A dynamically SVC based compact control algorithm for load balancing in distribution systems

A. Kazemi, A. Moradi Koochi and R. Rezaeipour

Abstract— An algorithm for applying a fixed capacitor-thyristor-controlled reactor (FC-TCR) type of static var compensator (SVC) for dynamically balancing a system is introduced. With a developed individual phase control scheme, an SVC can reduce negative-sequence current caused by the load to improve system balancing. In addition, the power factor can be improved simultaneously by selecting an appropriate amount of capacitive/inductive compensation. A compact control algorithm for reactive power compensation and load balancing with the static var compensator (SVC) in three-phase systems is used in this paper. Each phase susceptance of the SVC 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 sequence currents after compensation. This Method is simulated on the IEEE 13 node system balancing and total harmonic distortion (THD) is studied in unbalanced load node and Substation bus and results is presented.

Keywords—Distribution system, Negative-sequence current, Static var compensator, Load balancing.

I. INTRODUCTION

THE load is always changing and is normally unbalanced in a distribution system. Imbalance loading condition causes negative sequence current. Negative sequence current will increase the resistive losses in field winding and damper winding of generator [1]. Besides it may cause overheating and instability problems. In distribution system, unbalanced loading increases power loss in the line and prevent using the whole capacity of line. Furthermore it causes voltage asymmetry at utility ends. Voltage asymmetry of an order of only 3.5% may results in a 25% increase in motor temperaturerise [2], Power electronics devices appear to be sensitive to voltage asymmetry too. Namely supply asymmetry may cause generating current harmonics of non-characteristic orders such as third order harmonic [3]-[4]. There is also a mechanism in systems with induction motors that magnify the voltage asymmetry. Considering these problems in a three-phase system, it is necessary to balance the load so that active powers in three phases are equal.

Presently, feeder switching through manual or automatic control to reduce the unbalance of the load is used among industry. Since this is performed in a discrete manner, it cannot dynamically and effectively balance the system load.

In principle, the current of an unbalanced load can be divided into zero, positive, and negative-sequence components. The zero-sequence current only influences the vicinity of the load and can be blocked by a delta-wye grounded transformer. If a device could be found to correct the negative-sequence current in conjunction with the zero-sequence current blocking in the distribution system, one could obtain a balanced system, as viewed from the transmission level.

In this paper, the back ground of load balancing with SVC and different configuration of SVC is Reviewed, In part II. In part III, theory of SVC compensation is summarized. In part IV, compensation suseptance is come and the formulation is given. In part V, case study is presented and simulation are done. In part VI, the results of simulation are presented.

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II. BACK GROUNG

Thyristor-controlled susceptance (TCS) circuits, or commonly called static var compensators (SVCs), have been undergoing development since the 1970's [5]-[6]. The very first basic structure developed was just like the one presented in the above paper, namely, a TSI and a capacitor in parallel [7]. However, the applications of such TCS's have been limited to mainly balanced systems. It has been well known that a thyristor switched inductor is a great source of current harmonics, in particular, the third harmonic. A single-phase TCS with a basic structure may have a current harmonic distortion (CHD) of the order of 50% at some firing angles [7]. When three of such TCS's are connected in a delta configuration, with a symmetrical controlling of firing angles, this compensator is very effective for compensating the reactive power of the load without the injection of third harmonic current to the system. However, it may not be adequate for use in an unbalanced system, since it requires, most likely, an asymmetric controlling of firing angles. When this occurs, the third harmonic currents generated by three TSI branches are in phase, but different in their magnitudes, and therefore, a tremendous amount of CHD is introduced (mainly, the third harmonic) into the system.

There is another potential problem worth mentioning when using a TCS with such a structure, namely, a resonance between the shunt capacitor and the system inductance may occur. All of these above-mentioned drawbacks reduce the applicability of such a TCS.

To overcome the resonant problem between the shunt capacitor and the system inductance, a series inductor can be inserted. To eliminate the third harmonic current generated by a TSI, a harmonic filter tuned to the third harmonic frequency can be employed. A number of TCS's with various structures, as shown in Fig. 1, have been developed, studied, and presented [6],[8]. With the considerations of minimizing harmonic injection to the system and avoiding the resonance between the compensator's capacitor and system inductor with minimum increase of circuit complexity, it was concluded that TCS_SI_PF, having a fairly simple structure, could possibly reduce the CHD to the order of 1%.

A compensator with three TCS_SI_PF's in a delta configuration, could be used to balance an unbalanced system dynamically and, therefore, was termed an "adaptive balancing compensator" (ABC) [6], [9].

III. THEORY OF SVC COMPENSATION

To avoid the complication of other zero-sequence-related problems, a delta-connected SVC is used in the development., every branch has a fixed capacitor and a thyristor-controlled reactor. Equation (1) is the equivalent susceptance or admittance of each branch by controlling the firing delay angles (α) of thyristors. A bidirectional symmetrical control is normally adopted to avoid even-order harmonics.

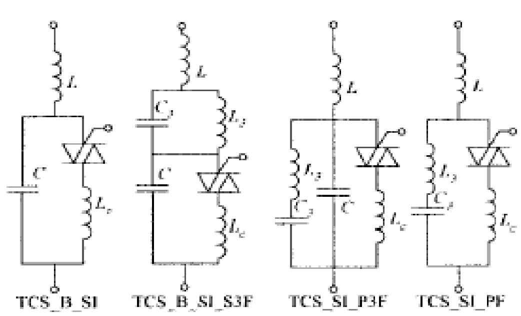

Fig. 1 Various circuit configuration of TCS,s

$$B(\alpha) = B_C - \frac{2\pi - 2\alpha - \sin 2\alpha}{\pi\omega L} \tag{1}$$

whee B_C is the susceptance of the fixed capacitors and L is the original inductance of the thyristor controlled reactor.

As shown in Fig. 2, the zero-sequence current can be blocked by the delta-connected transformer, but the negative-sequence current can still pass through the transformer and go into the transmission system to deteriorate the performance of generators or other machines. Therefore, the purpose of this paper is to derive an algorithm to block the negative-sequence component by adjusting the susceptance of the SVC.

Theoretically, a complete compensation can be obtained and the negative-sequence current can be compensated by an SVC. This idea is illustrated in

$$\begin{bmatrix} 1 & a^2 & a \end{bmatrix} \left(\begin{bmatrix} Y_{ab}+Y_{ca} & -Y_{ab} & -Y_{Ca} \\ -Y_{ab} & Y_{ab}+Y_{bc} & -Y_{bc} \\ -Y_{ca} & -Y_{bc} & Y_{bc}+Y_{ca} \end{bmatrix} \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} + \begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} \right) = 0 \tag{2}$$

where a is the symmetrical component operator e^{j120} and the admittance of the SVC is $Y_{ab}(jB_{ab})$, $Y_{bc}(jB_{bc})$ and $Y_{ca}(jB_{ca})$. Equation (2) can be divided into real and imaginary parts and will have three variables and two equations. An additional constraint has to be added to obtain a unique solution. From the practical point of view, the following constraint is selected:

$$B_{ab} + B_{bc} + B_{ca} = K \tag{3}$$

Where B_{ab} is suseptance of compensator between phases a and b, B_{bc} is suseptance of compensator between phases b and c, B_{ca} is suseptance of compensator between phases c and a. If the power factor of the load needs to be improved at the same time, the right side of equation (3) can be changed to the required value. For simplicity, K is set to zero in the following derivation. Combining equations (2) and (3), one can get all susceptances of the SVC from measured phase voltages and currents at the primary of the transformer[10].

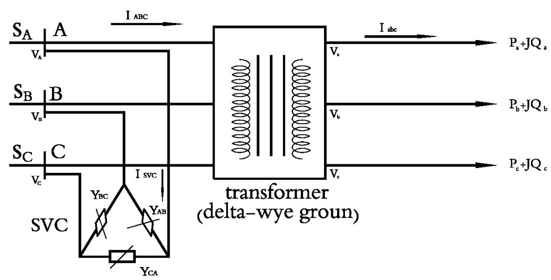

Fig. 2 Various installation of SVC to balance the distribution load

IV. COMPENSATION SUSCEPTANCE

The diagram of the studied system is shown in Fig. 3, where a substation feeds electric power to an unbalanced load through a three-phase 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 usual transformation matrix [11] is defined at first to relate the phase and sequence quantities as shown in Eq. (4).

$$\begin{bmatrix} \overline{V}_{ab} \\ \overline{V}_{bc} \\ \overline{V}_{ca} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} \overline{V}_0^L \\ \overline{V}_1^L \\ \overline{V}_2^L \end{bmatrix} = [T] \begin{bmatrix} \overline{V}_0^L \\ \overline{V}_1^L \\ \overline{V}_2^L \end{bmatrix} \tag{4}$$

Where V_{ab} is voltage between phases a and b, Where V_{bc} is voltage between phases b and c, Where V_{ca} is voltage between phases c and a, V_0^L is zero sequence value of voltage, V_1^L is positive sequence value of voltage, V_2^L is positive sequence value of voltage. In Fig. 3, it is assumed that the load is linear, and then the load current can be expressed as

$$\begin{bmatrix} \overline{I}_a^L \\ \overline{I}_b^L \\ \overline{I}_c^L \end{bmatrix} = \begin{bmatrix} Y_{ab}^L & 0 & -Y_{ca}^L \\ -Y_{ab}^L & Y_{bc}^L & 0 \\ 0 & -Y_{bc}^L & Y_{ca}^L \end{bmatrix} \begin{bmatrix} \overline{V_{ab}^L} \\ \overline{V_{bc}^L} \\ \overline{V_{ca}^L} \end{bmatrix} \tag{5}$$

Applying the symmetrical component transform in Eq. (4) to both side of Eq. (6), we have

$$\begin{aligned} \overline{I}_1^L &= (1-a)(Y_0^L \overline{V}_1^L + Y_2^L \overline{V}_2^L) \\ \overline{I}_2^L &= (1-a^2)(Y_1^L \overline{V}_1^L + Y_0^L \overline{V}_2^L) \end{aligned} \tag{6}$$

The negative sequence voltage $\overline{V}_2^L$ 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 negative sequence voltage is neglected, that is $\overline{V}^L = \overline{V_1^L}$

$$\begin{aligned} \overline{I}_1^L &= (1-a)(Y_0^L V^L) \\ \overline{I}_2^L &= (1-a^2)(Y_1^L V^L) \end{aligned} \tag{7}$$

In order to reduce the negative sequence currents and imaginary part of the positive sequence currents, it is required that

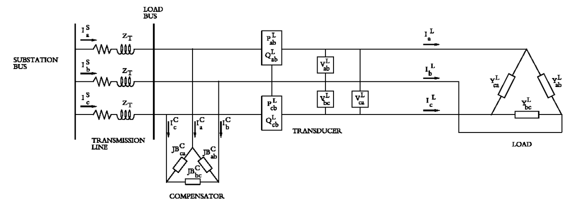

Fig. 3 A three phase system with an SVC at the load bus

$$\begin{aligned} \operatorname{Im}(Y_0^C) &= -\operatorname{Im}(Y_0^L) = -\operatorname{Im}\left[\frac{\overline{I}_1^L}{V^L(1-a^2)}\right] \\ Y_1^C &= -Y_1^L = -\left[\frac{\overline{I}_1^L}{V^L(1-\alpha^2)}\right] \end{aligned} \tag{8}$$

Because an ideal SVC contains no power-consuming element, it can be obtained from Eq. (6) that $Y_2^c = -(Y_1^c)$. Hence, the compensation susceptances of the SVC can be described by Y_1^C and Y_2^C as:

$$\begin{aligned} B_{ab}^C &= \operatorname{Im}(Y_0^C) = 2\operatorname{Im}(Y_1^C) \\ B_{bc}^C &= \operatorname{Im}(Y_0^C) = 2\operatorname{Im}(a^2 Y_1^C) \\ B_{ca}^C &= \operatorname{Im}(Y_0^C) = 2\operatorname{Im}(a Y_1^C) \end{aligned} \tag{9}$$

Substituting Eq. (6) into Eq. (9), the compensation susceptances can be expressed in terms of symmetrical components of the load currents.

$$\begin{aligned} B_{bc}^C &= \frac{-1}{3v^L}\operatorname{Im}\left[(1-a^2)\overline{I_1^L} + 2(a^2-1)\overline{I_2^L}\right] \\ B_{ca}^C &= \frac{-1}{3v^L}\operatorname{Im}\left[(1-a^2)\overline{I_1^L} + 2(a-a^2)\overline{I_2^L}\right] \end{aligned} \tag{10}$$

Four variables, magnitudes and angles of $\overline{I}_1^L$ and $\overline{I_2^L}$, are required to obtain the current information in Eq. (10). 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. 3, the so called two-wattmeter connection method, are used to acquire the four current variables in Eq. (10). In practical implementation, the voltage signal V^L in Eq. (10) 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:

$$\overline{V}_{ab}^L \left(\overline{I}_a^L\right)^* = V^L\left[\left(\overline{I}_1^L\right)^* + \left(\overline{I}_2^L\right)^*\right]$$

$$\overline{V}^L_{ab}\left(\overline{I}^L_a\right)^* = V^L\left[\left(\overline{I}^L_1\right)^* + \left(\overline{I}^L_2\right)^*\right] \tag{11}$$

$$\overline{V}^L_{cb}\left(\overline{I}^L_a\right)^* = -a^2V^L\left[a^2\left(\overline{I}^L_1\right)^* + a\left(\overline{I}^L_2\right)^*\right]$$

From Eq. (11), the positive and negative sequence currents can be expressed in terms of active and reactive powers.

$$\begin{bmatrix} \overline{I}^L_1 \\ \overline{I}^L_2 \end{bmatrix} = \frac{-1}{\left(V^L\right)^2\left(1-a^2\right)}\begin{bmatrix} -1 & -1 \\ a^2 & 1 \end{bmatrix}\begin{bmatrix} \left(\overline{V}^L_{ab}\right)^*\left(\overline{I}^L_a\right) \\ \left(\overline{V}^L_{cb}\right)^*\left(\overline{I}^L_c\right) \end{bmatrix} \tag{12}$$

Define four outputs of P-Q transducers as:

$$\begin{aligned} \left(\overline{V}^L_{ab}\right)^*\left(\overline{I}^L_a\right) &= P^L_{ab} - jQ^L_{ab} \\ \left(\overline{V}^L_{cb}\right)^*\left(\overline{I}^L_c\right) &= P^L_{cb} - jQcb \end{aligned} \tag{13}$$

where $(P_{ab} + P_{ca})$ and $(Q_{ab} + Q_{cd})$ are the active and reactive powers consumed by loads, respectively. Substituting Eq. (13) and Eq. (12) into Eq. (10), we get the on-line compensation formulas for the SVC.

The compensation formula shown in Eq. (14) is very compact and need only two single phase P-Q transducers, so that it is very suitable for on-line control.

$$\begin{aligned} B^C_{ab} &= \frac{1}{3(V^L)^2}(3Q^L_{ab} - \sqrt{3}P^L_{cb}) \\ B^C_{bc} &= \frac{1}{3(V^L)^2}(\sqrt{3}P^L_{ab} + 3Q^L_{cb}) \\ B^C_{ca} &= \frac{1}{3(V^L)^2}(-\sqrt{3}P^L_{ab} + \sqrt{3}P^L_{cb}) \end{aligned} \tag{14}$$

V. CASE STUDY

The implemented SVC is installed in a distribution system simulator as shown in Fig.4. IEEE 13 node distribution system represents the distribution system simulator. An unbalanced load is added to node 675. The SVC that consists of Δ-connected thyristor controlled reactors and fixed capacitors (TCR-FC) is installed at the load node (node no 675). 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 triggering signal is sent to each thyristor to control the conduction angle of the TCR in order to give the required compensation susceptances.

The actual values of reactive powers and voltages can be obtained similarly. These actual values are used to calculate compensation susceptances of the SVC using Eq. (14).

The needed susceptance of each phase of the TCR is given by the following.

$$B(\sigma)^C_{TCR} = B^C_{SVC}\left(P^L, Q^L, V^L\right) - B^C_{FC} \tag{15}$$

The relationship between conduction angles and corresponding susceptances of the TCR is shown in Eq. (1).

VI. SIMULATION RESULTS

Equations (11), (15) and (1) are used to balance load currents of node 675, while SVCs are connected to this node. THD, current waveforms, and RMS current of nodes 675 and 650 (Substation bus) are studied before and after SVCs connection presented in fig. 5 and 6. THDs before and after SVC connection is shown in table 1.

It can also be observed that the SVC generates harmonic currents. The induced harmonic currents from an SVC would flow to the power distribution system and harm the power quality. Harmonics mitigation techniques such as harmonic filters should be employed in the design of SVC.

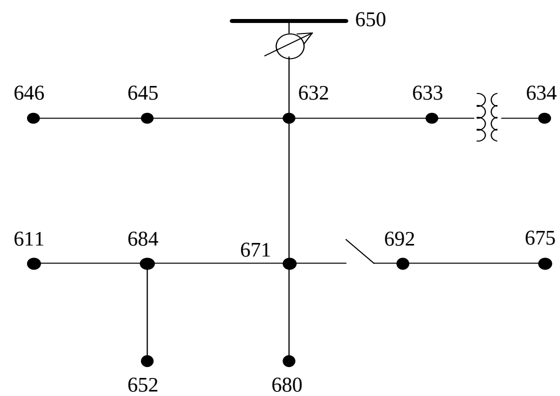

Fig. 4 IEEE 13 node network.

Fig. 5 Unbalanced load current without SVC.

	W/O SVC		With SVC	
	Node 675	Node 650	Node 675	Node 650
Ia (pu)	0.4582	0.2268	0.6102	0.2635
Ib (pu)	0.547	0.2508	0.5628	0.2969
Ic (pu)	0.1238	0.1638	0.5505	0.2873
THD	0.003596		0.000896	
I1 (pu)	0.6622	0.3207	0.8629	0.3726
I2 (pu)	8.37E-06	5.94E-06	2.00E-05	8.10E-06
I3 (pu)	6.34E-06	8.67E-06	2.80E-05	1.20E-05

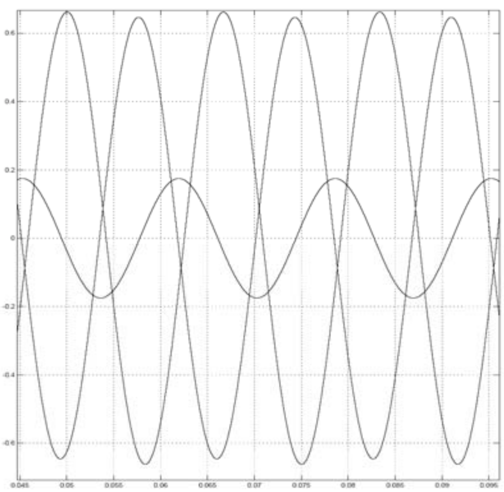

Fig. 5 Unbalanced load current without SVC.

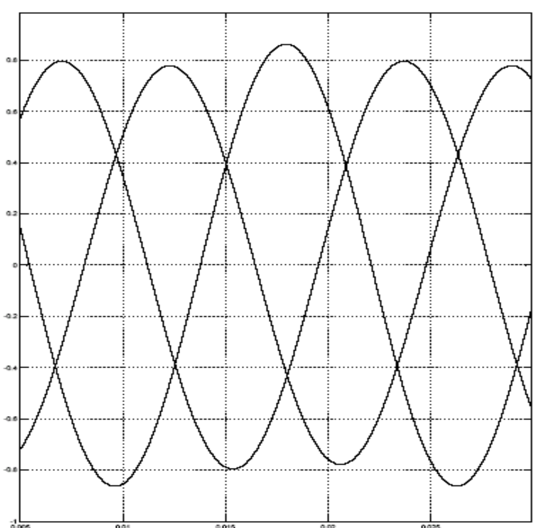

Fig. 6 Load current with SVC.

VII. Conclusion

An algorithm for applying a fixed capacitor-thyristor-controlled reactor (FC-TCR) type of static var compensator (SVC) for dynamically balancing a system is proposed in this paper. Since the phase susceptance 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 equipments are two single-phase P-Q transducers and a three-phase voltage transducer which are commercially available. Simulation results show that, with the SVC, THD is greatly reduced. The control approach can be easily adopted to other types of SVC.

Table1.RMS,THD,1st, 2nd & 3rd Harmonic of current in phase A

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