Multifunctional Uninterruptible Power Supply(UPS) System

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Abstract

This paper proposes a new control strategy of bidirectional uninterruptible power supply(UPS) with the performance of active power filter which compensate the harmonics and reactive power. To improve the transient response for the effective compensation in active power filter mode, it is considered that a simple and precise calculation method of the compensation reference current for the harmonics and reactive power compensation. So a novel closed-loop control strategy is used to calculate the reference current. The system model and control algorithm are described and the system performance is verified by the simulation and experimental results

1. Introduction

Uninterruptible power supply(UPS) systems have been used to keep the high quality power for the critical loads such as computers and delicate electronic equipments. They are designed not only to regulate the AC output voltage but also to suppress the harmful effects caused by the current harmonics in the source But the conventional UPS has a controlled rectifier for AC/DC battery charger, so the AC line source is polluted with the harmonics generated from the controlled rectifier Additionally, it uses two power stages, which are composed of AC/DC rectifier and DC/AC inverter, hence, the efficiency and power density are very low Moreover, since most of the critical electronic loads have the capability of "riding through" against the momentary power outage for durations up to several mili seconds, the conventional on-line UPS system can be never economic. It is clear from the fact that the standby power supply(SPS) system market is growing much faster than the on-line UPS system market for personal computer loads.[1-6]

In this paper, a bi-directional UPS with the performance of active power filter as shown in Fig.1 has been proposed as one of the counter methods to overcome these problems. With only one power stage, it is working simultaneously as the AC/DC rectifier/battery charger and DC/AC inverter to the operation of battery charging or back-up power supplying Moreover it is working as the active power filter(APF) to compensate the harmonics and reactive power in the line source due to the nonlinear load. Therefore the operation of the proposed system can be divided into two modes, such as the active power filter mode and the battery back-up power mode.

To improve the transient response for the effective compensation of harmonics and reactive power in active power filter mode, it is considered that a simple and precise calculation method of the compensation reference current for the compensation of harmonics and reactive power. So a novel closed-loop control strategy is used to calculate the reference current instantaneously. And, the current regulated instantaneous voltage control scheme is used in back-up power mode. The system model and control algorithm are described and analyzed

Finally, the performance of proposed multifunctional UPS is verified by the simulation and experimental results.

2. System description

Fig. 1 shows the configuration of the proposed UPS system. The bidirectional UPS system consists of a bilateral power converter and battery, and it is connected to the line through the LC low pass filter. In case of the normal line source, the thyristor switches are on-state so that the AC source supplies the AC power to the load. Then, the bidirectional UPS is working as APF for the compensation of the harmonics and reactive power being due to the nonlinear load. Otherwise, the thyristor switches are off - state, then the bidirectional UPS supplies the battery back- up power to the load.

The system equations to the AC input side of the bidirectional UPS can be expressed as Eq. (1) and Eq. (2).

$$\frac{di_a}{dt} = \frac{v_{con} - v_o}{L_a} \tag{1}$$

$$v_{con} = f(s) \cdot v_{dc} \tag{2}$$

where, v_{con} Input voltage of power converter

v_o : Filter capacitor voltage

$f(s)$. Switching function

In active power filter mode, the filter capacitor voltage is equal to the utility source voltage as Eq. (3).

$$v_o(t) = v_s(t) \tag{3}$$

In battery back-up power mode, the filter capacitor current and voltage can be expressed as the following Eq. (4) and Eq. (5).

$$i_c = i_a - i_o, \quad i_s = 0 \tag{4}$$

$$\frac{dv_o}{dt} = \frac{i_c}{C_a} \tag{5}$$

The system equations to the DC output side of the bidirectional UPS is given as Eq. (6), Eq. (7) and Eq. (8).

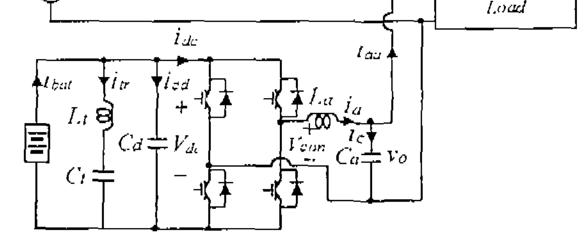

Fig. 1 Configuration of proposed multifunctional UPS system.

$$i_{dc} = f(s) \cdot i_d \tag{6}$$

$$i_{cd} = i_{bat} + i_{dc} - i_r \tag{7}$$

$$\frac{dV_{dc}}{dt} = \frac{i_{cd}}{C_d} \tag{8}$$

3. Active power filter(APF) mode

Operation principle

Under the normal condition, the utility power can be assumed as a sinusoidal voltage source.

$$v_s(t) = V_{sm} \sin \omega t \tag{9}$$

If a nonlinear load is applied, then the load current will distorted so that it consists of the fundamental component and the higher order harmonic components.

$$\begin{aligned} i_o(t) &= \sum_{n=1}^{\infty} I_{mn} \sin(n\omega t + \theta_n) \\ &= I_{m1} \sin(\omega t + \theta_1) + \sum_{n=2}^{\infty} I_{mn} \sin(n\omega t + \theta_n) \\ &= I_{mp} \sin \omega t + I_{mr} \cos \omega t + \sum_{n=2}^{\infty} I_{mn} \sin(\omega t + \theta_n) \end{aligned} \tag{10}$$

where $I_{mp} = I_{m1} \cos \theta_1$: magnitude of fundamental active component of load current. $I_{mr} = I_{m1} \sin \theta_1$: magnitude of fundamental reactive component of load current. I_{mn} : magnitude of harmonics reactive component of load current.

Then, the instantaneous load power can be expressed as followings.

$$\begin{aligned} p_o(t) &= v_s(t) \cdot i_o(t) \\ &= V_{sm} I_{m1} \sin^2 \omega t \cos \theta_1 + V_{sm} I_{m1} \sin \omega t \cos \omega t \sin \theta_1 \\ &\quad + \sum_{n=2}^{\infty} V_{sm} \sin \omega t \; I_{mn} \sin(n\omega t + \theta_n) \\ &= \frac{1}{2} V_{sm} I_{m1} \cos \theta_1 (1 - \cos 2\omega t) + \frac{1}{2} V_{sm} I_{m1} \sin \theta_1 \sin 2\omega t \\ &\quad + \sum_{n=2}^{\infty} V_{sm} \sin \omega t \; I_{mn} \sin(n\omega t + \theta_n) \\ &= p_s(t) + q_c(t) \end{aligned} \tag{11}$$

$$\text{where, } p_s(t) = \frac{1}{2} V_{sm} I_{m1} \cos \theta_1 (1 - \cos 2\omega t) \tag{12}$$

$$\begin{aligned} q_c(t) &= \frac{1}{2} V_{sm} I_{m1} \sin \theta_1 \sin 2\omega t \\ &\quad + \sum_{n=2}^{\infty} V_{sm} \sin \omega t \; I_{mn} \sin(n\omega t + \theta_n) \end{aligned} \tag{13}$$

The $p_s(t)$ and $q_c(t)$ are instantaneous value, and the first one means the active power which is always positive and the second one means the reactive power of which average value is always zero. Therefore, if the power converter supplies q_c, then p_s is supplied by the utility source. And, this means that the line source current is to be sinusoidal and same phase with the source voltage as Eq. (14).

$$\begin{aligned} i_p(t) &= \frac{p_s(t)}{v_s(t)} \\ &= \frac{\frac{1}{2} V_{sm} I_{m1} \cos \theta_1 (1 - \cos 2\omega t)}{V_{sm} \sin \omega t} \\ &= I_{m1} \cos \theta_1 \sin \omega t \end{aligned} \tag{14}$$

where, $I_{mp} = I_{m1} \cos \theta$

And then, the power converter which operates the active power filter supplies the reactive current as Eq. (15).

$$\begin{aligned} i_r(t) &= \frac{q_c(t)}{v_s(t)} \\ &= \frac{\frac{1}{2} V_{sm} I_{m1} \sin \theta_1 \sin 2\omega t + \sum_{n=2}^{\infty} V_{sm} \sin \omega t \; I_{mn} \sin(n\omega t + \theta_n)}{V_{sm} \sin \omega t} \\ &= I_{mr} \cos \omega t + \sum_{n=2}^{\infty} I_{mn} \sin(n\omega t - \theta_n) \end{aligned} \tag{15}$$

The load current can be divided by the active current component which is supplied from the utility source and the reactive current component which affects the line source current waveform and the power factor.

$$i_o(t) = i_p + i_r \tag{16}$$

where, i_p : Active load current component

i_r : Reactive load current component

From the load current as Eq. (16), if the power converter supplies the instantaneous reactive component current i_r, then line source current is to be sinusoidal and in phase with the utility source voltage.

$$i_s(t) = i_p(t) = I_{mp} \sin \omega t \tag{17}$$

Therefore, from Fig. 1, the reference value of the inductor current which is the output current of the power converter can be given as Eq. (18) under the assumption that $i_s = i_p$

$$\begin{aligned} i_a^* &= -i_s + i_o + i_c \\ &= -i_s + (i_p + i_r) + i_c \\ &= i_r + i_c \\ &= (i_o - i_p) + i_c \end{aligned} \tag{18}$$

If the inductor current is well controlled to follow the reference value, then the source current is same as the active load current and it is in phase with the utility voltage and pure sinusoidal.

Control scheme

Fig. 2 shows the control block diagram of the APF mode using the proposed algorithm.

The power converter has the performance of active power filter and battery charger in APF mode. To achieve this performance, the current reference value of power converter should be calculated based on Eq (18).

In Fig. 2, the magnitude of the utility source current, I_{sm} is determined by adding the magnitude of the active component of load current, I_{mr} and that of the battery current for charging, I_{bat}. Then, the reference value of utility source current, i_s^* is generated by the multiplication

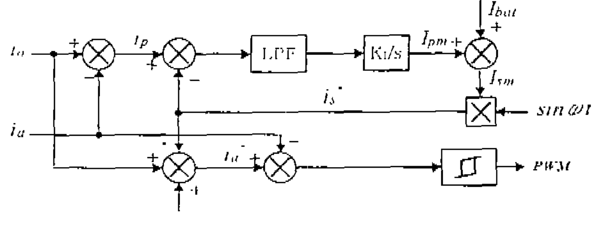

Fig 2 Control block diagram of the proposed APF mode.

of I_{sm} and $\sin\omega t$. Finally, the reference value of the filter inductor current, i_a^* is determined from Eq. (18), and then the filter inductor current, i_a is controlled to follow this reference value through the hysteresis PWM controller.

Therefore, if the PWM controller operates well, then the utility source current should be pure sinusoidal and in phase with the utility source voltage. To calculate the active component magnitude of load current, i_{mp}, the reference value of utility source current, i_s^* is used as the feedback value. That means that this proposed technique for the calculation of reference value to compensate the harmonics and reactive power, which the active component of load current is generated exactly by the closed-loop method, can be preciser than the conventional open-loop method.

4. Battery back-up power mode

Operation principle

If the utility source is failed or out of the standard voltage range, then the static switches will be open and the DC battery back-up power supplies the active power to the load through the bilateral power converter. Hence, the power converter operates as an inverter to convert the DC power to the AC power, and this corresponds to the battery back-up power mode in the proposed system. Since the utility line is switched off, the active power is always supplied from the battery to the load. In the back-up power mode, the converter AC output voltage is to be an ideal voltage source

The UPS system is usually connected with a nonlinear load. Therefore, it is important how to control the voltage instantaneously to improve the transient response. Because, the voltage waveform distortion depends on the performance of the transient response of voltage controller. In this paper, the current regulated instantaneous voltage controller is used.

Control scheme

Fig. 3 shows the control block diagram of the battery back-up power mode.

Inductor current can be expressed as the sum of the load current and the capacitor current. Therefore, the desired value of the converter output current is represented as Eq. (19).

$$i_a^* = i_o + i_c^* + i_{comp} \tag{19}$$

where, i_{comp} is the correction value for improving the output voltage regulation. To improve the transient response of the capacitor voltage controller, the inner capacitor current controller is nested in the outer voltage controller. The UPS output filter model is described

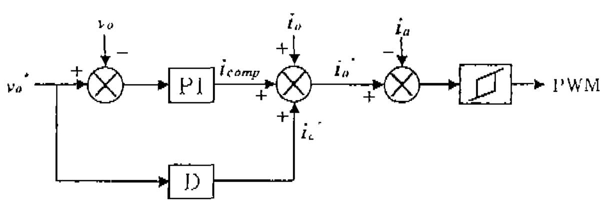

Fig. 3 Control block diagram of the battery back-up power mode (D: differenciator)

mathematically as Eq. (20)

$$i_c(s) = \frac{1}{s^2 L_a C_a + 1} v_{con}(s) + \frac{1}{s^2 L_a C_a + 1} i_o(s) \tag{20}$$

5. Simulation

Figs. 4, 5 and 6 show the simulation results for the proposed system. The capacitor-input diode bridge is connected to the line as a nonlinear load.

Fig. 4 shows the utility source current, the load current and the compensation current in case of the mode changes. When the utility source is normal, it is working as the APF. And the converter supplies the compensation current as the reactive current components. When the line source is failed, the converter supplies the ac load current. Fig. 5 shows the utility voltage, the UPS output voltage and the DC battery voltage at the same situation of the mode changes. The UPS output voltage is not changed even though the abnormal condition of the line utility condition. But the DC battery voltage at the same situation decreases as the discharging action to supply the AC load power. Fig. 6 shows the utility source current, the load current and the compensation current under the condition of load changing. As the increase or decrease of load current, the line source current is also increased or decreased but never distorted as the compensation of the harmonics and reactive power.

From the simulation results as shown from Fig. 4 to Fig. 6, it is verified that the proposed APF and battery back-up power modes are working well as the condition of utility line source. And also, the transient characteristics of the proposed system is good even though the utility fails and the load changes.

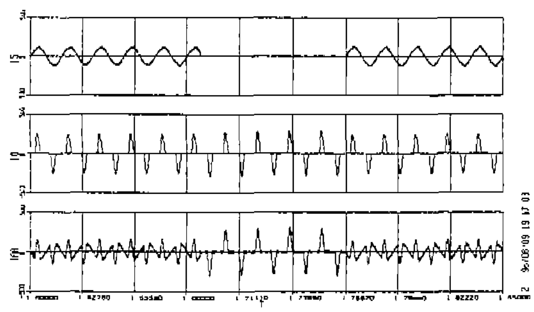

Fig. 4 Simulation results with the diode rectifier load; (upper) utility line current (middle) load current (lower) converter output current

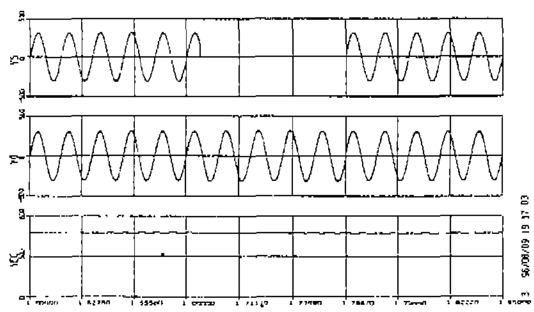

Fig. 5 Simulation results with the diode rectifier load: (upper) utility line voltage (middle) converter output voltage (lower) battery voltage

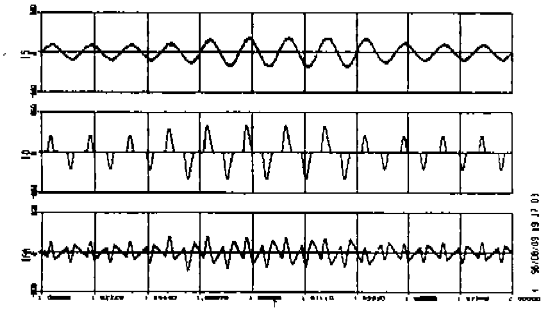

Fig. 6 Simulation results with the diode rectifier load under the load change: (upper) utility line current (middle) load current (lower) converter output current

6. Experiment

Fig. 7 shows the proposed total UPS system with active power filter ability.

The experimental results in APF mode are shown at from Fig. 8 to Fig. 9. From the experiments, it is also verified that the line source current is nearly sinusoidal and in phase with the line source voltage. And Fig 10 shows the UPS output voltage and load current in the battery back-up power mode. The output voltage is nearly sinusoidal under the nonlinear load, with the instantaneous voltage controller.

Fig. 11 and Fig. 12 show the harmonic spectra of the load current and the utility line current, respectively. The total harmonic distortion(THD) is decreased from 47.5% to 3.5% by the harmonics and reactive power compensation.

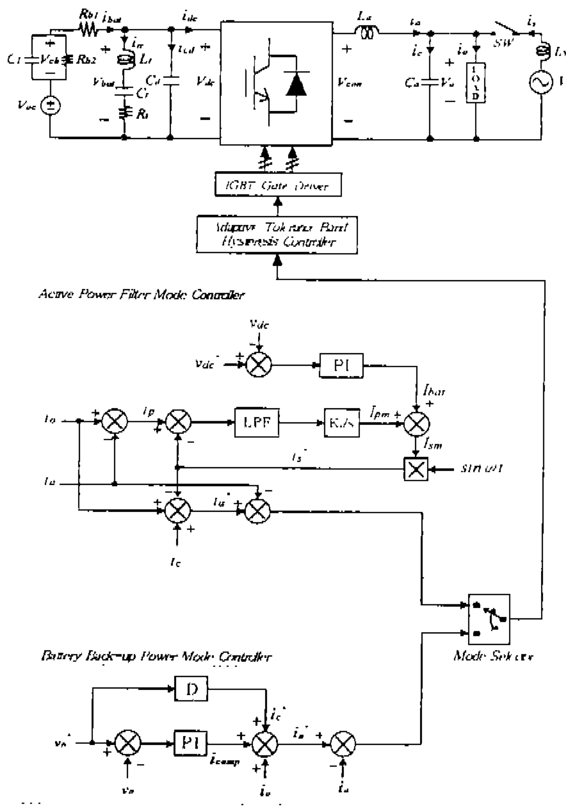

Fig. 7 Proposed UPS system.

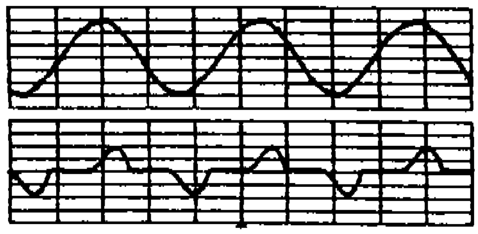

Fig. 8 Utility voltage(100V/div, 5ms/div) and load current (12A/div) in APF mode.

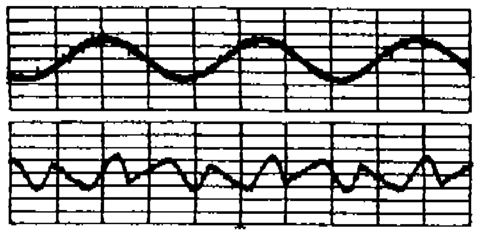

Fig. 9 Utility source current(6A/div, 5ms/div) and compensation current (12A/div) in APF mode.

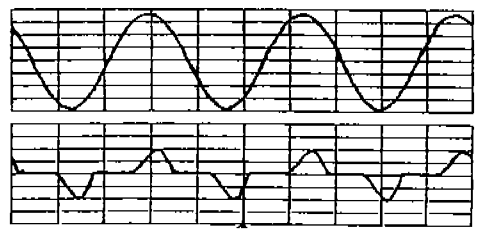

Fig. 10 Output voltage (70V/div, 5ms/div) and load current (12A/div) in back-up power mode.

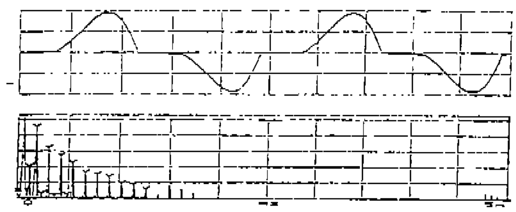

Fig 11 Load current and it's spectrum (THD=47.5%) before the compensation.

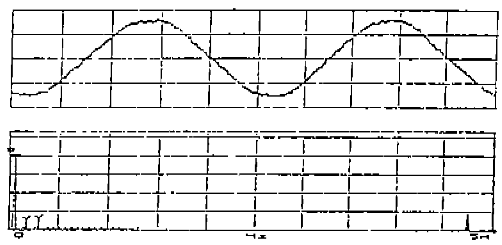

Fig. 12 Utility source current and it's spectrum (THD=3.4%) in APF mode.

7. Conclusion

The control strategy of a bidirectional UPS system with the performance of active power filter is proposed. Especially, a novel closed-loop control strategy, which has only one multiplier, is used to calculate the compensation reference current in APF mode. And also, this proposed control scheme is very simple and precise.

The proposed system has the following advantages.
1) Harmonics and reactive power compensation is achieved.
2) Compensation current calculation is precise because the active current of load is computed exactly by the closed-loop method.
3) Its efficiency, cost and dimension are satisfied.

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