\sqrt{3}V^L}$$
$$Y_1^C = -Y_1^L = \frac{-\bar{I}_2^L}{\sqrt{3}V^L \angle 60°} \quad (6)$$

where

$$\begin{bmatrix} Y_0^C \\ Y_1^C \\ Y_2^C \end{bmatrix} = [T]^{-1} \begin{bmatrix} jB_{ab}^C \\ jB_{bc}^C \\ jB_{ca}^C \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix} \begin{bmatrix} jB_{ab}^C \\ jB_{bc}^C \\ jB_{ca}^C \end{bmatrix} \quad (7)$$

Because an ideal SVC contains no power-consuming element, it can be obtained from Eq. (7) that $Y_2^C = -(Y_1^C)^*$. Using $-(Y_1^C)^*$ to replace Y_2^C and multiplying Eq. (7) by transformation matrix $[T]$, the compensation susceptances of the SVC can be described by Y_0^C and Y_1^C as:

$$B_{ab}^C = \mathrm{Im}(Y_0^C + 2Y_1^C)$$
$$B_{bc}^C = \mathrm{Im}(Y_0^C + 2\alpha^2 Y_1^C)$$
$$B_{ca}^C = \mathrm{Im}(Y_0^C + 2\alpha Y_1^C) \quad (8)$$

Substituting Eq. (6) into Eq. (8), the compensation susceptances can be expressed in terms of symmetrical components of the load currents:

$$B_{ab}^C = \frac{-1}{3V^L}\mathrm{Im}[\bar{I}_1^L + (2\angle -60°)\bar{I}_2^L]$$
$$B_{bc}^C = \frac{-1}{3V^L}\mathrm{Im}[\bar{I}_1^L + (2\angle 180°)\bar{I}_2^L]$$
$$B_{ca}^C = \frac{-1}{3V^L}\mathrm{Im}[\bar{I}_1^L + (2\angle 60°)\bar{I}_2^L] \quad (9)$$

Four variables, magnitutes and angles of $\bar{I}_1^L$ and $\bar{I}_2^L$, are required to obtain the current information in Eq. (9). Because the sum of three-phase currents is zero, the distribution condition of three-phase currents can be obtained by measuring only two line currents. Hence, only two single-phase P–Q meters, with voltage-coils connected to phase ab and cb and current-coils connected to phase a and c as that shown in Fig. 2, the so called two-wattmeter connection method, are used to acquire the four current variables in Eq. (9). In practical implementation, the voltage signal V^L in Eq. (9) is the average of three line to line voltages measured by a three-phase voltage transducer. Since the load bus voltage is assumed balanced, the complex form of the signals measured by the P–Q transducers can be described as:

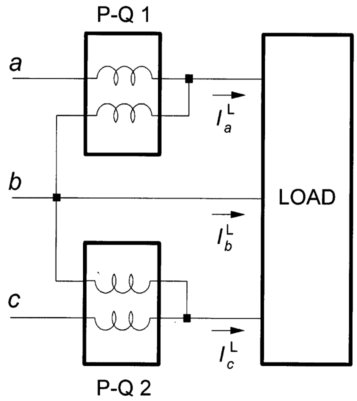

Fig. 2. P–Q transducer connections for SVC control.

$$\bar{V}_{ab}^L(\bar{I}_a^L)^* = V^L \angle 30°[(\bar{I}_1^L)^* + (\bar{I}_2^L)^*]$$
$$\bar{V}_{cb}^L(\bar{I}_c^L)^* = -\alpha^2 V^L \angle 30°[\alpha^2(\bar{I}_1^L)^* + \alpha(\bar{I}_2^L)^*] \quad (10)$$

From Eq. (10), the positive- and negative-sequence currents can be expressed in terms of active and reactive powers.

$$\begin{bmatrix} \bar{I}_1^L \\ \bar{I}_2^L \end{bmatrix} = \frac{-1}{\sqrt{3}V^L} \begin{bmatrix} -1 & -1 \\ \alpha^2 & 1 \end{bmatrix} \begin{bmatrix} (\bar{V}_{ab}^L)^*(\bar{I}_a^L) \\ (\bar{V}_{cb}^L)^*(\bar{I}_c^L) \end{bmatrix} \quad (11)$$

Define the outputs of P–Q transducers as:

$$(\bar{V}_{ab}^L)^*(\bar{I}_a^L) = P_{ab}^L - jQ_{ab}^L$$
$$(\bar{V}_{cb}^L)^*(\bar{I}_c^L) = P_{cb}^L - jQ_{cb}^L \quad (12)$$

where $(P_{ab}^L + P_{cb}^L)$ is the active power consumed by the load. Substituting Eqs. (11) and (12) into Eq. (9), we get the on-line compensation formulas for the SVC.

$$B_{ab}^C = \frac{1}{3(V^L)^2}(3Q_{ab}^L - \sqrt{3}P_{cb}^L)$$
$$B_{bc}^C = \frac{1}{3(V^L)^2}(\sqrt{3}P_{ab}^L + 3Q_{cb}^L)$$
$$B_{ca}^C = \frac{1}{3(V^L)^2}(-\sqrt{3}P_{ab}^L + \sqrt{3}P_{cb}^L) \quad (13)$$

The compensation formula shown in Eq. (13) is very compact and need only two single-phase P–Q transducers, hence it is very suitable for on-line control.

3. Simulation

To show the validity of Eq. (13) and the balanced load bus voltage assumption on the compensation results, a simulation with an unbalanced constant load is performed. The admittances of the unbalanced load shown in Fig. 1 are

$Y^{L}_{ab} = 0.003793 - j\,0.004483S$

$Y^{L}_{bc} = 0.003966 - j\,0.002414S$

$Y^{L}_{ca} = 0.017172 - j\,0.003931S$

Assume that the line voltage at substation bus is $6.9\sqrt{3}kV$, the transmission line impedance is $0.4 + j1.5\Omega$. The simulation results are shown in Fig. 3. The compensating cycle 0 means the insatant before the SVC started. Although the assumption of balanced load bus voltage is not practical, both the unbalanced condition and power factor are greatly improved after the first compensating cycle. After the second compensating cycle, the compensation results approach the balanced steady state. This is due to that the negative-sequence voltage is smaller than positive-sequence voltage, and the negative-sequence voltage is dependent on negative-sequence current with the relation

$$\bar{V}^{L}_{2} = -Z^{T}(1-\alpha)(\bar{I}^{L}_{2} + \bar{I}^{C}_{2}) \quad (14)$$

where the transmission line impedance is assumed to be balanced. The term $\bar{V}^{L}_{2}$ in Eq. (3) then can be eliminated by substituting Eq. (14) into Eq. (3) where the currents and the admittances now include both the load and the SVC.

$$(\bar{I}^{L}_{2} + \bar{I}^{C}_{2}) = \frac{(1-\alpha^{2})(Y^{L}_{1} + Y^{C}_{1})}{3[1 + (Y^{L}_{0} + Y^{C}_{0})]}\bar{V}^{L}_{1} \quad (15)$$

From Eq. (15), it can be shown that the negative-sequence currents in the transmission lines will be reduced to zero when $Y^{C}_{1} = -Y^{L}_{1}$. The conclusion is the same with that of Eq. (6). Why the required compensation susceptance Y^{C}_{1} can not be obtained at first compensating cycle is due to that there are negative-sequence voltages at load bus. However, after the first compensating cycle, the negative-sequence currents and voltages are reduced. For the balanced voltage assumption is more close to the practical condition, the calculated compensation susceptances with Eq. (13) are more close to the required values, that is the difference between Y^{C}_{1} and $-Y^{L}_{1}$ is more and more small. This explains why the compensation results after the second compensating cycle are better than those after the first compensating cycle. Although the assumption that the transmission line is balanced is not unreasonable, the unbalanced line impedances could effect the compensation results in practical system.

4. Implementation

4.1. System architecture

The implemented SVC is installed in a power system simulator as shown in Fig. 4 [13]. The simplified power system simulator represents a typical radial type distribution system. The power system simulator was designed originally for balanced conditions. A single-phase load is added to simulate an unbalanced

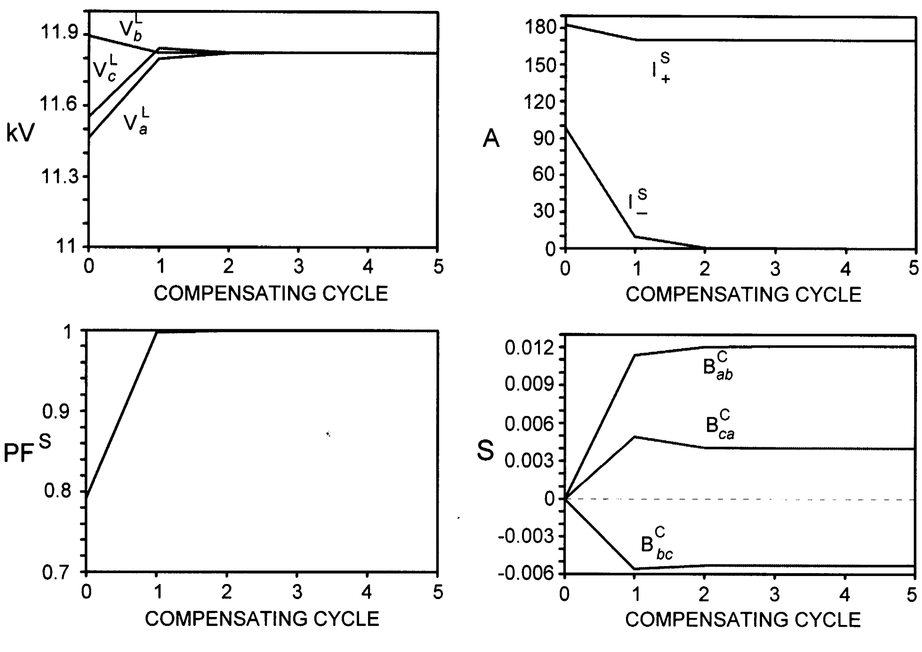

Fig. 3. Dynamic responses of the simulation with a constant unbalanced load.

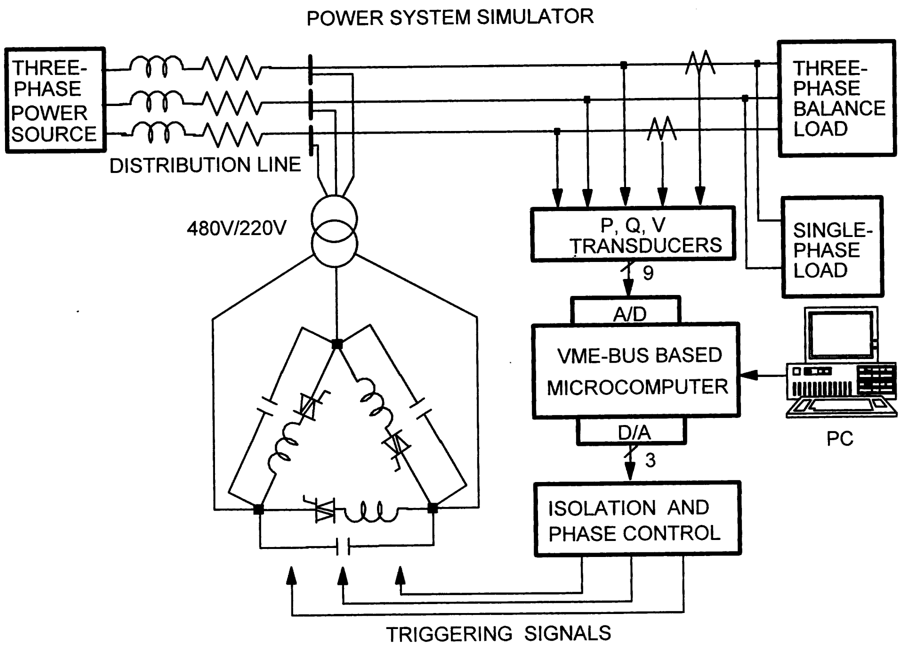

Fig. 4. The block diagram of SVC.

load condition. The SVC that consists of Δ-connected thyristor-controlled reactors and fixed capacitors (TCR-FC) is installed at the industrial load bus. A three-phase step-down transformer is used to reduce the SVC operation voltage. The transducer modules which consist of line-to-line active power (P), reactive power (Q), and voltage (V) transducers are installed near the unbalanced load. A commercially available Motorola VME-bus [14] based microcomputer system is used to synthesize the controller of the SVC. The microcomputer system is consisted of MVME-147 boards (MC68030CPU/MC68882FPU), A/D boards, D/A boards, and other auxiliary units. A PC is used to edit the control program for the microcomputer.

The compensation scheme of the SVC is implemented in the VME-Bus based microcomputer using Eq. (13). Triggering control signals are sent to three independent gating circuits. Each gating circuit includes a phase control circuit and an isolation circuit. The isolation circuit is needed to create an isolation between the controller and the power side. Finally a triggering signal is sent to each thyristor (TRIAC) to control the conduction angle of the TCR in order to give the required compensation susceptances. The flow chart of the control program is shown in Fig. 5. At first the microcomputer gets seven output voltages of transducers by a A/D converter, then re-scales those voltages to match actual power values according to the transducer gains and turn ratios of potential transformers and current transformers. The transducer gains and potential transformer and current transformer turn ratios are given in Appendix A. The actual values of reactive powers and voltages can be obtained similarly. These actual values are used to calculate compensation susceptances of the SVC, B^{C}_{SVC}, by using Eq. (13). The

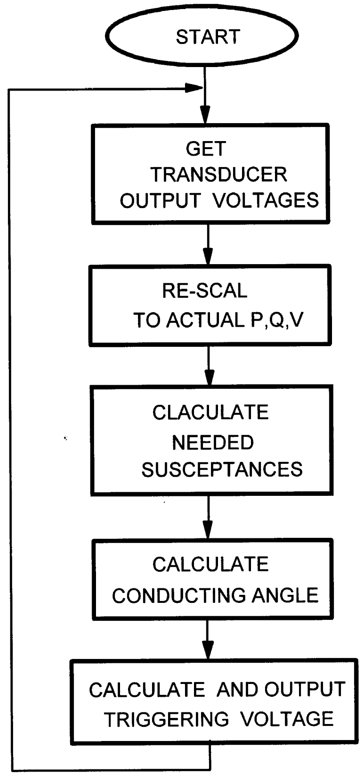

Fig. 5. The flow chart for microcomputer based controller.

needed susceptance of each phase of the TCR is given by the following:

$$B(\sigma)^{C}_{TCR} = B^{C}_{SVC}(P^{L}, Q^{L}, V^{L}) - B^{C}_{FC} \quad (16)$$

where σ is the conduction angle of the TCR and B^{C}_{FC} the susceptance of fixed capacitor in each phase.

The relationship between conduction angles and corresponding susceptances of the TCR is shown in Eq. (17).

$$B(\sigma)^{C}_{TCR} = \frac{\sigma - \sin\sigma}{\pi X_{R}} \quad (17)$$

where X_R is the reactance of the TCR reactor. The conduction angles are calculated by an on-line Newton–Raphson iteration. The three triggering angles are then calculated using the relationship $\alpha = \pi - \sigma/2$ and transferred to triggering voltages where 5–10 V represent 90–180°. Finally the triggering voltages are sent to three gating circuits by a D/A converter.

The control program is first developed in C-language, then compiled and linked to an execution file. The execution file is then down loaded to the VME-bus based microcomputer. The portable characteristics of C-language make the control program more flexible. The control program can be easily moved to any microcomputer that is equipped with a C-compiler and adequate I/O interfaces.

4.2. Test results

Two general unbalanced ratios and a wild recognized apparent power definition for unbalanced three-phase three-wire systems, as shown in Eqs. (18)–(20) [15], are adopted to evaluate the degree of unbalance and the compensation effect of SVC.

$$f_{UR1}(\%) = \frac{f_{-}}{f_{+}} \times 100\% \quad (18)$$

$$f_{UR2}(\%) = \frac{\mathrm{Max}(f_a, f_b, f_c) - \mathrm{Min}(f_a, f_b, f_c)}{\mathrm{Avg}(f_a, f_b, f_c)} \times 100\% \quad (19)$$

$$S = 3\sqrt{\frac{V^2_{ab} + V^2_{bc} + V^2_{ca}}{9}} \times \sqrt{\frac{I^2_a + I^2_b + I^2_c}{3}} \quad (20)$$

A digital recorder and an energy analyzer are used in this experiment to measure the power data. For the test of SVC, a single-phase load of 140 ohm is added to simulate an unbalanced loading condition. When the single-phase load is switched in, the dynamic triggering angle responses of three TCR legs are recorded in Fig. 6. The steady-state distribution line current waveforms with and without the SVC are shown in Fig. 7. The current waveforms of the TCR are shown in Fig. 8. Test results with and without the SVC are recorded in Table 1 for comparisons. It can be seen that the SVC obviously alleviates the degree of unbalances and corrects the power factor from 0.819 to almost unity. Due to the boost of load bus voltage, the loading capacity is also improved.

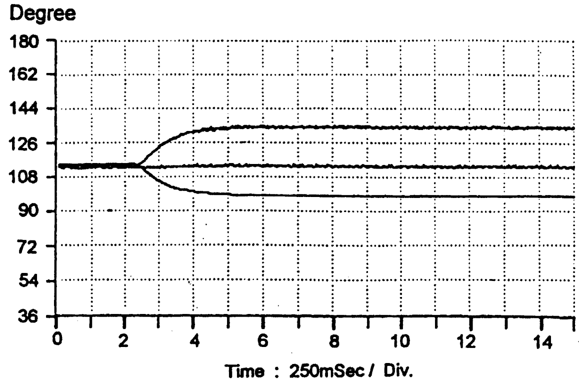

Fig. 6. Dynamic responses of triggering angles.

It can also be observed from Figs. 7 and 8 that the SVC generates harmonic currents. The harmonic problem could be devastation when the parallel resonant frequency caused by the fixed capacitor and the supply system impedance locates in the vicinity of harmonic frequencies of TCR currents. For, the induced harmonic currents from an SVC would flow to the power distribution system and harm the quality of power.

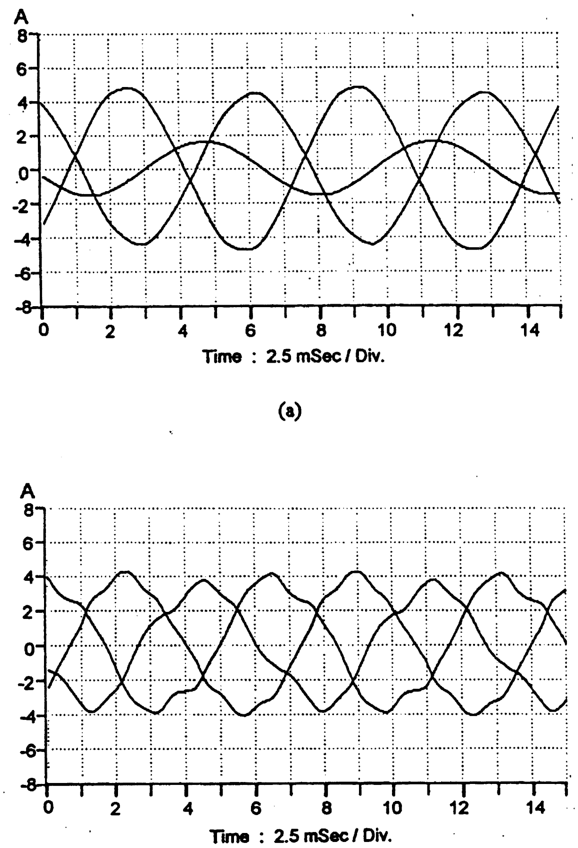

Fig. 7. Distribution line currents, (a) without SVC, (b) with SVC.

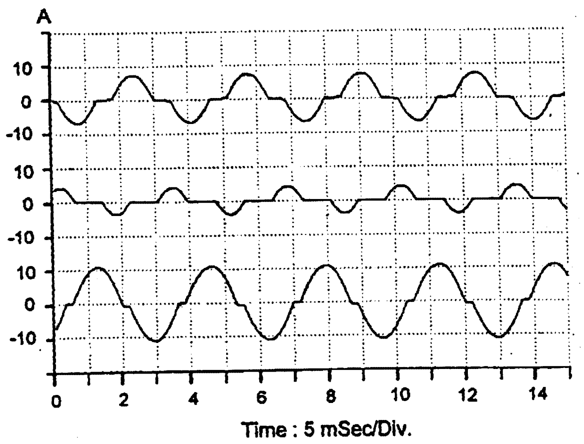

Fig. 8. Steady-state currents of TCR.

Harmonics mitigation techniques such as harmonic filters or more complicated configuration should be employed in the design of SVC [16].

5. Conclusion

A compact algorithm for an SVC which is designed for phase balancing and power factor correction in three-phase three-wire systems is proposed in this paper. For the compensation susceptances of the SVC can be obtained from a very simple function of voltage and power signals, the algorithm is very suitable for on-line control. The required measurement equipment are two single-phase P–Q transducers and a three-phase voltage transducer which are commercially available. Hence, the proposed algorithm is also easy to be implemented. However, when the time response is critical in the application, special circuits for the measurements of active and reactive powers may be needed. Both simulation and experiment results show that, with the SVC, the negative-sequence currents are greatly reduced and the power factor is raised close to unity. The control approach can be adopted easily to other types of SVC.

Table 1
Test results with and without SVC

	Without SVC	With SVC
V^S_{ab} (V)	404	404
V^S_{bc} (V)	402	402
V^S_{ca} (V)	405	405
I^S_a (A)	3.03	2.77
I^S_b (A)	3.38	2.81
I^S_c (A)	1.08	2.38
I^S_+ (A)	2.368	2.63
I^S_- (A)	1.316	0.26
I_{UR1} (%)	55.57[a]	9.89[a]
I_{UR2} (%)	92.12[a]	16.21[a]
V^L_{ab} (V)	346.2	361.9
V^L_{bc} (V)	367.7	363.4
V^L_{ca} (V)	384.5	371.7
V^L_+ (V)	365.4	365.2
V^L_- (V)	22.07	5.99
V_{UR1} (%)	6.04[a]	1.64[a]
V_{UR2} (%)	10.46[a]	2.68[a]
P^L (W)	1400	1664
S^L (VA)	1710[a]	1685[a]
PF^L	0.819[a]	0.988[a]

[a] Calculated values based on the definitions of Eqs. (18)–(20).

Acknowledgements

The authors would like to thank the National Science Council of ROC for the financial support, project number NSC84-0404-E-011-204.

Appendix A. Major system data

A.1. Power system simulator

Substation voltage: 400 V
Three-phase industrial load impedance (Δ-connection): $500 + j300\ \Omega$
Single-phase load impedance: 140 Ω

A.2. SVC module

V transducer gain: 30 V/V
P transducer gain: 250 W/V
Q transducer gain: 250 Var/V
Current transformer: 20 A/5 A
Potential transformer: 480 V/220 V
Per phase inductance of TCR: 50 mH
Per phase capacitance of FC: 80 μF
Sampling time of microcomputer: 2 ms

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