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Loss Reduction for Matrix Converter with Hybrid Six-step Operation in Flywheel Energy Storage System

Jun-ichi Itoh, Takumi Masuda
Nagaoka University of Technology
Nagaoka, Niigata, Japan
itoh@vos.nagaokaut.ac.jp

***Abstract*— This paper presents a hybrid six-step operation which utilizes both a pulse width modulation (PWM) operation and a six-step operation for a matrix converter. In the hybrid six-step operation, the control of the matrix converter is divided into a current source rectifier (CSR) control and a voltage source inverter (VSI) control. In particular, the CSR is implemented by the PWM operation and the VSI is controlled by the six-step operation. Consequently, the switching loss of the VSI with the six-step operation is reduced in compared with the PWM operation, because the switching of the VSI are only six times of the fundamental frequency. In addition, the input current total harmonic distortion (THD) is improved as compared with the six-step operation because the CSR is employed with the PWM operation. The experimental results, the converter loss of the hybrid six-step operation is reduced by 30.7% compared with the PWM operation in exchange for the increase of the input current THD by 3.71% compared with the PWM operation. Moreover, the efficiency of the charge and discharge with the hybrid six-step operation is improved by 1.80% compared with the PWM operation.**

I. Introduction

In recent years, renewable energy systems have been attracted many attentions [1]-[3]. In these systems, a power fluctuation occurs due to meteorological conditions. Therefore, renewable energy systems require energy storage components, e.g. EDLC , chemical battery or flywheels.

Table I depicts the characteristics of each energy storage device. EDLCs have a high charge and discharge efficiency. Moreover, the rapid charge and discharge are possible because the internal resistance is very small. However, similar to the battery, the lifetime decreases rapidly due to the influence of the ambient temperature [4]. On the other hand, batteries can achieve a high energy density at low cost. However, one of the problems in the battery energy storage is a short life time. In particular, the lifetime depends on the ambient and the number of charge and discharge time. In addition, the batteries cannot cope with rapid charge and discharge due to a large internal resistance. Therefore, energy storage systems using batteries require periodical maintenance due to short lifetime of the batteries. Compared with other methods to store electricity, flywheel energy storage systems (FESS) have long lifetime (lasting decades with little or no maintenance), and the charge and discharge characteristic of the flywheel does not depend on the temperature. In addition, a FESS can charge and discharge large electrical power from the renewable energy systems at a relatively short period. Therefore, the FESS can achieve a power leveling with high response to large power ripple [5].

TABLE I
CHARACTERISTICS OF ENERGY STORAGES

	Flywheel	EDLC	Battery
Energy storage	Kinetic energy	Ion transfer	Chemical reaction
Charge & Discharge of short period	Fast	Fast	Slow
Temperature characteristic	Excellent	Limited by temperature	Limited by temperature
Energy density	Good	Good	Excellent

Meanwhile, a matrix converter has attracted many attentions as a power converter to control the FESS due to its many desirable features. The matrix converter can achieve high efficiency, small size and long lifetime compared to Back-To-Back (BTB) system which consists of a PWM rectifier and inverter. Therefore, the power leveling system that combines the matrix converter and FESS can be operated with little or no maintenance [6]-[7].

Besides, the FESS is frequently used in the high flywheel rotational speed because the performance of the high flywheel rotational speed is better than the low flywheel rotational speed in the charge and discharge mode. However, the output voltage is limited by the input voltage during the high flywheel rotational speed. For this reason, a field-weakening control is applied during for the high flywheel rotational speed. However, the efficiency of the matrix converter employing the field-weakening control is decreased. In six-step operation, the high output voltage can be achieved compared with the PWM operation. In addition the switching loss is drastically reduced because the switching times is drastically decreased. However, the input current THD increases due to the 120 deg. conduction mode. Furthermore, the filter loss also increases due to the distortion of the input current.

In this paper, the hybrid six-step operation for the matrix converter is proposed to reduce the converter loss wish the FESS. In order to control the matrix converter, the control strategy is based on the virtual AC-DC-AC conversion strategy, where the matrix converter is separated into a CSR and a VSI as an indirect matrix converter [8]. In the hybrid six-step operation, the control system is separated into the CSR control and the VSI control, where the CSR is operated by PWM and the VSI is modulated by the six-step operation. The converter loss of the matrix converter applied with the hybrid six-step operation is reduced in compared with the PWM operation because the switching frequency of the six-step operation is only six times of the output frequency. Meanwhile, the input current THD does not drastically increased, because the input current THD is reduced by the PWM operation of the CSR. The hybrid six-step operation is confirmed by the experiment. In addition, the efficiency and the input current THD of the hybrid six-step operation are compared to that of the PWM operation.

II. System Configuration

A. Circuit Configuration

Fig. 1 shows a circuit diagram of the FESS employed with the matrix converter. The FESS consists of the matrix converter [9], the flywheel, the input filter and the snubber circuit. The FESS compensates the power ripple caused by the renewable energy systems in order to smooth the grid power. In the charge and discharge mode of the FESS, the FESS is frequently used in the high flywheel rotational speed because the performance of the high flywheel rotational speed is better than the low flywheel rotational speed. In terms of the matrix converter, the high output voltage can be achieve high performance of the FESS. On the other hand, the matrix converter is operated as the same condition in the standby mode of the FESS. The standby mode occurs the converter loss in which the switching loss is predominant in the mode. However, a PWM control which can regulate the input current as a sine wave introduces the large switching loss. Therefore, the matrix converter operation of a low switching loss is necessary in terms of a high efficiency. In addition, it is necessary to reduce the input filter loss which is increased by the input current distortion.

B. Flywheel Configuration

Fig. 2 shows the photograph of the prototype of FESS. In the FESS, the induction motor (IM) is operated as a generator during acceleration, where the electrical energy is stored as the kinetic energy. On the other hand, during deceleration; the kinetic energy is converted into the electrical energy. Therefore, this system employs a matrix converter. In Fig. 2, it can be observed that the shape of the flywheel is disk-shaped. The stored energy E is calculated by (1) from the rotational angular velocity ω and the moment of the inertia of the flywheel J.

$$E = \frac{1}{2} J \omega^2 \tag{1}$$

Therefore, the flywheel can store the large kinetic energy when the region is the large rotational angular velocity ω of the flywheel. In terms of the energy storage system for the renewable energy systems in order to smooth the grid power, the performance of the high flywheel rotational speed is better than the low flywheel rotational speed. The flywheel is capable of storing energy up to 3 MJ in the prototype to evaluate the fundamental operation. In addition, the pressure in the vacuum

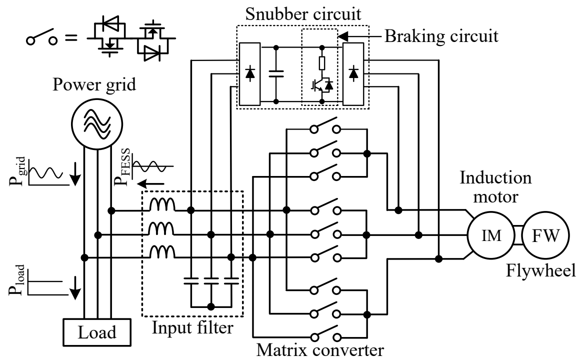


Fig. 1. FESS with matrix converter as power converter. The FESS consists of the matrix converter, the flywheel, the input filter and the snubber circuit.

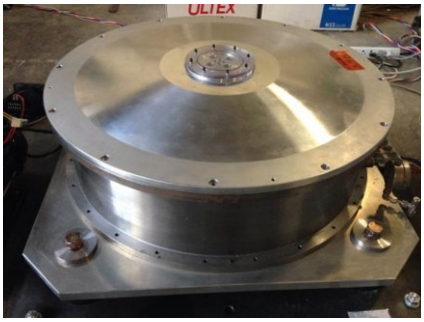


Fig. 2. Photograph of prototype FESS.

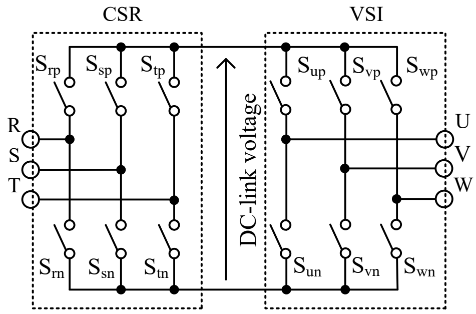


Fig. 3. Circuit diagram of indirect matrix converter. The matrix converter separates the CSR and the VSI by the virtual AC-DC-AC conversion strategy.

case is reduced by using the vacuum pump in order to further reduce the windage loss because the machine loss of the flywheel containing the windage loss decreases the efficiency of the FESS. During the acceleration and deceleration, the performance of energy storage system is evaluated by (2) from the total charge energy of the flywheel P_{IN} and the total discharge energy of the flywheel P_{OUT}. However, the total charge energy of the flywheel P_{IN} includes the flywheel loss of the iron loss and the copper loss.

$$\eta_{FW} = \frac{P_{OUT}}{P_{IN}} \tag{2}$$

III. CONTROL STRATEGY

A. Virtual AC-DC-AC Conversion

The control strategy of the direct matrix converter is complicated. In order to control the matrix converter simply, the control strategy is based on the virtual AC-DC-AC conversion strategy, where the matrix converter is separated into a CSR and a VSI as an indirect matrix converter [8]. Equation (3) expresses the relationship between the input voltage ${}^t[v_r\ v_s\ v_t]$ and the output voltage ${}^t[v_u\ v_v\ v_w]$ in the matrix converter.

$$\begin{bmatrix} v_u \\ v_v \\ v_w \end{bmatrix} = \begin{bmatrix} s_{ru} & s_{su} & s_{tu} \\ s_{rv} & s_{sv} & s_{tv} \\ s_{rw} & s_{sw} & s_{tw} \end{bmatrix} \begin{bmatrix} v_r \\ v_s \\ v_t \end{bmatrix} \tag{3},$$

where s_{mn} is a switching function of the switch S_{mn}. s_{mn} is 1 when S_{mn} is turned on, and s_{mn} is zero when S_{mn} is turned off.

Fig. 3 shows a circuit diagram of the indirect matrix converter applied the virtual AC-DC-AC conversion. The virtual AC-DC-AC conversion replaces the matrix converter by the combination of CSR and VSI as shown in Fig. 3 in order to obtain the designated switching pulse commands. In the indirect matrix converter, the relationship between the input voltage ${}^t[v_r\ v_s\ v_t]$ and the output voltage ${}^t[v_u\ v_v\ v_w]$ is represented by (4).

$$\begin{bmatrix} v_u \\ v_v \\ v_w \end{bmatrix} = \begin{bmatrix} s_{up} & s_{un} \\ s_{vp} & s_{vn} \\ s_{wp} & s_{wn} \end{bmatrix} \begin{bmatrix} s_{rp} & s_{sp} & s_{tp} \\ s_{rn} & s_{sn} & s_{tn} \end{bmatrix} \begin{bmatrix} v_r \\ v_s \\ v_t \end{bmatrix} \tag{4}$$

The relationship between the output voltage and the input voltage is determined solely by (4). In order to match the input and the output terminals of the indirect matrix converter assuming that the filter effect in Fig. 1 is excluded, (5) should be satisfied.

$$\begin{bmatrix} s_{ru} & s_{su} & s_{tu} \\ s_{rv} & s_{sv} & s_{tv} \\ s_{rw} & s_{sw} & s_{tw} \end{bmatrix} = \begin{bmatrix} s_{up} & s_{un} \\ s_{vp} & s_{vn} \\ s_{wp} & s_{wn} \end{bmatrix} \begin{bmatrix} s_{rp} & s_{sp} & s_{tp} \\ s_{rn} & s_{sn} & s_{tn} \end{bmatrix} \tag{5}$$

Fig. 4 shows a switching pulse generator based on the virtual AC-DC-AC conversion. The method of the switching pulse generator is represented by (5). Thus, this method clearly separates the input current control and the output voltage control.

B. Hybrid Six-step Operation

Table II shows the characteristics of the PWM operation, the six-step operation and the hybrid six-step operation. When the matrix converter is implemented with the PWM operation, all the switches of the CSR and the VSI are switched at high frequency. Consequently, a large switching loss occurs and decreases the efficiency of the energy storage system. In order to reduce the switching loss of the matrix converter, the six-step operation has been proposed. In the six-step operation, the switching of the CSR is synchronized with the three-phase input voltage, i.e. the 120 degree conduction, whereas the switching of the VSI is carried out at each 180 degree. This operation greatly reduces the switching loss in the trade of the high distortion of the input current. Therefore, a large input filter is required with the six-step operation. In order to reduce the switching loss without increasing the input filter loss, a hybrid six-step operation has been proposed. In the hybrid six-

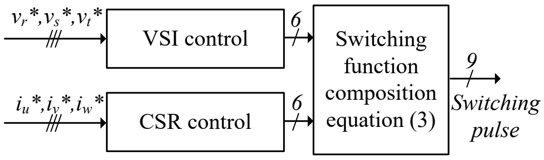


Fig. 4. Block diagram of switching pulse generator. The switching pulses are generated by the virtual CSR and the virtual VSI controls.

TABLE II
CHARACTERISTICS OF MATRIX CONVERTER CONTROL STRATEGIES

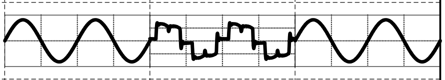
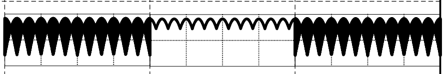
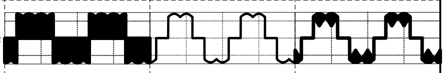
	PWM operation	Six-step operation	Hybrid six-step operation
Input current			
CSR	PWM conduction	120 deg. conduction	PWM conduction
DC-link voltage			
VSI	PWM conduction	180 deg. conduction	180 deg. conduction
Output voltage			
Switching loss	Large	Small	Nearly small
Input filter loss	Small	Large	Nearly small

TABLE III
EXPERIMENTAL CONDITIONS

Parameter		Value
Main circuit parameter	Switching device	SiC-MOSFET
	Rated power	10 kW
	Grid line voltage	200 V
	Input filter L	2.2 mH
	Input filter C	6.6 μF
	Carrier frequency	25 kHz
Flywheel parameter	Rated votage	200 V
	Rated current	44 Arms
	Rated power	11 kW
	Rated speed	5500 rpm
	IM Poles	4
	Rated enegry	3 MJ
	Vacuum	10,000 Pa

step operation as shown in Table II, the CSR is controlled by the PWM operation, whereas the VSI is operated with 180 deg. conduction mode. As a result, the switching loss is reduced as compared with the PWM operation, whereas the input current THD is improved as compared with the six-step operation. Thus, the input filter loss is reduced compared with the six-step operation.

IV. Experiment Results

In this section, the hybrid six-step operation with the prototype FESS of Fig. 1 is evaluated by the characteristics of the charge and the discharge, the converter loss and the input current THD.

Table III shows the experimental conditions. The characteristics of the charge and the discharge, the converter loss and the input current THD of the hybrid six-step operation is verified experimentally compared with the PWM operation at the same input voltage and flywheel rotational speed.

A. Field-weakening Region

Fig. 5 shows the V / f control of the voltage with the flywheel rotational speed. The V / f control includes the field-weakening control region from 3000 r / min to 5500 r / min because the rated voltage of IM stator with the flywheel is 400 V and the rated frequency of IM stator with the flywheel is 200Hz. Therefore, the matrix converter can not obtain the rated output voltage at 3000 r / min or more in FESS using 200 V grid. It is necessary for the FESS to use the field-weakening control of the PWM operation at 3000 r / min or more. On the othe hand, the hybrid six-step operation can achieve the higher output voltage compared with the PWM operation in the same field-weakening region.

B. Characteristics of Charge and Discharge

Fig. 6 shows the operation waveforms when both the CSR and the VSI are applied with the PWM operation. A sinusoidal output current is obtained with the input current THD of 9.92%. In addition, the converter efficiency is 94.5% at 6.7 kW.

Fig. 7 shows the operation waveforms when the matrix converter is applied with the hybrid six-step operation. The output voltage includes the switching ripple component around the peak of the output voltage. The output voltage nearly becomes the square waveform due to the 180 degree conduction mode of the , whereas the input current THD is 14.8% and the converter efficiency is 95.5% at 6.7 kW. Therefore, the converter loss is reduced by 18.2% owing to the hybrid six-step operation in compared with the PWM operation. On the other hand, the input current THD is increased by 4.88% at 6.7 kW.

Fig. 8 shows the characteristic of the charge when the matrix converter is applied with the PWM operation and the hybrid six-step operation. The characteristic of the charge is obtained when the flywheel rotational speed is changed from 3500 to 5500 r / min with the acceleration time is 400 s. The total charge energy of the charge with the PWM operaion and with the hybrid six-step operaion are 1.52 MJ and 1.50 MJ, respectively. Therefore, the charge power of the charge mode with the hybrid six-step operaion is reduced by 1.07% compared to the PWM operation with the same acceleration time.

Fig. 9 shows the characteristic of the discharge when the matrix converter is applied with the PWM operation and the hybrid six-step operation. The characteristic of the discharge is

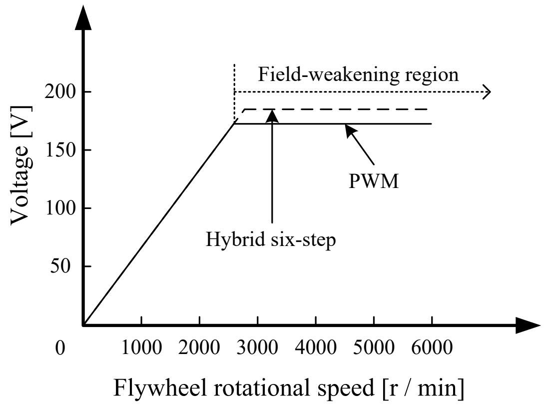


Fig. 5. V / f control of voltage and flywheel rotational speed. The V / f control includes the field-weakening control region from 3000 r / min to 5500 r / min

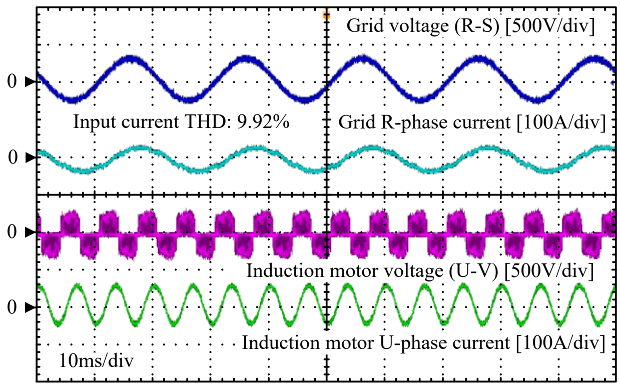


Fig. 6. Operation waveforms of PWM operation. The input current THD is 9.92%. The output power is 6.7 kW. The flywheel rotational speed is 4500 r / min.

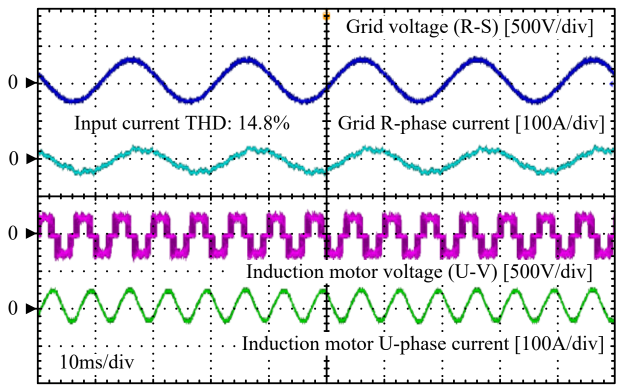


Fig. 7. Operation waveforms of hybrid six-step operation. The input current THD is 14.8%. The output power is 6.7 kW. The flywheel rotational speed of the flywheel is 4500 r / min.

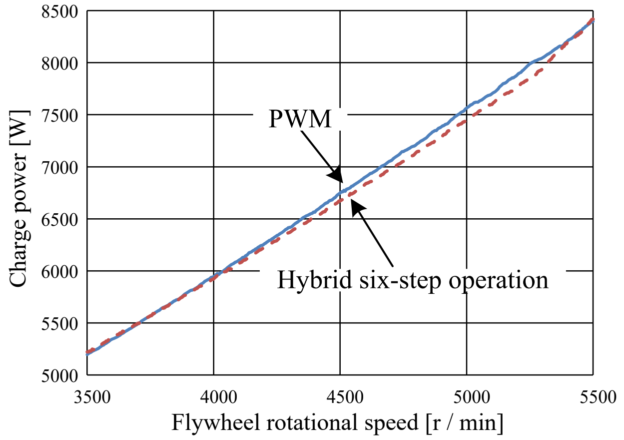


Fig. 8. Characteristic of charge mode. The characteristic of the charge mode is obtained when the flywheel rotational speed is changed from 3500 to 5500 r / min with the acceleration time is 400 s.

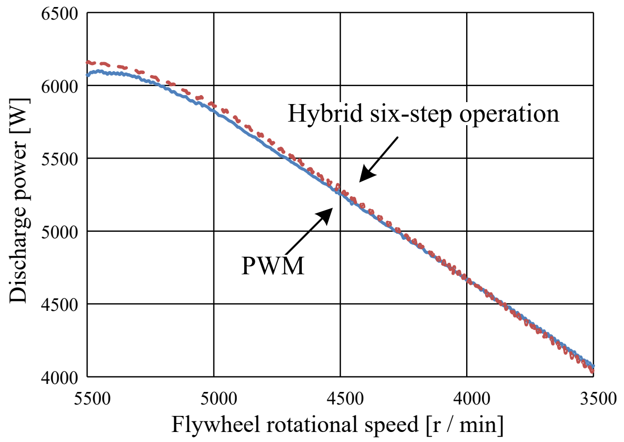


Fig. 9. Characteristic of discharge mode. The characteristic of the discharge mode is obtained when the flywheel rotational speed is changed from 5500 to 3500 r / min with the deceleration time is 400 s.

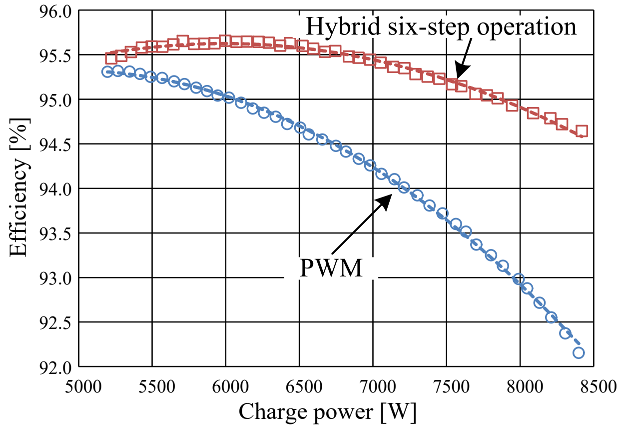


Fig. 10. Efficiency characteristic of charge mode. The characteristic of the charge mode is obtained when the flywheel rotational speed is changed from 3500 to 5500 r / min with the acceleration time is 400 s.

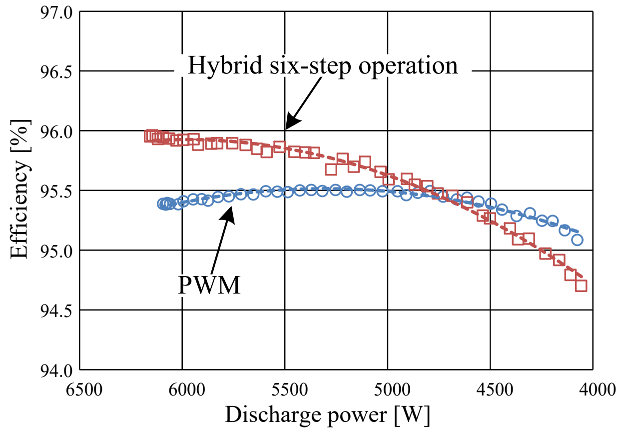


Fig. 11. Efficiency characteristic of discharge mode. The characteristic of the discharge mode is obtained when the flywheel rotational speed is changed from 5500 to 3500 r / min with the deceleration time is 400 s.

obtained when the flywheel rotational speed is changed from 5500 to 3500 r / min with the deceleration time is 400 s. The total discharge energy of the discharge with the PWM operaion and with the hybrid six-step operaion are 1.16 MJ and 1.17 MJ, respectively. Therefore, the discharge power of the discharge mode with the hybrid six-step operaion is improved by 0.741% compared to the PWM operation with the same deceleration time. In addition, the efficiency of the charge and discharge with the PWM operaion and with the hybrid six-step operaion are 76.4% and 77.8%, respectively. Therefore, the charge and discharge with the hybrid six-step operaion is improved by 1.80% compared to the PWM operation with the same acceleration and deceleration time. Thus, the hybrid six-step operation achieves higher efficiency than the PWM operation.

C. Converter Loss

Fig. 10 shows the characteristics of the converter efficiency against the output power. The output power are varied from 5.2 kW to 8.4 kW. The converter efficiency of the hybrid six-step operation is improved by 2.60% compared to the PWM operation at 8.4 kW. Therefore, the converter loss of hybrid six-step operation is reduced by 30.7% compared to the PWM operation. Besides, the average efficiency of the PWM over entire load range is above 94.3%. In addition, the maximum efficiency of the PWM is 95.3%. On the othe hand, the average efficiency of the hybrid six-step operation over entire load range is above 95.4%. In addition, the maximum efficiency of the hybrid six-step operation is 95.7%. Therefore, the hybrid six-step operation improves the the characteristic of the charge mode with the FESS.

Fig. 11 shows the characteristics of the converter efficiency against the output power. The output power are varied from 4.2 kW to 6.2 kW. The converter efficiency of the hybrid six-step operation is improved by 0.629% compared to the PWM operation at 6.1 kW. Therefore, the converter loss of hybrid six-step operation is reduced by 13.0% compared to the PWM operation. Besides, the average efficiency of the hybrid six-step operation over entire load range is above 95.6%. In addition, the maximum efficiency of the hybrid six-step operation is 96.0%. Therefore, the hybrid six-step operation improves the characteristic of the discharge mode with the FESS. Therefore, the hybrid six-step operation improves the

the characteristic of the discharge mode with the FESS. In terms of the energy storege system, the high efficiency of the charge and discharge improves the performance of the FESS.

Fig. 12 shows the efficiency of the standby mode. In Fig. 12, the standby loss is measured from 3000 to 5500 r / min. As a result, the standby loss of the hybrid six-step operation is increased by 9.45% compared with the PWM operation at 4500 r / min. In future work, it is necessary to evaluate the IM loss of the iron loss and the copper loss during standby mode, will be shown.

D. *Input Current THD*

Fig. 13 shows the characteristic of the input current THD when the flywheel rotational speed is changed from 3500 to 5500 r / min with the acceleration time is 400 s. The input current THD of the hybrid six-step operation increase to 3.71% compared to the PWM operation at 8.4 kW. Thus, the converter loss of the hybrid six-step operation is reduced by 30.7% in exchange for the increase of the input current THD by 3.71% compared with the PWM operation at 8.4 kW.

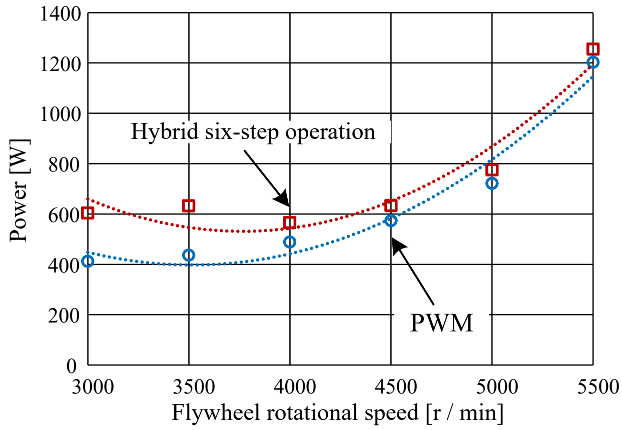


Fig. 12. Characteristic of standby mode. The characteristic shows the standby loss from 3000 to 5500 r / min

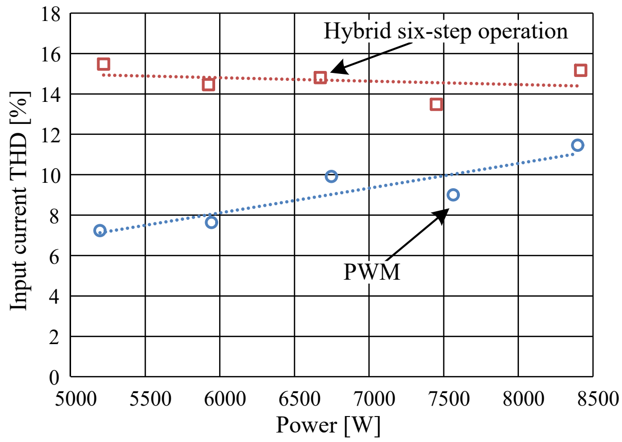


Fig. 13. Characteristic of input current THD.

V. Conclusion

This paper clarified the improvement effect of the hybrid six-step operation with the FESS. The hybrid six-step operation achieved the improvement of the output voltage and the reduction of the switching loss. In addition, the hybrid six-step operation reduced the converter loss with the FESS. In particular, the converter loss of the hybrid six-step operation is reduced by 30.7% in exchange for the increase of the input current THD by 3.71% compared with the PWM operation at 8.4 kW. However, the FESS is frequently used in the high flywheel rotational speed because The performance of the high flywheel rotational speed is better than the low flywheel rotational speed. In addition, the charge and discharge with the hybrid six-step operation was improved by 1.80% compared with the PWM operation in same acceleration and deceleration time. Besides, in terms of the energy storage system, the hybrid sixstep operation improved the performance of the FESS.

In future work, the performance of hybrid six-step operation with at lght load, will be shown.

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