Combined Operation of Unified Power-Quality Conditioner With Distributed Generation

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***Abstract*—This paper describes analysis results of a combined operation of the unified power quality conditioner with the distributed generation. The proposed system consists of a series inverter, a shunt inverter, and a distributed generator connected in the dc link through rectifier. The proposed system can compensate voltage sag and swell, voltage interruption, harmonics, and reactive power in both interconnected mode and islanding mode. The performance of proposed system was analyzed using simulations with power system computer aided design/electromagnetic transients dc analysis program, and experimental results with the hardware prototype. The proposed system can improve the power quality at the point of installation on power distribution systems or industrial power systems.**

***Index Terms*—Distributed generation (DG), power system computer-aided design/electromagnetic transients dc analysis program (PSCAD/EMTDC), unified power-quality conditioner (UPQC).**

I. Introduction

UNIFIED power-quality control was widely studied by many researchers as an ultimate method to improve power quality [1]–[5]. The function of unified power-quality conditioner (UPQC) is to mitigate the disturbance that affects the performance of the critical load. The UPQC, which has two inverters that share one dc link capacitor, can compensate the voltage sag and swell, the harmonic current and voltage, and control the power flow and voltage stability. However, UPQC cannot compensate the voltage interruption because it has no energy storage in the dc link.

The interest in distributed generation (DG) has been increasing rapidly because DG might play an important role in the future power system [6]–[8]. DG can solve many typical problems that the conventional ac power system has. For example, an energy security problem occurs in the large-scale power system because a few transmission facilities are responsible for serving electric power to a great number of customers. This security problem caused by some transmission-line trip can be alleviated if a large number of DGs are installed in the power system. Moreover, DG can yield economic benefits, such as reducing the loss of transmission line and the cost of high-voltage equipment. However, a small DG has some significant problems of frequency and voltage variation when it is operated in stand-alone mode. Therefore, a small DG should be interconnected with the power system in order to maintain the frequency and the voltage. Several studies proposed an interconnection system for DG with the power system through the inverter because the inverter gives versatile functions improving the ability of DG [9], [10].

This paper proposes a combined operation system of UPQC and DG, which is connected to the dc link through a rectifier. The advantage of the proposed system over the UPQC in [4] is to compensate the voltage interruption, as well as the voltage sag, voltage swell, harmonics, and reactive power. The operation of the proposed system was verified through simulations with power system computer-aided design/electromagnetic transients dc analysis program (PSCAD/EMTDC). The feasibility of hardware development was confirmed though experimental works with a prototype.

II. Proposed System

Normally, UPQC has two voltage-source inverters in three-phase four-wire or three-phase three-wire configuration. One inverter called the series inverter is connected through transformers between the source and the common connection point. The other inverter called the shunt inverter is connected in parallel with the common connection point through transformers. The series inverter operates as a voltage source, while the shunt inverter operates as a current source.

UPQC has compensation capabilities for the harmonic current, the reactive power compensation, the voltage disturbances, and the power-flow control. But UPQC has no capability in compensating the voltage interruption because there is no energy storage.

This paper proposes a new configuration of UPQC that has a DG connected to the dc link through the rectifier as shown in Fig. 1. The UPQC can compensate the voltage interruption in the source, while the DG supplies power to the source and load or the load only. There are two operation modes in the proposed system. One is called the interconnected mode, in which the DG provides power to the source and the load. The other is called the islanding mode, in which the DG provides power to the load only within its power rating.

III. Controller Design

The control structure of proposed system is shown in Fig. 2. Three major elements are the positive sequence detector, the series inverter control, and the shunt inverter control. The control strategy was designed for implementing the interconnected

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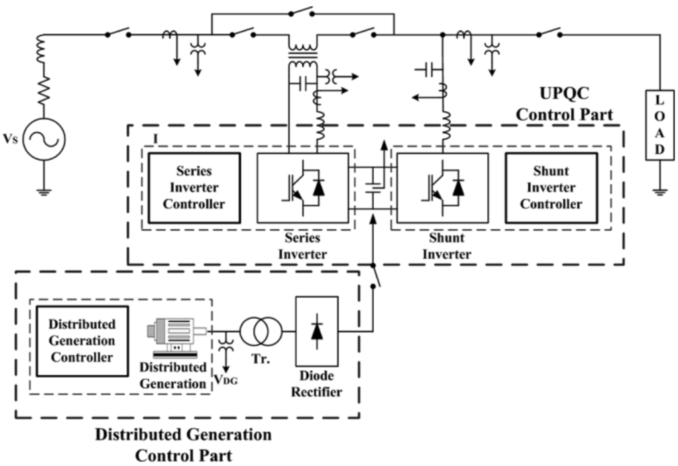

Fig. 1. Proposed UPQC system with DG.

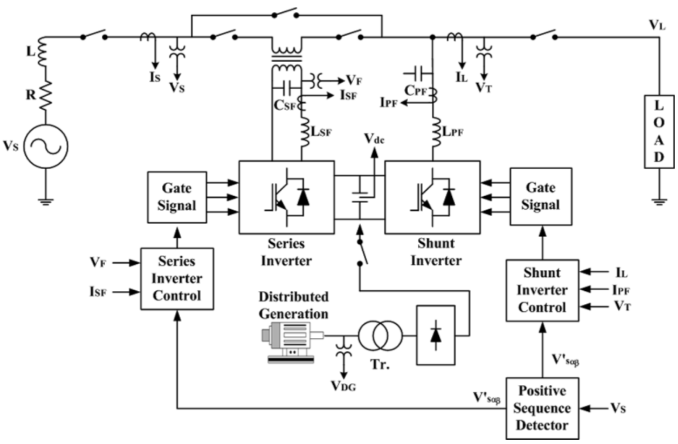

Fig. 2. Control block diagram.

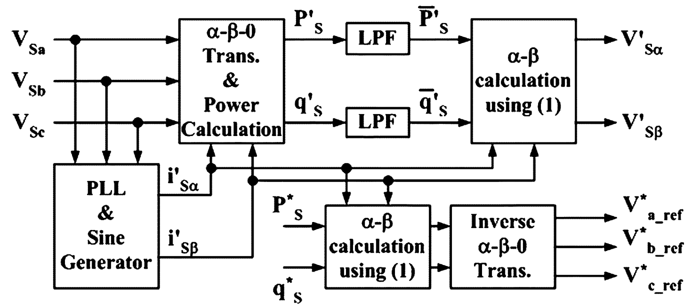

Fig. 3. Positive-sequence detector and voltage reference generator.

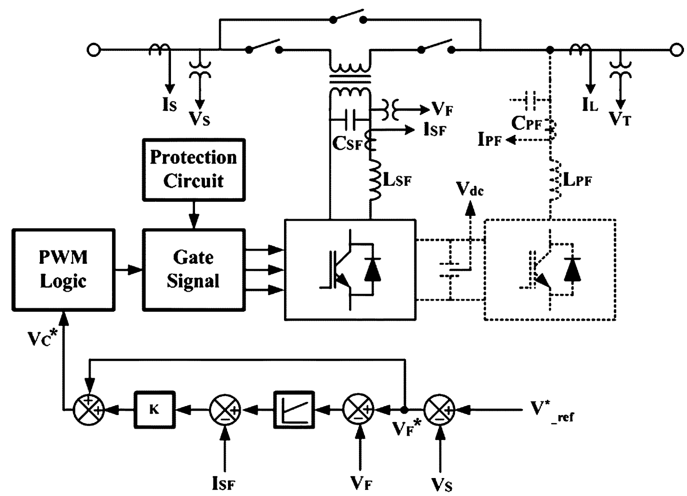

Fig. 4. Series inverter control block diagram.

mode and the islanding mode. The system works in interconnected mode when the DG and the main source supply power to the load in parallel. But it works in islanding mode when the voltage interruption occurs. Once the voltage interruption is removed, the system operation transfers from the islanding mode to the interconnected mode.

A. Positive-Sequence Detector and Voltage Reference Generator

The positive-sequence detector has a configuration shown in Fig. 3. The source voltage is detected to calculate the fundamental current component $i'_{S\alpha} = \sin(\omega_1 t)$ and $i'_{S\beta} = \cos(\omega_1 t)$ passing through the phase-locked loop (PLL) and the sine-wave generator. The source voltage is used to calculate the instantaneous active and reactive power p'_s and q'_s using the source current $i'_{S\alpha}$ and $i'_{S\beta}$, and $\alpha - \beta - 0$ transform. These values are passed through the low-pass filter to obtain the constant components of $\bar{p}'_S$ and $\bar{q}'_S$. The calculated $\bar{p}'_S$ and $\bar{q}'_S$ include only the positive-sequence fundamental component of the source voltage V_S. The reference voltage $V'_{S\alpha}$ and $V'_{S\beta}$ is calculated using (1)

$$\begin{bmatrix} V'_{S\alpha} \\ V'_{S\beta} \end{bmatrix} = \frac{1}{i'^2_\alpha + i'^2_\beta} \begin{bmatrix} i'_\alpha & i'_\beta \\ i'_\beta & -i'_\alpha \end{bmatrix} \begin{bmatrix} \bar{p}'_S \\ \bar{q}'_S \end{bmatrix}. \quad (1)$$

The reference voltage $V^*_{a\_\mathrm{ref}}$, $V^*_{b\_\mathrm{ref}}$, and $V^*_{c\_\mathrm{ref}}$ are derived from the nominal instantaneous active and reactive powerp^*_S and q^*_S, using (1) and inverse $\alpha - \beta - 0$ transformation.

B. Series Inverter Control

The function of series inverter is to compensate the voltage disturbance in the source side, which is due to the fault in the distribution line. The series inverter control calculates the reference value to be injected by the series inverter, comparing the positive-sequence component with the disturbed source voltage. Equation (2) shows the state equation of the series inverter

$$V^*_C = [K_{PI}\{(V^*_{\_\mathrm{ref}} - V_S) - V_F\} - I_{SF}] * K + V^*_F. \quad (2)$$

Fig. 4 shows the configuration of series inverter control, which is based on (2).

Fig. 5 shows the simulation result of voltage control, which confirms the fact that the output voltage of each phase tracks the reference value without large transient and steady-state errors.

C. Shunt Inverter Control

The shunt inverter described in this paper has two major functions. One is to compensate the current harmonics generated in the nonlinear load and the reactive power. The other is to supply the power to the load when the voltage interruption occurs in the source side. The control system for the shunt inverter has to be designed to cover these two functions. In normal operation, the

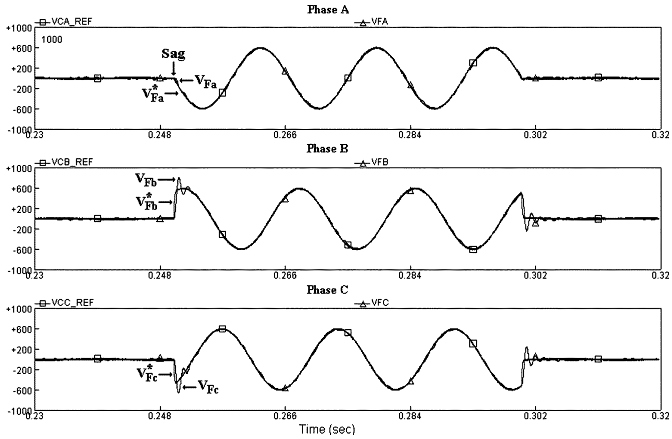

Fig. 5. Reference output voltage and actual output voltage of series inverter.

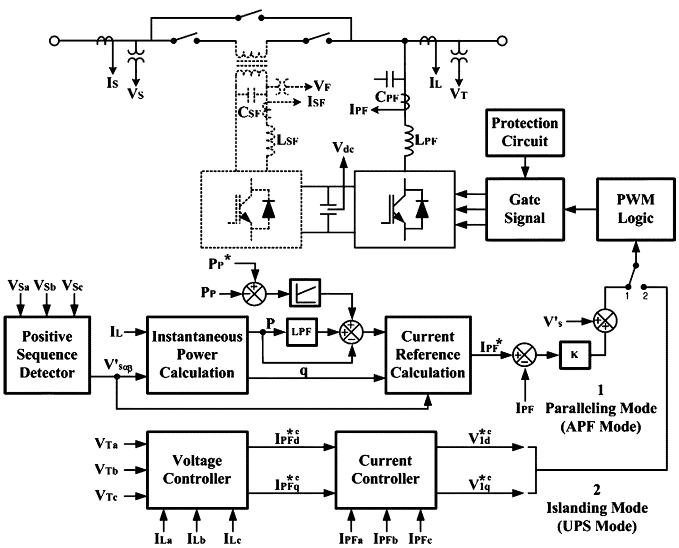

Fig. 6. Shunt inverter control block diagram.

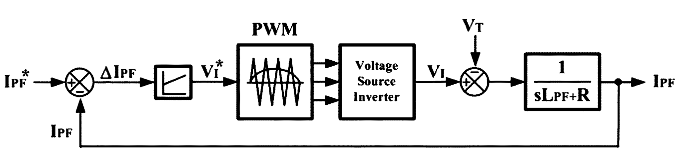

Fig. 7. Current control block diagram.

shunt control calculates the compensating current for the harmonic current and the reactive power, considering the power loss p_{loss} due to the system and inverter operation. This loss should be compensated to maintain the dc-link voltage during operation of the series inverter. The reference value of compensating current is derived using (3)

$$\begin{bmatrix} i_{C\alpha}^* \\ i_{C\beta}^* \end{bmatrix} = \frac{1}{V_{S\alpha}'^2 + V_{S\beta}'^2} \begin{bmatrix} V_{S\alpha}' & -V_{S\beta}' \\ V_{S\beta}' & V_{S\alpha}' \end{bmatrix} \begin{bmatrix} -\widetilde{p} + p_{\text{loss}} \\ -q \end{bmatrix}. \quad (3)$$

When the voltage interruption occurs in the source side, the shunt inverter control changes from the operation mode of active power filter to that of the uninterruptible power supply. Fig. 6 shows the configuration of whole system control, which includes three subcontrol elements, such as the current control for harmonic compensation, and the output voltage control in voltage interruption.

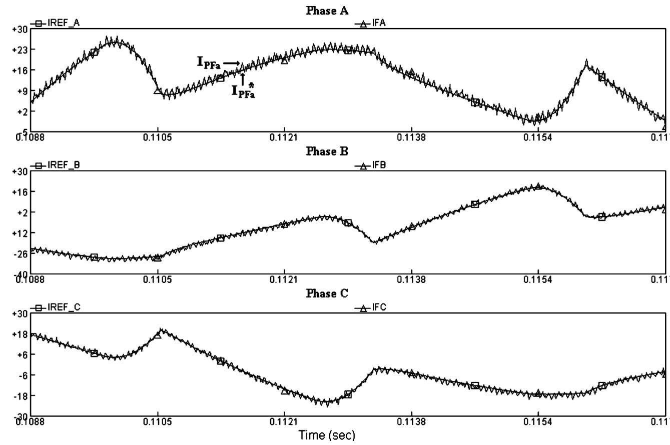

Fig. 8. Reference output current and actual output current of shunt inverter.

1) Current Control of Output Terminal: The reference voltage is determined using (4) and (5). The reference voltage V_1^* is expressed by the sum of the source voltage V_S' and the filter current difference ΔI_{PF} calculated by the proportional-integral (PI) controller

$$\Delta I_{PF} = I_{PF}^* - I_{PF} \quad (4)$$

$$V_1^* = k_P \Delta I_{PF} + k_I \int \Delta I_{PF} dt. \quad (5)$$

Fig. 7 shows the configuration of current control organized considering this feature.

If the shunt inverter is assumed to generate the reference voltage for each period of power frequency, the transfer function of the filter current can be derived as in (6)

$$\frac{I_{PF}}{I_{PF}^*} = \frac{\left(\frac{k_P}{L_{PF}}\right) s + \left(\frac{k_I}{L_{PF}}\right)}{s^2 + \left\{\frac{(k_P+R)}{L_{PF}}\right\} s + \left(\frac{k_I}{L_{PF}}\right)}. \quad (6)$$

Fig. 8 shows the simulation result of current control, which confirms that the output current of each phase tracks the reference current without large transient and steady-state errors.

2) Voltage Control Under Interruption: When the voltage interruption occurs, the operation mode is changed from the normal compensation to the interruption compensation. The DG provides the active power to maintain the load voltage constant. The shunt inverter starts to perform the voltage and current control using the PI controller. Fig. 9 shows the equivalent circuit when the shunt inverter compensates the voltage interruption.

The dynamic equations derived from the equivalent circuit can be expressed by (7) and (8). The state equations for the voltage control and the current control can be expressed by (9) and (10)

$$C_{PF} \frac{d}{dt} V_{T_{a,b,c}} = I_{PF_{a,b,c}} - I_{L_{a,b,c}} \quad (7)$$

$$L_{PF} \frac{d}{dt} I_{1_{a,b,c}} = DV_{1_{a,b,c}} - V_{T_{a,b,c}} \quad (8)$$

where $D = 1/3 \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}$

$$\begin{aligned} I_{PFd}^{*e} &= K_{PI}\left(V_{Td}^{*e} - V_{Td}^e\right) - \omega C_{PF} V_{Tq}^e + I_{Ld}^e \\ I_{PFq}^{*e} &= K_{PI}\left(V_{Tq}^{*e} - V_{Tq}^e\right) + \omega C_{PF} V_{Td}^e + I_{Lq}^e \quad (9) \\ V_{1d}^{*e} &= K_{PI}\left(I_{PFd}^{*e} - I_{PFd}^e\right) - \omega L_{PF} I_{PFq}^e + V_{Td}^e \end{aligned}$$

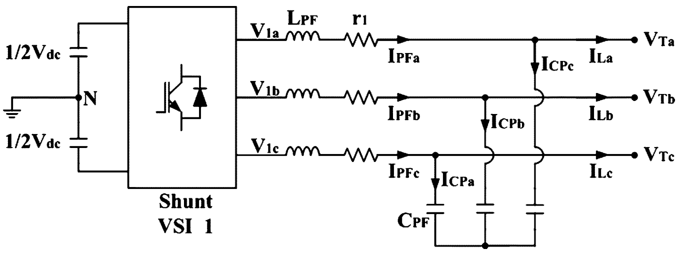

Fig. 9. Shunt inverter three-phase equivalent circuit.

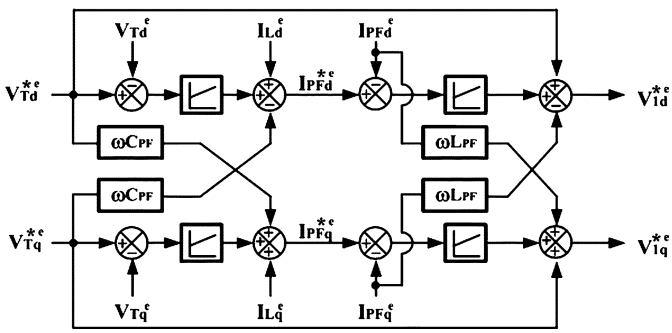

Fig. 10. Voltage control of the shunt inverter.

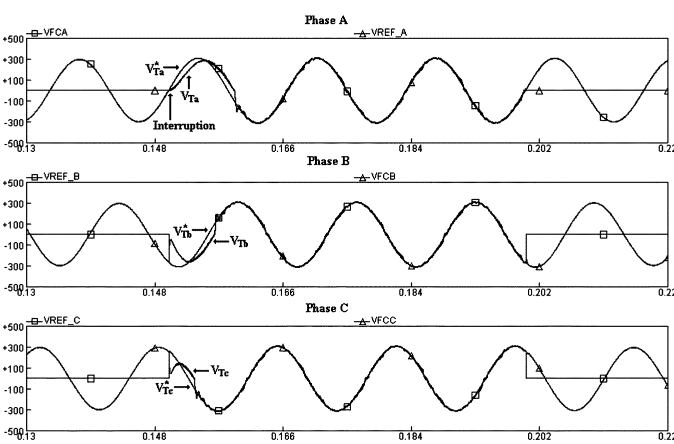

Fig. 11. Reference output voltage and actual output voltage of the shunt inverter.

$$V_{1q}^{*e} = K_{PI}\left(I_{PFq}^{*e} - I_{PFq}^{e}\right) + \omega L_{PF} I_{PFd}^{e} + V_{Tq}^{e}. \quad (10)$$

Fig. 10 shows the block diagram for implementing the above equations derived from the equivalent circuit.

Fig. 11 shows the simulation result of current control, which confirms that the output voltage of each phase tracks the reference current without large transient and steady-state errors.

IV. Computer Simulation

Many computer simulations with PSCAD/EMTDC software were performed for the purpose of analyzing the operation of the proposed system. The power circuit is modeled as a three-phase four-wire system with a nonlinear load that is composed of a three-phase diode bridge with the resistor and reactor (RL) load in the dc side. The DG was modeled using the built-in synchronous generator in the PSCAD/EMTDC software. The controller was modeled using the built-in control block in the PSCAD/EMTDC software. The circuit parameters that were used in the simulation are shown in Table I. The maximum simulation time was set up by 700 ms. It is assumed that the shunt inverter starts to operate at 100 ms, while the series inverter starts to operate at 200 ms.

TABLE I
Simulation Parameters

Source	Voltage	380V, 60Hz
	Impedance	R=0.001Ω, L=0.01mH
DC-Link	Capacitor	C1=6600uF, C2=6600uF
	Reference Voltage	700V
Shunt Inverter	Filter L, C	600uH, 40uF
	Switching Freq.	10kHz
Series Inverter	Filter L, C	600uH, 40uF
	Switching Freq.	10kHz
	Injection Trans.	500:100, 6kVA
Load	Non-linear Load	17.54kVA
	Linear Load	3.27kVA
Distributed Generation	AC Generator	30kW
	Transformer	380/500V
	Rectifier	700VDC

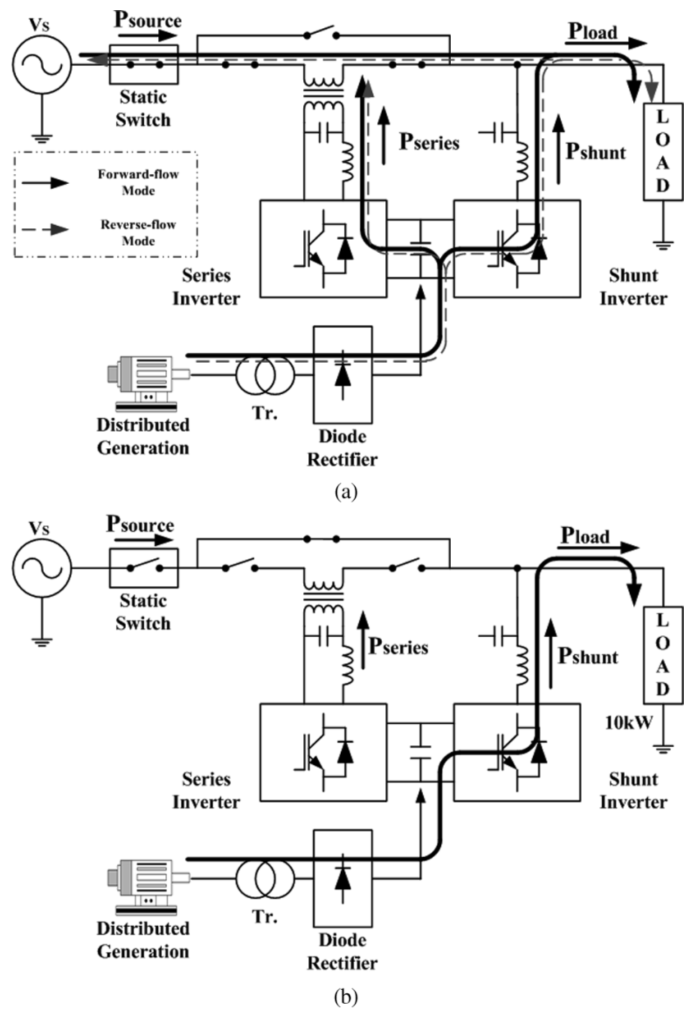

Fig. 12. System operation concept. (a) Interconnected mode. (b) Islanding mode.

Fig. 12 shows the system operation concept diagram of the proposed UPQC with the interconnected and the islanding mode. In the interconnected mode, the operation is divided into two submodes according to the direction of power flow. One is

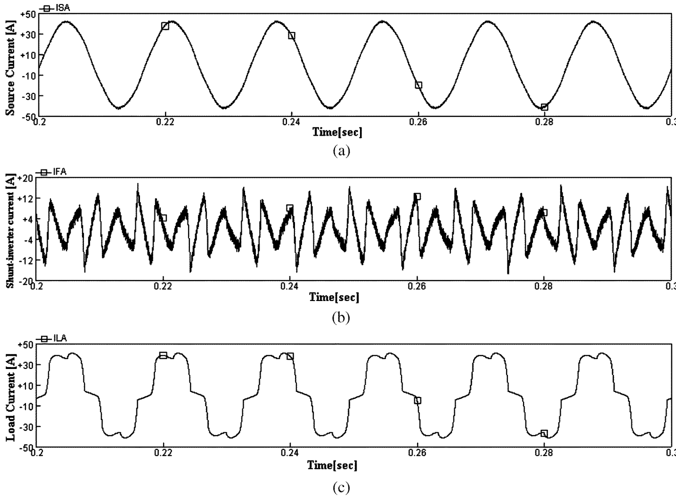

Fig. 13. Current harmonics compensation. (a) Source current. (b) Shunt-inverter current. (c) Load current.

called the forward-flow mode, in which the shunt inverter with the DG supplies power to the load in parallel with the main source. The other, called the reverse-flow mode, is when the shunt inverter with DG supplies power to the load and the main source. It is assumed that the shunt inverter and the main source provide 20-kW power to the load in the forward-flow mode, and the shunt inverter provide 10-kW power to the main source and 10-kW power to the load in the reverse-flow mode. When the voltage interruption occurrs, the proposed UPQC changes from the interconnected mode to the islanding mode, and the shunt inverter provides 10-kW power to the load.

A. Forward-Flow Mode

Fig. 13 shows the simulation results when the shunt inverter of UPQC operates as an active power filter. Fig. 13(a)–(c) shows, respectively, the current waveform of the source, the shunt inverter, and the load, in which the load current can be compensated by the shunt-inverter current to make the source current sinusoidal.

Fig. 14 shows the simulation results when the source has an unbalanced voltage sag for 0.1 s, in which phase A has 10% of swell, and Phases B and C have 30% of sag with 20° of phase jump, respectively. Fig. 14(a) and (b) shows the source voltage and the load voltage. The load voltage maintains a constant value as expected. Fig. 14(c) shows the active power of the load, the source, the shunt inverter, and the series inverter. During the sag interval, the series inverter provides active power for the load to cover the voltage sag.

Fig. 15 shows the simulation results when the source has a voltage interruption for 0.1 s from 0.3 to 0.4 s. Fig. 15(a) and (b) shows the source voltage and the load voltage. The load voltage maintains a constant value by the support of the shunt inverter voltage. Fig. 15(c) shows the active power of the load, the source, the shunt inverter, and the series inverter. In normal operation, the source and the shunt inverter share the load by providing 10-kW power, respectively. But during the voltage interruption, the shunt inverter only provides 20-kW power to the load. The load power maintains a constant value by the support

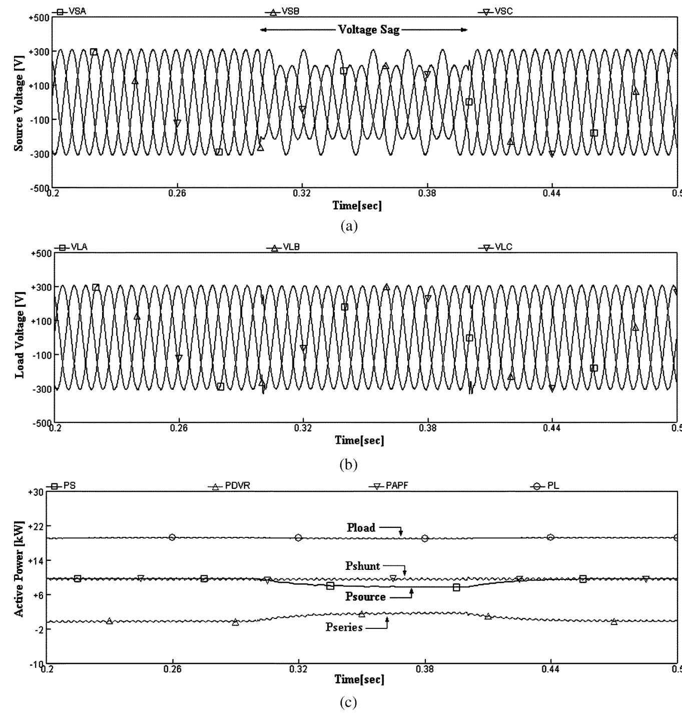

Fig. 14. Voltage sag compensation. (a) Source voltage. (b) Load voltage. (c) Active-power variation.

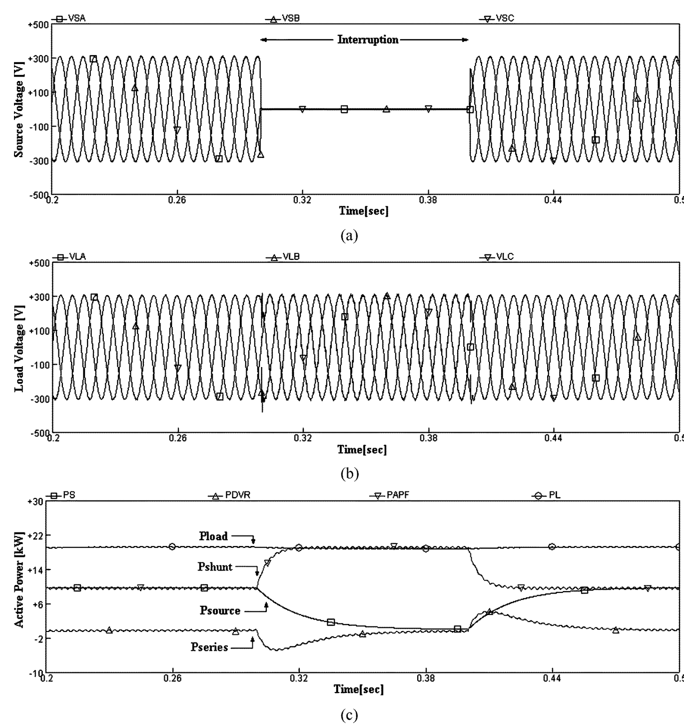

Fig. 15. Voltage-interruption compensation. (a) Source voltage. (b) Load voltage. (c) Active-power variation.

of shunt inverter power, even though the source power is zero during the voltage interruption.

B. Reverse-Flow Mode

Fig. 16 shows the simulation results when the source has 30% of three-phase voltage sag. Fig. 16(a) and (b) shows the source voltage and the load voltage. The load voltage maintains a constant value as expected. Fig. 16(c) shows the active

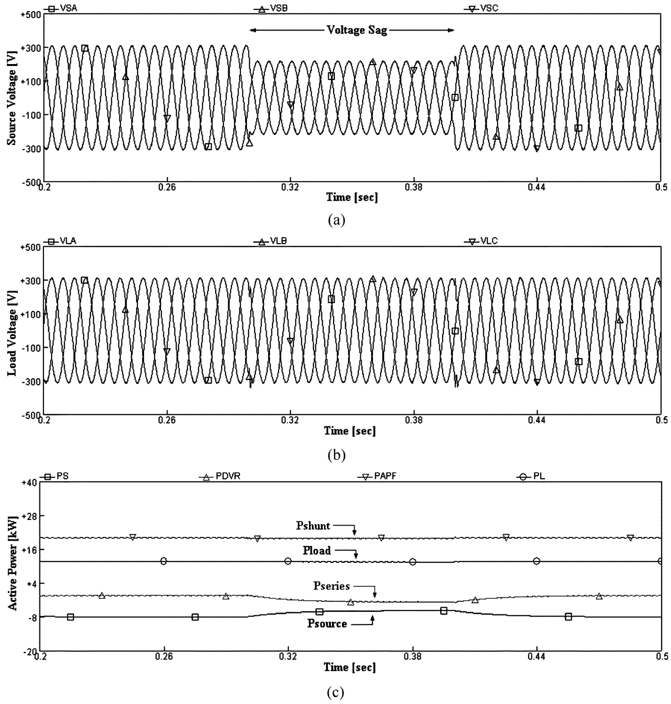

Fig. 16. Voltage sag compensation. (a) Source voltage. (b) Load voltage. (c) Active-power variation.

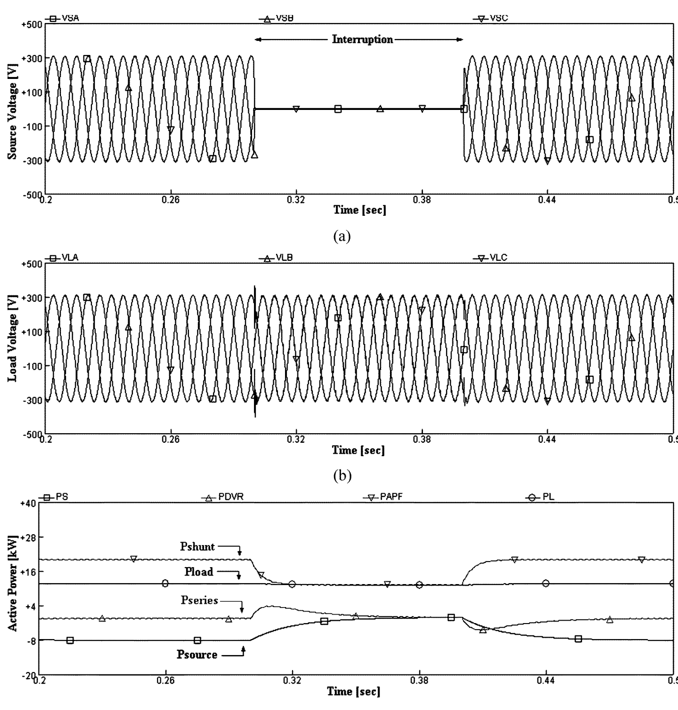

Fig. 17. Voltage-interruption compensation. (a) Source voltage. (b) Load voltage. (c) Active-power variation.

power of the load, the source, the shunt inverter, and the series inverter. During the sag interval, the reverse-flow source power is reduced and the series inverter covers this reduced amount to maintain the load power constant.

Fig. 17 shows the simulation results when the source has a voltage interruption for 0.1 s from 0.3 to 0.4 s. Fig. 17(a) and (b) shows the source voltage and the load voltage. The load voltage maintains constant value by the support of the shunt inverter voltage. Fig. 17(c) shows the active power of the load, the source, the shunt inverter, and the series inverter. In normal operation, the shunt inverter provides 10-kW power to the load and the source, respectively. But during the voltage interruption, the shunt inverter provides 10-kW power only to the load.

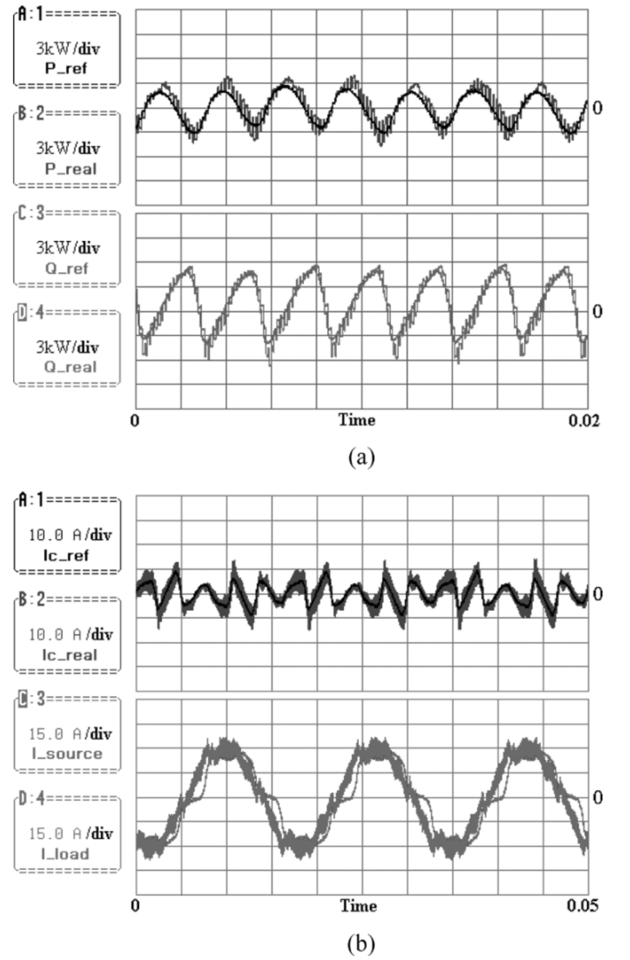

Fig. 18. Current harmonics compensation. (a) Instantaneous active and reactive power. (b) Shunt-inverter current, load, and source current.

V. Prototype Experiment

A prototype was built and tested to confirm the feasibility of actual hardware implementation. A 50-kW source simulator using two inverters with a digital signal processing (DSP) processor was built in a separate cabinet, which can generate the voltage sag, the voltage swell, and the voltage interruption to simulate the voltage disturbance in a distribution system. A 30-kW UPQC was also built in a cabinet using two inverters with one solid-state switch and a DSP processor. A 30-kW synchronous generator was connected in the dc link through a diode rectifier and transformer. Both linear and nonlinear loads are built for experimental work. All of the circuit parameters are exactly the same as those used in computer simulation. All of the experimental conditions are set up exactly the same as the simulation conditions.

Fig. 18(a) shows the tracking characteristic of the instantaneous active and reactive power for the reference value, which confirms the performance of the shunt inverter. Fig. 18(b) shows

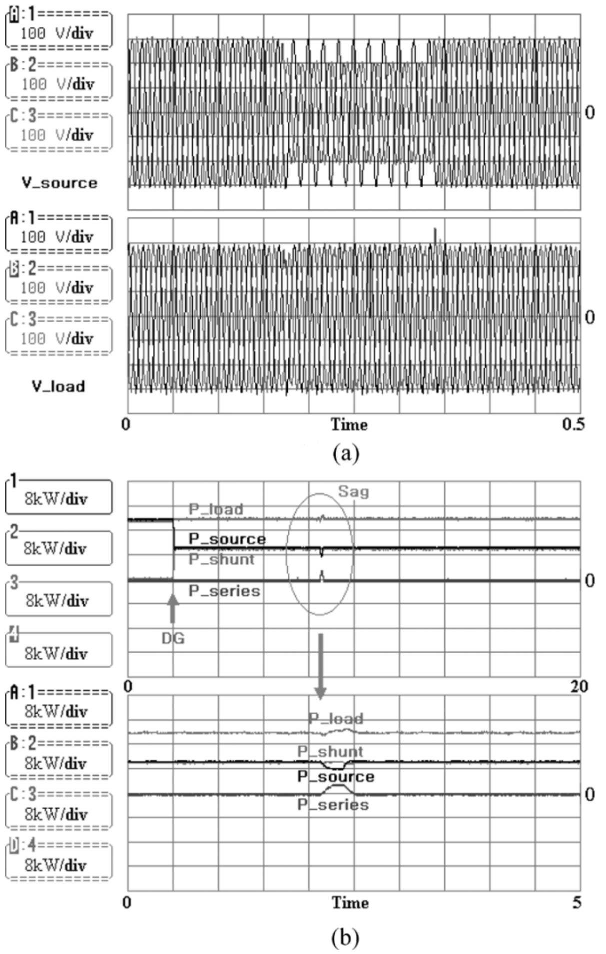

Fig. 19. Voltage sag compensation. (a) Source and load voltage. (b) Active-power variation.

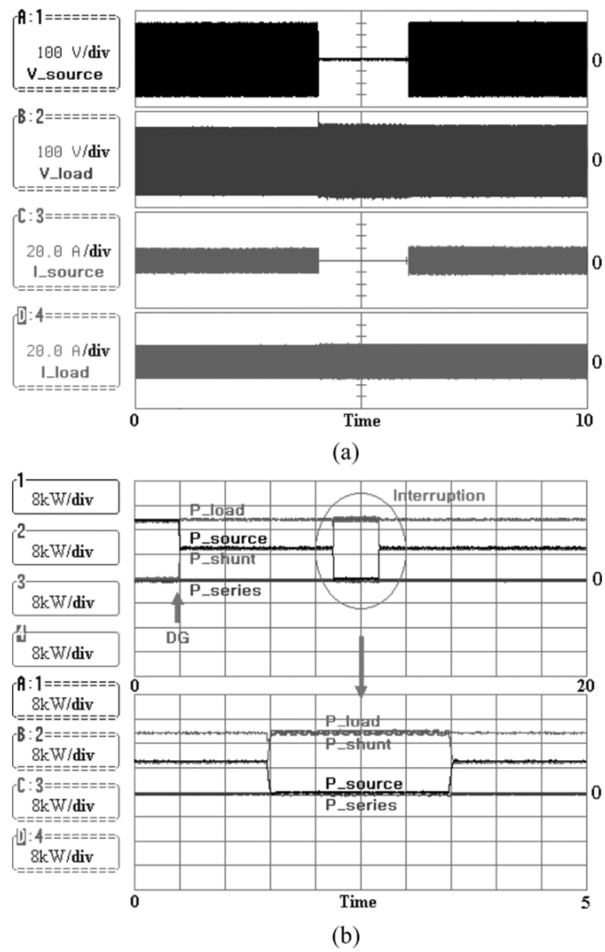

Fig. 20. Voltage-interruption compensation. (a) Voltage and current of source and load. (b) Active-power variation.

the active power filter operation, in which the harmonic current of the load is compensated using the shunt inverter. Although there are some high-frequency harmonics, the experimental result is very close to the simulation result.

A. Forward-Flow Mode

Fig. 19 shows the experimental results in the forward-flow mode when the unbalanced sag occurs. The first and the second graphs in Fig. 19(a) show the source voltage and the load voltage. The load voltage maintains constant value as confirmed in simulation. The graph in Fig. 19(b) shows the active powers of the source, the load, the shunt inverter, and the series inverter. The load power maintains constant value by the support of a series inverter power, even though the source power has a dip during the voltage sag.

Fig. 20 shows the experimental results when the voltage interruption occurs in the forward-flow mode. The first and second graphs in Fig. 20(a) show the source voltage and the load voltage in the voltage interruption for 2 s. There is a transient in the load voltage that rises up to 400 V at the instant of voltage interruption. This overvoltage occurs as the shunt inverter changes operation from the current control mode to the voltage-control mode. The transient voltage level depends on the instant when the voltage interruption occurs. The third and fourth graphs in Fig. 20(a) show the source current and the load current. The load current maintains a constant value as confirmed in simulation. The graph in Fig. 20(b) shows the active powers of the source, the load, the shunt inverter, and the series inverter. The load power maintains constant value by the support of shunt inverter power, even though the source power is 0 during the voltage interruption.

B. Reverse-Flow Mode

Fig. 21 shows the experimental results in the reverse-flow mode when the sag occurs. It is assumed that the source has 30% of voltage sag in all three phase. The first and the second graph in Fig. 21(a) show the source voltage and the load voltage. The load voltage maintains constant value as verified in the simulation. The graph in Fig. 21(b) shows the active powers of the source, the load, the shunt inverter, and the series inverter. During the sag, the reverse-flow source power is reduced and the series inverter covers this reduced amount to maintain the load power constant as confirmed in the simulation.

Fig. 22 shows the experimental results when the voltage interruption occurs in the reverse-flow mode. The first and second graphs in Fig. 22(a) show the source voltage and the load voltage in the voltage interruption for 2 s. The third and fourth graphs in Fig. 22(a) show the source current and the load current. The

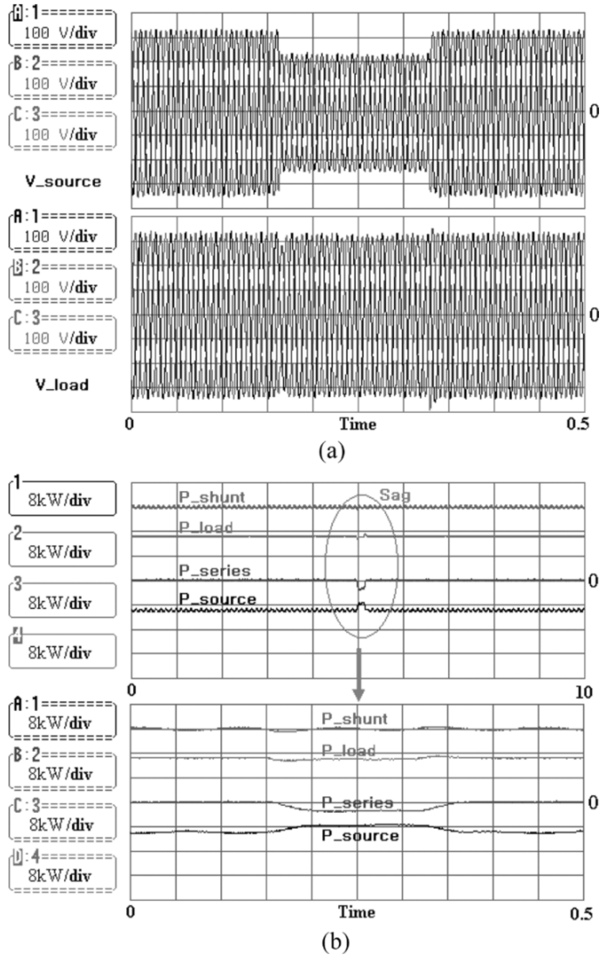

Fig. 21. Voltage sag compensation. (a) Source and load voltage. (b) Active-power variation.

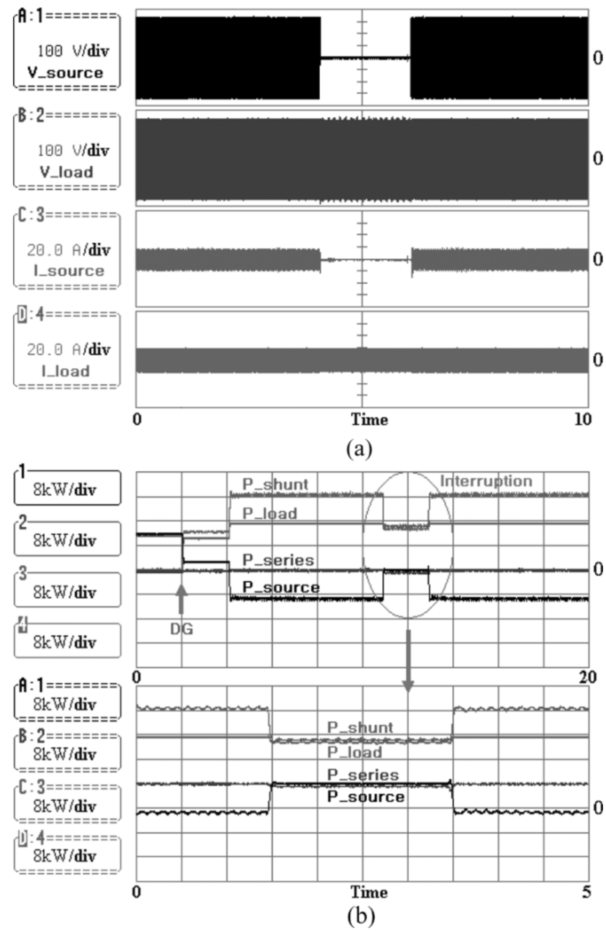

Fig. 22. Voltage-interruption compensation. (a) Voltage and current of source and load. (b) Active-power variation.

load current maintains a constant value as expected. The graph in Fig. 22(b) shows the active powers of the source, the load, the shunt inverter, and the series inverter. In normal operation, the shunt inverter provides 10-kW power to the load and the source, respectively. But during the interruption, the shunt inverter provides 10-kW power only to the load.

VI. Conclusion

This paper describes the analysis results of a combined operation of the UPQC with the DG. The proposed system consists of a series inverter, a shunt inverter, and a dispersed generator connected in the dc link through rectifier. The proposed system can compensate voltage sag and swell, voltage interruption, reactive power, and harmonics, in both interconnected operation mode and islanding operation mode. The performance of the proposed system was analyzed using simulations with PSCAD/EMTDC and experimental results with the hardware prototype of 20-kVA rating.

The proposed system can improve the power quality at the point of installation on power distribution systems or industrial power systems. The simulation model and hardware prototype described in this paper can be utilized for the development of hardware systems with higher power rating.

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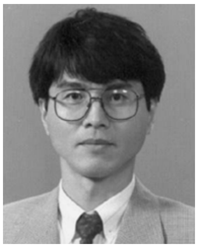

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