AN EFFECTIVE CONTROL ALGORITHM FOR A GRID-CONNECTED MULTIFUNCTIONAL POWER CONVERTER

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Abstract

An effective control algorithm for a grid-connected multifunctional power converter is proposed and verified through computer simulation using MATLAB software. The proposed control algorithm performs suppression of harmonics and reactive power and compensation of an unbalanced phase current with the conventional function of active and reactive power control of the energy storage system. This multifunctional control utilizes a grid-connected power converter to convert it into an uninterruptible power supply (UPS). In this paper, the proposed control algorithm using instantaneous power control theory is verified through simulation using MATLAB. The results are discussed in detail along with mathematical models.

Introduction

Power electronics technology has been widely applied to many major industrial systems. In these applications, a great deal of harmonic power is generated from the nonlinear loads of power equipment. The generated harmonics cause serious power-system interference and degrade power quality and system security as well [1] - [3]. Recent increases in power demand require more power plant construction; however, environmental problems and cost factors make it difficult to build as many new facilities as needed. Today, the battery energy storage system is considered an alternative for solving these short-term power-demand problems [4] - [8].

Battery energy storage in use with a second battery has the effect of daily peak load shedding by storing power at night and supplying power to the load during the daytime, thus improving the power factor (PF) by supplying reactive power. This system controls the active power by voltage phase difference and the reactive power by voltage magnitude using conventional power-control theory. However, with this system it is also necessary to establish additional compensation devices without compensation function for different orders of the harmonics and phase unbalance problems that frequently occur.

This paper proposes an operation control algorithm for a multifunctional battery energy storage system that adds an active filter function to eliminate harmonics to the active/reactive control function and phase unbalance compensation. The proposed control algorithm is based on instantaneous power-control theory and has the function of active power control, harmonics and reactive power suppression as well as unbalanced phase current compensation. In order to verify the effectiveness of the proposed algorithm, simulation using MATLAB was performed and the results are discussed in detail.

Multifunctional Power Converter Basic Structure

The multifunctional power converter is a unit that can perform the role of active power control, suppression of harmonics and reactive power, and phase unbalance compensation. The proposed multifunctional power converter system consists of a three-phase inverter, a battery for charging and discharging of power, and an output controller as shown in Figure 1. The main source of voltage is a three-phase 380V, 60Hz supply, which supplies 8kW to the load. The multifunctional power converter is designed to supply 10kW of power to the load. The voltage of the battery is between 300V and 400V dc. The turns ratio of the isolation transformer is 1:1.

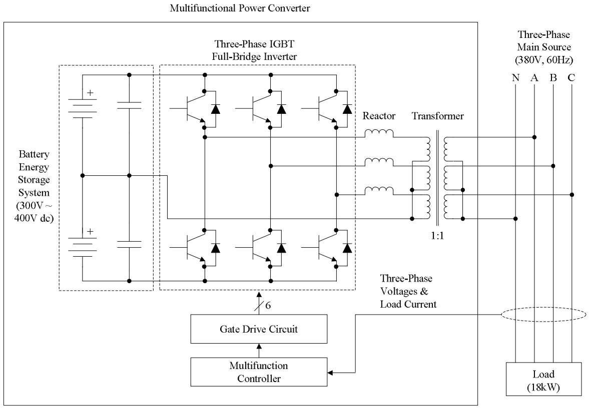

Figure 1. Basic structure of the proposed multifunctional power converter

The voltage-source inverter and the sinusoidal pulse-width modulator (SPWM) were adopted as the method of switching power devices utilizing insulated-gate bipolar transistors (IGBTs). The controller performs the on and off switching function of the IGBT device, according to the control algorithm presented below, by measuring the three-phase voltages and the load current. In general, the battery as an energy storage system is unnecessary for the active power filter itself; however, it is installed to control the active power in the proposed system.

Conventional Control Algorithm

Instantaneous power is divided into active and reactive power. Instantaneous reactive power includes the power component from all kinds of disturbances exclusive of active power, as well as reactive power as a quantity newly defined as instantaneous power.

The conventional control algorithm performs the function of harmonics and reactive power suppression by setting the calculated reactive power component as the reference value that needs to be compensated for by the device. For a general three-phase power system, the instantaneous voltage, v_a, v_b, v_c, and the current, i_a, i_b, i_c, are expressed as instantaneous space vectors as in equation (1).

$$\begin{aligned} \bar{v} &= \begin{bmatrix} v_a & v_b & v_c \end{bmatrix}^t \\ \bar{i} &= \begin{bmatrix} i_a & i_b & i_c \end{bmatrix}^t \end{aligned} \tag{1}$$

The instantaneous active power of a three-phase circuit, p, which is expressed as the dot product of the instantaneous voltage and the current space vectors, can then be given by

$$p = \bar{v} \cdot \bar{i} = v_a i_a + v_b i_b + v_c i_c \tag{2}$$

For the instantaneous reactive power, the vector product of the instantaneous voltage and the current space vectors can also be defined as a new instantaneous reactive power vector, q.

$$\bar{q} = \bar{v} \times \bar{i} \tag{3}$$

From equations (1) and (3), equation (4) is obtained.

$$\begin{aligned} \bar{q} &= \begin{bmatrix} q_a & q_b & q_c \end{bmatrix}^t \\ &= \begin{bmatrix} \begin{vmatrix} v_b & v_c \\ i_b & i_c \end{vmatrix} & \begin{vmatrix} v_c & v_a \\ i_c & i_a \end{vmatrix} & \begin{vmatrix} v_a & v_b \\ i_a & i_b \end{vmatrix} \end{bmatrix}^t \end{aligned} \tag{4}$$

The instantaneous reactive power vector defined in equation (3) is a non-active power component, that is, the component of extracting instantaneous active power from a three-phase circuit, which is defined as the instantaneous reactive power vector. The instantaneous active ($\bar{i}_p$) and reactive ($\bar{i}_q$) current vectors are defined using equations (2) and (3) as follows:

$$\bar{i}_p = \begin{bmatrix} i_{ap} & i_{bp} & i_{cp} \end{bmatrix}^T = \frac{p}{\bar{v} \cdot \bar{v}} \bar{v} \tag{5}$$

$$\bar{i}_q = \begin{bmatrix} i_{aq} & i_{bq} & i_{cq} \end{bmatrix}^T = \frac{q \times \bar{v}}{\bar{v} \cdot \bar{v}} \tag{6}$$

In order to prove the propriety of the instantaneous active and reactive current vectors, the following properties for i_p and i_q are considered.

$$\bar{i}_p + \bar{i}_q = \frac{p}{\bar{v} \cdot \bar{v}} \bar{v} + \frac{\bar{q} \times \bar{v}}{\bar{v} \cdot \bar{v}} = \frac{(\bar{v} \cdot \bar{i})\bar{v} + (\bar{v} \times \bar{i}) \times \bar{v}}{\bar{v} \cdot \bar{v}} \tag{7}$$

Using the vector product formula, $-(a \times b) \times c = -(b \cdot c)a + (a \cdot c)b$, equation (8) is obtained from equation (7).

$$\bar{i}_p + \bar{i}_q = \frac{(\bar{v} \cdot \bar{i})\bar{v} + \{-(\bar{i} \cdot \bar{v})\bar{v} + (\bar{v} \cdot \bar{v})\bar{i}\}}{\bar{v} \cdot \bar{v}} = \bar{i} \tag{8}$$

This shows that any three-phase current vector, i, can be reduced to two components, $\bar{i}_p$ and $\bar{i}_q$. The reactive current, $\bar{i}_q$, is orthogonal to the voltage vector, $\bar{v}$, and the active current, $\bar{i}_p$, is parallel to the voltage vector, $\bar{v}$. Only the instantaneous active current vector, $\bar{i}_p$, is related to the instantaneous active power because the instantaneous active power is the dot product of vectors. This theory is proved by showing that $\bar{v} \cdot \bar{i}_q = 0$ and $\bar{v} \times \bar{i}_p = 0$.

$$\bar{v} \cdot \bar{i}_q = \bar{v} \cdot \frac{(\bar{v} \times \bar{i}) \times \bar{v}}{\bar{v} \cdot \bar{v}} = \bar{v} \cdot \frac{-(\bar{i} \cdot \bar{v})\bar{v} + (\bar{v} \cdot \bar{v})\bar{i}}{\bar{v} \cdot \bar{v}} = 0 \tag{9}$$

$$\bar{v} \times \bar{i}_p = \bar{v} \times \left(\frac{p}{\bar{v} \cdot \bar{v}} \bar{v} \right) = 0 \tag{10}$$

Therefore, $\bar{i}_p$ is the active current component parallel to the voltage vector, $\bar{v}$, and $\bar{i}_q$ is the reactive current component orthogonal to $\bar{v}$. It is also shown that $\bar{i}_p$ and $\bar{i}_q$ are mutually orthogonal [9] - [12]. More detailed descriptions were derived from this work.

Proposed New Control Algorithm

A multifunctional control algorithm for active power, harmonics and reactive power suppression, and unbalanced phase-current compensation is proposed in this paper. The major goal of the algorithm is to maintain the three-phase, sinusoidal voltage and current relationships regardless of load conditions. This means that the source provides the only constant active power in parallel with the multifunctional power converter. The proposed control algorithm sets the instantaneous active power as the reference for the compensator.

As described above, with the instantaneous source voltage and the load current that are given in equation (1), the instantaneous active power provided from the source to the load is given as equation (2) and the instantaneous active current component can be presented as mentioned above. If the instantaneous active power given in equation (2) is a constant, the desired three-phase current component, $\overline{i_{sd}}$, which is required in order to provide the active power from the source, can be obtained by equation (5). Then, the multifunctional power supply is controlled to provide the sum of the components to subtract the source current from the load current, $\bar{i}_L$, and previously-determined active-current command, $\overline{i^*_{cp}}$, for the reactive power control. The current command, $\bar{i}^*_c$, which must be provided by the multifunctional power supply, is given in equation (11).

$$\bar{i}^*_c = \bar{i}_L - \bar{i}_{sd} + \bar{i}^*_{cp} \tag{11}$$

For a load such as the rectifier in which the oscillation occurs in three-phase active power, the dc component of active power can be extracted using a low-pass filter (LPF). The low-pass filter is designed with a cut-off frequency of 10Hz and -40dB/decade of roll-off. Equation (12) shows the transfer function of the designed filter, and Figure 2 depicts the frequency response of the filter, which is represented using a Bode plot.

$$LPF(s) = \frac{769.2}{s^2 + 50.8s + 769.2} \tag{12}$$

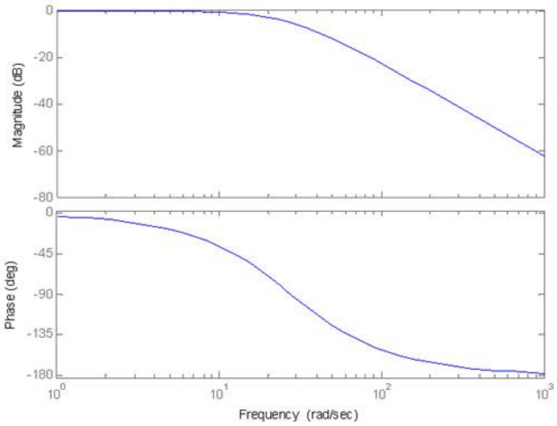

Figure 2. Frequency response of the low-pass filter

The dc component of the extracted active power is defined as p_{dc}, and the desired source current for providing P_{dc} is calculated using equation (5) as

$$\bar{i}_{sd} = \frac{p_{dc}}{\bar{v}\cdot\bar{v}}\bar{v} \tag{13}$$

The desired current command that must be provided by the multifunctional power supply is then expressed as follows:

$$\bar{i}^*_{cd} = \bar{i}_L - \bar{i}_{sd} \tag{14}$$

If the desired active power from the multifunctional power supply is defined as p_n, the active current command to provide p_n from the multifunctional power supply is represented as

$$\bar{i}^*_{cpn} = \frac{p_n}{\bar{v}\cdot\bar{v}}\bar{v} \tag{15}$$

Therefore, the final current command of the multifunctional power supply is expressed as

$$\bar{i}^*_c = \bar{i}^*_{cD} - \bar{i}^*_{cpn} \tag{16}$$

The block diagram of the control algorithm proposed in this paper is shown in Figure 3, and the controller performs functions such as active power control, reactive power and phase unbalance compensation, and harmonic suppression [13].

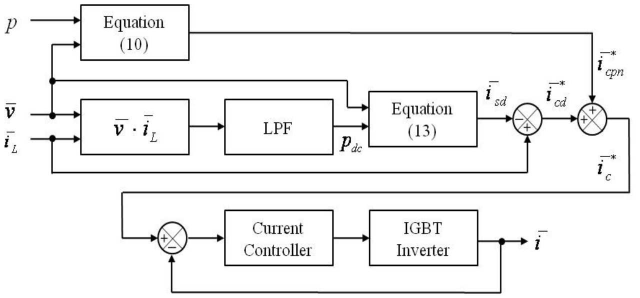

Figure 3. Block diagram of the proposed controller

Simulation Results

In order to show the effectiveness of the proposed control algorithm, simulation was performed using MATLAB software with the assumption of the parallel operation of the multifunction power supply. The simulation was performed for the following functions: active power control, harmonics and reactive power suppression, unbalanced phase current compensation, and the connection with a rectifier load. The simulation results on the horizontal axis are the time in seconds.

Real Power Control

An 18kW active-power load was connected to the power system. The simulation of a case where the source only supplies 8kW of active power was performed, setting the output command of active power of the multifunctional power supply at 10kW. The simulation results are illustrated in Figure 4. It shows that the multifunctional power supply provides 10kW of active power after about a 0.15s transient period. The transient is caused by the second-order response properties of the LPF.

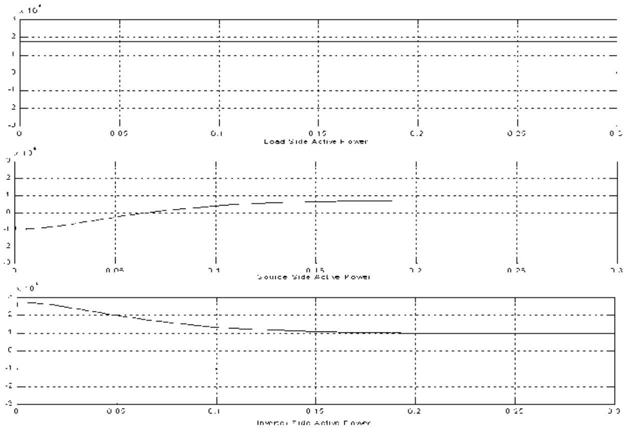

Figure 4. Real active power of the load, source, and inverter in W

Harmonics and Reactive Power Control

A simulation for including 20% of the third harmonics and 10% of the fifth harmonics in the current provided to the load was performed. Results for 20% of the third harmonics and 10% of the fifth harmonics of phase-A system voltage and phase-A load current are shown in Figure 5, which indicates that the load current includes a lot of harmonics.

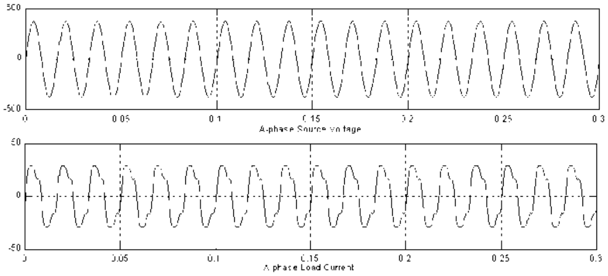

Figure 5. Waveforms of voltage in V and current in A including harmonics

In case the multifunctional power supply does not operate, the current shown in Figure 5 will be provided by the source. However, if the equipment does operate, then the sinusoidal current without any ripples will be supplied by the power supply after a transient phenomenon period of 0.15s as shown in Figure 6. The current waveform provided from the proposed equipment is shown in Figure 7.

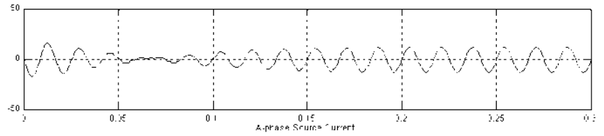

Figure 6. Current waveform in A after applying the proposed algorithm

For the current outputs in Figure 5 and Figure 7, the changes of active and reactive power are shown in Figure 8 and Figure 9, respectively. As indicated in Figure 8 and Figure 9, the source only supplies the DC voltage and the oscillation component of active power by the proposed algorithm, and the reactive power is provided from the multifunctional power supply.

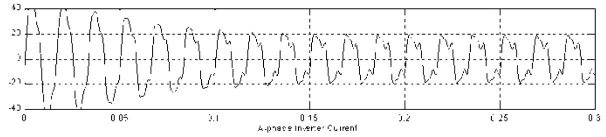

Figure 7. Current waveform in A of the multifunctional power supply

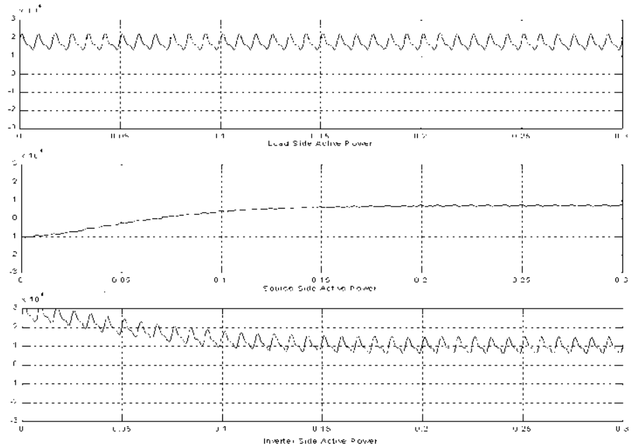

Figure 8. Active power of load, source and multifunctional power supply in W

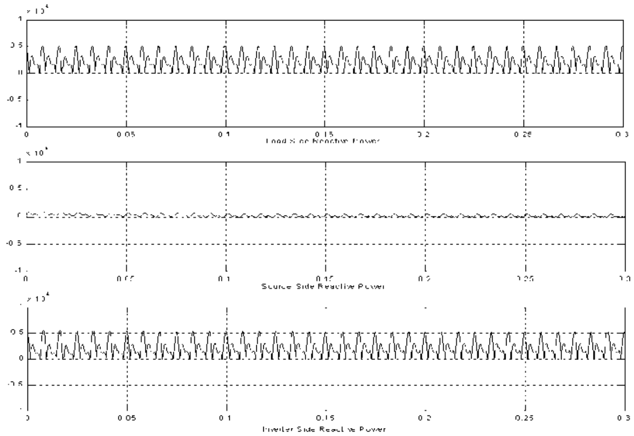

Figure 9. Reactive power of load, source and multifunctional power supply in W

Unbalanced Phase Current Compensation

In the three-phase system, the worst situation of unbalanced phase current occurs when only a phase current is supplied, and the other two phases have no current supply. The simulation results for this case are described in the following figures. The load-current waveform of the unbalanced phase is shown in Figure 10, and the current waveform supplied from the source is given in Figure 11. The current waveform supplied from the multifunctional power converter is illustrated in Figure 12. It is clearly shown, from Figure 10 to Figure 12, that the proposed control algorithm was successfully applied to the compensation of the unbalanced phase-current problem.

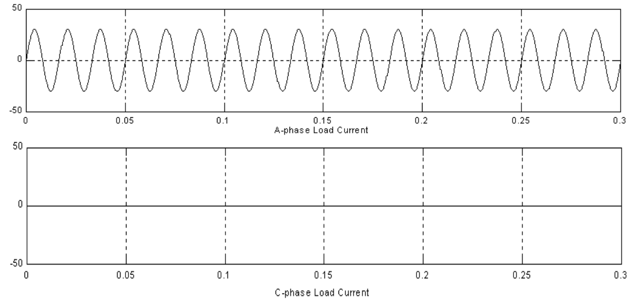

Figure 10. Waveforms of the phases A and B load currents in A for the unbalanced system

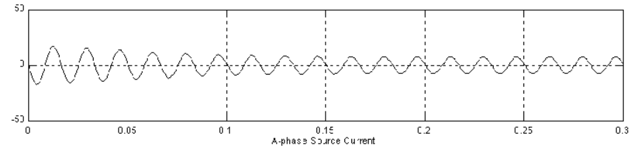

Figure 11. Waveform of phase-A current in A for unbalanced phase

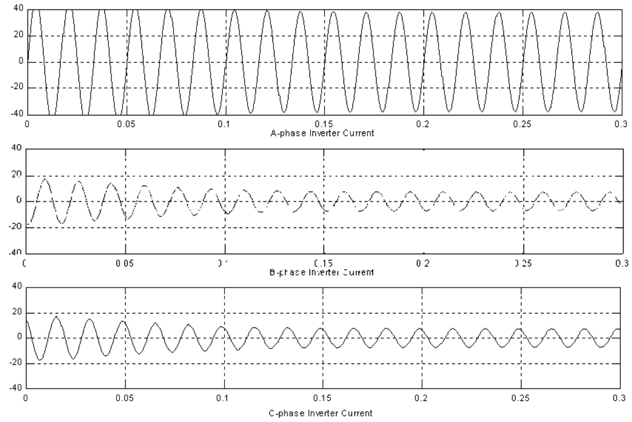

Figure 12. Waveforms of the three-phase current in A of the multifunctional power supply

Connection with the Rectifier Load

A simulation was also performed for the case of a rectifier connected as a load. The waveforms of the three-phase load currents are given in Figure13.

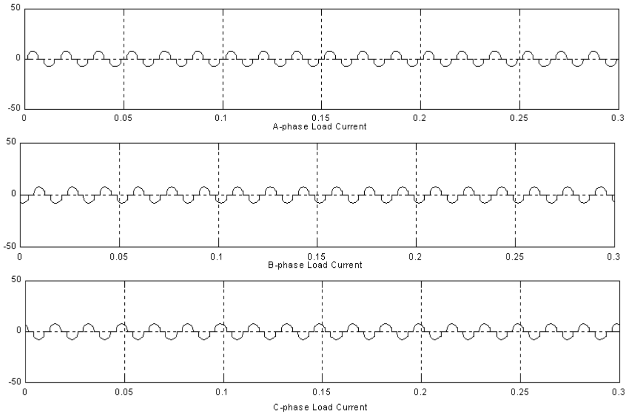

Figure 13. Waveforms of the rectifier load currents in A

The source voltage waveforms are shown in Figure 14 and indicate that the proposed algorithm functions successfully in this case also. Through several simulations, as mentioned above, it was proved that the proposed algorithm effectively performs real-power control, harmonics and reactive power suppression, and unbalanced phase current compensation as expected.

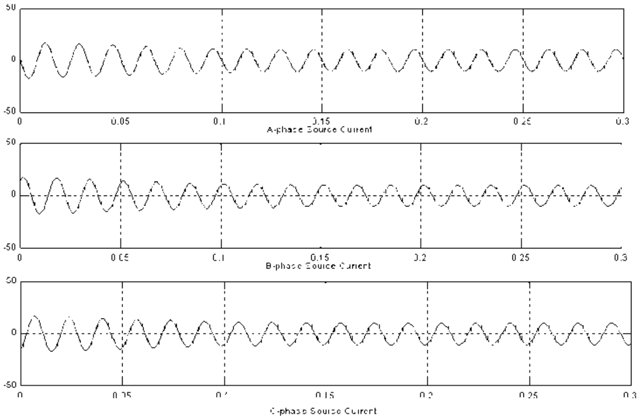

Figure 14. Waveforms of the source currents in A

Conclusions

The operation control algorithm of a multifunctional power supply was proposed by adding functions such as active filters, harmonics and reactive power suppression, and unbalanced phase compensation to a conventional energy storage system for peak load shedding and load equalization. The major goal of the algorithm is to maintain the three-phase, sinusoidal voltage and current relationships regardless of load conditions, which means that the source provides the only constant active power in parallel with the proposed multifunctional power converter. The proposed control algorithm was based on instantaneous power theory and setting the instantaneous active power as the reference for the compensator.

Through computer simulation using MATLAB, the effectiveness of the proposed control algorithm was demonstrated.

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