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Voltage and current unbalance compensation using a static var compensator

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Abstract: A three-phase insulated gate bipolar transistor (IGBT)-based static var compensator (STATCOM) is used for voltage and/or current unbalance compensation. An instantaneous power theory is adopted for real-time calculation and control. Three control schemes – current control, voltage control and integrated control – are proposed to compensate the unbalance of current, voltage or both. The compensation results of the different control schemes in unbalance cases (load current unbalance or voltage unbalance) are compared and analysed. The simulation and experimental results show that the control schemes can compensate the unbalance in load current or in the voltage source. Different compensation objectives can be achieved, that is, balanced and unity power factor source current, balanced and regulated voltage or both, by choosing appropriate control schemes.

1 Introduction

Power quality issues, especially current harmonics, current unbalance and voltage unbalance, have drawn much attention and much research work has been performed in this area. One means of correcting these power quality problems is to provide non-active power compensation by a parallel compensator. A static var compensator (STATCOM) is an effective way to eliminate or mitigate the harmonics and unbalance in current [1, 2]. However, there are still no standard definitions of instantaneous non-active power and instantaneous non-active current [3–6].

Voltage unbalance is generally not as severe as current unbalance; however, it may have a more severe impact on both loads and power system equipment. The negative impact of voltage unbalance on induction motors has been studied in depth [7, 8]. Series-connected converter-based compensators have been proposed for voltage unbalance compensation, voltage sag compensation and voltage regulation [9–13]. For both the compensation of voltage unbalance and load current harmonics, an active filter for voltage regulation, together with passive filters (fifth and seventhth) for current harmonics compensation, is proposed in [14]. Whereas in [15], a series active filter and a parallel active filter are connected to perform both voltage and current compensation tasks at the same time. A method of voltage unbalance mitigation using a STATCOM is also presented in [16].

The instantaneous power theory presented in [6] is used for the STATCOM presented in this paper because the definitions of instantaneous power and instantaneous non-active power are suitable for real-time non-active power compensation purpose. This instantaneous power theory will be elaborated in Section 3.

A feedback controller is presented in this paper to perform both voltage unbalance and current unbalance compensation in a STATCOM. The system can compensate the non-active power component and the unbalance in the load current and/or regulate and balance the system voltage. After compensation, the three-phase utility voltages are balanced despite the sources of the unbalance. Either one or both the tasks can be performed at the same time, depending on the compensation objectives and the compensation results to be achieved. The compensator can provide the non-active component in the load current such that the source current is balanced and has unity power factor or it can regulate the system voltage to a certain level by generating or consuming non-active power. Thus, it can compensate the voltage or current unbalance caused by the load.

2 System configuration

The system configuration of a parallel non-active power compensator is shown in Fig. 1. The compensator is connected in parallel with the load through a coupling inductor L_c and the rest of the system is simplified as an infinite utility voltage source with a system impedance of $R_s + j\omega L_s$. The parallel compensator is connected through the coupling inductor at the point of common coupling (PCC) and the PCC voltage is denoted as $\boldsymbol{v}_t$. The filtering capacitor C_f is used to mitigate the ripple in the compensator current $\boldsymbol{i}_c$. The compensator only provides (generates or consumes) non-active power and there is no energy source connected to the DC link. The DC link voltage v_{dc} is regulated by the compensator.

By providing a certain amount of non-active power, the compensator can eliminate or mitigate the unwanted components, such as non-active power, harmonics and unbalance in the load current; it can also regulate the voltage $\boldsymbol{v}_t$ to a certain level. The compensator can perform these two tasks individually or as an integrated control of the voltage and the current.

3 Instantaneous power theory

An instantaneous non-active power theory [6] is adopted to calculate the instantaneous variables based on the measurements (v_t, $\boldsymbol{i}_l$, $\boldsymbol{i}_c$ and $\boldsymbol{v}_{dc}$) and to implement control, depending on the compensation objectives and control schemes. In a three-phase system with a voltage vector $\boldsymbol{v}(t)$ and a current vector $\boldsymbol{i}(t)$ (vectors for voltage and current are denoted in bold)

$$\boldsymbol{v}(t) = [v_1(t), v_2(t), v_3(t)]^T \tag{1}$$

$$\boldsymbol{i}(t) = [i_1(t), i_2(t), i_3(t)]^T \tag{2}$$

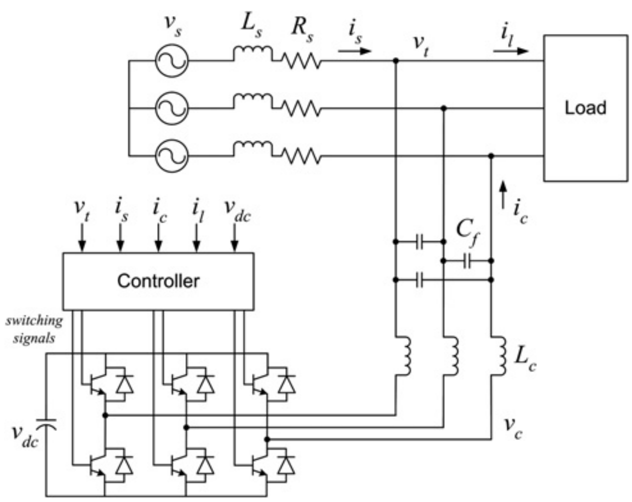

Figure 1 *System configuration of a STATCOM for voltage and current unbalance compensation*

The instantaneous power $p(t)$ and the average power $P(t)$ over the averaging interval $[t - T_c, t]$ are defined by (3) and (4)

$$p(t) = \boldsymbol{v}^T(t)\boldsymbol{i}(t) = \sum_{k=1}^{3} v_k(t)i_k(t) \tag{3}$$

$$P(t) = \frac{1}{T_c}\int_{t-T_c}^{t} p(\tau)\,d\tau \tag{4}$$

Theoretically, the averaging interval T_c can be chosen arbitrarily from zero to infinity and for different T_c values, the resulting active and non-active currents will have different characteristics. However, in practice, a specific value of T_c is chosen according to the specifications of the system. For example, in a periodic system with period T, T_c is chosen as the integer multiples of $T/2$ and all the definitions are consistent with the standard definitions. The detailed discussion of choice of T_c is presented in [17]. A three-phase sinusoidal system with voltage fundamental period T is studied in this paper and in this case, T_c is normally chosen as $T/2$ to eliminate current harmonics.

The instantaneous active current $\boldsymbol{i}_a(t)$ and instantaneous non-active current $\boldsymbol{i}_n(t)$ are defined by (5) and (6), respectively

$$\boldsymbol{i}_a(t) = \frac{P(t)}{V_p^2(t)}\boldsymbol{v}_p(t) \tag{5}$$

$$\boldsymbol{i}_n(t) = \boldsymbol{i}(t) - \boldsymbol{i}_a(t) \tag{6}$$

In (5), the voltage $\boldsymbol{v}_p(t)$ is the reference voltage, which is chosen based on the characteristics of the system and the compensation results to be achieved. In the three-phase sinusoidal system being studied, if the system voltage only contains a fundamental component and is balanced, then the reference voltage is usually chosen as the system voltage itself; otherwise the positive sequence component of the fundamental component of the system voltage is usually chosen as the reference voltage so that fundamental and balanced compensation results can be achieved. $V_p(t)$ is the rms value of the reference voltage $\boldsymbol{v}_p(t)$, that is.

$$V_p(t) = \sqrt{\frac{1}{T_c}\int_{t-T_c}^{t} \boldsymbol{v}_p^T(\tau)\boldsymbol{v}_p(\tau)\,d\tau} \tag{7}$$

The rms values of the voltage $\boldsymbol{v}(t)$ and the current $\boldsymbol{i}(t)$ are, respectively

$$V(t) = \sqrt{\frac{1}{T_c}\int_{t-T_c}^{t} \boldsymbol{v}^T(\tau)\boldsymbol{v}(\tau)\,d\tau} \tag{8}$$

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$$I(t) = \sqrt{\frac{1}{T_c}\int_{t-T_c}^{t} \boldsymbol{i}^{\mathrm{T}}(\tau)\boldsymbol{i}(\tau)\,\mathrm{d}\tau} \tag{9}$$

The definitions in (4) and (7) are average and rms values over averaging interval T_c, whose instantaneous values may change with time t because they are the average values over the interval $[t - T_c, t]$. In practice, T_c is not arbitrarily chosen. In a system with periodic voltages and currents, T_c is chosen as the integral multiples of $T/2$ (where T is the period of the system). By choosing this T_c, the definitions (4), (8) and (9) are constants and the same as the conventional definitions.

The standard definitions apply to three-phase sinusoidal steady-state balanced systems and in this case, the proposed instantaneous definitions are consistent with the standard definitions when T_c is chosen as the integral multiples of $T/2$ (where T is the period of the system). The instantaneous definitions extend the standard definitions to cases that are single phase, non-sinusoidal, unbalanced or non-periodic.

The definitions in this instantaneous non-active power theory are all consistent with the standard definitions for three-phase fundamental sinusoidal systems. They are also valid in other various cases, such as single-phase systems, non-sinusoidal systems and non-periodic systems as well, by changing the averaging interval T_c and the reference voltage $\boldsymbol{v}_p(t)$ [6]. More specifically, a three-phase system with unbalanced voltage, unbalanced current or both, is the study objective in the paper. In this theory, all the definitions are instantaneous values; therefore they are suitable for real-time control and provide advantages for the design of control schemes, which will be discussed in the next section.

4 Control schemes for unbalance compensation

In a three-phase power system, voltages or currents are balanced if the amplitudes of the three-phase voltages or currents are equal and the phase angles between consecutive phases are equal as well, which is $2\pi/3$ radians in a three-phase case. From the standpoint of the compensator connected in parallel with a load, there are two kinds of unbalance; one is an unbalanced load and the other one is an unbalanced voltage source (could be caused by other loads or by the generators in the system). In the first case, the load current $\boldsymbol{i}_l$ is not balanced, which results in unbalance in the voltage $\boldsymbol{v}_t$ as well because of the difference in voltage drop through the conductors caused by the unbalanced currents. If the unbalanced load is compensated so that a balanced current is drawn from the utility, then the voltage $\boldsymbol{v}_t$ will also be balanced, that is, the unbalance is compensated in the load current compensation. Whereas in the second case, the load draws unbalanced current because of the unbalanced voltage $\boldsymbol{v}_t$. This unbalance can only be compensated with voltage regulation by the STATCOM. After compensation, the three-phase PCC voltages are balanced and the load draws balanced current from the utility, however, the three-phase utility currents are still unbalanced because of the compensation currents injected by the STATCOM. Because the PCC voltage is balanced after the compensation, the unbalance caused by the voltage source does not have impact on the load.

In this section, a current unbalance compensation control scheme and a voltage unbalance compensation control scheme are presented and compared and an integrated control which combines the two control schemes together is also presented.

4.1 Current unbalance compensation

The control diagram of current control is shown in Fig. 2. The non-active component in the load current is calculated by the instantaneous power theory in Section 3 [(5) and (6)] and this non-active component is provided by the compensator; therefore a balanced, unity power factor source current is drawn from the utility. The compensator output voltage $\boldsymbol{v}_c$ is controlled so that the compensator current tracks the reference $\boldsymbol{i}_c^*$, as shown in (10)

$$\boldsymbol{v}_c^* = \boldsymbol{v}_t + K_{P1}(\boldsymbol{i}_c^* - \boldsymbol{i}_c) + K_{I1}\int_0^t (\boldsymbol{i}_c^* - \boldsymbol{i}_c)\,\mathrm{d}t \tag{10}$$

The output of the PI controller is the difference between the inverter output voltage $\boldsymbol{v}_c$ and the PCC voltage $\boldsymbol{v}_t$, which is also the voltage drop on the coupling inductance. In steady state, the proportional term [the second term in (10)] is zero and the integral term [the third term in (10)] is the voltage drop on the coupling inductance

$$\boldsymbol{i}_c^* = \boldsymbol{i}_{c1}^* + \boldsymbol{i}_{c2}^* \tag{11}$$

The reference compensator current $\boldsymbol{i}_c^*$ has two components, $\boldsymbol{i}_{c1}^*$ and $\boldsymbol{i}_{c2}^*$. The first component $\boldsymbol{i}_{c1}^*$ is the non-active component in the load current calculated by the instantaneous power theory. The system is assumed to be ideal in the instantaneous power theory; however, there are losses in the real compensator. Therefore if there is no active power provided to the compensator, the DC link capacitor voltage v_{dc} varies. V_{dc} is the average value of the

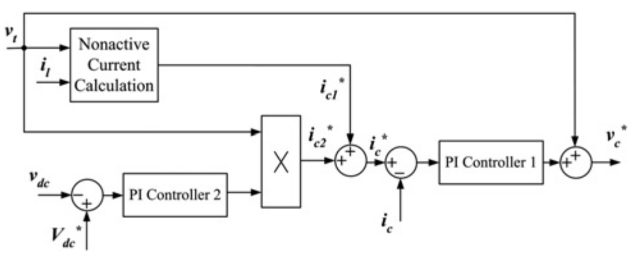

Figure 2 *Current control diagram*

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DC link voltage v_{dc} over one system fundamental cycle. To regulate the DC link voltage, some active power is drawn from the utility to meet the losses. This active current is referred to as $\boldsymbol{i}^*_{c2}$, which is in phase with the PCC voltage $\boldsymbol{v}_t$. Therefore a control loop is designed as shown in (12)

$$\boldsymbol{i}^*_{c2} = \left[K_{P2}(V^*_{dc} - V_{dc}) + K_{I2}\int_0^t (V^*_{dc} - V_{dc})\,dt\right]\boldsymbol{v}_t \quad (12)$$

The sum of $\boldsymbol{i}^*_{c1}$ and $\boldsymbol{i}^*_{c2}$ is the current that the compensator needs to provide, which is $\boldsymbol{i}^*_c$ as shown in (11).

4.2 Voltage unbalance compensation

In power systems, most voltage unbalance conditions are due to magnitude inequalities, whereas the phase angles are equal ($2\pi/3$) or nearly equal; therefore in this paper, unbalanced voltages with unequal magnitudes are considered and this kind of voltage unbalance can be compensated by a parallel compensator by providing non-active power. The principle is to control the compensator so that its output is only non-active power (if losses are neglected), which is accomplished by keeping the compensator output voltage $\boldsymbol{v}_c$ in phase with the voltage $\boldsymbol{v}_t$ and controlling the three-phase magnitudes of $\boldsymbol{v}_c$ independently. In each phase, when the magnitude of $\boldsymbol{v}_c$ is larger than that of $\boldsymbol{v}_t$, the compensator generates non-active power; if the magnitude of $\boldsymbol{v}_c$ is smaller than that of $\boldsymbol{v}_t$, the compensator consumes non-active power. By controlling the three-phase magnitudes of the compensator voltage $\boldsymbol{v}_c$ individually, the rms values of the three-phase voltages of $\boldsymbol{v}_t$ are controlled at a given level V^*_t, as shown in (13).

To account for losses in an actual system, the reference compensator voltage is shifted a small phase angle θ^* so that a small amount of active power is drawn by the compensator as shown in (14). The phase angle θ^* is controlled so that the DC link voltage v_{dc} is maintained at a given value. The control diagram is illustrated in Fig. 3

$$\boldsymbol{v}^*_c = \left[1 + K_{P1}(V^*_t - V_t) + K_{I1}\int_0^t (V^*_t - V_t)\,dt\right]\boldsymbol{v}_t(\omega t - \theta^*) \quad (13)$$

$$\theta^* = K_{P2}(V^*_{dc} - V_{dc}) + K_{I2}\int_0^t (V^*_{dc} - V_{dc})\,dt \quad (14)$$

In Fig. 3, the first input of the phase angle shift block is the compensator reference voltage calculated by the voltage regulation requirement. This compensator reference voltage is phase shifted in the phase angle shift block and the phase shift angle θ^* is determined by the DC link voltage control loop, which is the second input of the phase angle shift block.

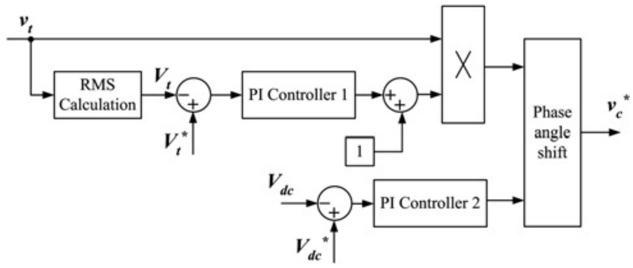

Figure 3 *Voltage control diagram*

4.3 Integrated compensation

Can the compensator regulate the voltage and compensate the load non-active power at the same time? An integrated compensation is proposed which approaches this goal. The control diagram is shown in Fig. 4, which is essentially a current control loop integrated with the voltage regulation. The reference current contains three components, the load non-active component $\boldsymbol{i}^*_{c1}$, the voltage regulation component $\boldsymbol{i}^*_{c3}$ and the DC link control component $\boldsymbol{i}^*_{c2}$, where $\boldsymbol{i}^*_{c1}$ and $\boldsymbol{i}^*_{c2}$ are the same as in Section 4.1 and the voltage regulation component $\boldsymbol{i}^*_{c3}$ is

$$\boldsymbol{i}^*_{c3} = \left[K_{P3}(V^*_t - V_t) + K_{I3}\int_0^t (V^*_t - V_t)\,dt\right]\boldsymbol{v}_t\left(\omega t - \frac{\pi}{2}\right) \quad (15)$$

The integrated control combines the current loop and the voltage control loop together. The two control loops can work independently by shutting down the other control loop (changing the control gains to zero) or work together. This provides the flexibility for the STATCOM to perform both voltage and current controls without any hardware reconfiguration. From Fig. 4, gains for PI controller 1 would be determined first which determines the magnitude of the compensator's inverter output voltage to compensate for load non-active current, then PI controller 3 gains modify the magnitude of the inverter output voltage for non-active power for voltage regulation and finally PI controller 2 gains are chosen which modify the inverter output voltage phase angle to draw a small amount of active power for inverter losses and to regulate the DC link voltage.

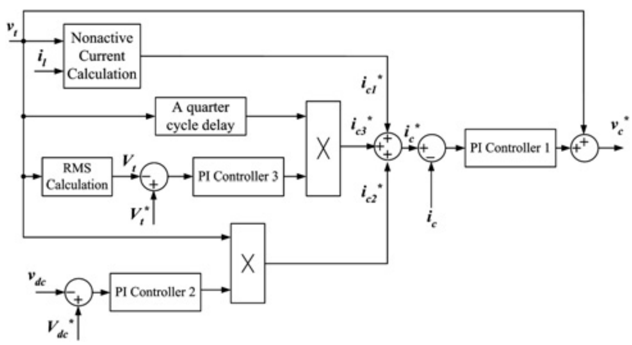

Figure 4 *Control diagram of the integrated current and voltage control*

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In all three control schemes, the controllers are applied to the three phases separately so that the voltage or current of each phase is controlled separately. K_P for the controllers is determined by how fast the STATCOM responds to step change in the voltage. A larger K_P will result in a faster response, but too large will result in overshoot by the compensator. K_I is determined by the maximum expected difference between two steady-state operating conditions. If K_I is too large, then stability issues arise even with steady-state conditions.

5 Simulation results

In the simulations presented in this section, the ac system voltage rating is 480 V (line-to-line rms value). The minimum DC link voltage is 784 V [18], whereas in the simulations the DC link voltage is 2200 V because the unbalance compensation requires a much higher DC voltage.

Considering there are two kinds of unbalance – load unbalance and voltage source unbalance – and there are three control schemes – current control, voltage control and integrated control – all the combinations of compensation and their results are listed in Table 1. The compensation results of the source current and the PCC voltage are compared. If the unbalance is caused by the load, the compensation results using different control schemes are shown in the third column in the table. If the unbalance is caused by the voltage source, the compensation results are shown in the fourth column. In the load unbalance case, the voltage is automatically balanced if the unbalance in the load is compensated. In the voltage source unbalance case, it is more complicated. The voltage can be compensated to be balanced or unbalanced depending on the compensation objectives. If a balanced voltage is desired for the load, it increases the source current unbalance and consequently, it deteriorates the power factor.

The simulation results of load unbalance compensation and voltage source unbalance compensation are shown below. Experimental results of load unbalance compensation are presented in the next section.

5.1 Load unbalance compensation

The three-phase load current together with phase *a* voltage is shown in Fig. 5*a*. The current is unbalanced and lagging the voltage. There is no compensation from $t = 0$ s to $t = 0.4$ s and and the rms values of the voltage $\boldsymbol{v}_t$, the source current $\boldsymbol{i}_s$ and the compensator current $\boldsymbol{i}_c$ are shown in Figs. 5*b*, 5*e* and 5*f*, respectively. Current compensation is performed from $t = 0.4$ s to $t = 0.8$ s to achieve balanced source currents and unity power factor (in phase with the voltage). As shown in the control diagram in Fig. 2, the parameters of PI controller 1 (non-active current control) are $K_P = 100$ and $K_I = 1000$, respectively and the parameters of PI controller 2 (DC link voltage control) are $K_P = 0.01$ and $K_I = 0.1$, respectively. The voltage is balanced since the load now draws balanced current from the utility and the magnitude is increased (Fig. 5*b*).

From $t = 0.8$ s to $t = 1.2$ s, the integrated compensation is performed. The reference line-to-neutral rms voltage is set to 277 V. The actual voltage is regulated at 277 V and balanced. As the control diagram shown in Fig. 4, the parameters of PI controller 1 (non-active current control) are $K_P = 80$ and $K_I = 1000$, respectively, the parameters of PI controller 2 (DC link voltage control) are $K_P = 0.01$ and $K_I = 0.1$, respectively and the parameters of PI controller 3 (PCC voltage control) are $K_P = 2$ and $K_I = 20$, respectively. With the integrated control, the source current is leading the voltage because there is some non-active power provided by the compensator to the utility to boost the voltage and the magnitude of the source current is increased some as shown in Fig. 5*e*. At both the current compensation and the integrated compensation, the compensator current is unbalanced and more non-active current is flowing to the system at the integrated compensation condition. Choosing too large controller gains can result in instability issues and controller gains are

Table 1 Voltage and current unbalance control

<table>
<tr><th>Control schemes</th><th>Compensation results</th><th>Load unbalance</th><th colspan="2">Voltage source unbalance</th></tr>
<tr><td rowspan="2">voltage control</td><td>source current</td><td>balanced, pf ≠ 1</td><td colspan="2">unbalanced, pf ≠ 1</td></tr>
<tr><td>PCC voltage</td><td>balanced, regulated magnitude</td><td colspan="2">balanced, regulated magnitude</td></tr>
<tr><td rowspan="2">current control</td><td>source current</td><td>balanced, pf = 1</td><td colspan="2">balanced, pf = 1</td></tr>
<tr><td>PCC voltage</td><td>balanced, unregulated magnitude</td><td colspan="2">unbalanced, unregulated magnitude</td></tr>
<tr><td rowspan="2">integrated control</td><td>source current</td><td>balanced, pf ≠ 1</td><td>balanced, pf ≠ 1</td><td>unbalanced, pf ≠ 1</td></tr>
<tr><td>PCC voltage</td><td>balanced, regulated magnitude</td><td>unbalanced, regulated magnitude</td><td>balanced, regulated magnitude</td></tr>
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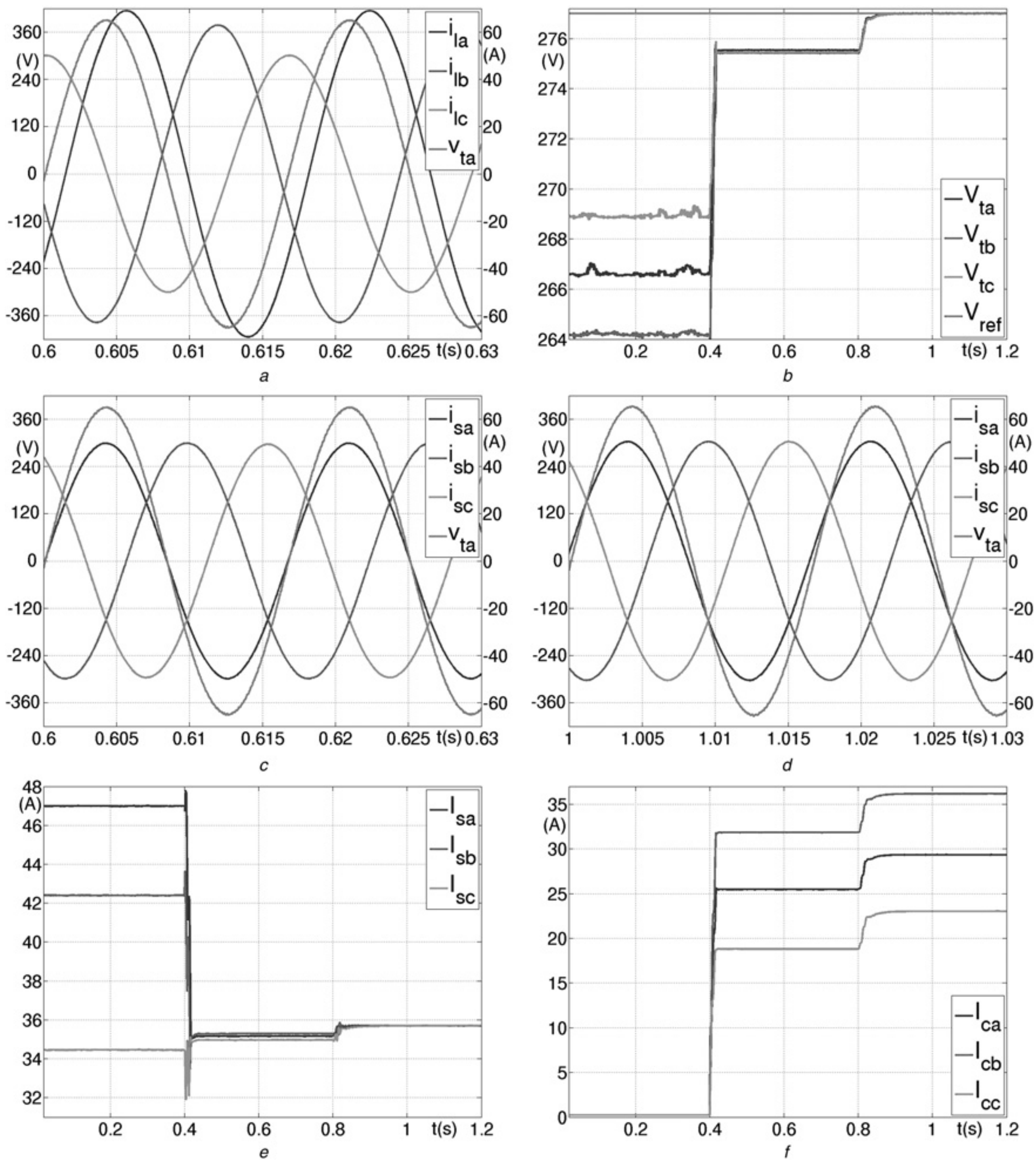

Figure 5 *Load current unbalance compensation (simulation)*

a Load current (A)
b PCC rms voltage (V)
c Source current (current control)
d Source current (integrated control)
e Source current rms (A)
f compensator current rms (A)

to some degree based on expected load current unbalance or resulting voltage unbalance.

As listed in Table 1, the voltage or the source current balance can be achieved using either current control or voltage control. In current control, the voltage magnitude is not regulated, but the source current is controlled to unity power factor, whereas in integrated control, the voltage magnitude is regulated, but the source current is not controlled to unity power factor (usually a leading power factor because non-active power is provided to the utility to boost the voltage).

5.2 Voltage source unbalance compensation

If the voltage source is unbalanced, the current compensation can make the source current balanced and unity power factor, whereas the voltage compensation can make the voltage balanced and magnitude regulated, as shown in Table 1. If

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the integrated control is used, either a balanced source current or a balanced voltage can be achieved, depending on the compensation objective.

Fig. 6 shows the simulation results of the current control and the integrated control with balanced voltage as compensation objective. The PI controllers' parameters are the same as in the case presented in the previous Section. The load current is shown in Fig. 6*a* with phase *a* voltage. The load current is lagging the voltage and is slightly unbalanced because of the unbalanced voltage. There is no compensation from $t = 0$ s to $t = 0.4$ s and the rms values of the voltage, the source current and the compensator current are shown in Figs. 6*b*, *e* and *f*, respectively.

Current compensation is performed from $t = 0.4$ s to $t = 0.8$ s and the source current is balanced and unity power factor (in phase with the voltage). The voltage is still unbalanced since the compensator only provides the compensation of the load current unbalance and non-active

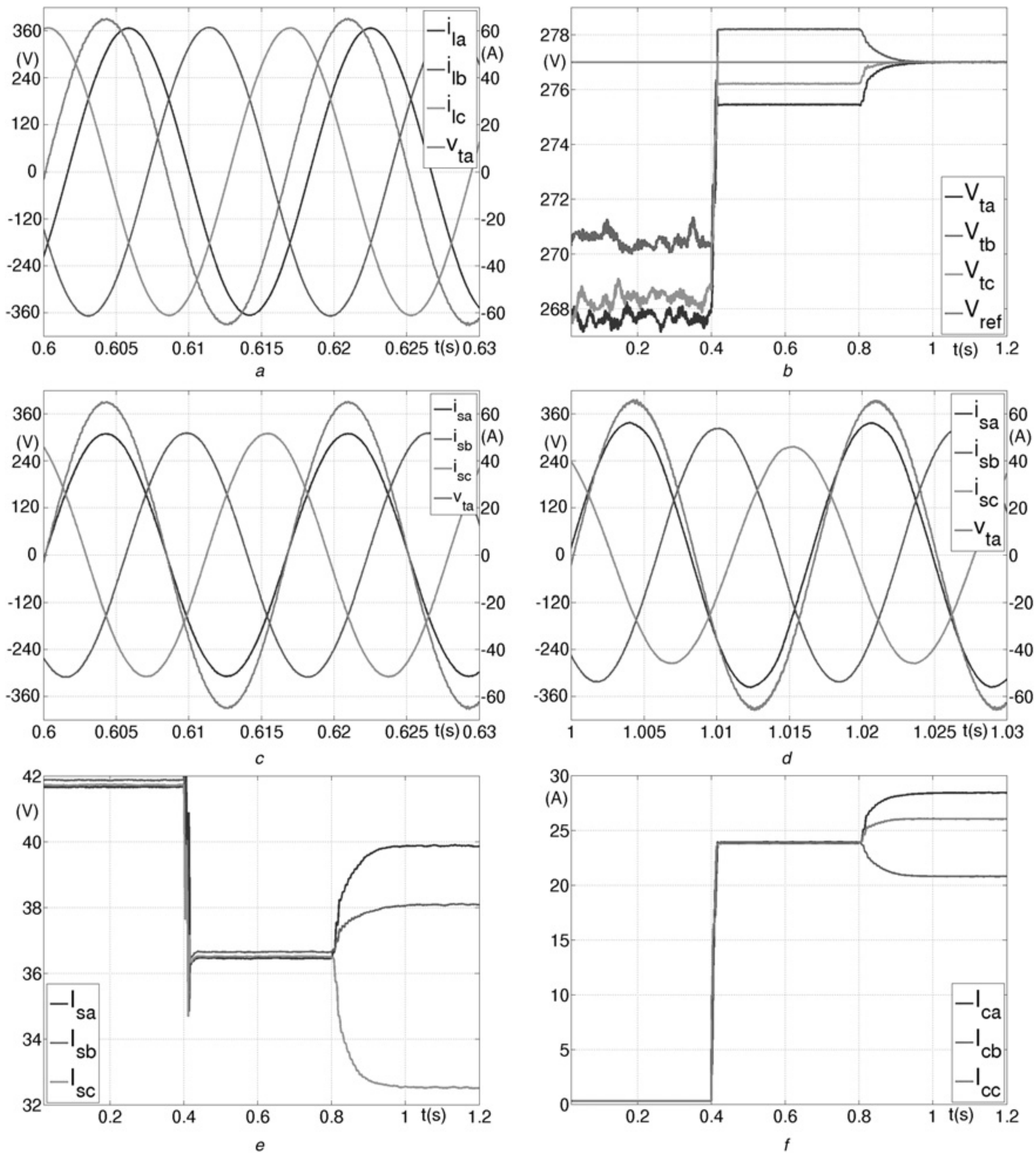

Figure 6 *Simulation of voltage source unbalance compensation (balanced voltage is desired)*

a Load current (A)
b PCC rms voltage (V)
c Source current (current control)
d Source current (integrated control)
e Source current rms (A)
f Compensator current rms (A)

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power and the unbalance in the voltage remains. The magnitude of the voltage is increased. The load now draws balanced current from the utility despite the unbalanced voltage. This is done by choosing the positive sequence of the voltage as the reference voltage $v_p(t)$ in (5). From $t = 0.8$ s to $t = 1.2$ s, the integrated compensation is performed with the reference line-to-neutral rms voltage set to 277 V. The voltage is regulated at 277 V and balanced. The source current is leading the voltage because there is some non-active power provided by the compensator to the utility and the source current is not balanced as shown in Fig. 6*e*. For both the current compensation and the integrated compensation, the compensator current is unbalanced and more non-active current is flowing to the system at the integrated compensation condition.

Fig. 7 shows the simulation results of the integrated control with balanced source current as the compensation objective. There is no compensation from $t = 0$ s to $t = 0.2$ s and integrated control from $t = 0.2$ s to $t = 0.8$ s. The average value of the three-phase rms voltages is regulated at 277 V; therefore the non-active power provided from the compensator is equal in each phase. Fig. 7*c* shows the source current, which is leading the voltage. In Fig. 7*d*, it shows that the source current is nearly balanced when the integrated control is performed. The reason that the unbalance is not completely compensated is because of the limited DC link voltage of the inverter. In the simulation, the DC link voltage is already set at 2200 V, which is much higher than the minimum DC voltage requirement (784 V) mentioned at the beginning of this section. Because of the unbalanced three-phase output of the inverter current, a very high DC link voltage is required to generate a much higher inverter output voltage v_c than the PCC voltage v_t. If the inverter only performs balanced compensation, the DC link voltage can be much lower (1000 V in the simulations).

6 Experimental results

A Powerex POW-R-PAK^{TM} configurable insulated gate bipolar transistor (IGBT)-based three-phase inverter was used as the inverter for the STATCOM. The ac system voltage rating is 208 V (line-to-line rms value). The DC link voltage of the inverter is 450 V. Danfysik ULTRASTAB$^{®}$ 866 current transducers were used for measuring the load current and the compensator current. LEM CV 3–500 voltage transducers were used for

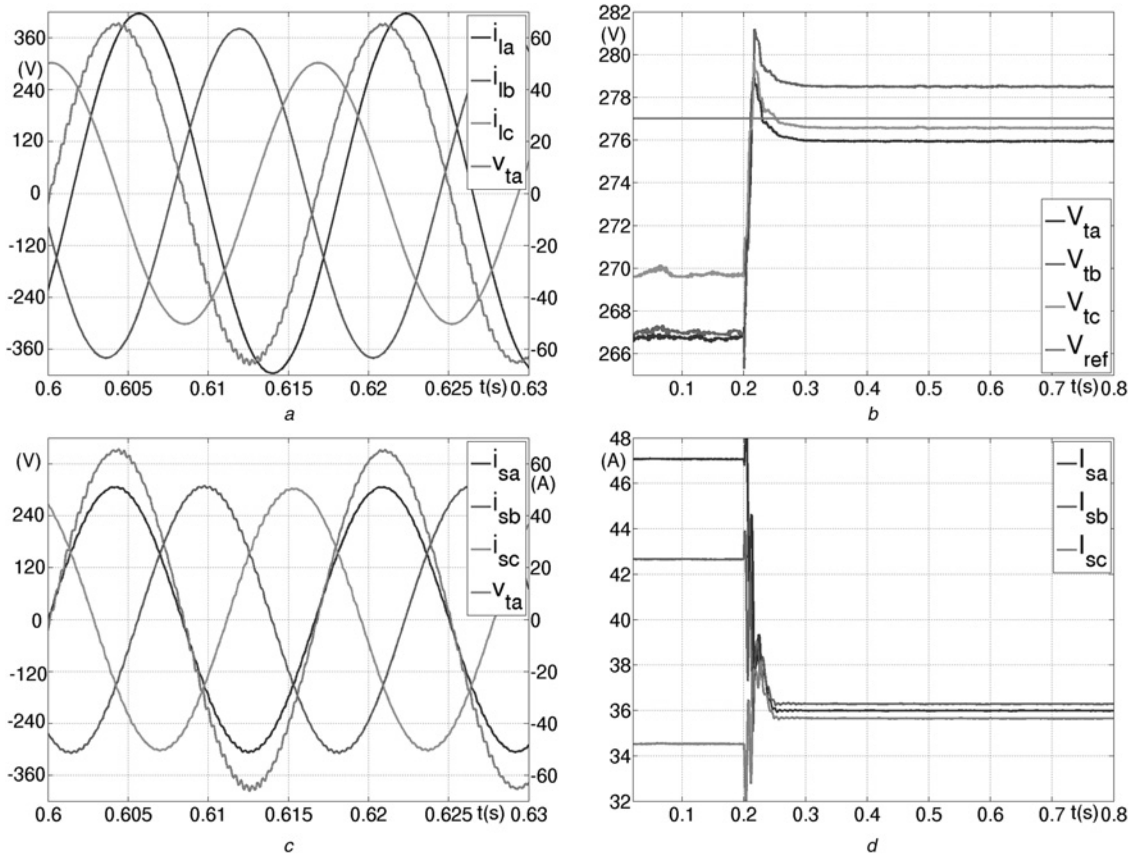

Figure 7 *Simulation of voltage source unbalance compensation (balanced source current is desired)*

a Load current (A)
b PCC rms voltage (V)
c Source current (integrated control)
d Source current rms (A)

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measuring the PCC voltage and the inverter DC link voltage. dSPACE, a real-time control platform, is used to implement the Simulink controller on hardware to perform the real-time control of the compensator. In all the experiments, the DC link voltage control loop parameters are $K_P = 0.2$ and $K_I = 0.05$, respectively.

6.1 Load unbalance compensation

An unbalanced resistive and inductive (RL) load is tested in this experiment. The inductors of the RL load are not equal in each phase; therefore the three-phase load currents are not balanced, as shown in Fig. 8*b*. The system line-to-neutral rms voltage is 120 V. The load resistor is 10.8 Ω in each phase and the load inductors are 30, 10 and 10 mH, respectively. The coupling inductor is 10 mH in each phase; the DC link voltage is 450 V. The three-phase system voltages are balanced, which is shown in Fig. 8*a*. The source current after compensation together with the phase *a* voltage is shown in Fig. 8*c*. The source current is nearly balanced compared to the load current and in phase with the voltage. The compensation current is shown in Fig. 8*d*, which is unbalanced and 90° out of phase with the voltage. Current control is used in the experiment, that is, the compensation objective is to provide the unbalance component and the non-active component in the load current so that the source current is balanced and unity power factor.

Current control is used in the experiment, that is, the compensation objective is to provide the unbalance component and the reactive component in the load current so that the source current is balanced and unity power factor. The PI controller parameters are $K_P = 40$ and $K_I = 1$, respectively.

The unbalance of the three-phase currents is calculated as

$$I_{\text{unbalance}} = \frac{\max\{|I_a - I_b|, |I_b - I_c|, |I_c - I_a|\}}{\text{Avg}(I_a, I_b, I_c)} \quad (16)$$

where

$$\text{Avg}(I_a, I_b, I_c) = (I_a + I_b + I_c)/3 \quad (17)$$

The rms values of the three-phase load currents and the source currents after compensation are listed in Table 2. The unbalance of the load currents and the source currents is also listed in the table. The unbalance of the load current is 38.97% and the unbalance of the source current is improved to 4.92% after compensation. A series compensator is a more effective method to compensate voltage source unbalance than this parallel compensator.

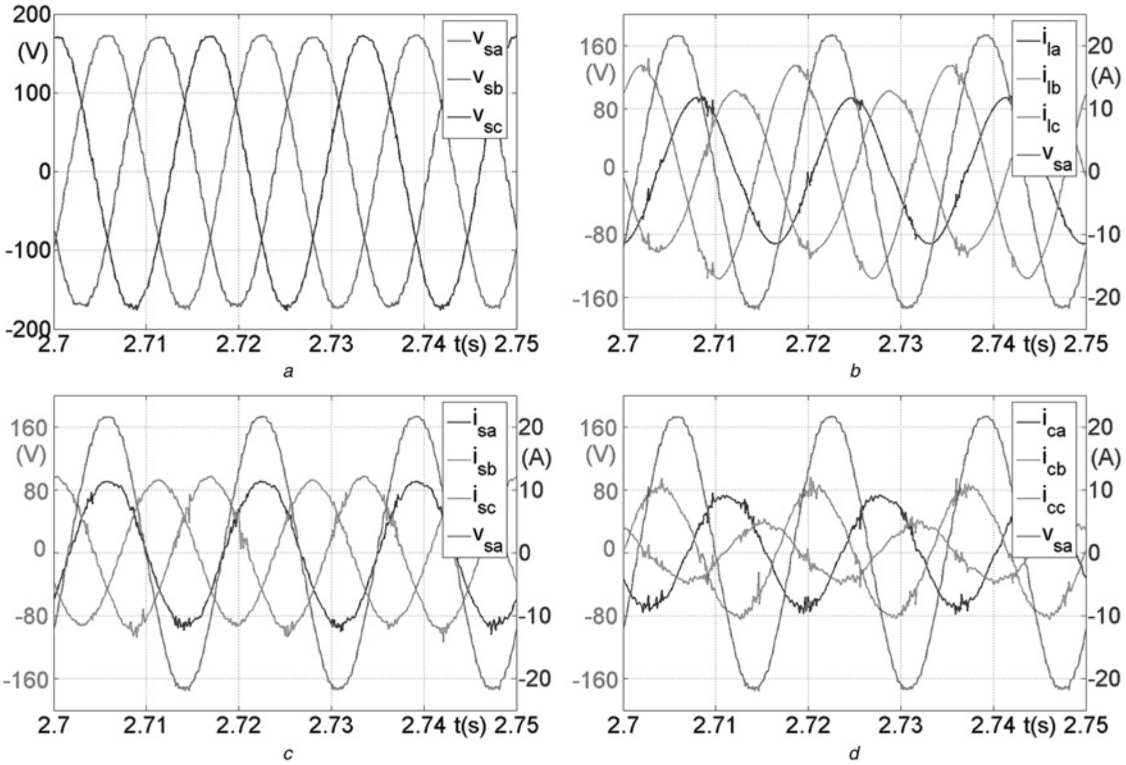

Figure 8 *Three-phase unbalanced RL load compensation (experiment)*

a System voltage against (t)
b Load current i_l (t)
c Source current
d Compensation current i_c (t)

Table 2 RMS values of current unbalance compensation

	I_l, A	I_s, A
Phase *a*	8.06	8.11
Phase *b*	9.00	7.95
Phase *c*	11.81	8.35
$I_{\text{unbalance}}$, %	38.97	4.92

Table 3 RMS current values of single-phase load compensation

	I_l, A	I_s, A
Phase *a*	7.20	4.44
Phase *b*	7.22	4.97
Phase *c*	0.43	3.97
$I_{\text{unbalance}}$, %	137.17	22.42

6.2 Single phase load on three-phase system compensation

Fig. 9 shows a single-phase load in a three-phase system. Fig. 9*a* is the three-phase system voltage, which is fundamental, sinusoidal and balanced. An RL load is connected between phases *a* and *b* and the three-phase load currents are shown in Fig. 9*b*. The phase *a* current and the phase *b* current are equal in magnitude and opposite in phase and the phase *c* current is zero. The rms values of the load currents are listed in the second column in Table 3. The rms value of phase *c* current is not zero because of the measurement error and noise. This single-phase load in a three-phase system can be viewed as an extreme case of load current unbalance. The unbalance of the three-phase load currents is listed in Table 3, which is 137.17%.

Current control is used in the experiment. The PI controller parameters are $K_P = 40$ and $K_I = 1$, respectively. The source current after compensation is shown in Fig. 9*c*. The magnitudes of phase *a* and phase *b* source currents are reduced and there is a current in phase *c*. The rms values of the three-phase source currents are shown in the third column of Table 3 and the unbalance of the source current is improved to 22.42%. The values of phases *a* and *b* are reduced and the three phases are more balanced after compensation.

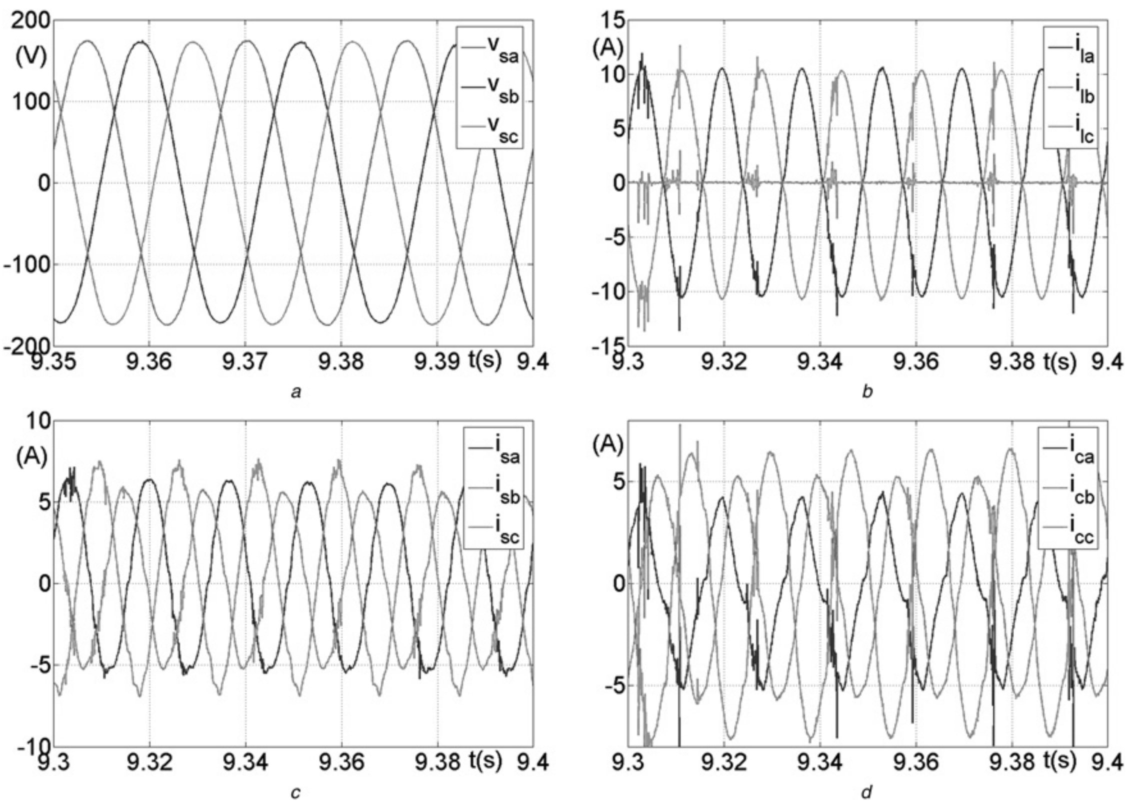

Figure 9 *Single-phase load in a three-phase system (experiment)*

a System voltage against (t)
b Load current i_l (t)
c Source current i_s (t)
d Compensation current $i_c(t)$

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7 Conclusions

A three-phase IGBT-based STATCOM is proposed for voltage and/or current unbalance compensation. An instantaneous power theory is used for real-time calculation and control. Three control schemes – current control, voltage control and integrated control – are proposed to compensate unbalanced voltage, unbalanced current or both.

The instantaneous power theory is suitable for STATCOM application, because it can provide real-time calculation and control for the compensator. The definitions of instantaneous active current and instantaneous non-active current are feasible for voltage and current unbalance compensation because the definitions of the three-phase voltages and currents are independent of each other.

Three control schemes are proposed. Either current unbalance (caused by the load) or voltage unbalance (caused by other loads or generators in the system) can be compensated using the STATCOM. Different compensation objectives can be achieved, that is, balanced and unity power factor source current, balanced and regulated voltage or both, by choosing appropriate control schemes. The integrated control has the flexibility to implement current control and voltage control separately or together. Thus, a STATCOM can perform both voltage unbalance compensation and/or current unbalance compensation without any hardware reconfiguration, which brings flexibility to the compensation system and reduces capital costs. In practice, because of the limited DC link voltage, sometimes the STATCOM cannot achieve 100% compensation.

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