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전력 계통내에서 순간 전압 강하에 빠른 응답 특성을 가진 DVR의 제어

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Synchronous PI control scheme for DVR against a voltage sag in the power system

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ABSTRACT

A new control strategy for dynamic voltage restorer (DVR) is proposed. It is based on synchronous PI control strategy which features fast response. Therefore, the proposed control strategy takes faster action against a voltage sag. Experimental results, executed by DSP, are shown to validate the proposed control strategy.

1. Introduction

In many ac distribution systems, due to the more sensitive nature of newer loads, users continue to demand higher power quality. On the other hand, power quality polluting loads are also becoming more numerous[1]. Power quality problems encompass a wide range of distribution system such as voltage sag and swell, flicker, harmonic distortion, impulse transients, and interruption[2].

Especially, such voltage deviations in the form of voltage sag, swell or temporary outage cause severe process disruptions resulting in millions of dollars of loss of revenue. As such, the proposition of a novel custom power device called dynamic voltage restorer for compensating voltage disturbances in the distribution system has generated a great deal of interest recently[3][4].

The synchronous PI control scheme is adopted as control strategy for driving DVR against the voltage disturbances such as voltage sag, swell, and flicker. There are many advantages in synchronous PI control scheme for injecting the compensation voltage against the voltage sag. This control scheme has the characteristics such as fast response in transient state and low error in steady state. The fast response in transient state guarantees faster action against the voltage sag and the low error in steady state guarantees enough voltage compensation against voltage sags. And then the coupling terms, as the result of Park's transformation, which deteriorate the linearity in control performance, will be removed. Therefore, the linearity can be retrieved so that it is easier to control d-q control variables independently.

The experiment for proposed control was implemented with TMS320C3x in a reduced scale 1kW.

2. Voltage sags in the power system

2.1 Voltage sags

When the voltage sag occurs in the power system, the supply voltage on consumer is shown as Fig.6. In Fig. 6, the magnitude of supply voltage is reduced about 20%. And then, the definition of voltage sag and the problem due to voltage sag will be explained in next section.

2.1.1 Definition

According to IEEE Standard 1100-1992, the voltage sag can be defined as follows;

"An rms reduction in the ac voltage, at the power frequency, for durations from a half-cycle to a few seconds"

2.1.2 Problems due to voltage sag

The problems 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 the other phases, which are referred to as swells. Swells can cause malfunction of electric motor controllers and ASDs. Swells may also stress delicate computer components sometimes leading to premature failure. Degradation of metal oxide surge arresters can also be caused by frequent exposure to high magnitude voltage swells.

2.2 Dynamic voltage restorer against voltage sag

The DVR mitigates voltage sags by injecting a compensating voltage into the power system in synchronous real time. The DVR is a high-speed switching power electronics converter that consists of an energy storage unit that feeds three independent voltage source PWM inverters.

2.2.1 Configuration of DVR

Fig. 1 shows the system configuration of DVR, which consists of DC link capacitor, transformer, ripple filter, and DSP control unit.

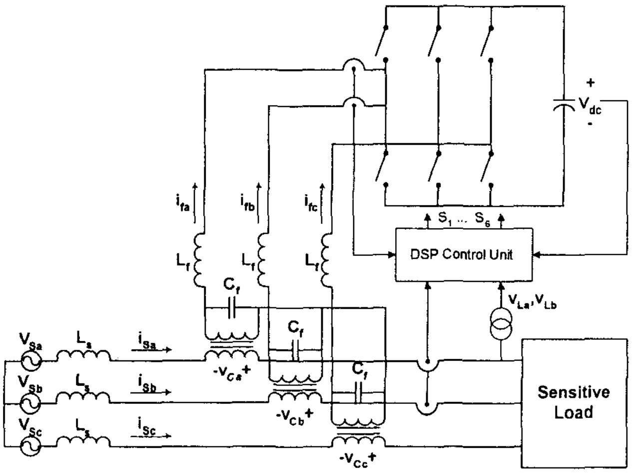

Fig. 1 System configuration of DVR

As shown in Fig. 1, the energy storage system for the DVR is a DC capacitor bank, which is interfaced with the PWM inverter by using a boost converter. The boost converter regulates the voltage across the dc link capacitor that serves as a common voltage source for the PWM inverters. However, the boost converter is not used in this prototype DVR. The three independent voltage source PWM inverters (dc to ac) synthesize the appropriate voltage waveform as determined by the DVR's DSP control system. This compensating voltage waveform is injected into the power system through three single-phase series injection transformers. The DVR control system compares the input voltage to an adaptive reference signal and injects voltage so that the output voltage remains within specifications. The turn ratio of three injection transformer is 1:1 respectively.

3. Controller design for DVR

3.1 Voltage equation of DVR

In order to establish the controller for DVR, it is necessary to derive the circuit equations of DVR. Consequently, the synchronous PI controller, as the controller for DVR, is selected because the basic concept of the controller is that the coupling terms, as the results of Park's transformation, will be removed and the d-q control variables can be controlled independently.

3.1.1 voltage equation

Fig. 2 shows the per phase simplified DVR circuit. In Fig. 2, the variable v_f denotes the output of inverter, the variable v_c does the compensation voltage by DVR, and the variable i_f does the current flowing through DVR.

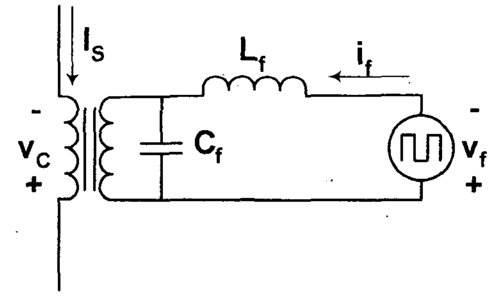

Fig. 2 Per phase simplified DVR circuit

As shown in Fig. 2, the circuit equation for 3 phase circuit can be expressed as (1).

$$\overrightarrow{i_{fabc}} = -C_f \cdot p\overrightarrow{v_{Cabc}} - \overrightarrow{i_{Sabc}}$$
$$\overrightarrow{v_{fabc}} = -L_f \cdot p\overrightarrow{i_{fabc}} + \overrightarrow{v_{Cabc}} \tag{1}$$

where

$$v_{Cabc} = [\ v_{Ca}\ v_{Cb}\ v_{Cc}\ ]^T$$
$$i_{fabc} = [\ i_{fa}\ i_{fb}\ i_{fc}\ ]^T$$
$$i_{Sabc} = [\ i_{Sa}\ i_{Sb}\ i_{Sc}\ ]^T \tag{2}$$

$$L_f = diag[\ L_f\ L_f\ L_f\ ]$$
$$C_f = diag[\ C_f\ C_f\ C_f\ ]$$

(3)

Based on these circuit equations, abc variables can be converted into d-q variables through Park's transformation.

3.1.2 phasor diagram

In order to determine the compensation voltage command for the control algorithm, it is necessary to describe the phasor diagram for supply voltages in the power system. The voltage magnitude decreases and the voltage phasor shifts in a phasor diagram when a voltage sag occurs. The compensation voltage supplied through DVR is the supply voltage difference due to voltage sag. The phasor diagram for the supply voltage change, due to voltage sag, can be shown as Fig. 3.

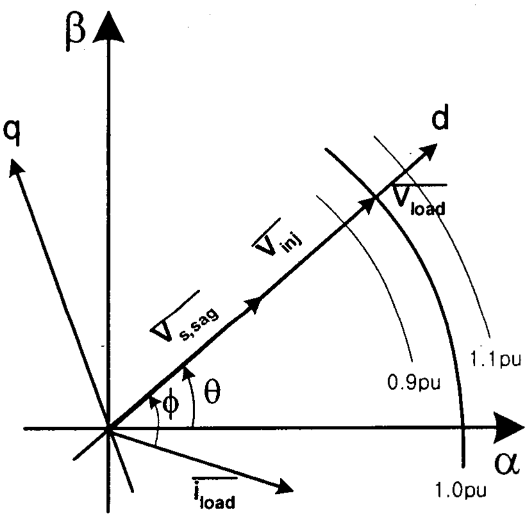

Fig. 3 phasor diagram for supply voltage in power system

In this figure, I and V denote the phasor representations of the instantaneous values of current and voltage in the steady state, and $V_{s,sag}$ denotes the phasor representation of the supply voltage after voltage sag occurs in the power system. And V_{inj} does the compensated voltages injected through transformer by DVR.

3.2 PI Controller for DVR

The control objective is to maintain the load voltage across the load in a pure sinusoidal waveform and constant amplitude. Therefore, the voltage commands of PI controller are the compensated voltage injected finally as the output by DVR. The compensation voltages, V_{Ca}, V_{Cb}, V_{Cc}, across the transformer can be as (4).

$$v_{Ca} = v_{sa} - v_{sa,sag}$$
$$v_{Cb} = v_{sb} - v_{sb,sag}$$
$$v_{Cc} = v_{sc} - v_{sc,sag}$$

(4)

In (4), V_{Sa}, V_{Sb}, V_{Sc} are the supply voltages before voltage sag occurs, and $V_{Sa,sag}$, $V_{Sb,sag}$, $V_{Sc,sag}$ are the supply voltages after voltage sag occurs in power system. The voltage differences due to voltage sag are the voltages supplied through DVR. Therefore, the voltage command of DVR is the voltage difference.

3.2.1 PI controller gain

In order to select controller gains, it is preliminarily necessary to transform three phase circuit equations to the circuit equations in the synchronous reference frame using Park's equation. The circuit equations in d-q axis can be expressed into predictive control form as (5).

$$i_{fq}^{*} = -C_f \frac{v_{Cq}^{*} - v_{Cq}}{T_s} - w_e C_f v_{Cd} - i_{Sq}$$
$$i_{fd}^{*} = -C_f \frac{v_{Cd}^{*} - v_{Cd}}{T_s} + w_e C_f v_{Cq} - i_{Sd}$$

(5)

From the equation (5), the first terms of right hand side of (5) are the tracking errors of compensation voltages, and the second and third terms are the coupling terms due to Park's transformation. From the first terms of right hand side of (5), the proportional gain for synchronous PI controller can be derived as (6). The integral gain is determined so that the controller has the time constant, τ_v, of 50[msec]. In equation (6), the subscript p and i denote proportional and integral gain respectively. And then the superscript v denotes voltage controller.

$$K_p^v = -\frac{C_f}{T_s}$$
$$K_i^v = \frac{K_p^v}{\tau_v}$$

(6)

The current reference expressed in (5) is used for current controller. With these references, voltage controller can be expressed as (7).

$$v_{fq}^{*} = -L_f \frac{i_{fq}^{*} - i_{fq}}{T_s} - w_e L_f i_{fd} + v_{Cq}$$

$$v_{fd}^{*} = -L_f \frac{i_{fd}^{*} - i_{fd}}{T_s} + w_e L_f i_{fq} + v_{Cd}$$

(7)

Similar to equation (5), the first terms of right hand side of (7) are the tracking errors of current flowing through the inductance of the ripple filter and the second and third terms are coupling terms. From the first term of right hand side of (7), the proportional gain for synchronous PI controller can be derived as (8). The integral gain is determined so that the controller has the time constant, τ_i, of 10[msec]. In equation (8), superscript i denotes current controller.

$$K_p^i = -\frac{L_f}{T_s}$$

$$K_i^i = \frac{K_p^i}{\tau_i}$$

(8)

As a consequence of (5) and (7), the voltages, produced by three phase inverter, are the left hand term, V_{fq} and V_{fd} of (7). Fig. 4 shows the block diagram of controller calculating the voltage references of inverter.

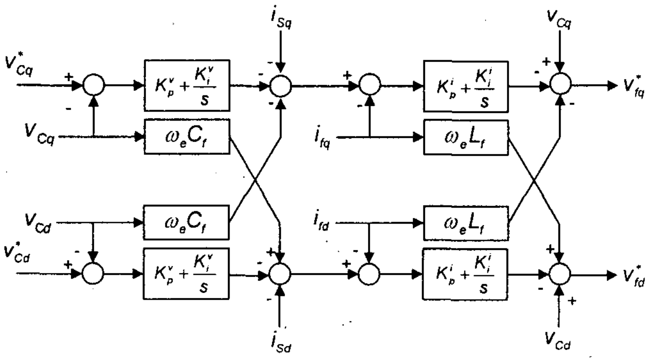

Fig. 4 Control Block Diagram

4. Experiment results

4.1 System specification of DVR

In order to validate the effectiveness of proposed control, a 1kV prototype DVR was 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[uF]
Switching frequency	5000[Hz]
Inverter ripple filter L	200[uH]
Inverter ripple filter C	200[uF]

4.2. Experimental results

The experimental result applied with proposed control are compared with that of conventional LPF. In the conventional LPF, the compensation voltage becomes the voltage command of inverter. On the contrary, the proposed control algorithm produces the voltage command of inverter according to the procedure explained previous section.

4.2.1 Conventional control

Fig. 5 shows the experimental result applied with conventional LPF.

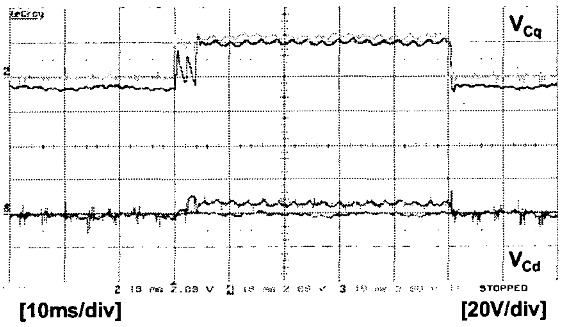

Fig. 5 control performances by conventional control method

In Fig. 5, the upper part shows the control performance of q axis of compensation voltages and the lower part does the control performance of d axis of compensation voltages. From Fig. 5, there is delay time in the transient state and steady state error in control responses. Due to this poor quality, the DVR cannot guarantee the fast action against voltage sag and the enough compensation for reduced amount of supply voltage. Fig. 6 shows the experimental waveform such as supply voltages, compensation voltages, and the load voltages in three phases.

Because of insufficient control performance, the DVR cannot inject the compensation voltages well. Therefore, the delivered voltages to the load are affected.

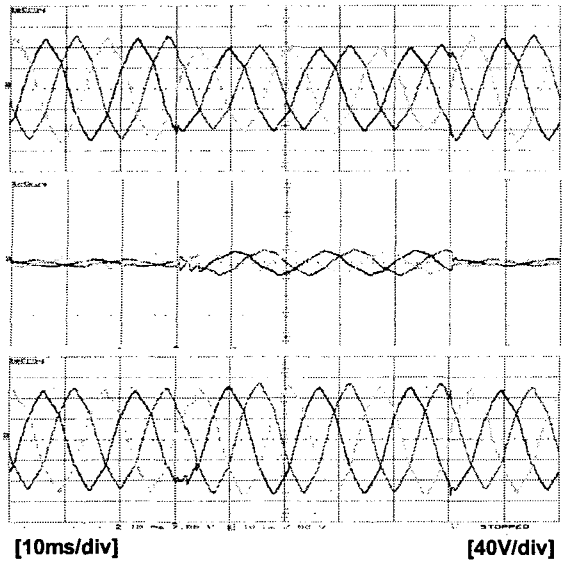

Fig. 6 voltage compensation results by conventional method

4.2.2 Synchronous PI control

Fig. 7 shows experimental results applied with proposed synchronous PI control scheme.

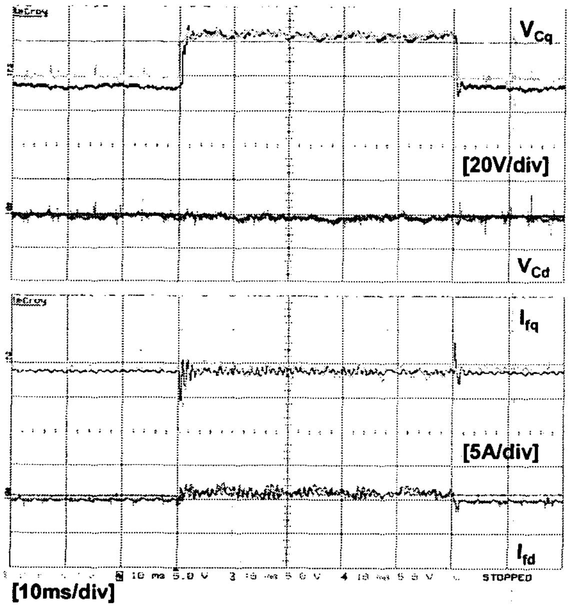

Fig. 7 control performance by synchronous PI control method

In Fig. 7, the upper part shows the control performances of the q and d axis compensation voltages and the lower part does the control performances of the q and d axis current flowing through the ripple filter inductance. As shown in Fig. 7, there is little delay time in transient state and steady state error.

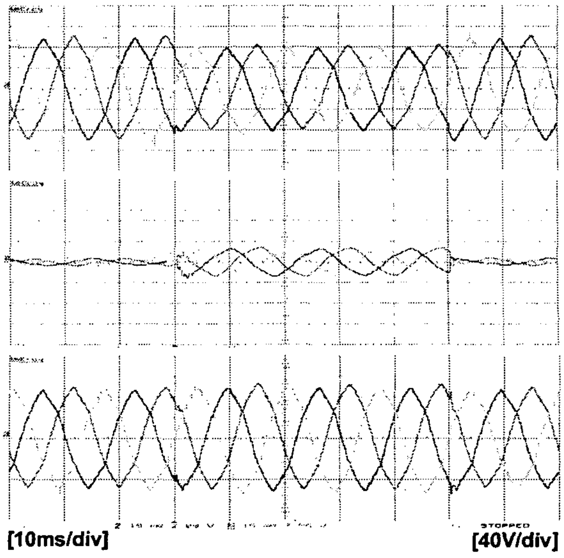

Fig. 8 voltage compensation results by synchronous PI controller

These control performance guarantee the faster action and the enough compensation against the voltage sag.

Fig. 8 shows the experimental waveform such as supply voltages, compensation voltages, and the load voltages in three phases. Comparing with conventional LPF, the delivered voltages to load are balanced voltages since the compensation voltages are injected almost exactly. Because there is little delay time, the faster action against voltage sag can be guaranteed. With these experimental results, it is possible to verify the effectiveness of proposed control scheme.

5. Conclusion

This paper proposes a DVR controller that compensates reduced source voltage caused by faults in the electric supply. The proposed synchronous PI 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 validity of the proposed control method was confirmed with experimental results. The experiment was implemented with TI DSP and was performed with a 1kVA prototype DVR system.

References

[1] Michael D. Stump, Gerald J. Keane, and Frederick K.S.

Leong, "The role of custom power products in enhancing power quality at industrial facilities," Proceedings of IEEE EMPD '98, pp.507-517, 1998

[2] H. Akagi, "New trends in active filters for power conditioning," IEEE Trans. Ind. Applicat., vol. 32, pp. 1312-1322, Nov./Dec. 1996

[3] Thomas Jauch, Alexander Kara, Mohamed Rahmani and Dirk Westermann, "Power quality ensured by dynamic voltage correction," ABB Review 4, 1998

[4] R.J. Nelson, N.H. Woodley, D.G. Ramey and E.M. Gulachenski, "Requirement for dynamic voltage restoration to relieve distribution voltage sags," Proc. of American Power Conf. 1995