JPE 4-3-6

Synchronous PI Decoupling Control Scheme for DVR against a Voltage Sag in the Power System

Myung-Bok Kim†, Seung-Hoon Lee**, Gun-Woo Moon*, and Myung-Joong Youn*

*Dept. of Electrical Engineering and Computer Science, KAIST, Daejeon, Republic of Korea
**Satellite Control System Dept., KARI, Daejeon, Republic of Korea

ABSTRACT

This paper proposes a new control strategy for the dynamic voltage restorer (DVR). It is based on a synchronous PI decoupling control strategy which features fast response time and low steady state error. Therefore, the proposed control strategy produces faster action time against voltage sag and guarantees more than enough compensation for reduced supply voltage. Experimental results, implemented with the TMS320C3x DSP control unit, are shown to validate the effectiveness of the proposed control strategy.

Keywords: Dynamic voltage restorer, Power quality, Synchronous PI decoupling control

1. Introduction

In many ac distribution systems, due to the highly sensitive nature of newer loads, users continue to demand higher power quality. However, power quality polluting loads are also becoming more numerous [1]. Power quality problems encompass a wide range of distribution systems such as voltage sag, swell, flicker, harmonic distortion, impulse transients, and interruption [2]. Specifically, such voltage deviations in the form of voltage sag, swell or temporary outage cause severe process disruptions resulting in millions of dollars of revenue loss. As such, the proposition of a novel custom power device called the dynamic voltage restorer for compensating voltage disturbances in the distribution system has generated a great deal of interest recently [3][4].

The low pass filter (LPF) method as the conventional method is generally used for driving DVR because of simplicity and facility. However, there are several drawbacks such as dependency on filter dynamics and sustained voltage oscillations in the distribution network. In addition, the steady state load voltage may not be compensated to the desired value owing to voltage drop across the transformer series impedance and filter [5][6].

The synchronous PI decoupling control scheme is adopted as a control strategy for driving DVR against voltage disturbances such as voltage sag, swell, and flicker. This control strategy is derived on the basis of the restoration of linearity in control performance using control variables such as inductor currents in the ripple filter and compensating voltages injected through the transformer. The coupling terms in circuit equations expressed in the synchronous reference frame, which

---

Manuscript received September 22, 2003; revised June.10, 2004.
†Corresponding Author: boks@rainbow.kaist.ac.kr, KAIST
Tel: +82-42-869-5422, Fax: +82-42-869-3498
* Dept. of Electrical Engineering and Computer Science, KAIST
** Satellite Control System Dept., KARI

deteriorate the linearity in control performance, can be easily removed by adding feed-forward terms. The linearity can be retrieved so that it is easier to control d-q control variables independently.

Consequently, there are many advantages in voltage compensation using the proposed control strategy for injecting the compensation voltage against the voltage sag. This control scheme has the characteristics such as a fast response in the transient state and a low number of errors in the steady state. The fast response in the transient state guarantees faster action against the voltage sag and the low error rate in the steady state guarantees enough voltage compensation against voltage sags.

The experiment for proposed control strategy is implemented with TMS320C3x in a reduced scale.

2. DVR against voltage sags

2.1 Problems due to voltage sag

The problems that are encountered due to voltage sag can be summarized as follows. Sensitive loads may trip due to voltage sags. Sags may lead to shutdowns in adjustable speed drives, upsets in electronic process controllers, and computer system crashes. Single-phase sags are often accompanied by temporary increases in the voltage on other phases, which are referred to as swells. Swells can cause malfunction of electric motor controllers and adjustable speed drives. Swells may also stress delicate computer components sometimes leading to premature failure. Degradation of metal oxide surge arresters also can be caused by frequent exposure to high magnitude voltage swells.

2.2 Dynamic voltage restorer against voltage sag

The DVR mitigates voltage sags effectively by synchronously injecting the precise compensating voltage for the reduced supply voltages into the power system. Figure 1 shows the system configuration of the dynamic voltage restorer in the power system. From this figure, the dynamic voltage restorer is a kind of switching power converter that consists of DC link capacitor, voltage source inverter stack, high frequency ripple filter, three-phase series transformer, and DSP control unit.

In detail, the DC link capacitor, which is interfaced with the PWM inverter by using a boost converter, is used as the energy storage system for the DVR. The boost converter regulates the voltage across the dc link capacitor that serves as a common voltage source for the PWM inverters. The boost converter, however, is not used in this prototype DVR. The three-phase voltage source PWM inverters play an important role in generating the appropriate voltages, which are determined by the DSP control system.

The DSP control unit compares the instantaneous load voltages to the pre-sag load voltages and generates appropriate switching patterns, which are denoted as $S_1 \sim S_6$ in Fig.1, for PWM inverters so that the load voltage remains within specifications.

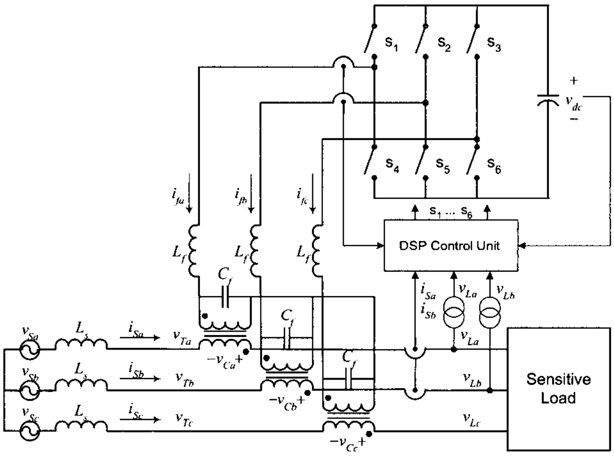


Fig. 1. System configuration of the dynamic voltage restorer

The high frequency ripple filters are formed as a series of inductors and capacitors, which are denoted as L_f and C_f. These filters are well-tuned so that the harmonic components of inverter output voltages can be filtered out. Thus, the pure sinusoidal compensation voltages can be injected into the power system through the three-phase series transformers. The turn ratio of the injection transformers is 1:1 respectively.

3. Controller design for driving the DVR

In order to drive the DVR, it is necessary to derive the appropriate inverter voltages. In the conventional method, there are the open loop control method and the closed loop control method [5]. The open loop control method is generally used for driving DVR because of simplicity and facility. However, there are several drawbacks, such as dependency on filter dynamics and sustained voltage oscillations, which result in oscillated compensation voltages. In addition, the steady state load voltage may not be compensated to the desired value owing to a voltage drop across the transformer series impedance and filter. At that point, the closed loop control method uses the filter capacitor voltage and the filter capacitor current as control variables. The control method uses the multi-loop control method so that the voltages can be regulated in the outer loop and the currents can be regulated in the inner loop. However, the control performance shown in the experimental results does not show improvement although the control method becomes more complex.

Therefore, it is necessary for the proposed control strategy to satisfy both a simple control algorithm and acceptable control performance simultaneously.

In order to establish the proposed control strategy for driving the DVR, it is necessary to derive the circuit equations of the DVR. Consequently, the synchronous PI decoupling control strategy is selected as the proposed control strategy for driving the DVR. The basic concept of the controller is that the coupling terms as the results of Park's transformation will be easily removed by adding the terms as feed-forward terms. Hence, the d-q control variables can be easily controlled independently and the proposed algorithm can be simply implemented.

3.1 Circuit equation through simplified DVR circuit

In order to establish the circuit equations for the proposed controller, it is convenient to simplify the per-phase simplified DVR circuit. Fig.2 shows the per-phase simplified DVR circuits both in view of the voltage and current circuit. In these figures, the variable v_{fabc} denotes the output voltages of inverter, the variable v_{Cabc} denotes the compensation voltages injected through the series transformers by the DVR, and the variable i_{fabc} denotes the currents flowing through the inductor of the ripple filter in the DVR.

From Fig.2, the governing equation for a 3-phase circuit can be expressed as follows:

$$\begin{aligned} \mathbf{i}_{\mathbf{fabc}} &= \mathbf{C}_{\mathbf{f}} \cdot p\mathbf{v}_{\mathbf{Cabc}} + \mathbf{i}_{\mathbf{Sabc}} \\ \mathbf{v}_{\mathbf{fabc}} &= \mathbf{L}_{\mathbf{f}} \cdot p\mathbf{i}_{\mathbf{fabc}} + \mathbf{v}_{\mathbf{Cabc}} \end{aligned} \tag{1}$$

where

$$\mathbf{v}_{\mathbf{Cabc}} = \begin{bmatrix} v_{Ca} & v_{Cb} & v_{Cc} \end{bmatrix}^T, \mathbf{v}_{\mathbf{fabc}} = \begin{bmatrix} v_{Ca} & v_{Cb} & v_{Cc} \end{bmatrix}^T$$

$$\mathbf{i}_{\mathbf{fabc}} = \begin{bmatrix} i_{fa} & i_{fb} & i_{fc} \end{bmatrix}^T, \mathbf{i}_{\mathbf{Sabc}} = \begin{bmatrix} i_{Sa} & i_{Sb} & i_{Sc} \end{bmatrix}^T$$

$$\mathbf{L}_{\mathbf{f}} = diag\begin{bmatrix} L_f & L_f & L_f \end{bmatrix}, \mathbf{C}_{\mathbf{f}} = diag\begin{bmatrix} C_f & C_f & C_f \end{bmatrix}.$$

Based on these circuit equations, it is easier to control the variables simply when the abc phase variables are transformed into the d-q variables in the synchronous reference frame through Park's transformation as follows:

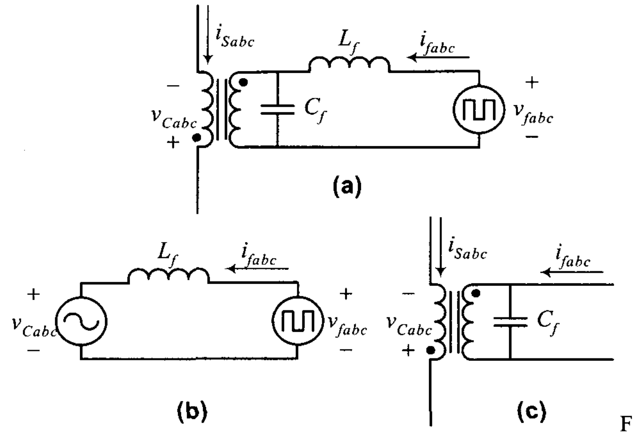


fig. 2. Per phase simplified circuit for modeling

$$\begin{aligned} i_{fq} &= C_f \frac{dv_{Cq}}{dt} + \omega_e C_f v_{Cd} + i_{Sq} \\ i_{fd} &= C_f \frac{dv_{Cd}}{dt} - \omega_e C_f v_{Cq} + i_{Sd} \\ v_{fq} &= L_f \frac{di_{fq}}{dt} + \omega_e L_f i_{fd} + v_{Cq} \\ v_{fd} &= L_f \frac{di_{fd}}{dt} - \omega_e L_f i_{fq} + v_{Cd}. \end{aligned} \tag{2}$$

Since v_{Cq}, v_{Cd}, i_{fq}, and i_{fd} are selected as control variables, the ripple filter currents and compensation voltages can be controlled within the desired specification. However, due to the coupling terms, such as $-\omega_e C_f v_{Cd} - i_{Sq}$, $-\omega_e C_f v_{Cq} - i_{Sd}$, $\omega_e L_f i_{fd} + v_{Cq}$, and $\omega_e L_f i_{fq} + v_{Cd}$ in (2), the linearity of controller may be deteriorated, resulting in an unsatisfactory performance. Therefore, in order to retrieve the linearity of the controller by adding the coupling terms as feed-forward terms and control the variables independently, a synchronous PI decoupling controller is adopted for driving the DVR.

3.2 Synchronous PI decoupling controller for driving the dynamic voltage restorer

In order to drive the DVR, it is necessary to derive the appropriate inverter voltages through the specific control method. There exist both the open loop and the closed loop control methods as the conventional methods [5]. The low pass filter method straightforwardly using the ripple filter is generally used as an open loop control method for driving the DVR because of its simplicity and facility. However, this method has several drawbacks such as the dependency on filter dynamics and sustained voltage oscillations, which result in the oscillatory compensation voltages. In addition, the load voltage may not be compensated for the desired value owing to the voltage drop across the transformer series impedance and filter. On the other hand, the closed loop control method uses the filter capacitor voltage and the filter capacitor current as control variables. This control method uses the multi-loop control method, where the voltages can be regulated in the outer loop and the currents can be regulated in the inner loop. Although the control method becomes more complex, the control performance does not show improvement. Therefore, it is necessary for the proposed control strategy to have both a simple control law and a good control performance at the same time.

Consequently, the synchronous PI decoupling controller is selected as the proposed controller for the DVR on the coupling terms. The results of Park's transformation will be removed so that they can be controlled independently and the proposed control strategy can be implemented simply. The PI control algorithm, due to its simplicity and facility, has been used in the application of controlling the linear plant. In addition, in order to improve the PI control, the control inputs are generally obtained using the PI plus the decoupling control law. From the first and second equations of (2), the reference for the current flowing through the filter inductance can be derived in a synchronous PI decoupling control strategy as follows:

$$\mathbf{i}^*_{\mathbf{fqd}} = \left(K_P^v + {K_I^v}\!\big/_{s}\right)\mathbf{e}_1 + \mathbf{d}_1 \tag{3}$$

where

$$\mathbf{i}^*_{\mathbf{fqd}} = \begin{bmatrix} i^*_{fq} & i^*_{fd} \end{bmatrix}^T$$

$$\mathbf{e}_1 = \begin{bmatrix} v^*_{Cq} - v_{Cq} & v^*_{Cd} - v_{Cd} \end{bmatrix}^T .$$

In equation (3), the subscripts P and I denote the proportional and integral gains, respectively. Hence, the current reference obtained from (3) is used to calculate the appropriate inverter voltages in a synchronous PI decoupling control strategy. However, when the inductor current reference is not restricted, it is unavoidable for the current to flow through the inductor excessively. Therefore, in order to avoid the surge current in the transient state, the current reference must be restricted to a permitted value in the power switching device. The current reference can be regulated by using the following function:

$$i^*_{fx} = sat(i^*_{fx}) \;\; for \; x = a, b, c \tag{4}$$

where

$$sat(x) = \begin{cases} -k & for \; x < -k \\ x & for \; -k \le x < k \\ k & for \; x \ge k \end{cases} .$$

After the regulation of the current reference through (4), the reference voltage for the space vector pulse width modulation voltage source inverter (SVPWM VSI) can be derived in a synchronous PI decoupling control strategy from the third and forth equations of (2) as follows:

$$\mathbf{v}^*_{\mathbf{fqd}} = \left(K_P^c + {K_I^c}\!\big/_{s}\right)\mathbf{e}_2 + \mathbf{d}_2 \tag{5}$$

where

$$\mathbf{v}^*_{\mathbf{fqd}} = \begin{bmatrix} v^*_{fq} & v^*_{fd} \end{bmatrix}^T$$

$$\mathbf{e}_2 = \begin{bmatrix} i^*_{fq} - i_{fq} & i^*_{fd} - i_{fd} \end{bmatrix}^T .$$

In (3) and (5), the superscripts v and c denote the voltage controller and the current controller. Consequently, the calculated inverter voltage is used to generate the appropriate switching pattern for the PWM VSI through the DSP control unit. Fig. 3 shows the whole control block diagram for calculating the voltage references of the inverter.

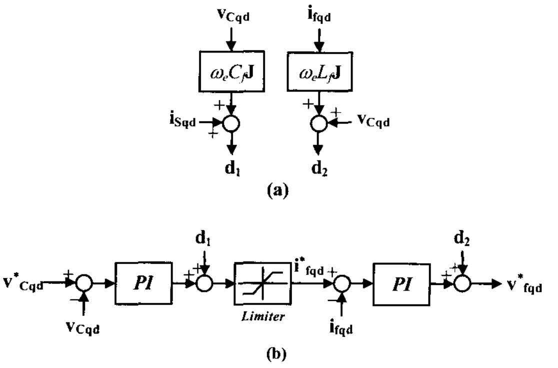


Fig. 3 control block diagram for the proposed control strategy

4.2 Selection of controller gains

In order to select controller gains, it is preliminarily necessary to apply the synchronous PI decoupling control strategy to the real plant expressed in (2). When the calculated inverter voltage is applied, the transfer function from the current reference, $\mathbf{i}^*_{fqd}$, with respect to the real current, $\mathbf{i}_{fqd}$, flowing through the ripple filter inductor can be expressed as follows:

$$\mathbf{i}_{fqd} = \frac{as+b}{s^2+as+b}\mathbf{i}^*_{fqd} \tag{6}$$

where

$$a = \frac{K^c_P}{L_f},\ b = \frac{K^c_I}{L_f}.$$

Hence, the controller gains, K^c_P and K^c_I, must be determined to have fast dynamics so that the inductor current can track the reference value immediately. In this case, the compensation voltages, $\mathbf{v}_{Cqd}$, with respect to the voltage reference, $\mathbf{v}^*_{Cqd}$, can be expressed as follows:

$$\mathbf{v}_{Cqd} = \frac{cs+d}{s^2+cs+d}\mathbf{v}^*_{Cqd} \tag{7}$$

where

$$c = \frac{K^v_P}{C_f},\ d = \frac{K^v_I}{C_f}.$$

Since the ripple filter current dynamics of (6) must be faster than the compensation voltage dynamics of (7), the controller gains (K^c_P, K^c_I) of (6) must be determined so that the controller has the time constant (τ_c) of 1[msec]. This is the result of the tradeoff between the maximum permitted time for preventing damage due to the voltage sags and the minimum required time for the DSP control unit to implement the proposed control strategy in the practical experiment. In addition, the controller gains (K^v_P, K^v_I) of (7) is determined so that the controller has the time constant (τ_v) of 3[msec], as much as three times the time constant of the current controller. In this result, the dynamics of the current controller can be three times as fast as the dynamics of the voltage controller so that it is possible for these controllers to obtain the desired control specification.

4. EXPERIMENTAL RESULTS

4.1 System specification of DVR

In order to validate the effectiveness of the proposed control, a reduced scale prototype DVR is manufactured. Table I shows the parameters used in this DVR system.

Table I. Parameters for DVR system

Source voltage (V_{L-L})	125[V]
Source frequency	60[Hz]
DC link capacitance	1000[μF]
Switching frequency	5000[Hz]
Inverter ripple filter L	200[μH]
Inverter ripple filter C	200[μF]

4.2. Experimental results

The experimental results applied with proposed control are compared with that of conventional LPF as demonstrated in [5]. In the conventional LPF, the compensation voltage becomes the voltage command of the inverter. On the contrary, the proposed control algorithm produces the voltage command of the inverter according to the procedure explained in the previous section.

4.2.1 Experimental results applied with conventional LPF method

Fig.4 shows the experimental result applied with conventional LPF.

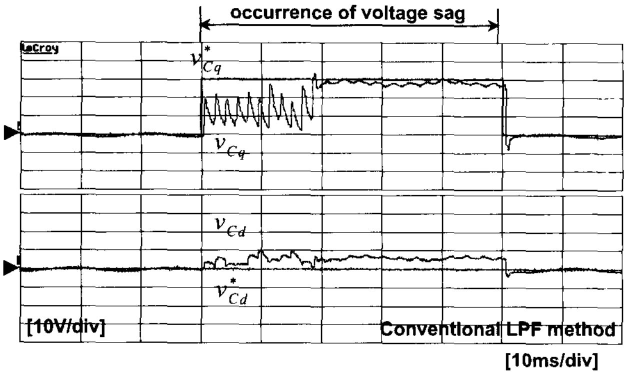


Fig.4. Control performances by conventional control method

In Fig.4, the top trace shows the control performance of q axis compensation voltage and the bottom trace shows the control performance of d axis compensation voltage. From this figure, there is oscillation and time delay in the transient state and steady state error in control responses when applying the conventional LPF method. Due to this poor control performance, the DVR cannot guarantee the fast action against voltage sag and enough compensation for the reduced amount of supply voltage.

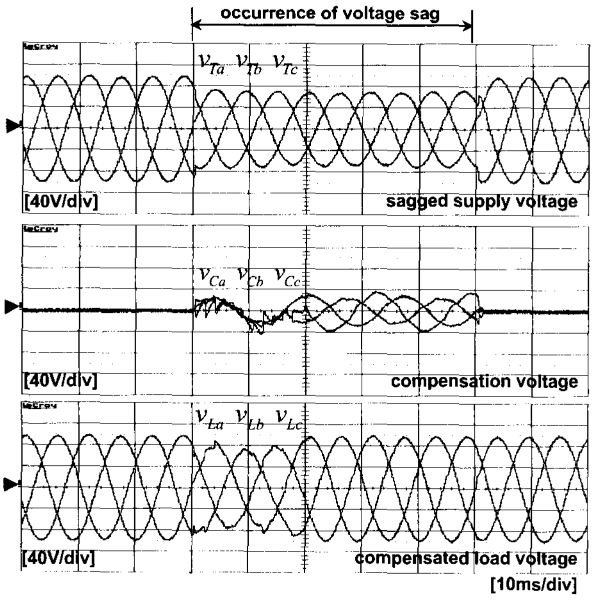


Fig.5. Voltage compensation results by conventional method

Fig.5 shows the experimental waveform such as supply voltages, compensation voltages, and load voltages in three phases. In this figure, the top trace shows the sagged supply voltages, the middle trace shows the compensation voltages injected through the DVR, and the bottom trace shows the compensated load voltages.

Due to this insufficient control performance, the DVR cannot compensate the sagged supply voltages well. Therefore, the compensated load voltages are affected so that poor voltages are delivered to the sensitive load.

4.2.2 Experimental results applied with synchronous PI decoupling control

Fig.6 shows experimental results of control performance applied with proposed synchronous PI decoupling control scheme. From these figures, the top and bottom traces of the first figure show the control performances of the q and d axis compensation voltages injected through three phase series transformers. The top and bottom traces of the second figure show the control performances of the q and d axis current flowing through the ripple filter inductance. In these results, there is little delay in time in the transient state and steady state error. These control performance guarantee faster action and enough compensation against the voltage sag.

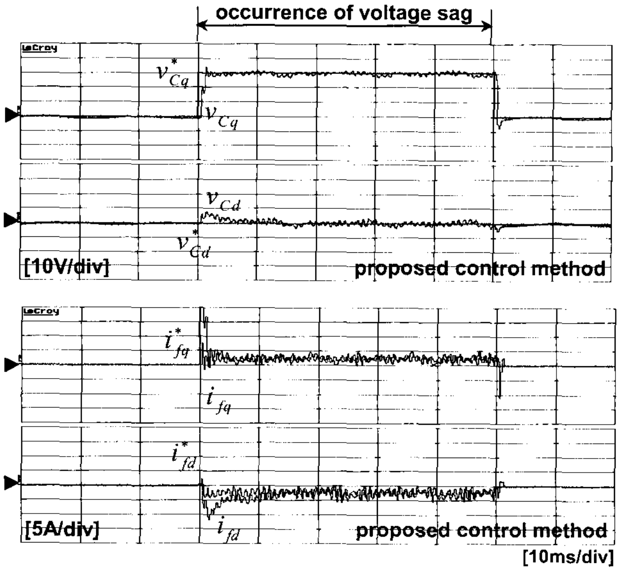


Fig.6. Control performance by synchronous PI decoupling control method

Fig.7 shows the experimental waveform such as supply voltages, compensation voltages, and load voltages in three phases. In this figure, the top trace shows the sagged supply voltages, the middle trace shows the compensation voltage injected by DVR, and the bottom trace shows the compensated load voltages.

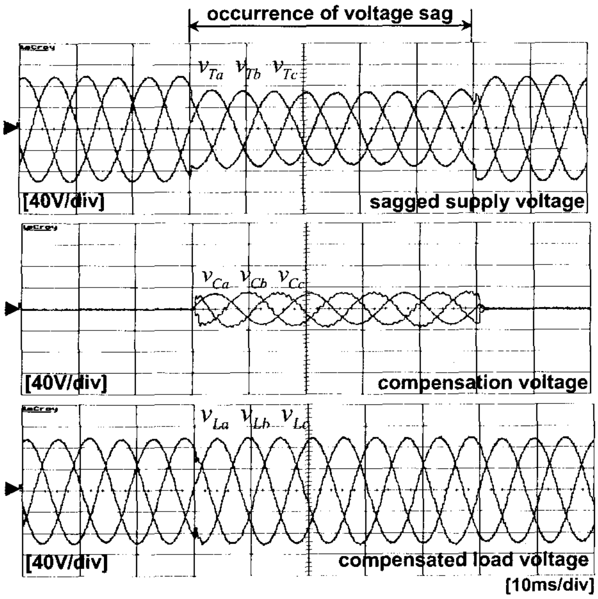


Fig.7. Voltage compensation results by synchronous PI decoupling controller

Compared with a conventional LPF, the delivered load voltages are well balanced voltages since the compensation voltages are injected almost exactly. Since there is no oscillation and little delay time, the faster action against voltage sag can be guaranteed. In addition, because there is no steady state error, the load voltage can be sufficiently compensated. With these experimental results, it is possible to verify the effectiveness of proposed control scheme.

5. CONCLUSION

This paper presents the synchronous PI decoupling controller as the proposed control strategy for DVR that compensates sagged supply voltages caused by faults in the electric supply. The proposed synchronous PI decoupling controller compensated the reduced amount of source voltage with fast response characteristics and improved the performance compared with a DVR system used as only the conventional LPF. The experimental results have been presented to confirm the effectiveness of the proposed control strategy.

References

[1] STUMP, M.D., KEANE, G.J., and LEONG, F.K.S., "The role of custom power products in enhancing power quality at industrial facilities," *Proceedings of IEEE EMPD*, 1998, pp.507-517, 1998

[2] AKAGI, H., "New trends in active filters for power conditioning," *IEEE Trans. Ind. Appl.*, 1996, 32, (6), pp.1312-1322

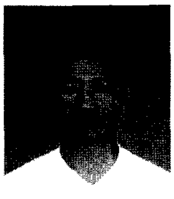
[3] JAUCH, T., KARA, A., RAHMANI, M., and WESTERMANN, D., "Power quality ensured by dynamic voltage correction," *ABB Review*, 1998, 4

[4] NELSON, R.J., WOODLEY, N.H., RAMEY, D.G., and GULACHENSKI, E.M., "Requirement for dynamic voltage restoration to relieve distribution voltage sags," *Proc. of American Power Conf.* 1995

[5] GREBE, T.E, "Application of distribution system capacitor banks and their impact on power quality," *IEEE Transaction on Industry Application*, 1996, 32, (3), pp.714-719

[6] VILATHGAMUWA, M., PERERA, A.A.D.R., and CHOI, S.S., "Performance improvement of the dynamic voltage restorer with closed-loop load voltage and current-mode control," *IEEE Trans. Power Electronics*, 2002, 17, (9), pp.824-834

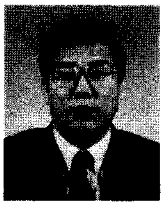
[7] RAMACHANDARAMURTHY, V.K., FITZER, C., ARULAMPALAM, A., ZHAN, C. BARNES, M., and JENKINS, N., "Control of a battery supported dynamic voltage restorer," *IEE Proceeding Generation, Transmission and Distribution*, 2002, 149, (9), pp.533-542



Myung-Bok Kim was born in Gyeong-Buk, Korea, on October 23, 1973. He received the B.S. degree in Electronics Engineering from Kyungpook National University, Daegu, Korea, in 1996, and M.S. degree in Electrical Engineering from Korea Advance Institute of Science and Technology, Daejeon, Korea, in 1998. He has currently studied for Ph.D. degree in KAIST.

Seung-Hoon Lee was born in Inchoen, Korea, on July 25, 1975. He received the B.S. degrees in Electrical Engineering from the Korea University, Seoul, Korea, in 2002, and the M.S. degree in Electrical Engineering from Korea Advanced Institute of Science and Technology, Daejeon, Korea, in 2004. He has currently worked in Korea Aerospace Research Institute, Daejeon, Korea.

Gun-Woo Moon was born in Korea in 1966. He received the B.S. degree from Han-Yang University, Seoul, Korea, in 1990, and the M.S. and Ph.D. degrees in Electrical Engineering from the Korea Advanced Institute of Science and Technology (KAIST), Daejon, Korea, in 1992 and 1996, respec tively. He is currently an assistant professor in the department of Electrical Engineering and Computer Science, KAIST. His research interests include modeling, design and control of power converter, soft switching power converter, resonant inverters, distributed power systems, power factor correction, electric drive systems, driver circuit of PDP and flexible AC transmission systems (FACTS). Dr. Moon is an associate member of IEEE, a member of the Korean Institute of Power Electronics (KIPE), Korean Institute of Electrical Engineers (KIEE), Korea Institute of Telematics and Electronics (KITE), and Korea Institute of Illunimation Electronics and Industrial Equipment (KIIEIE).



Myung-Joong Youn was born in Seoul, Korea, on November 26, 1946. He received the B.S. degree from Seoul National University, Seoul, Korea, in 1970 and the M.S. and Ph.D. degrees in Electrical Engineering from the University of Missouri, Columbia, in 1974 and 1978, respectively. In 1978, he joined the Air-Craft Equipment Division of General Electric Company, Erie, PA, where he was an Individual Contributor on Aerospace Electrical System Engineering. Since1983, he has been a Professor at the Korea Advanced Institute of Science and Technology (KAIST), Daejeon, Korea. His research activities are in the areas of power electronics and control, which include the drive systems, rotating electrical machine design, and high -performance switching regulators. Prof. Youn is a senior member of IEEE, a member of the Institution of Electrical Engineers (IEE), Korean Institute of Power Electronics (KIPE), Korean Institute of Electrical Engineers (KIEE), and Korea Institute of Telematics and Electronics (KITE).