Improvement of Electric Power Quality Using a Small Flywheel with a Squirrel-cage Induction Motor

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Abstract - Flywheel energy storage systems are focused as uninterruptible power supplies (UPS) from the view point of a clean ecological energy storage system. This paper proposes applications using a small flywheel induction motor such as; 1) Voltage sag compensator using a capacitor self-excited induction generator without semiconductor converters. 2) UPS composed of a hybrid system of a flywheel and an engine generator. In this hybrid system, a flywheel largely improves the load response of an engine generator.

1. Introduction

With rapid progresses in automations of production lines, requirements of high quality power supplies have increased. Some factors of power disturbances are lightning strikes to the power lines and line-to-ground fault. Figure 1 shows one of the results of monitoring power disturbances for almost three years across the U.S. and Canada [1]. The nationwide monitoring system network consists of over 1300 large industrial plants. Figure 1 shows that over 90% of these power disturbances are short duration voltage sags within about 20 cycles (0.3 s). The situation of power disturbances is really the same as the one in Japan. In Japan, annual economic losses that caused by these short duration power disturbances is estimated to be 4 trillion Yen.

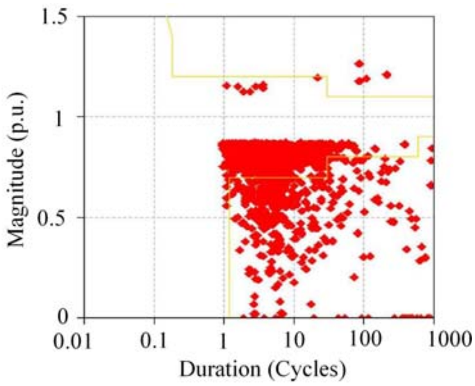

Figure 1 Voltage Sag Distribution
(1 cycle = 1/60 s)

In order to prevent these power disturbances, battery systems are generally used as electrical energy storage systems. Although this energy storage has many advantages, it also has problems such as very high construction and running cost, and disposing batteries will give bad effects on environment. On the other hand, a flywheel system is suitable as energy storage system because of its high durability, high-speed charge/discharge performance and lower running cost. But one of disadvantages of flywheel system is it needs semiconductor converters such as inverters and rectifiers. These converters are very expensive and generate higher harmonics.

2. Voltage Sag Compensator using Capacitor Self-excited Flywheel Induction Generator

In order to protect against voltage sags, this paper proposes one of the simplest flywheel devices that is called capacitor self-excited flywheel induction generator (SEIG[2]) without semiconductor converters. Figure 2 shows an external appearance of the flywheel induction motor and table 1 shows the specifications of the flywheel induction motor of this system. This system can be constituted at low cost and has high reliability because of quite easy fabrication (only a squirrel-cage induction motor, a flywheel, a capacitor, a reactor and AC switches are needed). And no higher harmonics are generated because semiconductor converters are not used.

2.1 System Configuration and Operation

Figure 3 shows the system configuration of voltage sag compensator. In a start-up mode, this flywheel induction motor is started up through a reactor of 0.75 in p.u. for current limitation. In an idling mode, SW1 and SW2 are kept turned on. AC system provides electric power to a specific load and the flywheel induction motor and idling losses of the flywheel

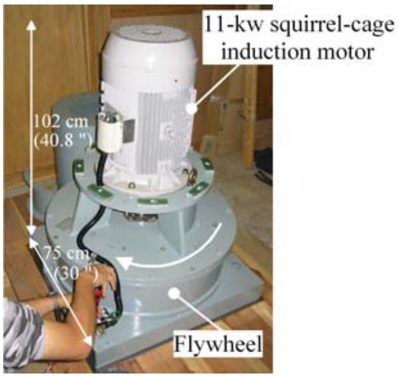

Figure 2 Photo of the Flywheel Induction Motor

Table 1 Specifications of the Flywheel Induction Motor

Stored energy	220 kJ at 1500 min^{-1}
Available energy	100 kJ (10kW,10s)
Rated voltage	200 V
Rated current	42.8 A
Pole	4
Flywheel diameter	64 cm
Total weight	745 kg
Flywheel weight	350 kg (Fe)
Inantia	17.9 kg m^2
Rated speed	1500 min^{-1}

induction motor is about 630 W. When voltage sag occurs, this system rapidly shifts to a protection mode. SW1 is immediately turned off. At the same time, the flywheel induction motor is used as the SEIG.. The SEIG with the flywheel discharges the stored energy to the specific load. During compensation of the SEIG, the specific load voltage and frequency can be maintained because of large inertia of the flywheel. After the AC system voltage recovers, this system shifts to a recovery mode. SW1 is turned on and at the same time SW2 is turned off in order to protect the AC system from rush current due to voltage phase difference between the SEIG and the AC system. After the rotating speed of the induction motor reached the rated speed, this system returns to the idling mode again.

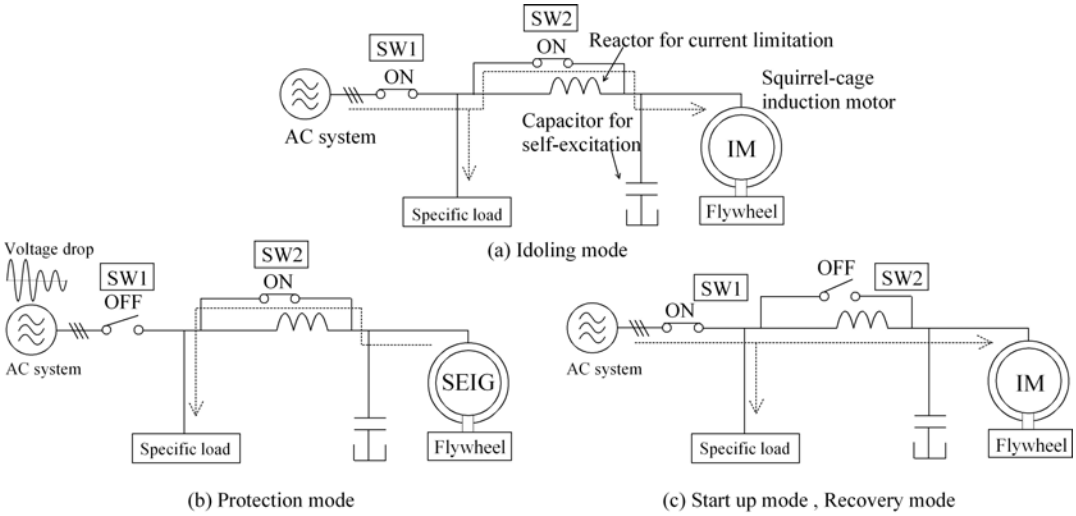

Figure 3 System Configurations for Voltage Sag Compensator

2.2 Load Voltage Characteristics of the SEIG

Under protection mode, the SEIG generates the output voltage resonating with the self-excited capacitor and magnetizing reactance of it. Therefore, the output voltage of the SEIG varies with the capacitance of capacitor. Of course, the output voltage also varies with the load capacity and rotating speed of the SEIG.. In order to protect against voltage sags, it is necessary to comprehend the output voltage characteristics with varying capacitance of capacitor and the load capacity. Thus, optimal capacitances of capacitor depending on the load capacity of the SEIG in 0.3 s after the load was shut out from the AC system are investigated.

Figure 4 shows the load voltage characteristics after 0.3 s when the AC system was shut out. This figure shows that the optimal capacitances exist in order to compensate the rated voltage, 200 V. Figure 5 shows the optimal relationship curve between the self-excited capacitor and the load capacity. From these results, in order to compensate 10 kW, 0.3 s, the capacitor of star-connected 830 μF is optimal.

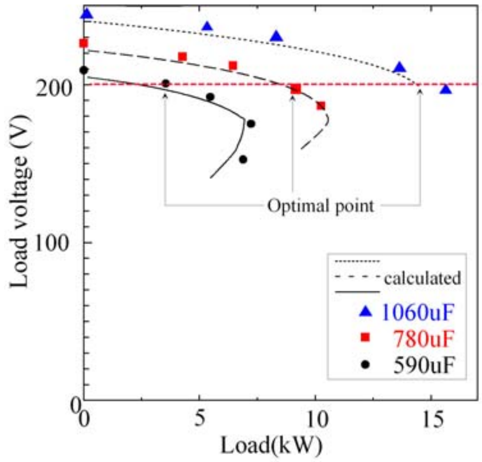

Figure 4 Load Voltage Characteristics of the SEIG

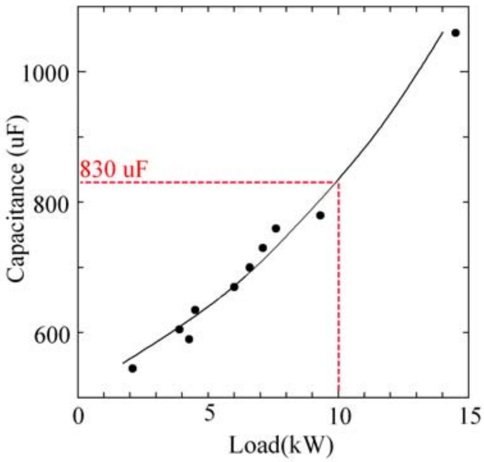

Figure 5 Optimal Relationship of the SEIG

2.3 Test Result of the Voltage Sag Compensator

Figure 6 shows one of typical experimental results of the voltage sag compensation. The experimental condition was optimal with the resistive load of 3.7 kW and the capacitance of capacitor for self-excitation of 545 μF. It shows that this system can compensate the voltage sag without any influence on the load. Higher harmonics can be reduced because no semiconductor converters were used.

Table 2 shows the comparisons of cost effectiveness between the proposed flywheel system shown in Fig. 7 and a typical battery system. The manufacturing cost of this flywheel system is about 1/3 of the battery system. The life time of this flywheel system is about 4 times (or more) longer than that of the battery system. Consequently, this flywheel induction motor system realizes a more economical voltage sag compensator.

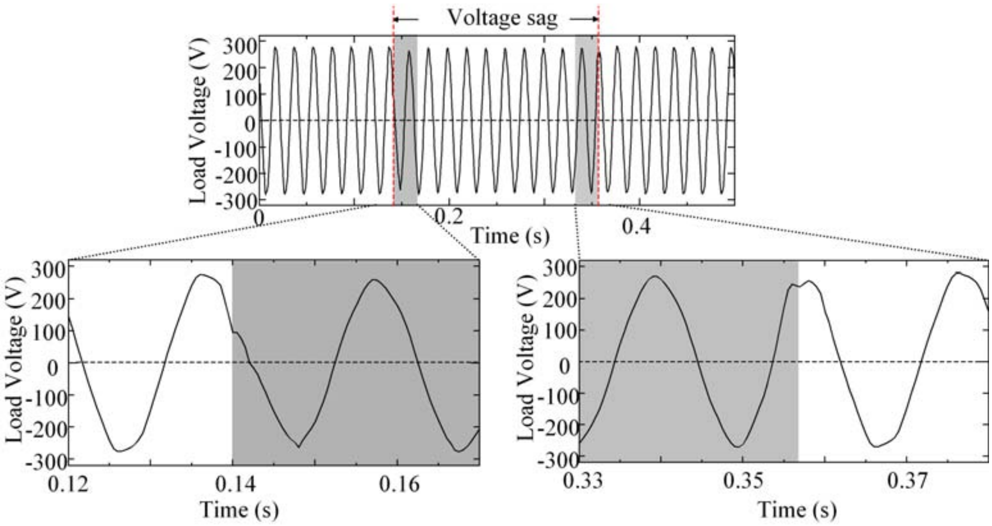

Figure 6 Experimental Result of Load Voltage Waveforms during Voltage Sag Compensation¥

Table 2 Comparisons of Two Voltage Sag compensators

	Battery system	Proposal system
Capital cost	$ 330,000	$ 108,000
Life time	7 year	20 year or more
Annual electricity cost	$ 3,000	$ 660
Volume	1	1/3

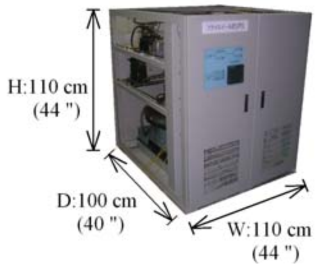

Figure 7 Prototype of Voltage Sag Compensator

3. Hybrid UPS

In this chapter, a hybrid UPS system that is composed of the SEIG with a flywheel and an engine generator (EG) is proposed. This system realizes effective and economical protections of voltage sag and blackout without any battery. Furthermore, the flywheel largely improves the load response against load fluctuations.

3.1 Hybrid UPS System Configuration

A system configuration of the hybrid UPS is shown in Fig.8. This system is composed of the SEIG with flywheel and an EG. The SEIG with flywheel compensates for short time and an EG compensates for long time. Figure 9 also shows a timing chart of this hybrid UPS system.

When the voltage drop occurs, SW 1 is immediately turned off. Then the flywheel discharges the storage energy to the specific load. The EG is started up unless the AC system recovers. Until the EG carried out stable operation, if the load voltage drops under the required voltage, SW 2 for additional connection of self-excited capacitor is turned on in order to regulate the load voltage. After the start-up operation of the EG is completed, SW 3 is turned on by synchronous switching. One of the key points of this system is that the output frequency of the SEIG decreases gradually during short time compensation. However, some of the electronic devices are not affected by a little fluctuation of line frequency because AC/DC converters are installed in them.

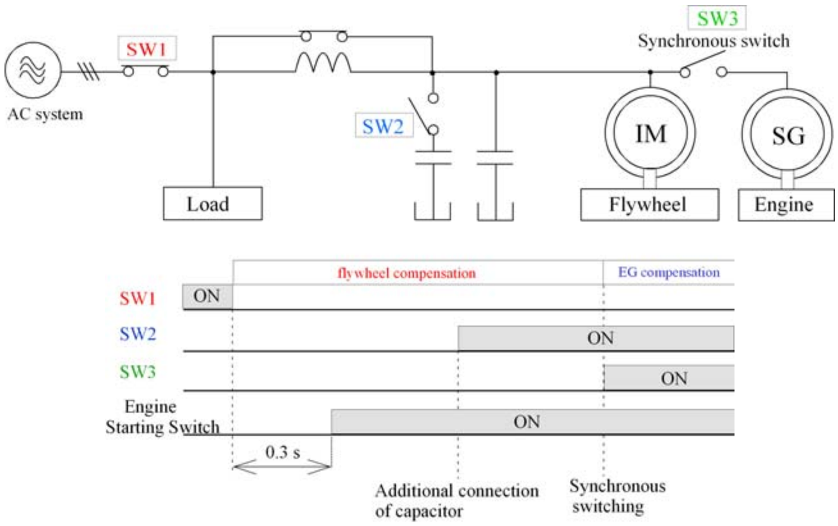

Figure 8 System Configuration and Operation of the Proposal Hybrid UPS System

3.2 Start Characteristics of an Engine Generator

To determine the period of short time compensation with the flywheel energy storage, there is a necessary to comprehend start characteristics of an EG. Therefore start-up time until stable operation of the EG are measured. The specifications of EG were 3 phase, 5 kVA, 200 V. Figure 9 shows one of typical results of start-up tests, and it can be confirmed that the EG does the stable operation within 2.5 s. Thus the short time compensation with the flywheel is assumed to be about 2.8 s (2.5 s+0.3 s).

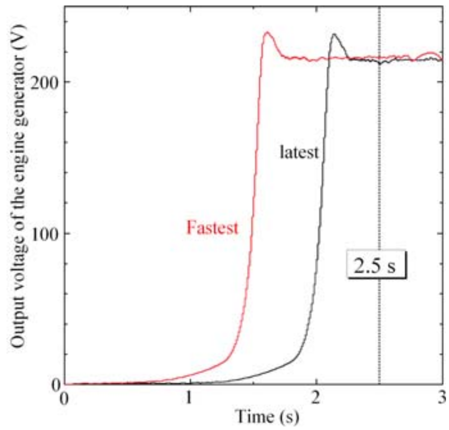

Figure 9 Start-up Characteristics of the Engine Generator

3.3 Experimental Result of Load Voltage Regulation

It is necessary to extend the compensation time with the flywheel from 0.3 s to 2.8 s. In order to extend the compensation time with the flywheel, one of the simplest methods of the load voltage regulation that is additional connection of other self-excited capacitor is adopted. Figure 10 shows the experimental result of load voltage regulation. This experimental condition of the resistive load was 5 kW. At the beginning of compensation with the flywheel, the capacitance of capacitor was 750 μF. The load voltage decreases gradually due to the reduction of rotating speed. At 2.2 s, to regulate the load voltage, an additional 100 μF is connected when the instantaneous value of load voltage crosses zero point and the total capacitance becomes 850 μF. From these experimental results of the load voltage regulation, it is confirmed that the load voltage is compensated within the range between lower limit of 200 V and higher limit of 210 V. Thus, it enables us to compensate the voltage sag for several seconds by connecting additional self-excited capacitor.

3.4 Demonstration of the Hybrid UPS

Figure 11 shows one of typical experimental results of the hybrid UPS operation. This experimental condition of the resistive load was 3.2 kW. At the beginning of compensation, the load voltage reaches higher limit 210 V. After the start-up operation of the EG has been completed, the EG was connected to the SEIG by synchronous switching at 2.8 s. At the same time, the EG provided power to the flywheel induction motor and the load. It is confirmed that the hybrid

UPS system can replace a conventional battery UPS.

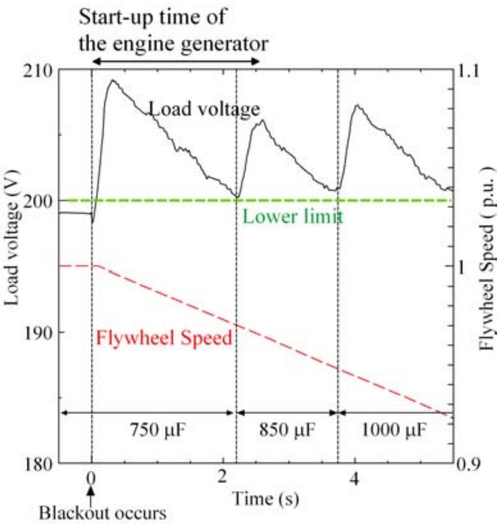

Figure 10 Experimental Result of Load Voltage Regulation

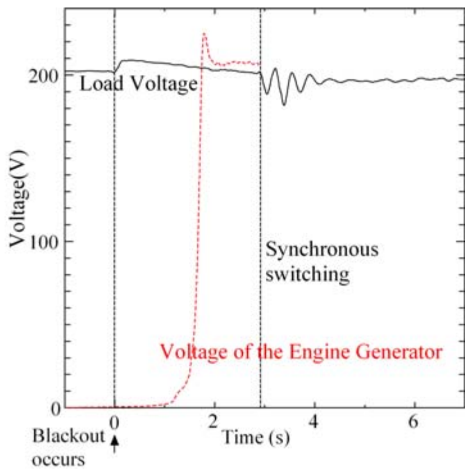

Figure 11 Demonstration of Hybrid UPS Operation

3.5 Improvement of the Load Response of an Engine Generator

In general, an EG is unstable against steep load fluctuations. However, this hybrid UPS system has an advantage of improved load response.

Figure 12 shows the experimental circuit for improvement of the load response by the flywheel effect. The load fluctuations are demonstrated by turning on and off the load switch. The experimental conditions of resistive load fluctuations were 4.5 kW, square wave of 0.5 Hz. Figure 13 shows one of typical experimental results of the load response. Without the flywheel, the rotating speed and output voltage of the EG largely fluctuate in synchronization with the load fluctuation period although the EG has an auto voltage regulator (AVR). On the other hand, with the flywheel, both of them don’t change much. It is confirmed that the flywheel induction motor levels the rotating speed and output voltage of the EG against the load fluctuations without any governor control.

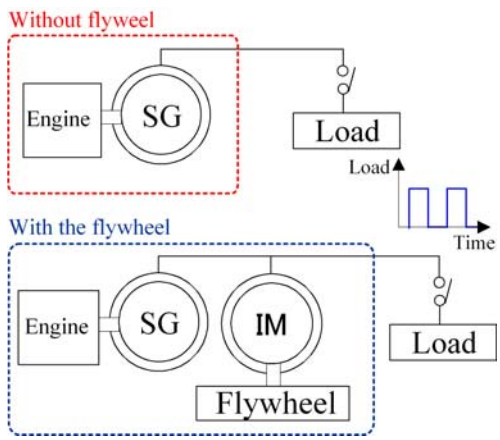

Figure 12 Experimental Circuits of the Load Response

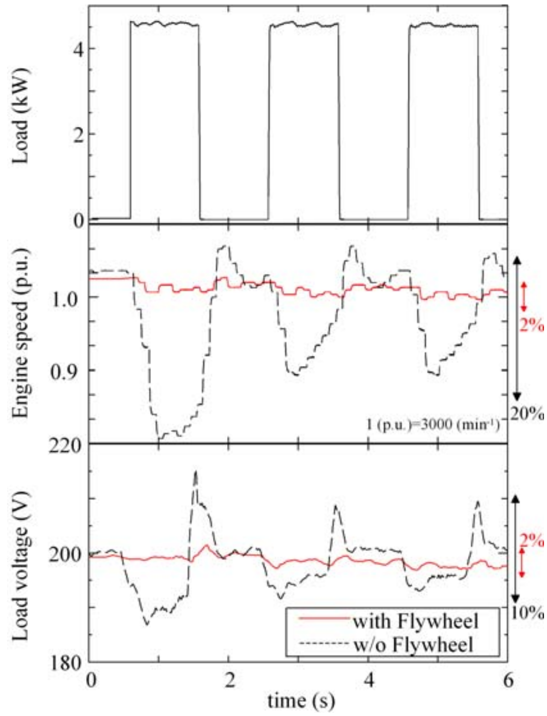

Figure 13 Experimental Results of the Load Response

4. Summary

This paper proposed applications of a flywheel energy storage system using a squirrel-cage induction motor as follow;

(1) A very simple voltage sag compensator with a SEIG and a flywheel is developed. The manufacturing cost of this flywheel system is about 1/3 of a conventional battery system. The lifetime of this flywheel system is about 4 times (or more) longer than that of battery system. This flywheel system realizes a more economical voltage sag compensator.

(2) A hybrid UPS system that is composed of a SEIG with a flywheel and an EG is proposed. This hybrid UPS is more appropriate than a conventional battery UPS if the specific load can allow short time frequency fluctuations. In addition, this hybrid UPS system has an advantage of improved load response (fluctuations of rotating speed and load voltage at levels of lower than 2%) of the EG without any governor control.

References

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