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Compensating Characteristics of Voltage Sag Compensator Utilizing Single-Phase Matrix Converter

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Abstract – By using simulation, compensating characteristics of a voltage sag compensator utilizing single-phase matrix converter is examined. System configuration is described and mathematical model of single-phase matrix converter is derived by using the state space averaging method. In addition, the single-phase matrix converter is stabilized by phase-lead compensation. Finally, compensating characteristics of the compensator is investigated for 500 W R-L load and it is demonstrated that the compensator can operate correctly for loads for the range of power factor 0.6 (lagging) – 0.8 (leading) and for up to 50% voltage sag.

Keywords: Single-phase matrix converter, Voltage sag compensator

1. Introduction

Power service interruptions cause problems in various facilities. Even voltage sag may give rise to serious problems in computer systems or electronic equipments. The uninterruptible power system (UPS) has been used to compensate for the power service interruptions [1]. The system, however, needs a large battery and high cost. On the other side, the voltage sag compensator was presented for instantaneous voltage sag compensation [2]. In this case, the compensator has shorter compensating time than that of the UPS. However, the compensator has possibility to offer more compact and lower costed countermeasure for voltage sags.

The authors already proposed an instantaneous voltage sag compensator utilizing single-phase matrix converter [3]. The compensator can compensate for voltage sags up to 50%. Matrix converters are circuits which convert an AC voltage into other AC voltage directly. The matrix converters have some good features such as high efficiency and downsized volume compared to conventional inverters. In general, single-phase matrix converters need a large capacitor to produce non-zero output voltage when the input voltage is near zero [4]. In application of the single-phase matrix converter to the instantaneous voltage sag compensator, however, the frequency of the output voltage is the same as that of input voltage. In this case, the output voltage reference is also near zero when the input voltage is near zero. Therefore, single-phase matrix converters can be used for the application to the instantaneous voltage sag compensator without any capacitor.

In this paper, we investigate the compensating characteristics of proposed compensator by simulation.

2. Voltage Sag Compensator Utilizing Single-Phase Matrix Converter

The system configuration of proposed instantaneous voltage sag compensator utilizing single-phase matrix converter is shown in Fig. 1. This compensator consists of the single-phase matrix converter which generates compensation voltage V_C from source voltage V_S, two filters which reduce voltage or current ripples, and transformer which adds compensation voltage V_C to source voltage V_S.

Operating principle of the compensator is explained, here. Load voltage V_L equals to source voltage V_S. When the voltage sag occurs in the source voltage V_S, the compensation voltage V_C will be produced by the matrix converter and added to V_S through a transformer, as a result, the load voltage V_L will be maintained to the normal load voltage V_L*. To compensate the steady state error of V_C, we used feed forward gain K. The compensation voltage reference V_C* is calculated from the difference between V_L* and V_S, and V_C is controlled by proportional controller. Output signal from proportional controller is compared with the triangle carrier wave modulated by amplitude of V_S. And gate signals for each switches of the matrix converter are produced. Sampling period is 100 μs. Finally, the desired compensation voltage V_C is generated.

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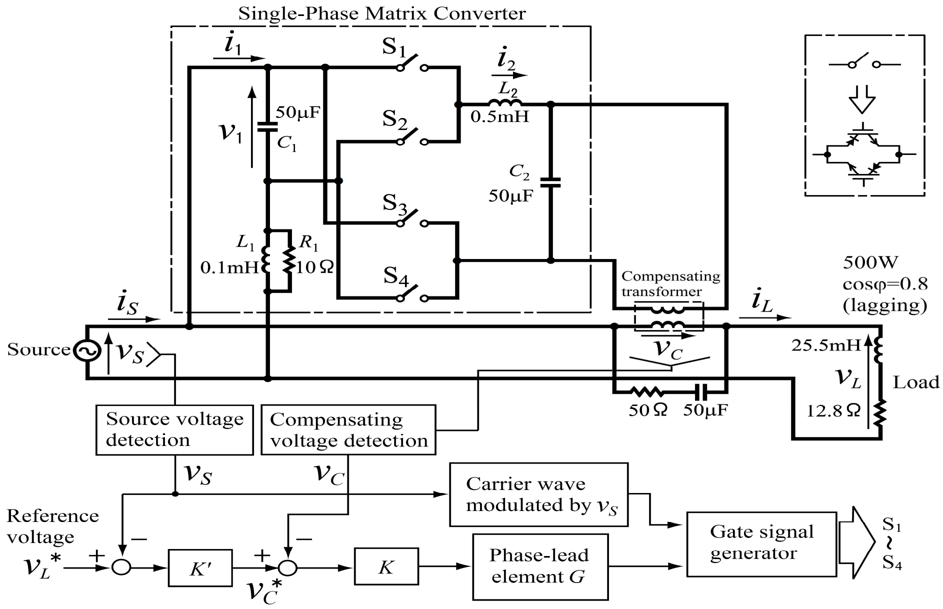


Fig. 1. System configuration of instantaneous voltage sag compensator using a single-phase matrix converter.

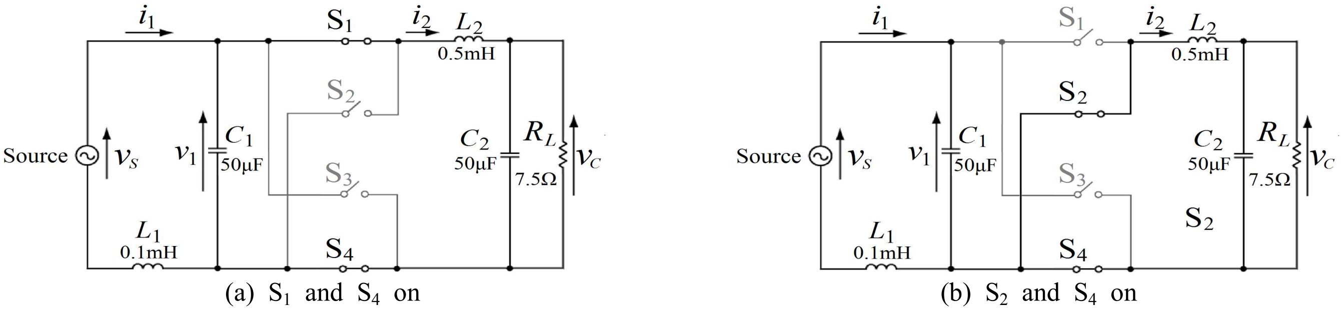


Fig. 2. Simple model for single-phase matrix converter connected to load resistance $R_L = 7.5\ \Omega$.

3. System Analysis by State Space Averaging Method

For simplicity, a simple model where the single-phase matrix converter was connected to the source and a load resistance $R_L = 7.5\ \Omega$ was examined. The proposed compensator can compensate for voltage sag in the case that switch S_3 is off and switch S_4 is on. On the other hand, this compensator can also compensate for voltage swell in the case that switch S_3 is on and switch S_4 is off. Here, because of only the voltage sag compensation, switch S_3 is always off and S_4 is always on. Fig. 2 (a) illustrates the circuit of the single-phase matrix converter in the case that S_1 and S_4 are on, and Fig. 2 (b) illustrates the circuit in the case that S_2 and S_4 are on. Equations (1)-(4) are obtained from the circuit in Fig. 2 (a).

$$C_1 \frac{dv_1}{dt} = i_1 - i_2 \tag{1}$$

$$v_S - L_1 \frac{di_1}{dt} = v_1 \tag{2}$$

$$-v_1 + L_2 \frac{di_2}{dt} + v_C = 0 \tag{3}$$

$$i_2 - C_2 \frac{dv_C}{dt} - \frac{v_C}{R_L} = 0 \tag{4}$$

Similarly, equations (5)-(8) are obtained from the circuit in Fig. 2 (b).

$$C_1 \frac{dv_1}{dt} = i_1 \tag{5}$$

$$v_S - L_1 \frac{di_1}{dt} = v_1 \tag{6}$$

$$L_2 \frac{di_2}{dt} + v_C = 0 \tag{7}$$

$$i_2 - C_2\frac{dv_C}{dt} - \frac{v_C}{R_L} = 0 \tag{8}$$

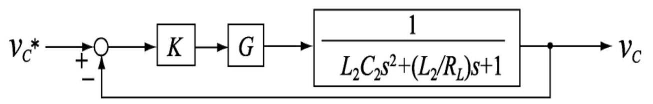
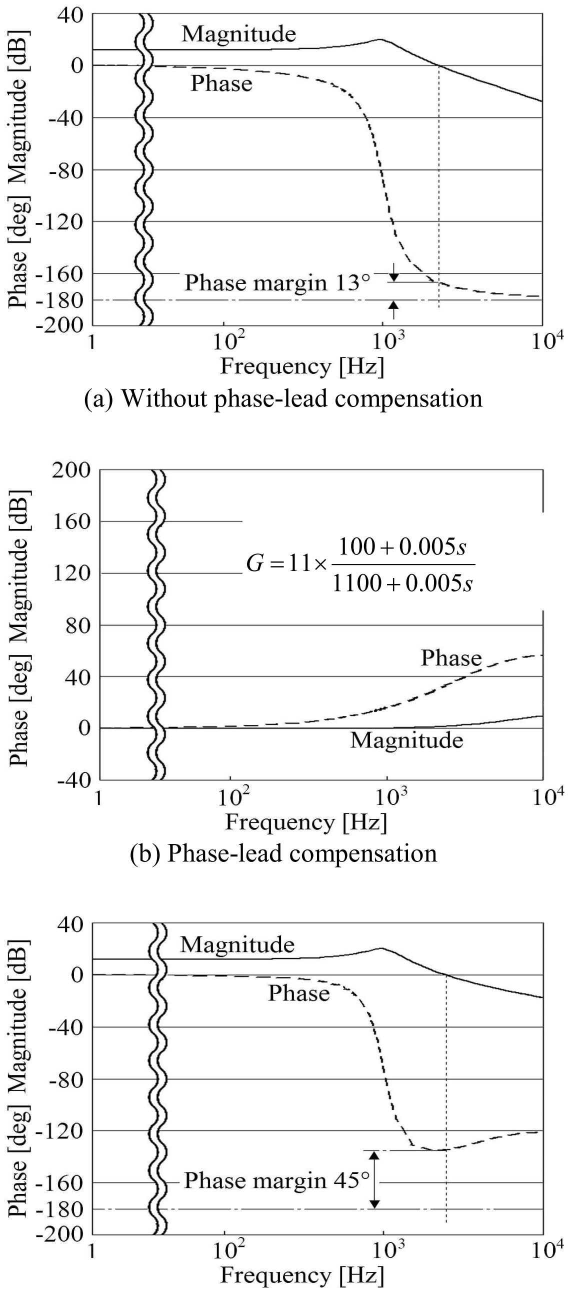


Fig. 3. Block diagram of the compensator.



(a) Without phase-lead compensation

(b) Phase-lead compensation

(c) With phase-lead compensation

Fig. 4. Bode diagram of the compensator.

Matrix equation (9) is derived from (1)-(4), and matrix equation (10) is derived from (5)-(8).

$$\begin{bmatrix}\frac{di_1}{dt}\\ \frac{di_2}{dt}\\ \frac{dv_1}{dt}\\ \frac{dv_C}{dt}\end{bmatrix} = \begin{bmatrix} 0 & 0 & -\frac{1}{L_1} & 0\\ 0 & 0 & \frac{1}{L_2} & -\frac{1}{L_2}\\ \frac{1}{C_1} & -\frac{1}{C_1} & 0 & 0\\ 0 & \frac{1}{C_2} & 0 & -\frac{1}{R_LC_2}\end{bmatrix}\begin{bmatrix} i_1\\ i_2\\ v_1\\ v_C\end{bmatrix} + \begin{bmatrix}\frac{1}{L_1}\\ 0\\ 0\\ 0\end{bmatrix} v_S \tag{9}$$

$$\begin{bmatrix}\frac{di_1}{dt}\\ \frac{di_2}{dt}\\ \frac{dv_1}{dt}\\ \frac{dv_C}{dt}\end{bmatrix} = \begin{bmatrix} 0 & 0 & -\frac{1}{L_1} & 0\\ 0 & 0 & 0 & -\frac{1}{L_2}\\ \frac{1}{C_1} & 0 & 0 & 0\\ 0 & \frac{1}{C_2} & 0 & -\frac{1}{R_LC_2}\end{bmatrix}\begin{bmatrix} i_1\\ i_2\\ v_1\\ v_C\end{bmatrix} + \begin{bmatrix}\frac{1}{L_1}\\ 0\\ 0\\ 0\end{bmatrix} v_S \tag{10}$$

We used duty ratio D for switch S_1 and $1-D$ for switch S_2 in our mathematical model. By the state space averaging method, matrix equation (11) is obtained from (9) and (10),

$$\begin{bmatrix}\frac{di_1}{dt}\\ \frac{di_2}{dt}\\ \frac{dv_1}{dt}\\ \frac{dv_C}{dt}\end{bmatrix} = \begin{bmatrix} 0 & 0 & -\frac{1}{L_1} & 0\\ 0 & 0 & \frac{D}{L_2} & -\frac{1}{L_2}\\ \frac{1}{C_1} & -\frac{D}{C_1} & 0 & 0\\ 0 & \frac{1}{C_2} & 0 & -\frac{1}{R_LC_2}\end{bmatrix}\begin{bmatrix} i_1\\ i_2\\ v_1\\ v_C\end{bmatrix} + \begin{bmatrix}\frac{1}{L_1}\\ 0\\ 0\\ 0\end{bmatrix} v_S \tag{11}$$

where duty ratio D is as the following;

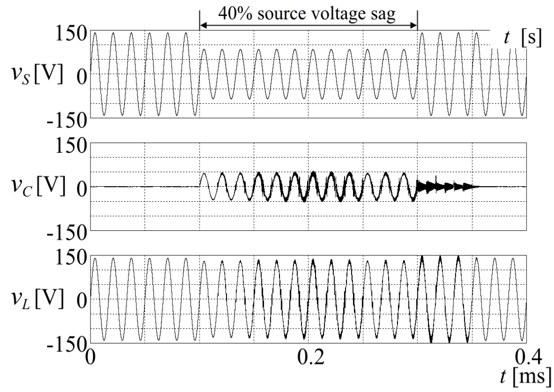
$$D = KG(v_C^* - v_C)/v_S \tag{12}$$

For simplicity, we ignored the input filter, that is, we assumed that voltage across the input filter capacitance v1 is equal to the source voltage vS. As a result, the transfer function of the compensator is obtained from 2nd row and 4th row of (11) as the following.

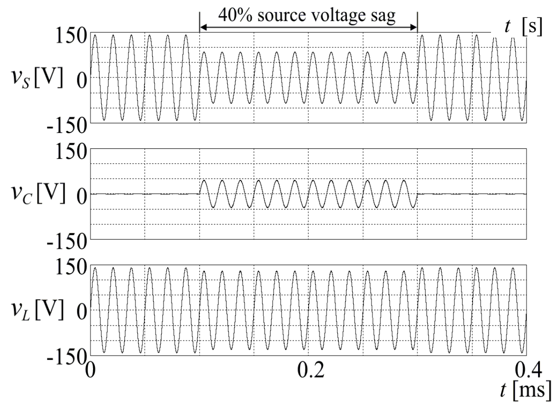
$$\begin{aligned}\frac{v_C}{v_C^*} &= \frac{KG}{L_2C_2s^2+(L_2/R_L)s+1+KG}\\ &= \frac{KG\left(\frac{1}{L_2C_2s^2+(L_2/R_L)s+1+KG}\right)}{1+KG\left(\frac{1}{L_2C_2s^2+(L_2/R_L)s+1+KG}\right)}\end{aligned} \tag{13}$$

A block diagram in Fig. 3 can be obtained from (13). A bode diagram of loop transfer function for the block diagram in Fig. 3 is shown in Fig. 4 (a). The parameters were chosen as K = 4 and G = 1 for the diagram. It is clear from the Fig. 4 (a) that the operation of the compensator is likely to be unstable because of very small phase margin. In order to improve this small phase margin, we used the phase-lead compensation given by (14).

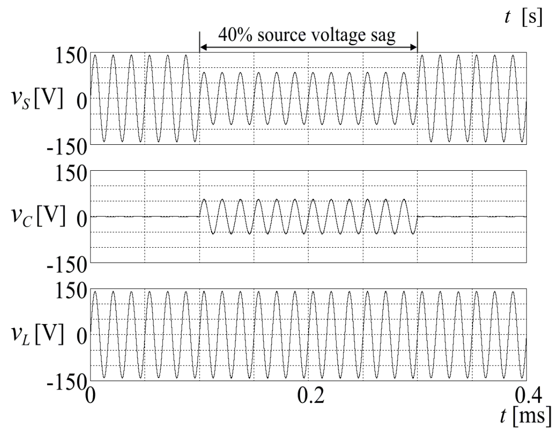
$$G = 11 \times \frac{100 + 0.005s}{1100 + 0.005s} \tag{14}$$



(a) Without phase-lead compensation, $K' = 1.0$

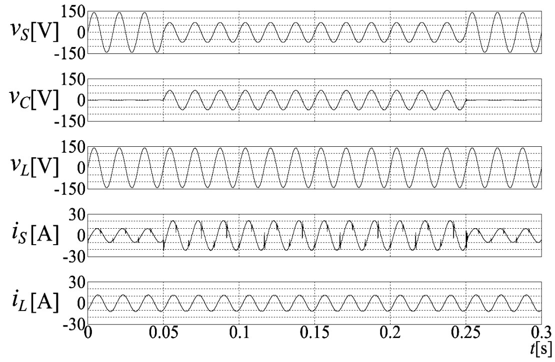


(b) With phase-lead compensation, $K' = 1.0$

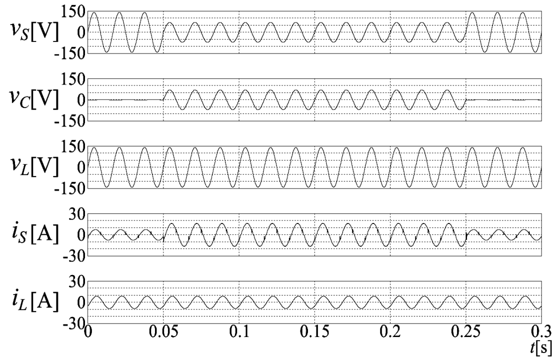


(c) With phase-lead compensation, $K' = 1.25$

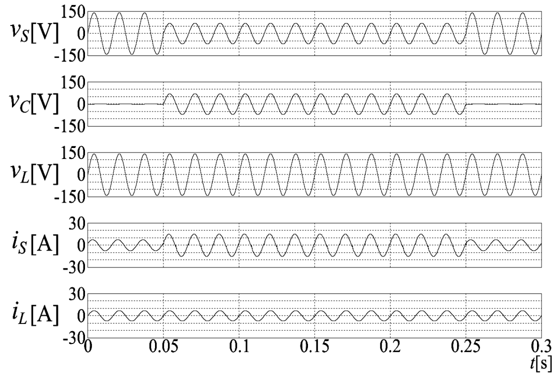
Fig. 5. Simulated waveforms of proposed compensator (source voltage v_S, compensating voltage v_C, load voltage v_L).



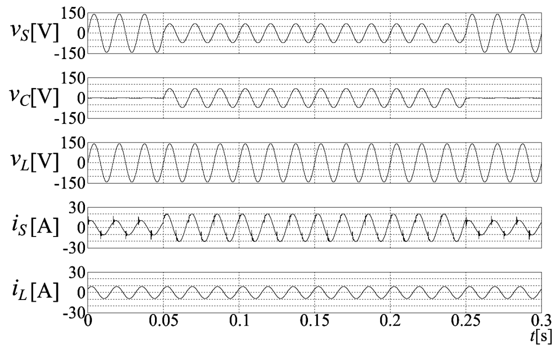
(a) Lagging power factor 0.6



(b) Lagging power factor 0.8



(c) Unity power factor



(d) Leading power factor 0.8

Fig. 6. Various waveforms of compensator for different power factor (50% voltage sag, during 0.05-0.25 sec), source voltage v_S, compensating voltage v_C, load voltage v_L, source current i_S, load current i_L.

The bode diagram of the phase-lead compensation is shown in Fig. 4 (b). When the phase-lead compensation was applied to single-phase matrix converter, the bode diagram of the single-phase matrix converter with phase-lead compensation is shown in Fig. 4 (c). In Fig. 4 (c), phase margin is improved. And we can expect that the compensator is operated stably.

By using simulation, various waveforms of compensator were examined for the system in Fig. 1. The simulation was performed for the case that the source voltage dropped to 40% of the normal voltage during 0.1-0.3 sec with 500 W R-L load and lagging power factor 0.8. Fig. 5 shows various waveforms for proportional control of the proportional gain K = 4. The waveforms without phase-lead compensation and with K' = 1.0 are shown in Fig. 5 (a), and those with phase-lead compensation and with K' = 1.0 are shown in Fig. 5 (b). In Fig. 5 (a), a lot of ripples are found in the compensation voltage vC and those show unstable operation of the compensator. In Fig. 5 (b), we introduced the phase-lead compensation. As a result, ripples of the compensation voltage vC decreased and the figure demonstrates that the compensator was stabilized. However, in Fig. 5 (b), the compensation voltage vC has steady state error. To solve this issue, we calculated the gain value of (13) for the source frequency of 60 Hz, and obtained (15).

$$\left|\frac{v_C}{v_C^*}\right| = 0.8 \tag{15}$$

Equation (15) shows that vC will be 0.8 times of vC* for 60 Hz. So, we choose the value of the feedforward gain K' as 1.25 (1/0.8). Various waveforms with phase-lead compensation and K' = 1.0 are shown in Fig. 5 (c). From Fig.5 (c), it is clear that the compensation voltage of vC is stabilized and the steady state error of vC is improved.

4. Compensating Characteristics

Compensating characteristics of the compensator were examined for several loads in order to clear the compensating range of the single-phase matrix converter. When the source voltage dropped to 50% of the normal voltage, operations of the system were investigated for load power factors 0.6 (lagging), 0.8 (lagging), 1.0, and 0.8 (leading). Various waveforms of compensator for various power factors are shown in Fig. 6. One can find that the load voltage v_L was successfully compensated for about 50% voltage sag, but pulsations in the source current i_S are getting worse as the power factor becomes poor.

5. Conclusion

By using simulation, stability and steady state error of a voltage sag compensator utilizing single-phase matrix converter were investigated, and compensating characteristics of a voltage sag compensator utilizing single-phase matrix converter were demonstrated.

First, the system configuration and operation principle of the compensator were presented. And then, the mathematical model of the single-phase matrix converter was derived by the state space averaging method, and transfer function of a simple model of the voltage sag compensator was decided.

Moreover, by using bode diagrams of the simple model; the stability of the system was investigated. On the basis of investigation, we introduced the phase-lead compensation. As a result, ripples of the compensation voltage v_C decreased and the compensator was stabilized. The steady state error of v_C was also improved with feed forward gain *K'*.

Finally, Compensating characteristics of the compensator were examined for various load power factor. And it was found that the voltage sag compensator can compensate loads for the range of power factor 0.6 (lagging) - 0.8 (leading) and for up to 50% voltage sag.

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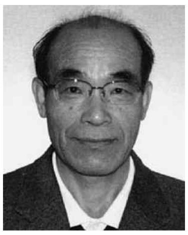

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