ON–LINE REACTIVE POWER COMPENSATION SCHEMES FOR UNBALANCED THREE PHASE FOUR WIRE DISTRIBUTION FEEDERS

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Abstract: A new reactive power compensation method is developed to reduce the negative and zero sequence components of load currents and to improve the load bus power factor of unbalanced three–phase four–wire distribution feeders. Negative and zero sequence currents may cause additional losses and damages to power systems. Load compensation at the load bus is an effective method to eliminate those undesired sequence currents. The compensation technique uses a Y–connected and a Δ–connected static reactive power compensators to give a different amount of reactive power compensation to each phase. The compensation formulas are very suitable for on–line control by measuring phase voltages and currents in the real time. The compensation effect can also be achieved even if one leg of the SVCs is out of service. In addition to balancing effect and power factor improvement at the load bus, the SVCs can also be used to support the load bus voltage and to maintain the substation feeder at unity power factor. Digital simulations are made with the load data measured from an 11.4kV secondary substation feeder.

Key words:reactive power compensation, negative sequence current, zero sequence current

1. Introduction

An electrical power system is expected to operate in a balanced three–phase condition. But unbalanced loads in a three–phase four–wire system produce undesired negative and zero sequence currents. Negative sequence currents will cause excessive heating of alternator rotors, saturation of transformers, and ripple in rectifiers [1–2]. Sometimes they may cause severe instability problems of generators. If a synchronous generator works at 60 Hz, the negative sequence currents build a revolving field on the generator stator in the counter–direction of the rotor at a speed of 60 Hz. A 120 Hz component of current appears in the rotor field winding. The frequency is in the range of the so called supersynchronous frequencies [3–4]. This supersynchronous current produces a supersynchronous torque on the rotor shaft that causes the rotor to oscillate at the supersynchronous frequency. If one of the natural mode frequencies of the rotor shaft is very close to 120 Hz, the induced supersynchronous torque will coincide with the shaft natural mode and cause a severe supersynchronous resonant oscillation. The shaft may be damaged by this resonance. Negative sequence currents must be reduced to avoid the undesired induced torque.

Zero sequence currents cause not only excessive power losses in neutral lines but also protection and interference problems [2]. It is hard to distinguish this component produced by single line–to–ground faults from that by heavy unbalanced loads. Zero sequence currents may inductively induce voltages in the neighboring communication circuits, gas pipelines, and water pipelines by resistive or magnetic coupling in urban and rural areas [5]. It is also better to reduce the zero sequence currents produced by unbalanced loads for economic and safe operation considerations.

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Most industry loads have lagging power factors [1], i.e., they consume reactive power. The line currents carrying the reactive power cause additional losses and voltage drop on the transmission lines. It is better to supply the required reactive power as close as possible to the load, i.e., to correct the power factor at the load bus.

It is known for a long time in using static reactive power compensators (SVCs) to balance load currents and to improve power factor of unbalanced power systems. Each phase of the SVCs can be independently controlled and give a different amount of reactive power compensation. In Gyugyi's frequently referred paper [6], the derivation of load balancing theorem is based on the symmetrical component method. However, the same results can also be obtained by minimizing the quadratic sum of three–phase currents [7]. Recently, most of the studies about SVCs concentrate on application techniques, such as using high speed programmable controllers [8] or microprocessors [9–10] and solving suboptimal solutions when discrete–tap compensators [11] are used. However, all the papers mentioned consider three–phase three–wire systems, and their methods can only eliminate the negative sequence currents.

The 11.4kV and/or 22.8kV (line–to–line) voltage level three–phase four–wire distribution lines are used in the Taipower system. Both negative and zero sequence currents may be produced by unbalanced loads. In this paper, a new reactive power compensation method is developed to reduce the negative and zero sequence currents and to improve the load bus power factor. The technique uses a Y–connected SVC (Y–SVC) and a Δ–connected SVC (Δ–SVC) to give a different amount of reactive power compensation to each phase. While the Δ–SVC is used to eliminate the negative sequence currents, the Y–SVC is used to eliminate the zero sequence currents and the imaginary part of the positive sequence currents. Digital simulations are made with a 24–hour load data measured from an 11.4kV secondary substation feeder. The effects of ten compensation schemes are compared. Simulation results show that the SVCs not only give the balancing effect but also support the load bus voltage. The energy losses due to the distribution line resistances are greatly reduced by the SVCs. Only the Y–SVC or the Δ–SVC used alone can not simultaneously eliminate negative and zero sequence currents.

2. Fundamental load compensation

Consider the three–phase four–wire distribution system as shown in Fig.1, where the substation is assumed to be a constant balanced voltage source and the three distribution line impedances are equal. The load is represented by three–phase Y–connected admittances. Load admittances can be obtained from the measurement of load side voltages and currents. If the load is unbalanced, the distribution line currents are unbalanced and cause unequal voltage drop on the distribution lines such that the load bus voltages are unbalanced. In order to balance the line currents and improve the power factor, a Y–connected SVC (Y–SVC) and a Δ–connected SVC (Δ–SVC) are placed at the load bus to provide a different amount of reactive power compensation to each phase. The symmetric component method

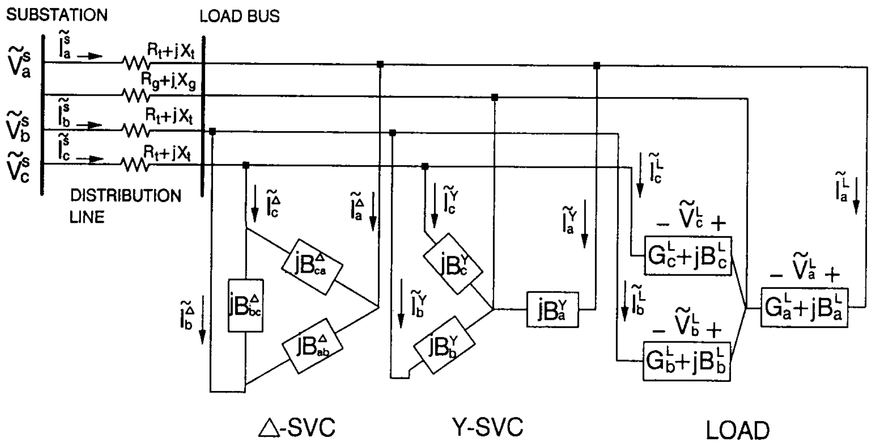

Fig.1 An unbalanced three–phase four–wire distribution system with SVCs placed at the load bus.

is used in the derivation process of the compensation formulas. Although the load is unbalanced, it is balanced viewed at the load bus if the SVCs are incorporated. Then, at first, it is convenient to assume that the load bus voltages are balanced.

$$\tilde{V}_a^L=\tilde{V},\quad \tilde{V}_b^L=a^2\tilde{V},\quad \tilde{V}_c^L=a\tilde{V} \tag{1}$$

where $a=e^{j(2/3)\pi}=-1/2+j\sqrt{3}/2$ and $\tilde{V}=V/\underline{0}$. For an arbitrary three–phase load, the load currents expressed in terms of load admittances are

$$\begin{aligned}\tilde{I}_a^L&=(G_a^L+jB_a^L)V\\ \tilde{I}_b^L&=a^2(G_b^L+jB_b^L)V\\ \tilde{I}_c^L&=a(G_c^L+jB_c^L)V\end{aligned} \tag{2}$$

The symmetric components of the load currents are

$$\begin{aligned}\tilde{I}_0^L&=(1/3)[G_a^L+a^2G_b^L+aG_c^L+j(B_a^L+a^2B_b^L+aB_c^L)]V\\ \tilde{I}_1^L&=(1/3)[G_a^L+G_b^L+G_c^L+j(B_a^L+B_b^L+B_c^L)]V\\ \tilde{I}_2^L&=(1/3)[G_a^L+aG_b^L+a^2G_c^L+j(B_a^L+aB_b^L+a^2B_c^L)]V\end{aligned} \tag{3}$$

Similarly, the symmetric components of the Y–SVC currents are

$$\begin{aligned}\tilde{I}_0^Y&=j(1/3)(B_a^Y+a^2B_b^Y+aB_c^Y)V\\ \tilde{I}_1^Y&=j(1/3)(B_a^Y+B_b^Y+B_c^Y)V\\ \tilde{I}_2^Y&=j(1/3)(B_a^Y+aB_b^Y+a^2B_c^Y)V\end{aligned} \tag{4}$$

And the symmetric components of the Δ–SVC currents are

$$\begin{aligned}\tilde{I}_0^\Delta&=0\\ \tilde{I}_1^\Delta&=j(B_{ab}^\Delta+B_{bc}^\Delta+B_{ca}^\Delta)V\\ \tilde{I}_2^\Delta&=-j(a^2B_{ab}^\Delta+B_{bc}^\Delta+aB_{ca}^\Delta)V\end{aligned} \tag{5}$$

With the SVCs, it is expected that the negative and zero sequence components of the load currents are eliminated and the power factor at the load bus is unity. Then

$$\begin{aligned}&\mathrm{Re}[\tilde{I}_2^L]+\mathrm{Re}[\tilde{I}_2^Y]+\mathrm{Re}[\tilde{I}_2^\Delta]=0\\ &\mathrm{Im}[\tilde{I}_2^L]+\mathrm{Im}[\tilde{I}_2^Y]+\mathrm{Im}[\tilde{I}_2^\Delta]=0\\ &\mathrm{Re}[\tilde{I}_0^L]+\mathrm{Re}[\tilde{I}_0^Y]=0\\ &\mathrm{Im}[\tilde{I}_0^L]+\mathrm{Im}[\tilde{I}_0^Y]=0\\ &\mathrm{Im}[\tilde{I}_1^L]+\mathrm{Im}[\tilde{I}_1^Y]+\mathrm{Im}[\tilde{I}_1^\Delta]=0\end{aligned} \tag{6}$$

Substitution of eqs.(3), (4), and (5) into eq.(6) gives

$$\begin{aligned}&B_a^Y-(1/2)B_b^Y-(1/2)B_c^Y\\ &=-B_a^L+(1/2)B_b^L+(1/2)B_c^L+(\sqrt{3}/2)G_b^L-(\sqrt{3}/2)G_c^L\\ &(\sqrt{3}/2)B_b^Y-(\sqrt{3}/2)B_c^Y\\ &=-G_a^L+(1/2)G_b^L+(1/2)G_c^L+(\sqrt{3}/2)B_c^L-(\sqrt{3}/2)B_b^L\\ &(1/3)(B_a^Y+B_b^Y+B_c^Y)+(B_{ab}^\Delta+B_{bc}^\Delta+B_{ca}^\Delta)\\ &=-(1/3)(B_a^L+B_b^L+B_c^L)\\ &(1/2)B_{ab}^\Delta-B_{bc}^\Delta+(1/2)B_{ca}^\Delta+(1/3)(B_a^Y-(1/2)B_b^Y-(1/2)B_c^Y)\\ &=(1/3)[-B_a^L+(1/2)B_b^L+(1/2)B_c^L-(\sqrt{3}/2)G_b^L+(\sqrt{3}/2)G_c^L]\\ &-(\sqrt{3}/2)B_{ab}^\Delta+(\sqrt{3}/2)B_{ca}^\Delta+(1/3)[-(\sqrt{3}/2)B_b^Y+(\sqrt{3}/2)B_c^Y]\\ &=(1/3)[-G_a^L+(1/2)G_b^L+(1/2)G_c^L+(\sqrt{3}/2)B_b^L-(\sqrt{3}/2)B_c^L]\end{aligned} \tag{7}$$

Eq.(7) has infinite solutions because there are six unknowns (susceptances of the Y–SVC and the Δ–SVC) with five constraints. An additional constraint together with the five in eq.(7) will offer a unique solution. In this paper, the first suggested constraint is that the imaginary part of the positive sequence component of load currents is eliminated by the Y–SVC alone, i.e., the Δ–SVC doesn't generate imaginary part of positive sequence currents. Then the new constraint is

$$B_{ab}^\Delta+B_{bc}^\Delta+B_{ca}^\Delta=0 \tag{8}$$

With the new constraint, the solution of eq.(7) gives the compensation susceptances of the Y–SVC and the Δ–SVC, which are expressed in terms of load conductances and susceptances

$$\begin{aligned}
B_a^Y &= -B_a^L + (1/\sqrt{3})G_b^L - (1/\sqrt{3})G_c^L \\
B_b^Y &= -B_b^L + (1/\sqrt{3})G_c^L - (1/\sqrt{3})G_a^L \\
B_c^Y &= -B_c^L + (1/\sqrt{3})G_a^L - (1/\sqrt{3})G_b^L \\
B_{ab}^\Delta &= (2/3\sqrt{3})(G_a^L - G_b^L) \\
B_{bc}^\Delta &= (2/3\sqrt{3})(G_b^L - G_c^L) \\
B_{ca}^\Delta &= (2/3\sqrt{3})(G_c^L - G_a^L)
\end{aligned} \tag{9}$$

It is observed in eq.(9) that the compensation susceptances are independently on the load bus voltages. The assumption that the load bus voltages are balanced automatically disappears. Although the load is unbalanced, the load bus is balanced if the SVCs are used.

The compensation susceptances expressed in terms of load admittances are compact, however they are useless for on–line compensation because the load admittances are varying day and night. The load admittances can be obtained from the measurement of load voltages and currents.

$$\begin{aligned}
G_a^L &= \frac{I_a^L}{V_a^L}\cos\theta_a \\
B_a^L &= -\frac{I_a^L}{V_a^L}\sin\theta_a \\
G_b^L &= \frac{I_b^L}{V_b^L}\cos\theta_b \\
B_b^L &= -\frac{I_b^L}{V_b^L}\sin\theta_b \\
G_c^L &= \frac{I_c^L}{V_c^L}\cos\theta_c \\
B_c^L &= -\frac{I_c^L}{V_c^L}\sin\theta_c
\end{aligned} \tag{10}$$

where $\theta_i = \angle V_i^L - \angle I_i^L$, i=a, b, and c. Substituting eq.(10) into eq.(9), we get the on–line compensation formulas for the SVCs.

$$\begin{aligned}
B_a^Y &= \frac{I_a^L}{V_a^L}\sin\theta_a + \frac{1}{\sqrt{3}}\frac{I_b^L}{V_b^L}\cos\theta_b - \frac{1}{\sqrt{3}}\frac{I_c^L}{V_c^L}\cos\theta_c \\
B_b^Y &= -\frac{1}{\sqrt{3}}\frac{I_a^L}{V_a^L}\cos\theta_a + \frac{I_b^L}{V_b^L}\sin\theta_b + \frac{1}{\sqrt{3}}\frac{I_c^L}{V_c^L}\cos\theta_c \\
B_c^Y &= \frac{1}{\sqrt{3}}\frac{I_a^L}{V_a^L}\cos\theta_a - \frac{1}{\sqrt{3}}\frac{I_b^L}{V_b^L}\cos\theta_b + \frac{I_c^L}{V_c^L}\sin\theta_c \\
B_{ab}^\Delta &= (2/3\sqrt{3})\left(\frac{I_a^L}{V_a^L}\cos\theta_a - \frac{I_b^L}{V_b^L}\cos\theta_b\right) \\
B_{bc}^\Delta &= (2/3\sqrt{3})\left(\frac{I_b^L}{V_b^L}\cos\theta_b - \frac{I_c^L}{V_c^L}\cos\theta_c\right) \\
B_{ca}^\Delta &= (2/3\sqrt{3})\left(\frac{I_c^L}{V_c^L}\cos\theta_c - \frac{I_a^L}{V_a^L}\cos\theta_a\right)
\end{aligned} \tag{11}$$

3. Compensation under minimum quadratic sum of SVCs currents or reactive powers

In the previous section there are infinite solutions of compensation susceptances unless an additional constraint is added. Another two additional constraints may be used. One is the condition of minimum quadratic sum of SVC currents, and the other of minimum quadratic sum of SVC reactive powers. Two benefits can be obtained. One is a less amount of power loss caused by the SVCs, and the other a less capacity size of the SVCs.

At first, the condition of minimum quadratic sum of SVC currents is discussed. From eq.(7), if B_a^Y is given, the other compensation susceptances are obtained as follows:

$$\begin{aligned}
B_b^Y &= B_a^Y - \tfrac{1}{\sqrt{3}}G_a^L - \tfrac{1}{\sqrt{3}}G_b^L + \tfrac{2}{\sqrt{3}}G_c^L + B_a^L - B_b^L \\
B_c^Y &= B_a^Y + \tfrac{1}{\sqrt{3}}G_a^L - \tfrac{2}{\sqrt{3}}G_b^L + \tfrac{1}{\sqrt{3}}G_c^L + B_a^L - B_c^L \\
B_{ab}^\Delta &= (1/3)(-B_a^Y + \tfrac{2}{\sqrt{3}}G_a^L - \tfrac{1}{\sqrt{3}}G_b^L - \tfrac{1}{\sqrt{3}}G_c^L - B_a^L) \\
B_{bc}^\Delta &= (1/3)(-B_a^Y + \sqrt{3}G_b^L - \sqrt{3}G_c^L - B_a^L) \\
B_{ca}^\Delta &= (1/3)(-B_a^Y - \tfrac{2}{\sqrt{3}}G_a^L + \tfrac{1}{\sqrt{3}}G_b^L + \tfrac{1}{\sqrt{3}}G_c^L - B_a^L)
\end{aligned} \tag{12}$$

Define the object function of SVC currents

$$\begin{aligned}
F = &(B_a^Y V)^2 + (B_b^Y V)^2 + (B_c^Y V)^2 \\
&+ (B_{ab}^\Delta \sqrt{3}V)^2 + (B_{bc}^\Delta \sqrt{3}V)^2 + (B_{ca}^\Delta \sqrt{3}V)^2
\end{aligned} \tag{13}$$

Substituting eq.(12) into eq.(13), we get

$$F = [2B_a^Y(2B_a^Y - \tfrac{4}{\sqrt{3}}G_b^L + \tfrac{4}{\sqrt{3}}G_c^L + 3B_a^L - B_b^L - B_c^L) + K]V^2 \tag{14}$$

where K contains others terms independent on B_a^Y. The solution of B_a^Y is obtained by

$$dF/dB_a^Y = 0 \tag{15}$$

, which gives

$$B_a^Y = \tfrac{1}{\sqrt{3}}G_b^L - \tfrac{1}{\sqrt{3}}G_c^L - \tfrac{3}{4}B_a^L + \tfrac{1}{4}B_b^L + \tfrac{1}{4}B_c^L \tag{16}$$

The other compensation susceptances can be obtained by substituting eq.(16) into eq.(12).

The derivation procedure with the condition of a minimum quadratic sum of SVC reactive powers can be done in a similar way. Define the object function of the SVC reactive powers

$$\begin{aligned}
H = &(B_a^Y V^2)^2 + (B_b^Y V^2)^2 + (B_c^Y V^2)^2 \\
&+ (B_{ab}^\Delta 3V^2)^2 + (B_{bc}^\Delta 3V^2)^2 + (B_{ca}^\Delta 3V^2)^2
\end{aligned} \tag{17}$$

The solution of B_a^Y can be obtained from

$$dH/dB_a^Y = 0 \tag{18}$$

That gives

$$B_a^Y = \tfrac{1}{\sqrt{3}}G_b^L - \tfrac{1}{\sqrt{3}}G_c^L - \tfrac{5}{6}B_a^L + \tfrac{1}{6}B_b^L + \tfrac{1}{6}B_c^L \tag{19}$$

The other compensation susceptances can also be obtained by substituting eq.(19) into eq.(7).

4. Compensation under one leg of the SVCs out of service

If one leg of the SVCs is out of service due to maintenance or outage, the other five legs can also give the desired compensation effect declared in eq.(6). If leg–a of the Y–SVC is out of service, i.e., $B^{Y}_{a}=0$, the other five compensation susceptances obtained from eq.(7) are

$$\begin{aligned}
B^{Y}_{b}&=-\tfrac{1}{\sqrt{3}}G^{L}_{a}-\tfrac{1}{\sqrt{3}}G^{L}_{b}+\tfrac{2}{\sqrt{3}}G^{L}_{c}+B^{L}_{a}-B^{L}_{b}\\
B^{Y}_{c}&=\tfrac{1}{\sqrt{3}}G^{L}_{a}-\tfrac{2}{\sqrt{3}}G^{L}_{b}+\tfrac{1}{\sqrt{3}}G^{L}_{c}+B^{L}_{a}-B^{L}_{c}\\
B^{Y}_{ab}&=(1/3)(\tfrac{2}{\sqrt{3}}G^{L}_{a}-\tfrac{1}{\sqrt{3}}G^{L}_{b}-\tfrac{1}{\sqrt{3}}G^{L}_{c}-B^{L}_{a})\\
B^{Y}_{bc}&=(1/3)(\sqrt{3}G^{L}_{b}-\sqrt{3}G^{L}_{c}-B^{L}_{a})\\
B^{Y}_{ca}&=(1/3)(-\tfrac{2}{\sqrt{3}}G^{L}_{a}+\tfrac{1}{\sqrt{3}}G^{L}_{b}+\tfrac{1}{\sqrt{3}}G^{L}_{c}-B^{L}_{a})
\end{aligned} \tag{20}$$

Another case is that leg–ab of the Δ–SVC is out of service, i.e., $B^{\Delta}_{ab}=0$. Similarly, from eq.(7)

$$\begin{aligned}
B^{Y}_{a}&=\tfrac{2}{\sqrt{3}}G^{L}_{a}-\tfrac{1}{\sqrt{3}}G^{L}_{b}-\tfrac{1}{\sqrt{3}}G^{L}_{c}-B^{L}_{a}\\
B^{Y}_{b}&=\tfrac{1}{\sqrt{3}}G^{L}_{a}-\tfrac{2}{\sqrt{3}}G^{L}_{b}+\tfrac{1}{\sqrt{3}}G^{L}_{c}-B^{L}_{b}\\
B^{Y}_{c}&=\sqrt{3}G^{L}_{a}-\sqrt{3}G^{L}_{b}-B^{L}_{c}\\
B^{Y}_{bc}&=(1/3)(-\tfrac{2}{\sqrt{3}}G^{L}_{a}+\tfrac{4}{\sqrt{3}}G^{L}_{b}-\tfrac{2}{\sqrt{3}}G^{L}_{c})\\
B^{Y}_{ca}&=(1/3)(-\tfrac{4}{\sqrt{3}}G^{L}_{a}+\tfrac{2}{\sqrt{3}}G^{L}_{b}+\tfrac{2}{\sqrt{3}}G^{L}_{c})
\end{aligned} \tag{21}$$

5. Compensation under voltage support

In addition to the balancing effect and power factor correction, the SVCs can also be used for voltage regulation. It is better to keep the load side voltage level the same with the source side, that is, to recover the voltage drop on the distribution lines. If the SVCs with their susceptances tuned by the previous formulas are used, the load bus is equivalent to a balanced three phase systems. The equivalent one–line diagram of Fig.1 is given in Fig.2, where

$$G_{e}=\tfrac{1}{3}(G^{L}_{a}+G^{L}_{b}+G^{L}_{c}) \tag{22}$$

To maintain the load bus voltage magnitude equal to that of the substation, an additional compensation susceptance, B_e, needs to be added to each phase. The voltage equation is

$$\left|\frac{V^{s}}{R_{t}+jX_{t}+\frac{1}{G_{e}+jB_{e}}}\right|\left|\frac{1}{G_{e}+jB_{e}}\right|=V^{s} \tag{23}$$

Then

$$B_{e}=\frac{X_{t}\pm\sqrt{X_{t}^{2}-(X_{t}^{2}+R_{t}^{2})(2R_{t}G_{e}+R_{t}^{2}G_{e}^{2}+X_{t}^{2}G_{e}^{2})}}{R_{t}^{2}+X_{t}^{2}} \tag{24}$$

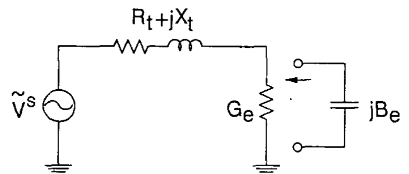

Fig.2 Equivalent diagram of the system after compensation.

Usually the minus sign is selected so that a smaller SVC can satisfy the compensation effect. B_e can be added to each phase of the Y–SVC. Another way is to add $(1/3)B_e$ to each phase of the Δ–SVC.

6. Compensation under unity power factor at substation end

Although with the Y–SVC and the Δ–SVC, the power factor at the load bus is unity, it is required to maintain the substation feeders at unity power factor for higher energy efficiency. The distribution lines and the loads viewed from the substation are pure resistance loads. Then

$$\mathrm{Im}(R_{t}+jX_{t}+\frac{1}{G_{e}+jB_{e}})=0 \tag{24}$$

The additional compensation susceptance to each phase is

$$B_{e}=\frac{1-\sqrt{1-4X_{t}^{2}G_{e}^{2}}}{2X_{t}} \tag{25}$$

7. Compensation only by Y–SVC or Δ–SVC alone

Partial compensation effect can be achieved if only the Y–SVC or the Δ–SVC is used. If the Δ–SVC is used alone to eliminate the negative sequence currents and the imaginary part of positive sequence currents, the compensation susceptances are

$$\begin{aligned}
B^{\Delta}_{ab}&=(1/9)(\sqrt{3}G^{L}_{a}-\sqrt{3}G^{L}_{b}-2B^{L}_{a}-2B^{L}_{b}+B^{L}_{c})\\
B^{\Delta}_{bc}&=(1/9)(\sqrt{3}G^{L}_{b}-\sqrt{3}G^{L}_{c}+B^{L}_{a}-2B^{L}_{b}-2B^{L}_{c})\\
B^{\Delta}_{ca}&=(1/9)(-\sqrt{3}G^{L}_{a}+\sqrt{3}G^{L}_{c}-2B^{L}_{a}+B^{L}_{b}-2B^{L}_{c})
\end{aligned} \tag{26}$$

On the other hand, if the Y–SVC is used alone to eliminate the zero sequence currents and the imaginary part of the positive sequence currents, the compensation susceptances are

$$\begin{aligned}
B^{Y}_{a}&=\tfrac{1}{\sqrt{3}}G^{L}_{b}-\tfrac{1}{\sqrt{3}}G^{L}_{c}-B^{L}_{a}\\
B^{Y}_{b}&=-\tfrac{1}{\sqrt{3}}G^{L}_{a}+\tfrac{1}{\sqrt{3}}G^{L}_{c}-B^{L}_{b}\\
B^{Y}_{c}&=\tfrac{1}{\sqrt{3}}G^{L}_{a}-\tfrac{1}{\sqrt{3}}G^{L}_{b}-B^{L}_{c}
\end{aligned} \tag{27}$$

8. Simulations

In order to demonstrate the compensation capability of the SVCs, simulations are made with the load data measured at feeder 14 of the Huahcherng secondary substation on October 17, 1991. This 6.9kV (rms, line–to–neutral) feeder supplies electric power to small industry plants, stores, and apartments. The distribution line impedances in Fig.1 are $R_t+jX_t=0.4+j1.5\Omega$ and $R_g+jX_g=0.6+j2.2\Omega$. The radius of neutral lines is smaller than that of phase lines.

There are ten compensation schemes for comparison:

scheme 1: without SVC.

scheme 2: with Y–SVC and Δ–SVC. The imaginary part of positive sequence component of load currents is eliminated by the Y–SVC. The compensation formula is given in eq.(9).

scheme 3: with Y–SVC and Δ–SVC, and the minimum quadratic sum of SVC currents condition.

scheme 4: with Y–SVC and Δ–SVC, and the minimum quadratic sum of SVC reactive powers.

scheme 5: with Y–SVC and Δ–SVC, but leg–a of the Y–SVC out of service.

Table 1 Results of simulation 1.

		scheme 1	scheme 2	scheme 3	scheme 4	scheme 5	scheme 6	scheme 7	scheme 8	scheme 9	scheme10
substation	I_a^s, A	232.02	179.89	179.89	179.89	179.89	179.89	189.4	180.3	195.2	215.23
	I_b^s, A	149.13	179.89	179.89	179.89	179.89	179.89	189.4	180.3	187.52	145.41
	I_c^s, A	182.79	179.89	179.89	179.89	179.89	179.89	189.4	180.3	156.73	186.04
	I_0^s, A	22.83	0	0	0	0	0	0	0	22.39	0.3545
	I_1^s, A	185.98	179.89	179.89	179.89	179.89	179.89	189.4	180.3	179.07	179.9
	I_2^s, A	37.23	0	0	0	0	0	0	0	0.7618	40.78
	I_0^s/I_1^s, %	12.28	0	0	0	0	0	0	0	12.5	0.2
	I_2^s/I_1^s, %	20.02	0	0	0	0	0	0	0	0.43	22.67
	PF^s	0.928	0.999	0.999	0.999	0.999	0.999	–0.972	1	0.995	0.986
Load Bus	V_a^L, V	6513	6822	6822	6822	6822	6822	6900	6833	6653	6777
	V_b^L, V	6928	6822	6822	6822	6822	6822	6900	6833	6993	6806
	V_c^L, V	6774	6822	6822	6822	6822	6822	6900	6833	6830	6886
	PF^L,	0.76	1	1	1	1	1	–0.961	–0.999	0.995	0.987
Distribution line	P_{Loss}, W	46610	38831	38831	38831	38831	38831	43047	39012	42087	40833
Y–SVC	B_a^Y, Ω^{-1}	0	0.01342	0.006839	0.009033	0	0.02551	0.02106	0.01446	0	0.01342
	B_b^Y, Ω^{-1}	0	0.0009708	–0.00561	–0.003416	–0.01245	0.01306	0.008607	0.002015	0	0.000971
	B_c^Y, Ω^{-1}	0	0.01193	0.005351	0.007544	–0.001488	0.02402	0.01957	0.01298	0	0.01193
Δ–SVC	B_{ab}^{Δ}, Ω^{-1}	0	0.00403	0.006223	0.005492	0.008503	0	0.00403	0.00403	0.005902	0
	B_{bc}^{Δ}, Ω^{-1}	0	–0.001997	0.0001968	–0.000534	0.002476	–0.006026	–0.001997	–0.001997	–0.000621	0
	B_{ca}^{Δ}, Ω^{-1}	0	–0.002033	0.0001605	–0.000571	0.00244	–0.006062	–0.00203	–0.00203	0.003493	0

scheme 6: with Y–SVC and Δ–SVC, but leg–ab of the Δ–SVC out of service.

scheme 7: with Y–SVC and Δ–SVC, and voltage support.

scheme 8: with Y–SVC and Δ–SVC, and unity power factor at substation.

scheme 9: with Δ–SVC alone.

scheme 10: with Y–SVC alone.

Simulation 1: Constant admittance load

In order to compare the compensation effect and demonstrate the compensation formulas, at first, a constant load with admittances $G_a^L+jB_a^L=0.03162-j0.01641\Omega^{-1}$, $G_b^L+jB_b^L=0.02115-j0.00402\Omega^{-1}$, and $G_c^L+jB_c^L=0.02633-j0.00589\Omega^{-1}$ is used. The computation results are listed together in Table 1 for the ten compensation schemes. The compensation effects of scheme 2 to scheme 6 are the same. The negative and zero sequence currents are eliminated and the load bus power factor is improved to unity. The load bus voltages are raised and balanced. There is 7779W reduction in distribution line power loss. The maximal susceptance size in schemes 3 and 4 is smaller than that in schemes 2, 5, and 6. In additional to the balancing effect, scheme 7 can raise the load bus voltage to the substation's level, and scheme 8 can further improve the substation feeder power factor to unity. Since scheme 9 is designed to eliminate the negative sequence currents, there is little effect to the zero sequence currents. The small amount of negative currents is due to the distribution line impedance effect. On the other hand, scheme 10 can only greatly reduce the zero sequence currents. The load bus is a little unbalanced with scheme 9 or 10, but the distribution line power loss is also reduced.

Simulation 2: 24–hour loads

The 24–hour measured data at the Huahcherng substation feeder are used to examine the on–line compensation capability. As mentioned in Section 2, the feedback signals are load bus voltages and currents. The measured and calculated data for the system without the SVCs are plotted in Fig.3. The load bus is unbalanced as shown in voltages and currents. The maximum values of negative and zero sequence currents are 24A and 37A, respectively. Distribution line power loss due to line resistances is proportional to the quadratic sum of line currents. The end users's shunt capacitors are not switched off, so that the substation feeder power factor is leading during the off–peak period. Fig.4 gives the curves of compensation results for the system with schemes 2–8. Several curves are drawn together in some graphs for comparison. Schemes 2–6 provide the same compensation effect. The system is balanced with the proposed compensation schemes. Scheme 7 can always maintain the load bus voltages. The substation feeder power factor can be kept at unity by scheme 8. But schemes 2–6 always have less distribution line power losses. The power loss curve of scheme 8 almost overlaps with that of schemes 2–6. The compensation susceptances of the two SVCs in schemes 2–8 are shown in Fig.5. Schemes 2–6 require different compensation susceptances. The susceptances of the SVCs must be updated according to system conditions. The results of the system with the Δ–SVC or the Y–SVC alone are given in Fig.6 and Fig.7, respectively. These two schemes can not simultaneously eliminate negative and zero sequence currents. The compensation susceptances of the Y–SVC are the same in schemes 2–6. The 24–hour energy losses on the distribution lines for the ten schemes are revealed in Table 2. The energy loss of schemes 2–6 is the least.

Table 2 Energy losses on distribution lines of simulation 2.

	scheme 1	schemes 2–6	scheme 7	scheme 8	scheme 9	scheme 10
loss, kWH	919.6	747.7	832.0	752.0	782.6	770.7

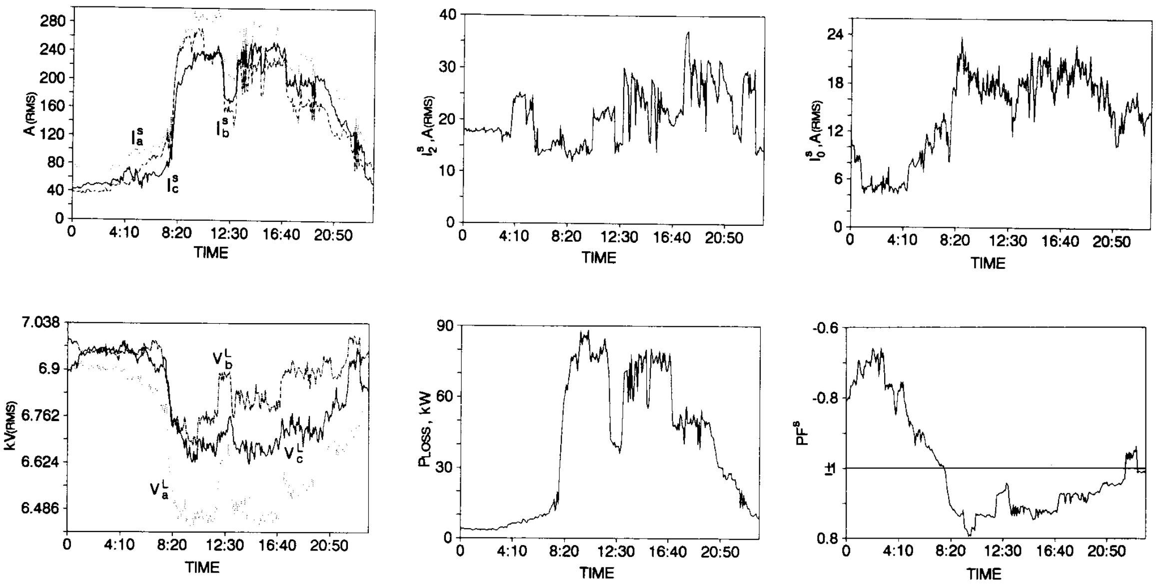

Fig.3 Dynamic responses of simulation 2 without SVC (scheme 1).

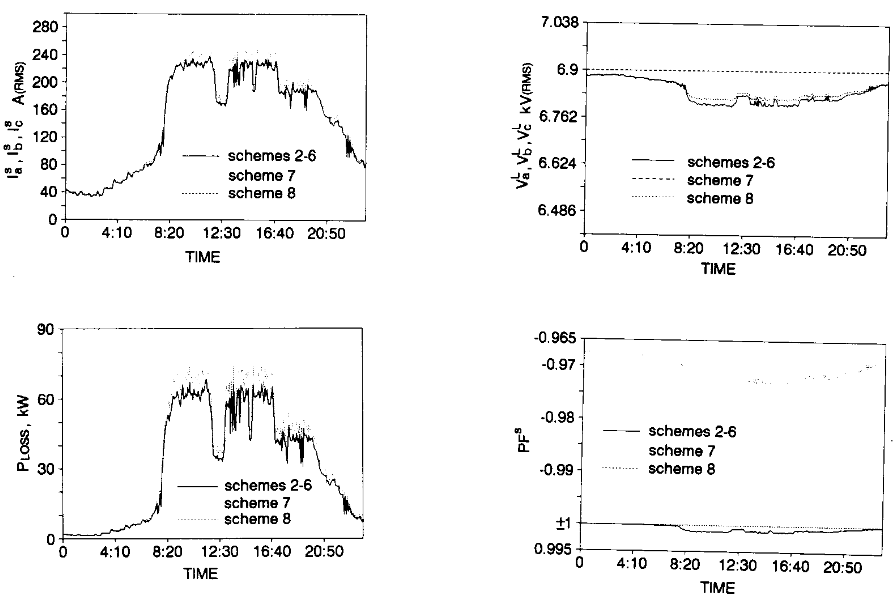

Fig.4 Dynamic responses of simulation 2 with Y–SVC and Δ–SVC (schemes 2–8). In the graphs of currents and power losses, the curve of scheme 8 almost overlaps with that of schemes 2–6.

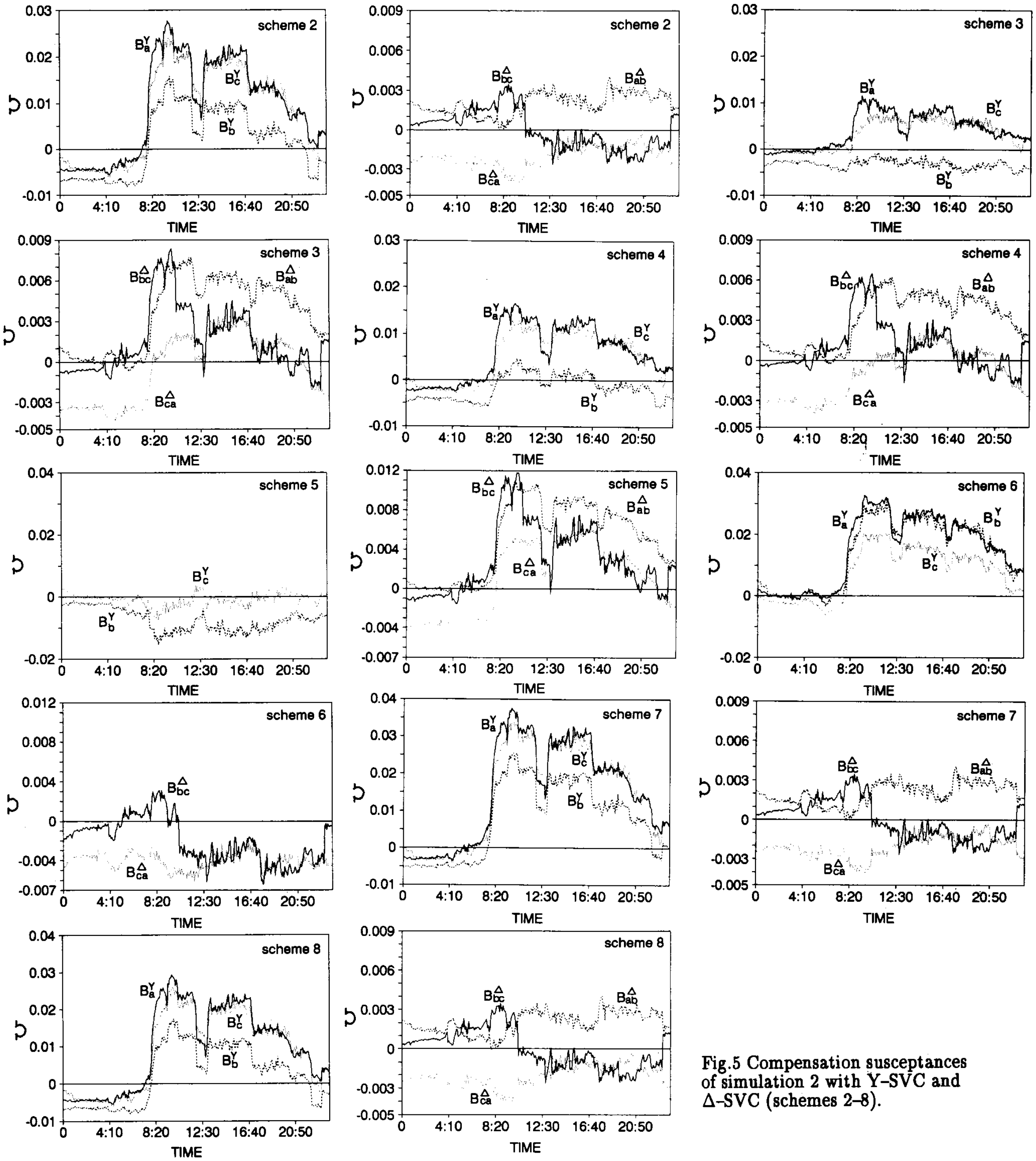

Fig.5 Compensation susceptances of simulation 2 with Y-SVC and Δ-SVC (schemes 2–8).

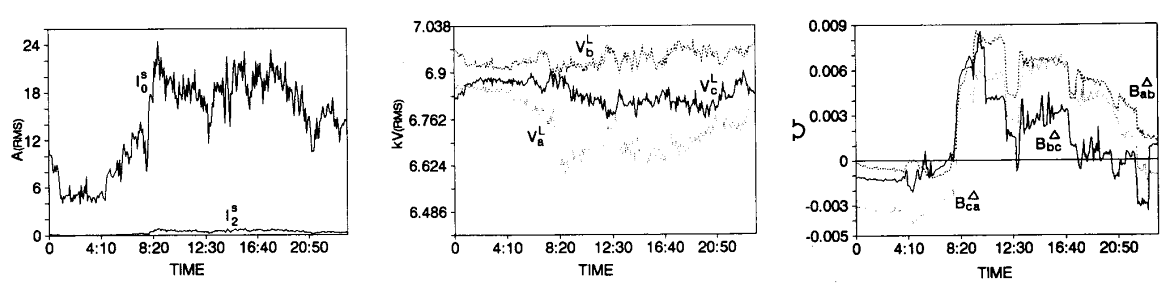

Fig.6 Dynamic responses of simulation 2 with Δ–SVC (scheme 9).

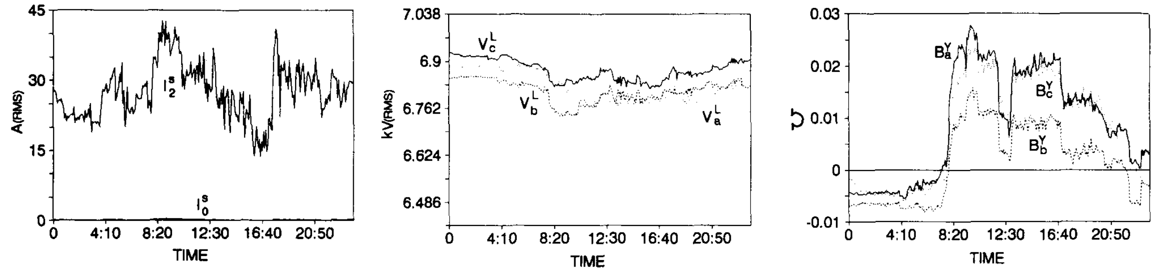

Fig.7 Dynamic responses of simulation 2 with Y–SVC (scheme 10).

9. Conclusions

Ten reactive power compensation schemes are designed and compared for a three–phase four–wire distribution feeder to eliminate the negative and zero sequence currents. The load bus voltages and currents are used to calculate the on–line compensation susceptance values of the SVCs. The SVCs can provide a different amount of reactive power to each phase such that although the load is unbalanced, the system is balanced viewed from the load bus. Digital simulations with the load data measured from a substation feeder are used to demonstrate the compensation capability of the SVCs. A Y–SVC and a Δ–SVC together can completely eliminate the negative and zero sequence currents caused by unbalanced loads. The energy losses on the distribution lines are also reduced. The SVCs can also support the load bus voltage in addition to the balancing effect.

Although the measured load data are used, ideal SVCs are assumed in the calculation procedure of the compensation susceptances. In practical applications, power losses of reactors, capacitors, and step–down transformers must be considered.

10. List of principal symbols

<u>general</u>

Re	=real part
Im	=imaginary part
P	=active power
V	=voltage
I	=current
PF	=power factor
G	=conductance
B	=susceptance
R	=resistance
X	=reactance

<u>subscripts</u>

a,b,c	=phase a, b, c
ab,bc,ca	=phase ab, bc, ca
0	=zero sequence component
1	=positive sequence component
2	=negative sequence component
t	=distribution line
e	=equivalent load
g	=neutral line

<u>superscripts</u>

s	=substation
Y	=Y–connected SVC
Δ	=Δ–connected SVC
L	=load

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