Voltage and Current Unbalance Compensation Using a Parallel Active Filter

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***Abstract*—A three-phase insulated gate bipolar transistor (IGBT)-based parallel active filter is used for current and/or voltage 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 unbalance or voltage source unbalance) are compared and analyzed. 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, i.e., balanced and unity power factor source current, balanced and regulated voltage, or both, by choosing appropriate control schemes.**

***Index Terms*—current unbalance, voltage unbalance, nonactive power, current control, voltage control**

I. Introduction

Power quality, especially current unbalance, current harmonics, and voltage unbalance, has drawn much attention, and much research work has been performed in this area. One means of correcting these power quality problems is to provide nonactive power compensation. However, there are still no standard definitions of instantaneous nonactive power and instantaneous nonactive current [1-4]. A parallel active filter is an effective way to eliminate or mitigate the harmonics and unbalance in current [5-6].

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 motor has been studied in depth [7-8]. Series connected converter-based compensator 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 (5th and 7th) for current harmonics compensation is proposed in [14]. While 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 parallel active filter is also presented in [16].

The instantaneous power theory presented in [4] is used for the active filter presented in this paper because the definitions of instantaneous power and instantaneous nonactive power are suitable for real-time nonactive power compensation purpose. This instantaneous power theory will be elaborated in Section III.

A feedback controller is presented in this paper to perform both voltage unbalance and current unbalance compensation in a parallel active filter. The system can compensate the nonactive power component and/or the unbalance in the load current, and/or regulate and balance the system voltage. Either one or both of the tasks can be performed at the same time, depending on the compensation objectives. The compensator can provide the nonactive component in the load current if a balanced and unity power factor source current is desired; or regulate the system voltage to a certain level by injecting nonactive power to the system. Thus, it can compensate the unbalance from the utility or from the load.

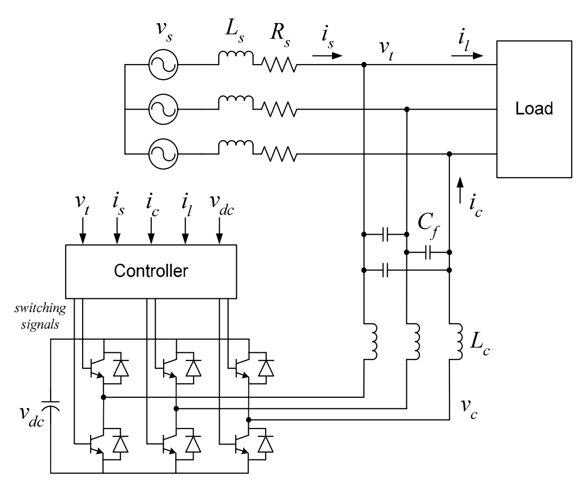

Fig. 1. System configuration of a parallel active filter.

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II. System Configuration

The system configuration of a parallel nonactive power compensator is shown in Fig. 1. The compensator is connected in parallel with the load, 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 L_c 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) nonactive power, and there is no energy source connected to the DC link. The DC link voltage v_{dc} is regulated by the compensator at a given level.

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

III. Instantaneous Power Theory

An instantaneous nonactive power theory [4] is adopted to calculate the instantaneous variables based on the measurements ($\boldsymbol{v_t}$, $\boldsymbol{i_l}$, $\boldsymbol{i_c}$, 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 will be denoted in bold),

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

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

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):

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

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

The averaging interval T_c can be chosen arbitrarily from zero to infinity, and for different T_c values, the resulting active current and nonactive current will have different characteristics [17]. In a periodic system with period T, T_c is normally chosen as integral multiples of $T/2$ to eliminate current harmonics.

The instantaneous active current $\boldsymbol{i_a}(t)$ and instantaneous nonactive current $\boldsymbol{i_n}(t)$ are defined by, respectively,

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

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

The voltage $\boldsymbol{v_p}(t)$ is the reference voltage, which is chosen based on the characteristics of the system and the desired compensation results. $V_p(t)$ is the rms value of the reference voltage $\boldsymbol{v_p}(t)$, i.e.,

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

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

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

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

The definitions in this instantaneous nonactive 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 $\boldsymbol{v_p}(t)$. 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.

IV. Control Schemes of the 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 also equal, and in a three-phase case, the phase angle is 2π/3. 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 $\boldsymbol{v_t}$. 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. While 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.

In this section, a current unbalance compensation control

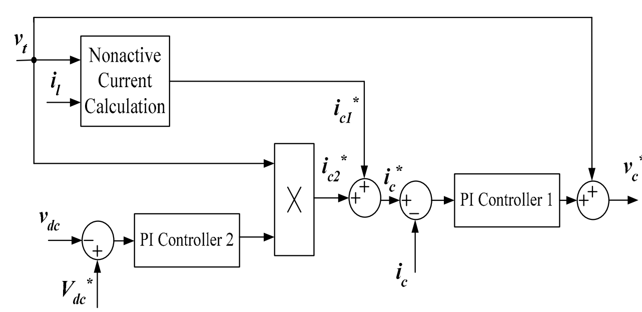


Fig. 2. Current control diagram.

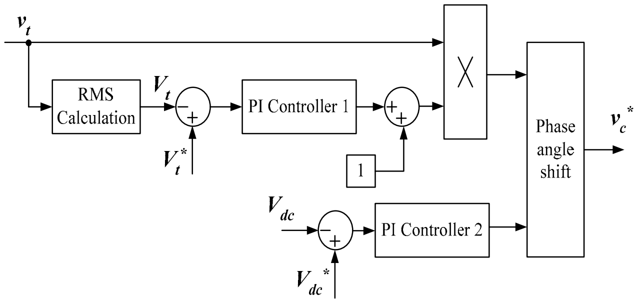


Fig. 3. Voltage control diagram.

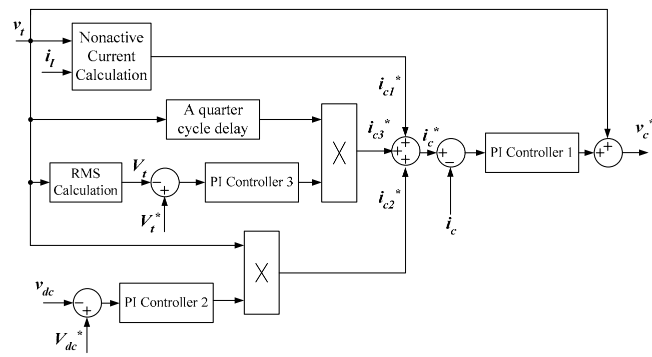


Fig. 4. Control diagram of the integrated current and voltage control.

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.

A. *Current Unbalance Compensation*

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

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

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

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 nonactive 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 no active power is provided to the compensator, the DC link capacitor voltage v_{dc} will vary. V_{dc} is the average value of the DC link voltage v_{dc} over one 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).

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

The sum of $\boldsymbol{i}_{c1}^*$ and $\boldsymbol{i}_{c2}^*$ is the current that the compensator needs to provide.

B. *Voltage Unbalance Compensation*

In power systems, most voltage unbalance conditions are due to magnitude inequalities while the phase-angles are equal (2π/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 nonactive power. The control principle is to control the compensator so that its output is only nonactive 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 $\boldsymbol{v}_c$. In each phase, when the magnitude of $\boldsymbol{v}_c$ is larger than that of $\boldsymbol{v}_t$, the compensator generates nonactive power; if the magnitude of $\boldsymbol{v}_c$ is smaller than that of $\boldsymbol{v}_t$, the compensator consumes nonactive 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 $\boldsymbol{V}_t^*$.

To meet the losses, the reference compensator voltage is shifted a small phase angle θ^* so that a small amount of active power is drawn by the compensator. 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.

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

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

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 decided by the DC link voltage control loop, which is the second input of the phase angle shift block.

C. *Integrated Compensation*

Can the compensator regulate the voltage and compensate the load nonactive 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 nonactive 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 subsection IV.A, and the voltage

TABLE I. VOLTAGE AND CURRENT UNBALANCE CONTROL

Control schemes	Compensation results	Load unbalance	Voltage source unbalance	
Voltage control	Source current	Balanced, pf ≠ 1	Unbalanced, pf ≠ 1	
	PCC voltage	Balanced, regulated magnitude	Balanced, regulated magnitude	
Current control	Source current	Balanced, pf = 1	Balanced, pf = 1	
	PCC voltage	Balanced, unregulated magnitude	Unbalanced, unregulated magnitude	
Integrated control	Source current	Balanced, pf ≠ 1	Balanced, pf ≠ 1	Unbalanced, pf ≠ 1
	PCC voltage	Balanced, regulated magnitude	Unbalanced, regulated magnitude	Balanced, regulated magnitude

regulation component $\boldsymbol{i}_{c3}^*$ is

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

The integrated control combines the current loop and the voltage control loop together. The two control loops can work individually by shutting down the other control loop (turning the control gains to zero), or work together. This provides the flexibility for the parallel active filter to do both current and voltage control without any hardware reconfiguration.

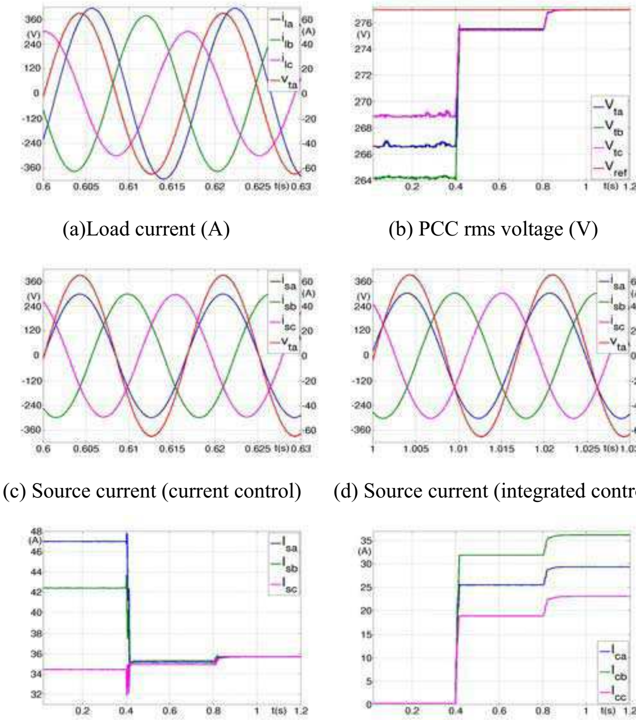
V. SIMULATION AND EXPERIMENTAL RESULTS

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 I. The compensation results of the source current and the PCC voltage are compared.

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

A. Load Unbalance (Simulation)

The three-phase load current together with phase *a* voltage is shown in Fig. 5a. The current is unbalanced and lagging the voltage. There is no compensation from t = 0 s to t = 0.4 s, 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. 5b, 5e, and 5f, 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). The voltage is balanced since the load now draws balanced current from the utility, and the magnitude is increased.



(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)

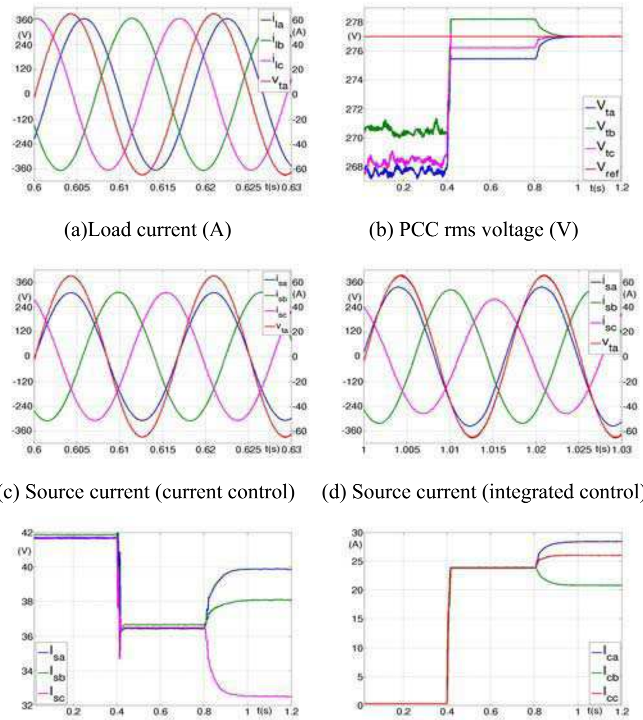
Fig. 5. Load unbalance compensation (simulation).

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 nonactive power provided by the compensator to the utility, and the magnitude of the source current is increased some as shown in Fig. 5e. At both the current compensation and the integrated compensation, the compensator current is unbalanced and more nonactive current is flowing to the system at the integrated compensation condition.

As listed in Table I, both the voltage and 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, while in voltage control, the voltage magnitude is regulated, but the source current is not controlled to unity power factor (usually a leading power factor because nonactive power is provided to the utility to boost the voltage).

B. Voltage Source Unbalance (Simulation)

If the voltage source is unbalanced, the current compensation can make the source current balanced and unity power factor, while the voltage compensation can make the voltage balanced and magnitude regulated, as shown in Table I. If the integrated control is used, either a balanced



(a)Load current (A) (b) PCC rms voltage (V)

(c) Source current (current control) (d) Source current (integrated control)

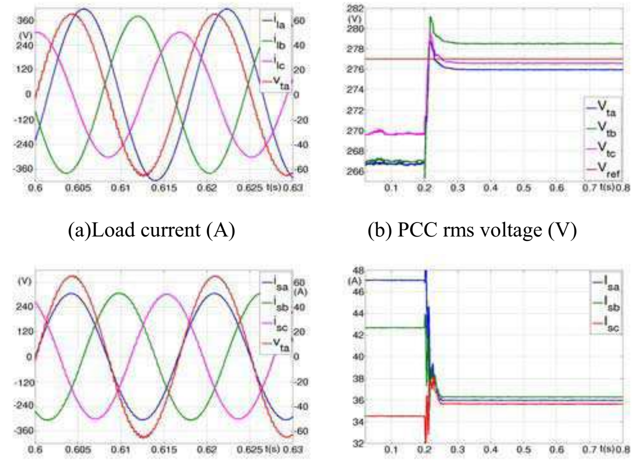
(e) Source current rms (A) (f) Compensator current rms (A)

Fig. 6. Simulation of voltage source unbalance compensation (balanced voltage is desired).

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 load current is shown in Fig. 6a 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. 6b, 6e, and 6f, 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 unbalance and nonactive 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 $\boldsymbol{v}_p(t)$ 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 nonactive power provided by the compensator to the utility, and the source current is not balanced as shown in Fig. 5e. At both the current compensation and the integrated compensation, the compensator current is unbalanced and more nonactive current is flowing to the system at the integrated compensation condition.



(a)Load current (A) (b) PCC rms voltage (V)

(c) Source current (integrated control) (d) Source current rms (A)

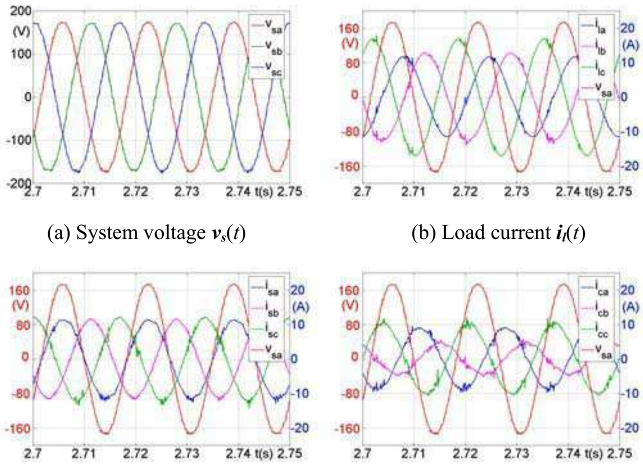
Fig. 7. Simulation of voltage source unbalance compensation (balanced source current is desired).

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 are regulated at 277 V, therefore the nonactive power provided from the compensator is equal in each phase. Fig. 7c shows the source current, which is leading the voltage. In Fig. 7d, it shows that the source current is nearly balanced when the integrated control is performed.

C. Load Unbalance (Experiment)

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 Figure 8b. 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 mH, 10 mH, 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. 8a. The source current after compensation together with the phase *a* voltage is shown in Fig. 8c. The source current is nearly balanced compared to the load current, and in phase with the voltage. The compensation current is shown in Fig. 8d, which is unbalanced and 90º out of phase with the voltage. Current control is used in the experiment, i.e., the compensation objective is to provide the unbalance component and the nonactive component in the load current so that the source current is balanced and unity power factor.

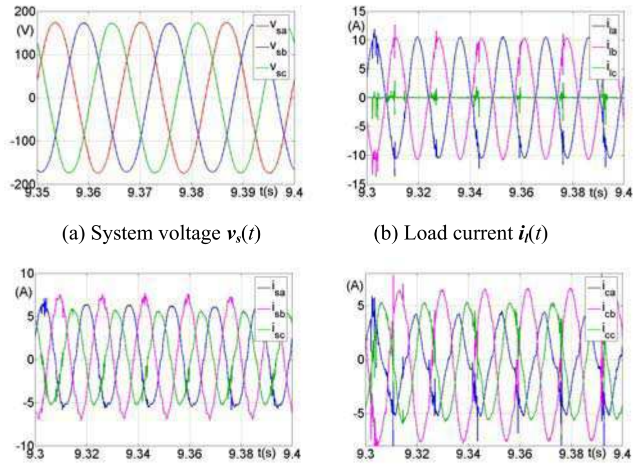
Current control is used in the experiment, i.e., the compensation objective is to provide the unbalance



(a) System voltage $\boldsymbol{v}_s(t)$ (b) Load current $\boldsymbol{i}_l(t)$

(c) Source current (d) Compensation current $\boldsymbol{i}_c(t)$

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



(a) System voltage $\boldsymbol{v}_s(t)$ (b) Load current $\boldsymbol{i}_l(t)$

(c) Source current $\boldsymbol{i}_s(t)$ (d) Compensation current $\boldsymbol{i}_c(t)$

Fig. 9. Single-phase load in a three-phase system (experiment).

TABLE II. RMS VALUES OF THE 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
$I_{unbalance}$	38.97%	4.92%

TABLE III. RMS VALUES OF THE 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%

component and the reactive component in the load current so that the source current is balanced and unity power factor.

The unbalance of the three-phase currents is calculated as

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

where

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

The rms values of the three phase load currents and the source currents after compensation are listed in Table II. 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.

Fig. 9 shows a single-phase load in a three-phase system. Fig. 9a is the three-phase system voltage, which is fundamental sinusoidal and balanced. An *RL* load is connected between phase *a* and phase *b*, and the three-phase load currents are shown in Fig. 9b. 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 III. 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 III, which is 137.17%.

The source current after compensation is shown in Fig. 9c. 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 III, and the unbalance of the source current is improved to 22.42%. The values of phase *a* and phase *b* are reduced and the three phases are more balanced after compensation.

VI. CONCLUSIONS

A three-phase IGBT-based parallel connected nonactive power compensator is presented for current and/or voltage 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 current, unbalanced voltage, or both.

The instantaneous power theory is suitable for parallel active filter application, because it can provide real-time calculation and control for the compensator. The definitions of instantaneous active current and instantaneous nonactive current are feasible for current and voltage unbalance compensation because the definitions of the three-phase currents and voltages 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 parallel active filter. Different compensation objectives can be achieved, i.e., 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 parallel active filter can perform both current unbalance compensation and/or voltage unbalance compensation without any hardware reconfiguration, which brings flexibility to the compensation system and reduces capital costs.

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