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Characteristics of Voltage Sag/Swell Compensator Utilizing Single-Phase Matrix Converter

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Abstract – Compensating characteristics of a voltage sag/swell compensator utilizing single-phase matrix converter is examined. First, system configuration and operation for both voltage sag and swell are described. Next, in order to suppress pulsations of the source voltage, a countermeasure using low pass filter and all pass filter is introduced. Then, compensating characteristics of the compensator are investigated for *R-L* load by simulation. Finally, the validity of the simulated results is confirmed by the experimental results.

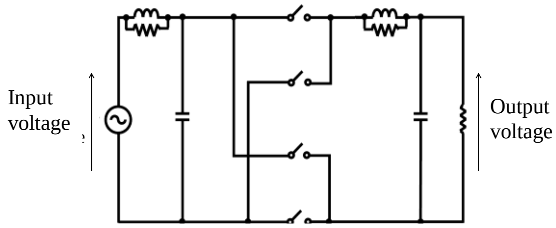
Keywords: Single-phase matrix converter, Voltage sag/swell compensator

1. Introduction

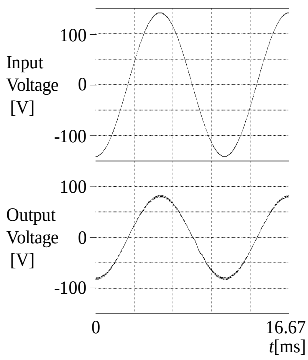
Power service interruptions cause problems in various facilities. Even voltage sag/swell may cause to serious problems in computer systems or electronic equipments. The uninterruptible power system (UPS) has been used to compensate for the power service interruptions [1]. However, the system needs a large battery and high cost. On the other hand, 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. The compensator, however, has possibility to offer more compact and lower cost countermeasure for voltage sags/swells.

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/swell 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 (see Fig. 1). Therefore, single-phase matrix converters can be used for the application to the instantaneous voltage sag/swell compensator without any large capacitor.

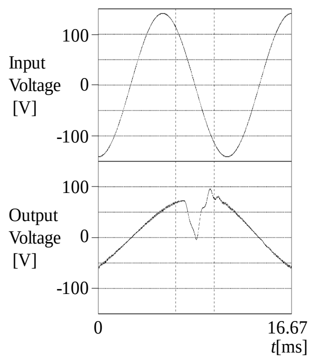
In this paper, system configuration and operation for both voltage sag and swell are described at first. Next, to suppress pulsations of the source voltage, a countermeasure using analog low pass filter (LPF) and analog all pass filter (APF) is introduced. Then, compensating characteristics of the voltage sag/swell compensator are investigated for *R-L* load by simulation. Finally, the validity of the simulated results is confirmed by the experimental results.



(a) Single-phase matrix converter



(b) Same frequency ($f_{in} = f_{out}$)



(c) Different frequency ($f_{in} \neq f_{out}$).

Fig. 1. Typical waveforms of input and output voltages in a single-phase matrix converter.

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2. Voltage Sag/Swell Compensator Utilizing Single-Phase Matrix Converter

The system configuration of proposed instantaneous voltage sag/swell compensator utilizing single-phase matrix converter is shown in Fig. 2. The main circuit of 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 at input side and output side, and transformer which adds compensation voltage v_C to source voltage v_S.

Operating principle of the compensator is explained, here. In normal situation, 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* as shown in Fig. 3. In Fig. 2, the compensation voltage reference v_C* is calculated from the difference between v_L* and v_S. And v_C* is compared with the triangle carrier wave modulated by amplitude of v_S. And then, gate signals for each switches of the matrix converter areproduced in a FPGA. Sampling period of DSP (TMS320F2808) was 100 μs. The proposed compensator can compensate for not only voltage sag but also voltage swell.

Theoretical limit of voltage sag compensation is 50 % of normal voltage because 1:1 transformer is used in the system (It depends on the turns ratio of the transformer.). And there is no theoretical limit of voltage swell

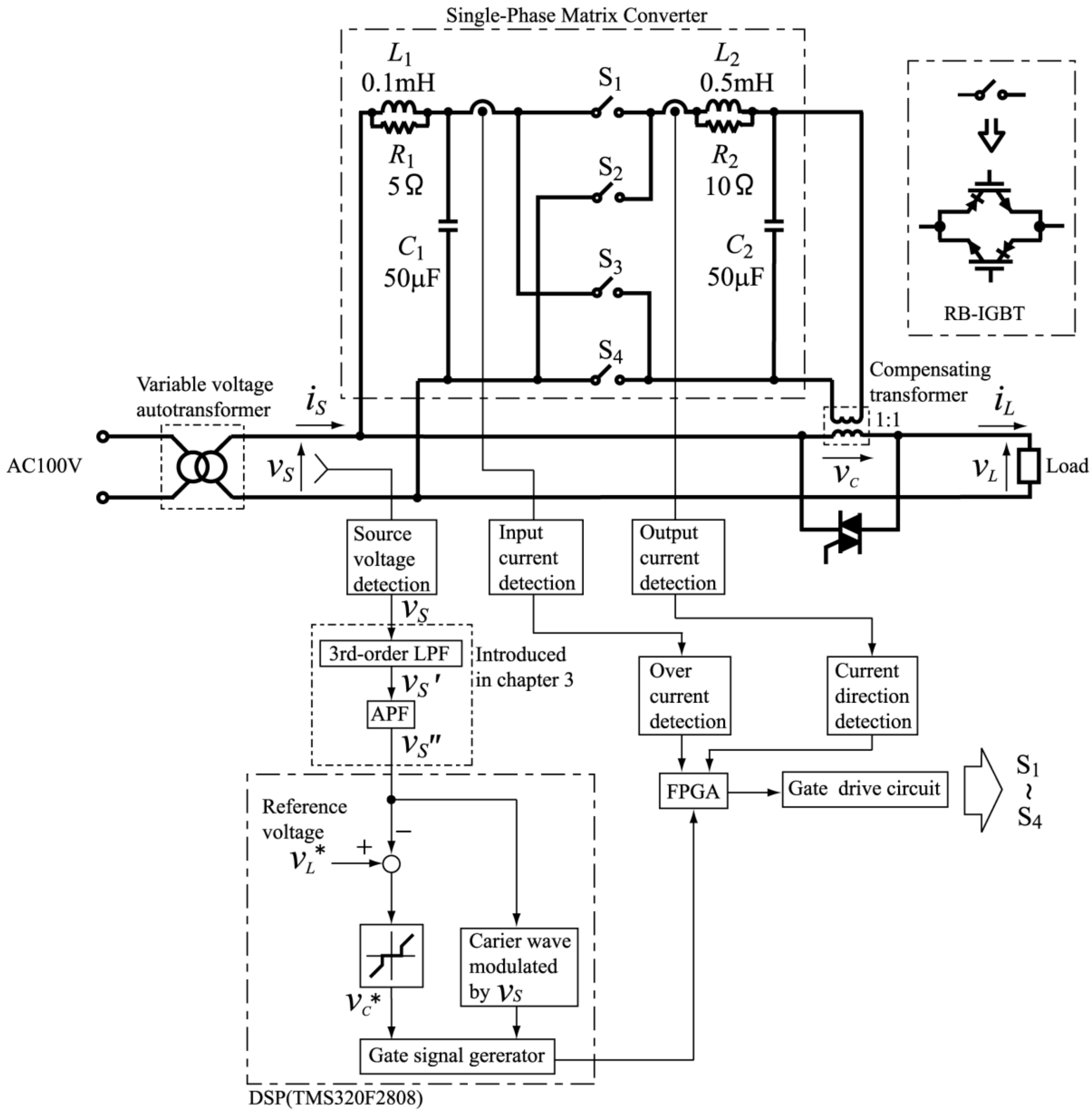


Fig. 2. System configuration of instantaneous voltage sag compensator using a single-phase matrix converter.

compensation (It depends on the rated current of the system which is the lower value of the rated current of transformer or voltage source.).

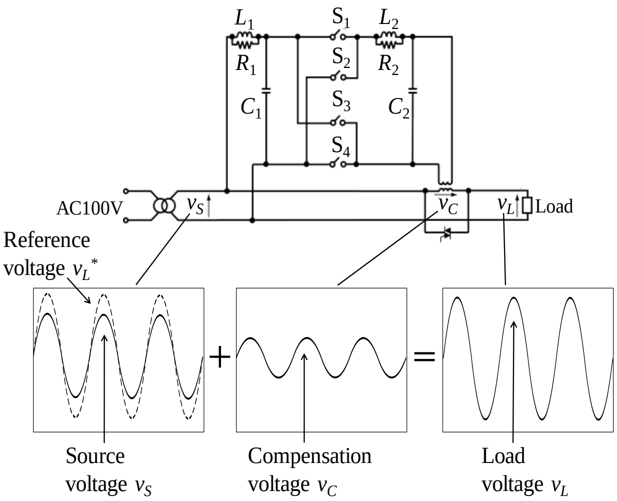


Fig. 3. Operating principle of the voltage sag/swell compensator.

In the case of voltage sag compensation, switch S_3 is always off and switch S_4 is always on, and switch S_1 and S_2 are switched complementary, depending on the compensation voltage reference v_C*. On the other hand, in the case of voltage swell compensation, switch S_3 is always on and switch S_4 is always off, and switch S_1 and S_2 switched complementary, depending on v_C*. To prevent frequently changes between voltage sag compensating mode and voltage swell compensating mode, a dead band is added. That is, v_C*=0 for the values of v_C* between -3.4 V and 3.4 V.

3. Simulation of Voltage Sag/Swell Compensator

3.1 Pulsation of Compensation Voltage

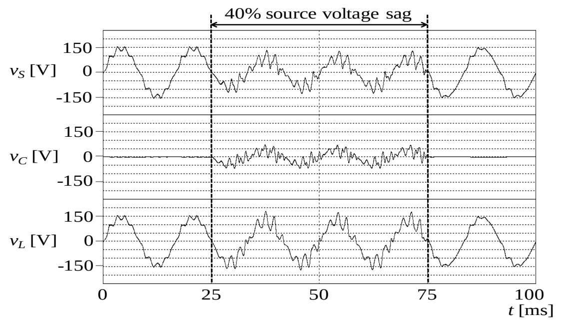
In this section, simulations of voltage sag/swell compensator are described. A simulation was performed for 250W-load. The power factor of the load was 1.0. Fig. 4 (a) shows simulated waveforms of the compensator. We can see lots of pulsations on the source voltage v_S, the compensation voltage v_C and the load voltage v_L.

In the previous paper [3], such pulsations were not observed because a resistance and a switch were used to imitate voltage sags. When switch was turned off, the resistance was inserted to the circuit in series and the voltage drop caused voltage sag. In this case, the resistance functioned as a damping resistance for the system.

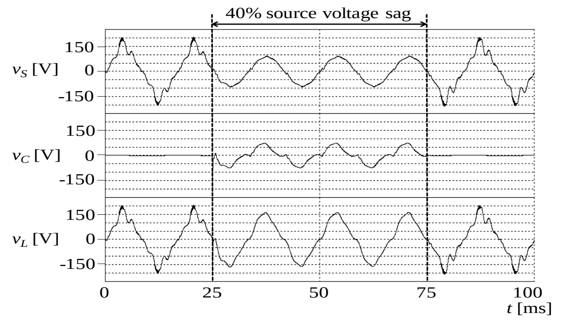
On the contrary, in this paper, an autotransformer was used to imitate the voltage sags and swells because resistance cannot imitate voltage swells. As a result, the total leakage inductance of autotransformer and voltage source was inserted into the circuit in series instead of damping resistance. It caused the pulsations in Fig. 4 (a). For this simulation, 1.4 mH, which was measured for the experimental system, was used as a value of total leakage inductance.

3.2 Suppression of the Pulsations of Compensation Voltage

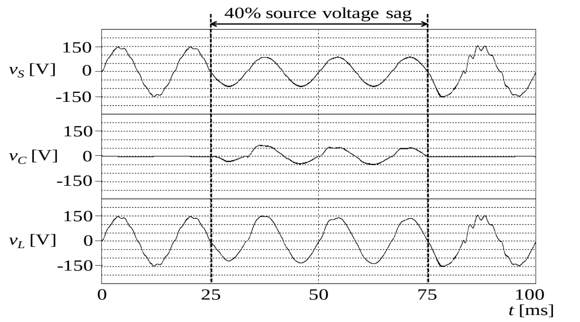
To suppress the pulsations in Fig. 4 (a), a third order LPF was introduced for the detected source voltage v_S, and the filtered signal is v_S' in Fig. 2. Thus, the compensation



(a) Without third order low pass filter and all pass filter



(b) With third order low pass filter



(c) With third order low pass filter and all pass filter

Fig. 4. Simulated waveforms of compensator (source voltage v_S, compensating voltage v_C, load voltage v_L, unity power factor).

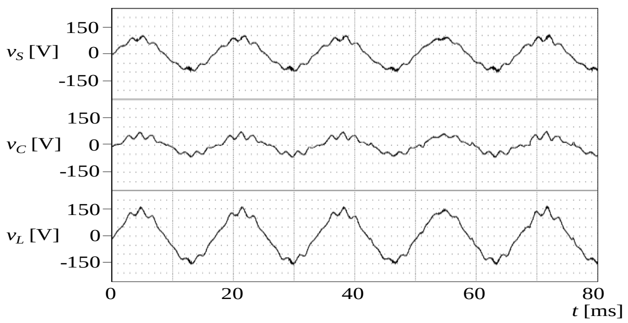
voltage reference v_C* becomes the difference between v_L*and v_S', and the simulated waveforms for this v_C* are shown in Fig. 4 (b). The pulsations were decreased but lower order pulsations are remained. Cause of lower order pulsations was examined and it was clear that main cause was phase lag in the LPF. So, an APF was added and v_S' was passed through the filter. The signal v_S' was leaded in the APF. This filtered signal is v_S'' in Fig. 2. Thus, v_C* becomes the difference between v_L* and v_S'', and the simulated waveforms for this v_C* are shown in Fig. 4 (c). In the figure, the pulsations are almost suppressed.

Experimental waveforms corresponding to those in Fig. 4 (a) and (c) are shown in Fig. 5 (a) and (b), respectively. In these experiments, we were not able to change the source voltage instantaneously because we used autotransformer to change the source voltage. So, experimental results include no transient state but only steady state. We can find from the figures that the experimental waveforms agree well with the simulated waveforms and those simulations are valid. And it was confirmed that the countermeasure of LPF and APF functioned correctly.

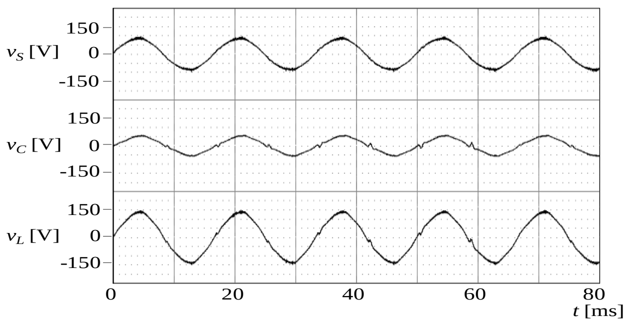
3.3 Simulation of Proposed Voltage Sag/Swell Compensator

By simulations, compensating characteristics of the compensator were examined for several loads in order to confirm the operation of the compensator. When the source voltage dropped to 40% of the normal voltage, operations of the system were investigated for load power factors 1.0, 0.8 (leading), 0.8 (lagging), and 0.6 (lagging). Simulated waveforms of compensator for various power factors are shown in Fig. 6. In addition, when the source voltage rose to 30% (limited by the specification of the autotransformer in the experimental system) of the normal voltage, operations of the system were investigated for load power factors same as the voltage dropping to 40%. For this case, simulated waveforms of compensator for various power factors are shown in Fig. 7.

- Load voltages v_L and load currents i_S for various loads can be kept at almost constant amplitude of correct value in spite of voltage sags or sells.
- For leading load currents, pulsations of i_S and v_S are very low. And, more lagging load current makes more remarkable pulsation with higher frequency.
- Larger current for poor power factor causes larger pulsations of v_S because of larger voltage drop in the leakage inductance of autotransformer.
- Transient pulsations are observed in the source current $i_{S,}$ when triac turns on.



(a) Without third order low pass filter and all pass filter



(b) With third order low pass filter and all pass filter

Fig. 5. Experimental waveforms of compensator (source voltage v_S, compensating voltage v_C, load voltage v_L, unity power factor).

4. Experimental Results of Voltage Sag/Swell Compensator

By experiments, compensating characteristics of the compensator were investigated for the same loads as those used in the simulation for Figs. 6 and 7. The experimental results are shown in Figs. 8 and 9.

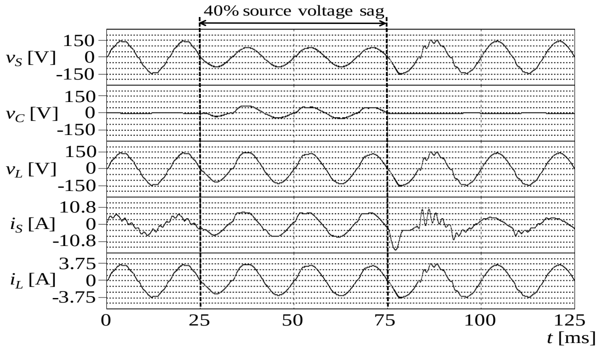
From Figs. 8 and 9, one can find as the following;

- Similar to the simulated results in Figs. 6 and 7, load voltages v_L and load currents i_S for various loads can be kept at almost constant amplitude of correct value in spite of voltage sags or swells.
- In the experimental results, the pulsations of v_L and i_S are not so large as those in the simulated results.

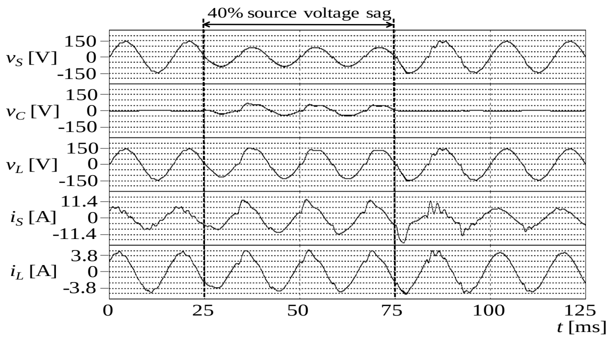
  In the experimental results, the pulsations of 10 kHz, which is a switching frequency, are observed on the v_S, v_L and i_S. The reason of 10 kHz pulsations is considered as switching noises from switching devices because switching source voltage v_S increases in the voltage swell condition.

From the comparison between simulated and experimental results, one can find as the following;

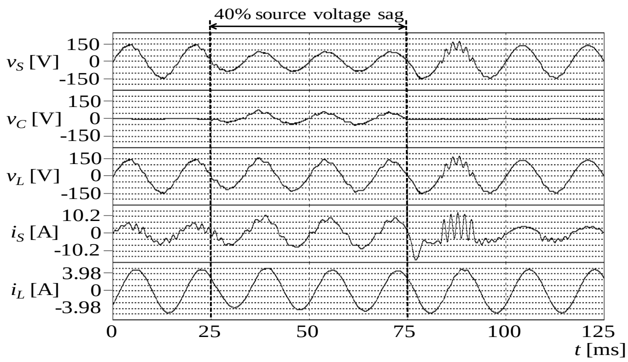
- Coincidence of simulated and experimental results in Figs. 6-9 demonstrates the validity of the simulated results.



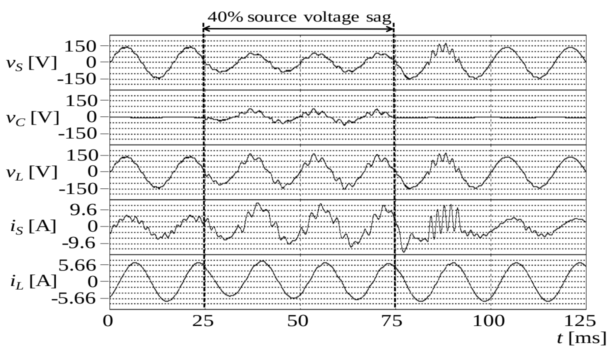
(a) Unity power factor



(b) Leading power factor 0.8

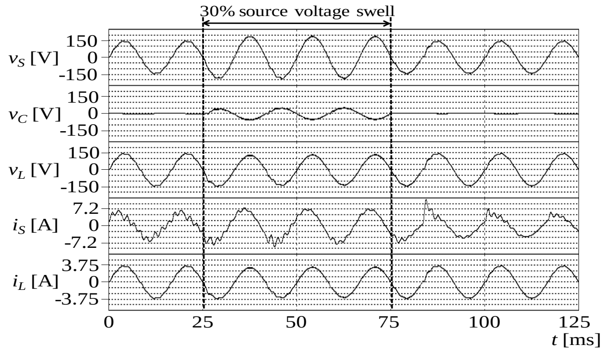


(c) Lagging power factor 0.8

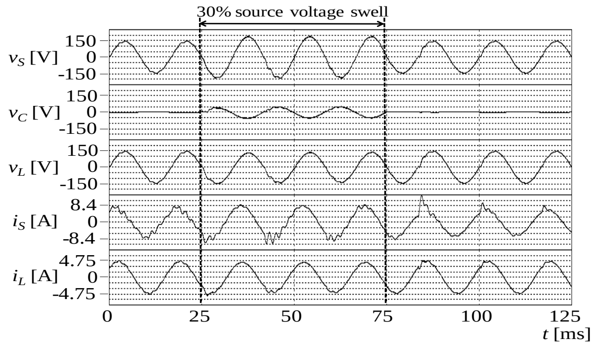


(d) Lagging power factor 0.6

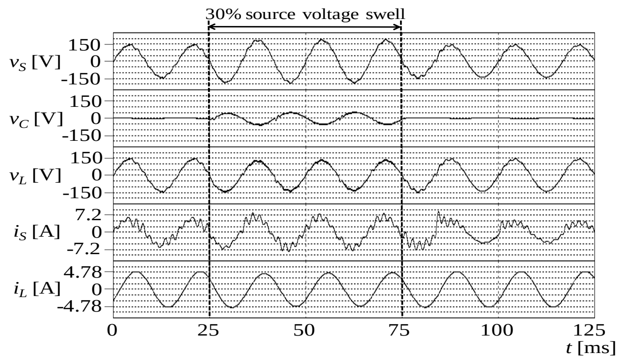
Fig. 6. Simulated waveforms of compensator for different power factor (40% voltage sag, during 25-75ms), source voltage v_S, compensating voltage v_C, load voltage v_L, source current i_S, load current i_L.



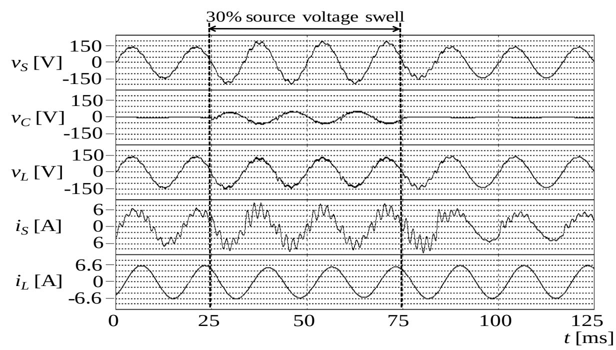
(a) Unity power factor



(b) Leading power factor 0.8

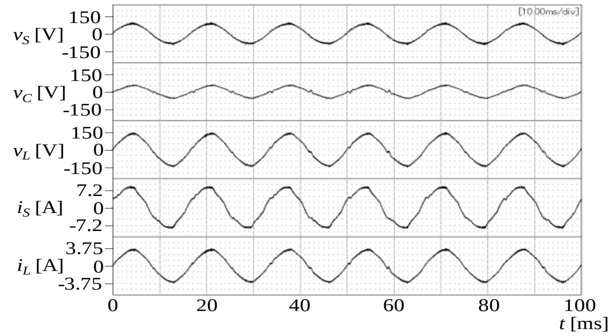


(c) Lagging power factor 0.8

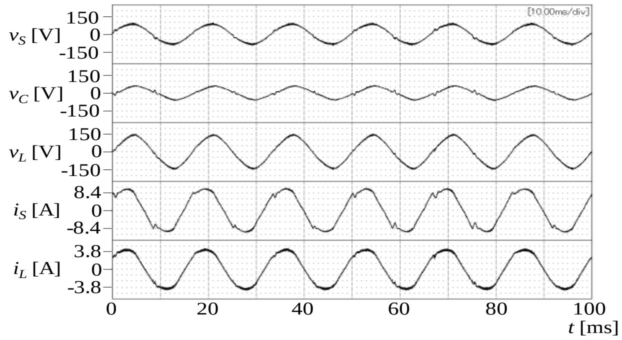


(d) Lagging power factor 0.6

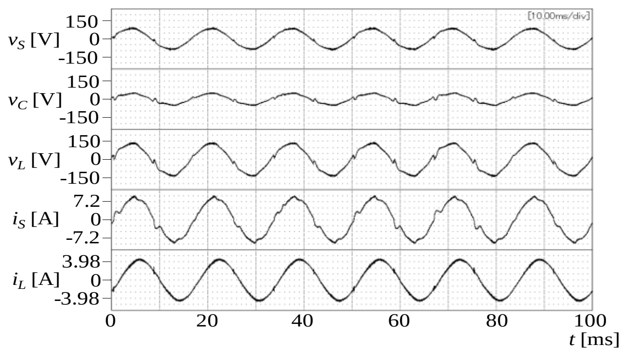
Fig. 7. Simulated waveforms of compensator for different power factor (30% voltage swell, during 25-75ms), source voltage v_S, compensating voltage v_C, load voltage v_L, source current i_S, load current i_L.



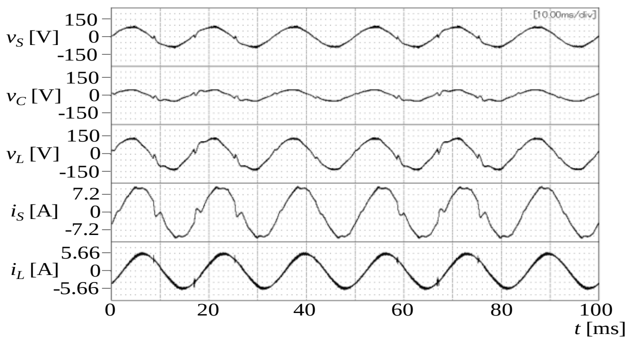
(a) Unity power factor



(b) Leading power factor 0.8

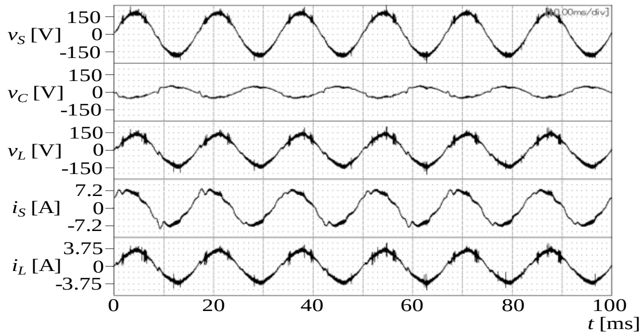


(c) Lagging power factor 0.8

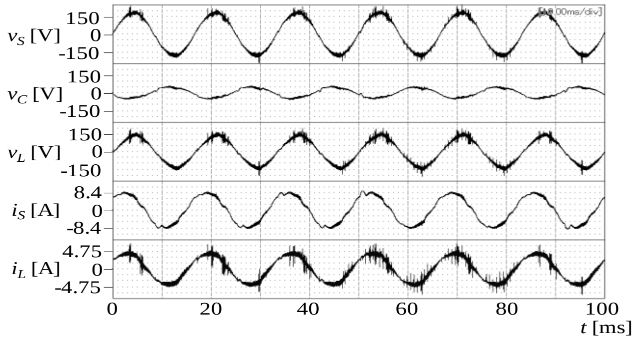


(d) Lagging power factor 0.6

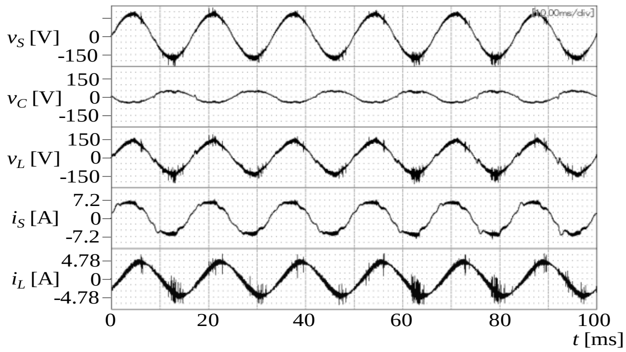
Fig. 8. Experimental waveforms of compensator for different power factor (40% voltage sag), source voltage v_S, compensating voltage v_C, load voltage v_L, source current i_S, load current i_L.



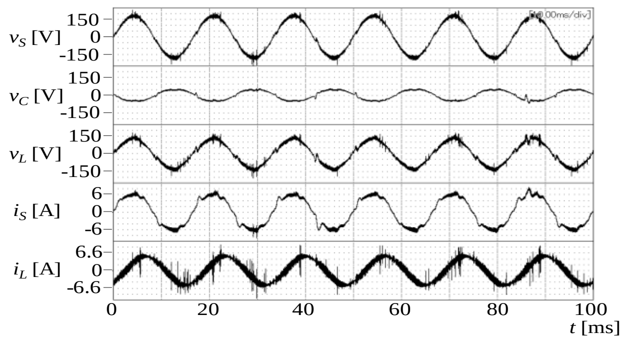
(a) Unity power factor



(b) Leading power factor 0.8



(c) Lagging power factor 0.8



(d) Lagging power factor 0.6

Fig. 9. Experimental waveforms of compensator for different power factor (30% voltage swell), source voltage v_S, compensating voltage v_C, load voltage v_L, source current i_S, load current i_L.

-The difference of pulsations between simulated and experimental results would be caused by the difference of the values of leakage inductances and line resistances.

From the results obtained above, more investigation for suppressing the pulsations will be needed to extend the compensating range for the loads. In addition, consideration of the leakage inductance in the voltage source is very important and the pulsations become larger for larger leakage inductance.

5. Conclusion

Compensating characteristics of a voltage sag/swell compensator utilizing single-phase matrix converter was investigated. First, system configuration and operation for both voltage sag and swell were described. To suppress pulsations of the source voltage, a countermeasure using LPF and APF was introduced. Compensating characteristics of the voltage sag/swell compensator were investigated for *R-L* load by simulation. Finally, the validity of the simulated results was confirmed by the experimental results.

From the results, we conclude as the following.

- The leakage inductance of autotransformer and voltage source causes the pulsations on the source voltage and compensation voltage.
- Proposed countermeasure of LPF and APF are effective for suppressing the pulsations of source voltage and compensation voltage.
- Simulated results agree well with the experimental results.
- More investigation for suppressing the pulsations will be needed to extend the compensating range for loads.

Acknowledgements

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