 itation information: DOI 10.1109/TASC.2018.2806914, IEEE

Combination of Flywheel Energy Storage System and Boosting Modular Multilevel Cascade Converter

Masamichi Murayama†, Shuhei Kato††, Hiroaki Tsutsui†, Shunji Tsuji-Iio† and Ryuichi Shimada†

***Abstract*—This paper deals with a pulsed power supply system combining flywheel energy storage system (FESS) and a modular multilevel cascade converter (MMCC) for power compensation in performing rapid excitation of highly inductive and pulsed heavy loads. The FESS system consists of an induction motor with a flywheel to store kinetic energy. Parallelly connected capacitors cause self-excitation phenomena in an induction motor, and it works as an induction generator. Furthermore, the induction generator generates more than twice of electric power of its rated value for a short time. We can apply the proposed FESS to particle accelerators for physics experiments or medical use, and plasma shape and position control in pulsed nuclear fusion devices that require pulsed high-power. In addition, the coils in these applications that generate magnetic fields have large inductances. In plasma control and repetitive operation applications, it is necessary to change current rapidly. We can realize high-speed current control by using the proposed MMCC which can output a voltage higher than the input voltage. By combining the FESS and MMCC, a power supply may be realized with the ability to implement rapid current control while compensating for large power consumption and without significant load disturbance on the power grid.**

***Index Terms*—modular multilevel cascade converter, flywheel energy storage, induction generator, accelerator, tokamak**

I. Introduction

High current pulsed power demands on the electrical power grid has the potential to cause significant disturbances to the grid itself and also to surrounding facilities. In particular, inductive loads demand high reactive power not normally supplied by the power grid. A repetitive, large demand in reactive power may lead to instability in power quality and cascade further resulting in voltage sags or even local power interruptions. When these problems occur, some energy storage is often used such as capacitors, flywheels or a superconducting energy storage system.

Accelerators and tokamak devices have many large coils. For example, Main Ring of J-PARC has 96 bending magnets and 216 quadrupoles [1]. In tokamak devices, there are many coils to control shape and plasma position or to induce the plasma current. Normal conducting electromagnetic coils in such devices constitute a large inductive load and pose a significant demand on the electric power grid.

JT-60, a large tokamak device, needs more than 1000 MW to excite toroidal and poloidal field coils. Even for small tokamaks, the peak power consumption reaches 1 MW. Some of these electromagnet coils require rapid control as is the case when performing frequent experiments in particle accelerators and controling plasma position and shape in tokamak devices. In these cases, pulsed power regeneration from the coils toward the power supply occurs during a decrease in coil currents. To reduce the regenerative power flow, KEK developed a neutral point clamp multilevel converter using power absorbing capacitors on coil excitation converters [2]–[5]. CERN is planning to update the present power supply system into a system using power absorbing capacitors [6].

In this paper, we deal with the combination of a flywheel energy storage system (FESS) and a H-bridge modular multilevel cascade converter (MMCC) with magnet energy absorbing capacitors. The FESS uses an induction generator and stores energy with a rotating iron wheel. It realizes a compact and robust power supply system to withstand repetitive and momentary overloaded operation. Combining MMCC with floating and magnet energy absorbing capacitors, the power supply can boost operation voltage beyond the FESS terminal voltage. Finally, we have demonstrated the effectiveness of the combined FESS and MMCC power supply via experimental measurements. In this experiment, an electric power rating greater than twice the induction motor's rated power output was obtained while maintaining the capacitor voltages with operation of the MMCC.

II. Pulsed Magnet Power Supply by Self-excited Induction Generator with Flywheel

A flywheel energy storage system (FESS) is often used as a pulsed magnet power supply to suppress a disturbance to the electric power grid. That is because the peak power sometimes goes up to several hundreds of megawatts. For magnet power supply, synchronous generators are often used to convert kinetic energy stored in the flywheel to electric energy. For example, all of the three flywheels of JT-60 are equipped with synchronous generators for its toroidal field coils, poloidal field coils, and other heating devices. However, synchronous generators are expensive and large because they require excitation windings and slip rings or permanent magnets. In contrast, this section describes a FESS that uses a robust and cost-effective solution of a squirrel-cage induction machine as a self-excited generator without need for inverters.

A. Self-excited induction generators

Since an induction machine has no permanent magnet and excitation winding inside, to generate magnetic flux required for generator operation, a capacitive reactive power supply is necessary from outside of the armature winding terminal. As the simplest method, by connecting an appropriate capacity capacitor to the terminal, the induction machine can operate

Authors(†) are with the Laboratory for Advanced Nuclear Energy, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo, Japan. Author(††) is with College of Industrial Technology, Nihon University. (e-mail: murayama.masamichi@torus.nr.titech.ac.jp).

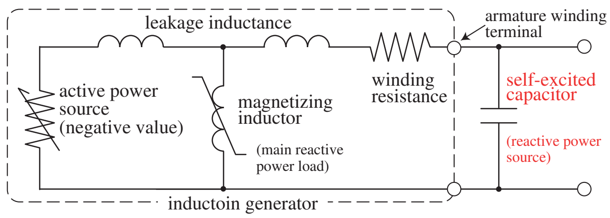


Fig. 1: An equivalent circuit of a self-excited induction generator. A self-excited capacitor is necessary as a reactive power source to supply reactive power to a magnetizing inductor.

as a standalone power supply called self-excited induction generator (SEIG). The equivalent circuit is shown in Fig. 1. To roughly describe the capacitance selection of self-excited capacitor, its capacitance should be balanced with or less than the magnetizing reactance of the induction machine [7]. SEIGs are used for hydroelectric generators and wind turbine generators in MW range. The proposed configuration of a pulsed magnet power supply using the SEIG will be described below.

B. Proposed system configuration

Fig. 2 shows the proposed configuration of the pulsed magnet power supply using the SEIG with a flywheel. The operation sequence of the proposed system is shown in Fig.3 The induction machine with the flywheel is started-up by reducing the terminal voltage from the electric power grid through a starting reactor. After the flywheel started up, the induction machine automatically operates as the SEIG by separating the electric power grid. A simple and inexpensive diode bridge rectifies AC voltage generated by the SEIG. An inverter is unnecessary for the SEIG control since the rectified DC voltage is appropriately converted and supplied to the magnet coils by multilevel converters in the final stage. During discharging to the magnet coil, the frequency of the SEIG drops due to a decrease in the rotation speed of the flywheel. However, the frequency is not crucial because of DC application by the diode bridge. The diode bridge can not regenerate energy from the coils to the FESS. However, when the coil current drops rapidly, the amount of change in the magnetic energy moves from the coils to a floating capacitor of the MMCC. Therefore, the system does not need to regenerate to the flywheel and a simple diode bridge can be adopted.

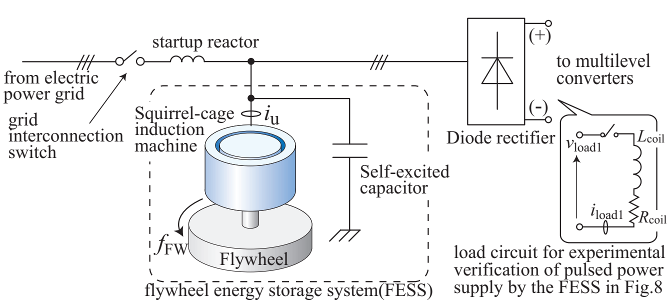


Fig. 2: The proposed system configuration of pulsed magnet power supply by the SEIG with a flywheel. This system consists of a grid interconnection switch, a starting reactor, an induction machine with a flywheel, a diode rectifier.

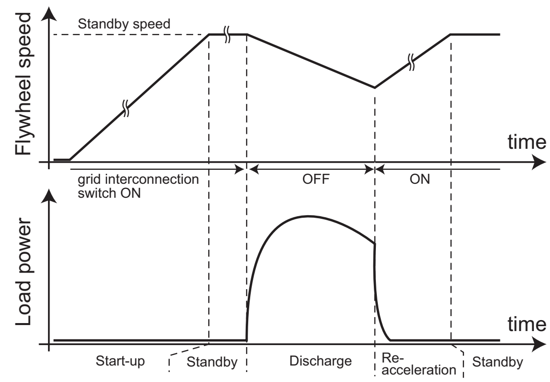
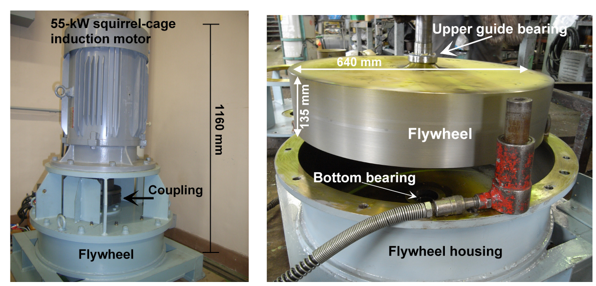


Fig. 3: The operation sequence of the proposed flywheel system. The figure shows the time variation of flywheel rotating speed and power consumption in load magnet coils.



(a) External appearance (b) Flywheel iron disk

Fig. 4: The prototype of a flywheel energy storage system. The squirrel-cage induction machine connects directly to the iron flywheel with a coupling.

TABLE I: Specifications of the FESS

Moment of inertia	I	17.9 kgm^2
Flywheel dimensions	D, H	D = 640 mm, H = 135 mm
Rated voltage	V	200 V (L to L, RMS)
Output power	P	100 kW
Standby speed	N	1500 min^{-1} (4 poles, 50 Hz)
Stored energy	E	220 kJ at standby speed

C. 100 kW class flywheel energy storage system (FESS)

The prototype of FESS is shown in Fig. 4. The specifications are summarized in Table I. The off-the-shelf squirrel-cage induction motor has four poles. The rated frequency is 50 Hz, and the rated output power is 55 kW. The flywheel is made of iron, with a weight of 343 kg and a diameter of 640 mm, and has a moment of inertia of 17.9 kgm^2. Therefore, the stored energy is 220 kJ at 1500 min^{-1} when it is in a standby state at a frequency of 50 Hz. The axis of flywheel rotation is vertical to prevent vibration. Two angular bearings at the bottom of the housing support the flywheel. It directly connects to the motor shaft with a coupling. The flywheel housing is not sealed, and the flywheel rotates in atmosphere. In this system, the SEIG works under an overload condition that is about twice the induction machine rating as short-pulse magnet power supply. Accordingly, we developed the pulsed magnet power supply of about 100 kW or more by using the FESS with a 55 kW rated induction machine.

III. Boosting Multilevel Modular Cascade Converter

Multilevel converter is a technique to broaden the range of application in power electronics [8]–[15]. By using a multilevel converter, there are the advantages with respect to the switching frequency and withstand voltage of semiconductors. We can obtain a higher equivalent switching frequency with multilevel converters, reducing filtering requirements and switching losses. Furthermore, a multilevel converter can efficiently handle larger ratings because switching losses are reduced due to a smaller change in voltage at each switching instant.

Modular multilevel cascade converter (MMCC) is similar to multilevel converters. It consists of the same converters, and their output terminals are also connected in series. An MMCC driving a motor has input terminals at both ends of series connected converters and must be supplied with a higher voltage than its output voltage.

A. Boosting modular multilevel cascade converter

Fig. 5 shows a type of MMCC that has floating capacitors allowing for a higher output voltage than its input voltage. In the application of MMCC to drive a highly inductive load, however, the MMCC has to output high voltage only in a current ramp-up phase. After ramp-up, the converter output voltage needed is not as large as during the ramp-up. Consequently, the role of the modular converters can be divided into two levels. In the first, they rapidly supply high voltage during current ramp up. Converters connected to floating capacitors are the key elements here. Magnetic energy for the inductive load is supplied from the floating capacitors during the ramp-up of load current. It is important that the floating capacitors are rated to have sufficient capacitance to sustain the voltage after ramp-up. In the second, converters sustain a constant current after the ramp-up. Converters supplied from the FESS drive this current.

Both of the two-level converters are switched using PWM (pulse width modulation). The control method shown in Fig. 6 gives the voltage command value of each converter. We refer to this MMCC as a boosting MMCC.

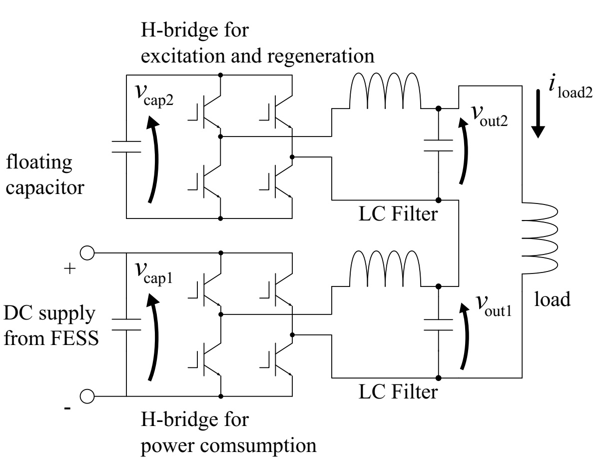


Fig. 5: The proposed configuration of modular multilevel cascade converter. This system consists of H-bridge converters, a floating capacitor and LC filters. One converter connects to the FESS, and the other connects to a floating capacitor.

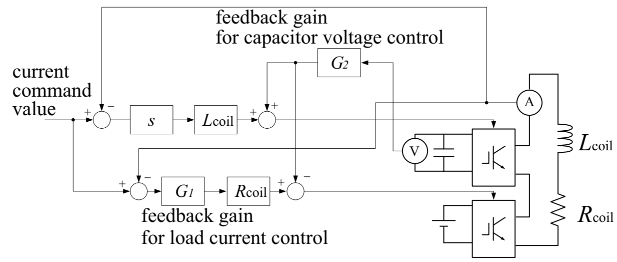


Fig. 6: The proposed control method of the modular multilevel cascade converter. The control requires instruments to monitor the floating capacitor voltage and the load current.

B. Proposed control method

Fig. 6 shows proposed control method of the boosting MMCC. Load resistance and load inductance are known before the operation. There are three feedback loops for control. First one is to control load current using proportional control. The second one is for rapid current excitation using derivative control. The third one is for keeping capacitor voltages prepared for rapid current excitation at any time. The capacitor voltage control is necessary since there are errors in resistance and inductance and noise in the measurement.

C. Experimental configuration

The prototype of boosting MMCC is shown in Fig. 7 and the specifications are summarized in Table II. There are two H-bridges in this system. One connects to a DC power supply, and the other connects to a floating capacitor. The grid supplies the DC power through an autotransformer and a rectifier. The two H-bridges receive different command duties, but the carrier waves for the triangular wave comparison has the same amplitude and phase.

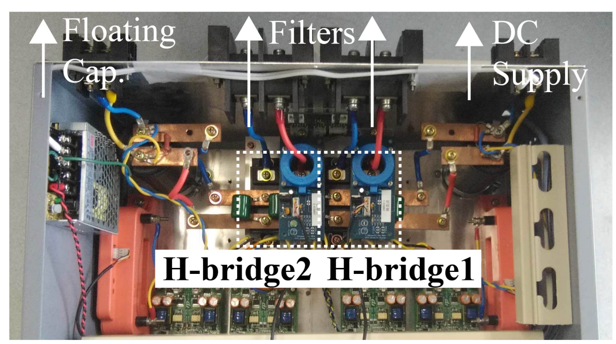


Fig. 7: Converters used for the experiment. We installed two H-bridges in a box. The arrows in the figure show the connected devices of terminals.

TABLE II: Prototype MMCC and load configuration

Coil resistance	R_{coil}	0.8 Ω
Coil inductance	L_{coil}	2 mH
Initial voltage of a floating capacitor	V_{c2}	120 V
Target current	i^{*}_{load2}	70 A
Switching Frequency (bipolar switching)	f_{sw}	16 kHz

itation information: DOI 10.1109/TASC.2018.2806914, IEEE

IV. Coil Excitation Experiment

Fig. 8 shows the operation of self-excited induction generator using the 55 kW induction generator. Before the procedure, the flywheel is accelerated up to 1500 rpm. After the build-up of the excitation current, the load connecting contactor closes. Load power consumption p_{coil} shows that the generator fed electric power to the load immediately. The peak power was 140 kW, and the generator can supply 110 kW or twice the rated power for 0.1 seconds. The operation stopped due to a decrease in the flywheel revolution.

Fig. 9 shows the operation of the boosting modular multilevel cascade converter. The initial voltage of the floating capacitor was charge up to 100 V through the load coils. The converter maintained the current at 0 A and the floating capacitor voltage at 100 V before the operation. The converter works to output constant current throughout the operation. The converter with a floating capacitor output positive voltage and boosted the current at the start of the operation since the derivative control in Fig.6 is working properly. At the end of the operation, it outputs negative voltage to generate the current. During the operation, grid-connected converter output positive voltage to sustain the load current.

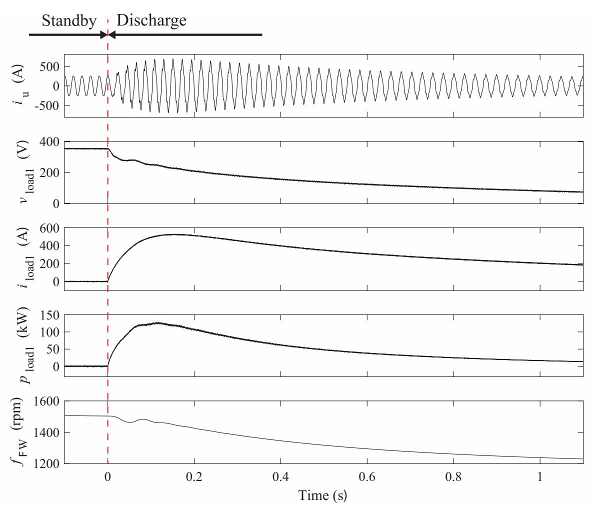


Fig. 8: It is the experimental waveforms of SEIG operation. In this operation, we succeed in generating 140 kW using a 55 kW induction generator. After the operation, the revolution decreased in 80% of the initial value.

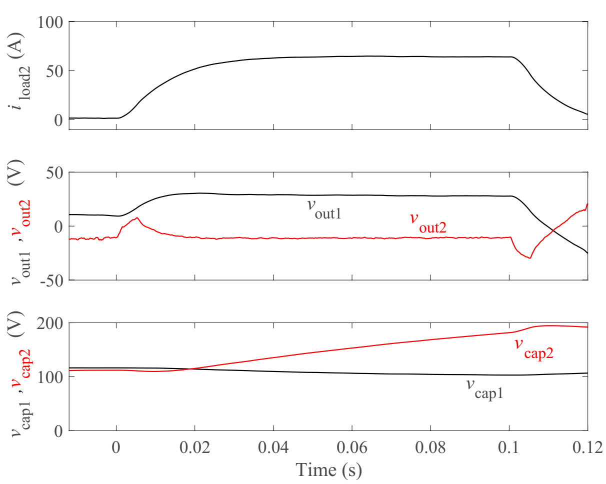


Fig. 9: Experimental result of the modular multilevel cascade converter's operation. The converter connected to the floating capacitor boosts the load voltage during ramp-up of i_{load2}.

V. Summary

We designed a repetitively pulsed power supply using a flywheel energy storage system (FESS) and a boosting modular multilevel cascade converter (Boosting MMCC). Because FESS and Boosting MMCC work as energy buffers, they significantly reduce power fluctuations that may lead disturbance on power grids. FESS and Boosting MMCC can be applied to frequently repetitive and highly inductive load to decrease the peak power consumption and to avoid the impact on the surrounding facilities. Furthermore, Boosting MMCC enables us to excite inductive load at a higher voltage than the rectified FESS's voltage and to enhance load current response.

Finally, we presented experimental data. In this experiment, we succeeded in obtaining electric power more than twice the rated power of the induction motor and succeeded in using a Boosting MMCC to sustain the capacitor voltages.

References

[1] Y. YAMAZAKI *et al.*, "Accelerator Technical Design Report for J-PARC," KEK, Tech. Rep., 2003.

[2] T. T. Takanori Isobe and R. Shimada, "Magnetic energy recovery switch for high repetition and high voltage pulse power supply," in *Power Electronics Technology Exhibition and Conference*, 2004.

[3] J. N. Taku Takaku, Takanori Isobe and R. Shimada, "Power supply for pulsed magnets with magnetic energy recovery current switch," *IEEE Trans. on A.S.*, vol. 14, no. 2, pp. 1794–1797, 2004.

[4] R. Shimada and T. Takaku, "Pulse power supply for regenerating magnetic energy," patent, 2002.

[5] T. T. Takanori Isobe, T. Munakata, H. Tsutsui, S. Tsuji-Iio, T. Matsukawa, and R. Shimada, "Fusion power supplies using magnetic energy recovery switch," in *Symposium on Fusion Engineering 2005*, 2005.

[6] F. B. C. Fahrni, A. Rufer and J. Burnet, "A novel 60 MW pulsed power system based on capacitive energy storage for particle accelerators," in *European Conference on Power Electronics and Applications*, 2007.

[7] T.F.Chan, "Analysis of self-excited induction generators using an iterative method," *IEEE Trans.E.C.*, vol. 10, pp. 502–506, 1995.

[8] C. Govindaraju and K. Baskaran, "Efficient Sequential Switching Hybrid-Modulation Techniques for Cascaded Multilevel Inverters," *IEEE Trans. P.E.*, vol. 26, no. 6, pp. 1639–1648, 2011.

[9] I. Colak, E. Kabalci, and R. Bayindir, "Review of multilevel voltage source inverter topologies and control schemes," *Energy Conversion and Management*, vol. 52, pp. 1114–1128, 2011.

[10] E. Babaei and S. H. Hosseini, "New cascaded multilevel inverter topology with minimum number of switches," *Energy Conversion and Management*, vol. 50, pp. 2761–2767, 2009.

[11] H. Liu, L. M. Tolbert *et al.*, "Hybrid Cascaded Multilevel Inverter with PWM Control Method," in *Power Electronics Specialists Conference*. IEEE, 2008, pp. 162–166.

[12] A. M, M. J *et al.*, "Simulation of a transistor clamped h-bridge multilevel inverter and its comparison with a conventional h-bridge multilevel inverter," in *International Conference on Circuit Power and Computing Technologies*. IEEE, 2014, pp. 958–963.

[13] A. Beig and A. Dekka, "Experimental verification of multilevel inverter-based standalone power supply for low-voltage and low-power applications," *IET Power Electronics*, vol. 5, no. 6, pp. 635–643, 2012.

[14] M. Banaei, H. khounjahan *et al.*, "Single-source cascaded transformers multilevel inverter with reduced number of switches," *IET Power Electronics*, vol. 5, no. 9, pp. 1748–1753, 2012.

[15] M. Malinowski, K. Gopakumar *et al.*, "A Survey on Cascaded Multilevel Inverters," *IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS*, vol. 57, no. 7, pp. 2197–2206, 2010.