Fusion Power Supplies using Magnetic Energy Recovery Switch

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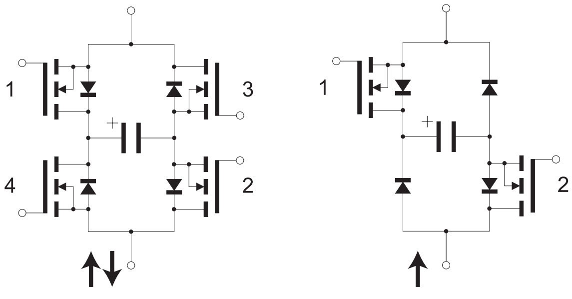
Abstract— **In this paper, a new concept of pulse power supplies that can boost up the pulse current and/or can reduce the voltage rating of the power supplies is proposed. A magnetic energy recovery switch (MERS) consists of four MOSFETs or IGBTs and a capacitor. The MERS is connected in series to a power supply and a coil. The MERS is a switch module and it has no power supply in itself. When the current of coil decrease, the MERS absorbs the magnetic energy stored in the coil and re-generates a high voltage in the capacitor. When the current increases, the MERS adds the voltage to raise currents faster than the time constant of the coil. Because the MERS re-generates a voltage required for the inductance of the coil by using the previous magnetic energy. So, the power supply only has to supply a voltage required for the resistance of the coil. The MERS can reduce a voltage rating and capacity of the power supply. By using the MERS with a power supply of a pulsed magnet, high-repetition pulsed current can be realized with a comparatively small capacity of the power supply. Some applications require a controlled current waveform. By controlling the MERS using PWM, the controlled current waveform is obtained. Operation principles and characteristics of the MERS are described. Some experiments were carried out. Experimental results confirm that the MERS can reduce voltage ratings of power supplies and/or generate high-repetition pulsed boost-up currents.**

I. INTRODUCTION

IN order to sustain high-β steady-state operation of large tokamak fusion research, an active control using feedback coils is planned [1], [2]. In general, a high voltage is required to control a high current in a high frequency. Consequently the power supply becomes comparatively large scale. Power supplies using LC resonance can reduce their voltage ratings. However these types of power supply can not change output current frequency. In addition, aged deterioration of capacitor may cause some problems.

The authors proposed some types of power supply using Magnetic Energy Recovery Switch (MERS) [3]. In this paper, power supplies for magnetic field coils using MERS are proposed. MERS is a switch module with a capacitor. From other point of view, it is a capacitor controlled by semi-conductor devices. The power supplies using MERS can reduce their voltage ratings regardless of resonance frequencies by using forced LC resonance. These power supplies can be applied to the active control of tokamak plasma and other fusion power supplies.



(a) bi-directional (b) mono-directional

Fig. 1. Magnetic Energy Recovery Switch (MERS). (a)Bi-directional type of MERS consists of four MOSFETs and a capacitor. The pair of MOSFETs 1 and 2 are used to control upward current and the other pair of MOSFETs are used to control downward current. (b)Mono-directional type of MERS consists of two MOSFETs and two diodes and a capacitor.

II. MAGNETIC ENERGY RECOVERY SWITCH (MERS)

A. Circuit diagram

Fig. 1(a) shows bi-directional type MERS. Four MOSFETs are connected in two parallel arms. Each arm is consist of two MOSFETs conected in series. Four MOSFETs are connected in reverse direction each other in both of series and parallel connection. The middle points of series are connected to a capacitor. Semi-conductor devices which can turn off current are needed for MERS. Therefore, MOSFETs may be replaced with IGBTs.

In the case of upward current control in Fig. 1(a), MOSFETs 1 and 2 are controlled, 3 and 4 are left turned off and used as diodes. Therefore, mono-directional MERS can consist of two MOSFETs and two diodes and a capacitor as Fig. 1(b).

The circuit diagram of MERS is similar to full-bridge converter; however, there are two different points. First, MERS is connected in series to circuit. Since MERS is inserted between power supply and load, the MERS can control current flowing to the load. Second, the voltage of the DC capacitor of MERS is allowd to change dynamically and even becomes zero because the capacitor is not connected to DC power supply.

B. Operation principle

MERS is usually used with a inductive load. Fig. 2 shows operation modes of MERS. When a pair of MOSFETs are

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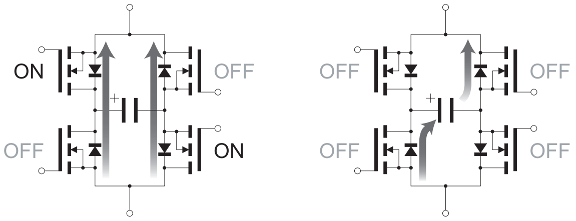
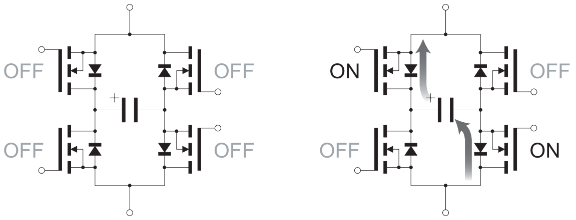


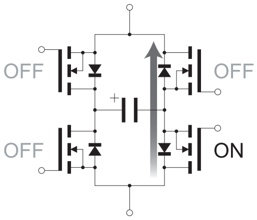
(a) Parallel conduction mode

(b) Charging capacitor mode



(c) Shut off mode

(d) Discharging capacitor mode



(e) By-path mode

Fig. 2. Operation modes of MERS. The MERS has four modes to control current in each direction. (a)When the capacitor is not charged and a pair of MOSFETs are turned on, current flows through two ways. (b)When current flows and the MOSFETs are turned off, the current charges the capacitor through diodes. (c)When the current becomes zero and the MOSFETs are kept turned off, no current flows. (d)When the capacitor is charged and the MOSFETs are turned on, the capacitor discharges. (e)When the capacitor is charged and one of the MOSFETs is turned on, current flows through the MERS.

turned on, current flows through two ways as Fig. 2(a). Next, when the MOSFETs are turned off, the current charges the capacitor through diodes as Fig. 2(b). Current decreases gradually and it becomes zero. After this time, no current flows because of diodes as Fig. 2(c). The magnetic energy stored at the inductive load is absorbed to the capacitor, and converted to electrostatic energy.

Next, when the MOSFETs are turned on, the electrostatic energy of the capacitor raises current as Fig. 2(d). The voltage of the capacitor decreases gradually and it becomes zero. After this time, the current flows through also diodes, so it becomes parallel conduction mode as Fig. 2(a). The magnetic energy is recovered from the electrostatic energy.

III. FUSION POWER SUPPLIES USING MERS

Power supplies for magnetic field coils such as the active control of tokamak plasma are suitable applications for MERS. Most of the energy given to the coil is stored on magnetic field. Therefore most of energy shuttles between power source and the coil in each cycle. By using MERS, the energy shuttles between the MERS and the coil, and the power source supplies only losses at the coil and switching devices, etc.

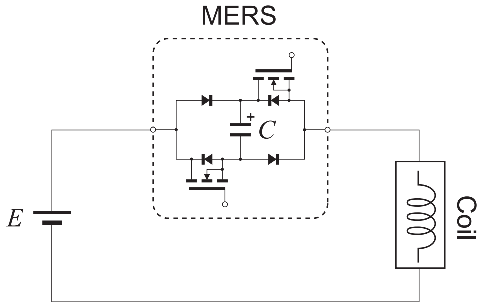


Fig. 3. Circuit configuration of power supply using MERS for mono-directional current control. A mono-directional MERS is connected in series to a DC power source.

A. Power supply for mono-directional current control

Fig. 3 shows circuit configuration of the power supply using MERS for mono-directional current control. In this circuit, a mono-directional MERS is connected in series to a DC power source. By switching MOSFETs of the MERS, pulsed currents are generated from the DC power source. Moreover, the MERS absorbs and supplies magnetic energy of the coil in each cycle.

Fig. 4 shows schematic waveforms of generated current and voltage of the capacitor of the MERS. In mode (b), when MOSFETs are turned off, the current decreases and the voltage of the capacitor increases. In mode (d), the current increases and the voltage decreases. These phenomena are part of LC resonance. Consequently t_{chg} and t_{dis} are given by

$$t_{\mathrm{chg}} = t_{\mathrm{dis}} = \frac{\pi}{2}\sqrt{LC}, \tag{1}$$

where L is the inductance of the magnet and C is the capacitance of the MERS. In general, it is much shorter than the time constant of the coil.

In mode (a), the current flows through the MERS and only the voltage of the power source is applied to the magnet. The current raised in mode (d) is equivalent to the current shut off in mode (b). Therefore, after some cycles, I_{p} becomes as

$$I_{\mathrm{p}} = \frac{E}{R}, \tag{2}$$

where E is the voltage of the power source and R is the total resistance of the circuit. Since the electrostatic energy stored in the capacitor when mode is (c) is equivalent to the magnetic energy stored at the magnet when mode is (a), V_{p} is given by

$$V_{\mathrm{p}} = I_{\mathrm{p}}\sqrt{\frac{L}{C}}. \tag{3}$$

Current control by PWM method can be applied to obtain controlled current waveforms. When current is flowing, by using mode (b), (d) and (e) of Fig.2, voltages of negative, positive and zero can be applied to the coil respectively. Therefore, by controlling gate pattern by PWM control methods, controlled current waveforms are obtained.

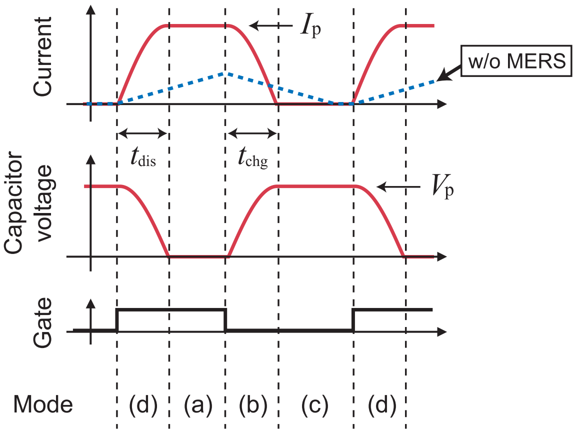


Fig. 4. Schematic waveforms of generated current i and capacitor voltage v_{c} by the circuit of Fig.3. t_{chg} and t_{dis} mean times to charge and discharge the capacitor respectively. I_{p} and V_{p} mean peak values of i and v_{c} respectively. Mode symbols are refered to Fig. 2. Current waveform shown as dotted line indicates schematic current waveform when the MERS is not used.

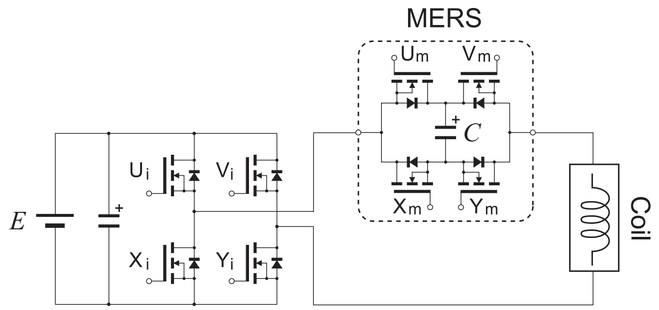


Fig. 5. Circuit configuration of power supply using MERS for bi-directional current control. A bi-directional MERS is connected to a full-bridge inverter.

B. Power supply for bi-directional current control

Fig. 5 shows the circuit configuration of a proposing power supply for bi-directional current control. The power supply consists of a full-bridge inverter and a bi-directional MERS conneced in series. MOSFETs $\mathrm{U_i}$, $\mathrm{V_i}$, $\mathrm{U_m}$, and $\mathrm{V_m}$ are turned on and off at the same time with $\mathrm{Y_i}$, $\mathrm{X_i}$, $\mathrm{Y_m}$, and $\mathrm{X_m}$ respectively. $\mathrm{U_i}$ and $\mathrm{Y_i}$ are always opposite condition to $\mathrm{V_i}$ and $\mathrm{X_i}$ and $\mathrm{U_m}$ and $\mathrm{Y_m}$ are also always opposite condition to $\mathrm{V_m}$ and $\mathrm{X_m}$. The MERS absorbs and supplies magnetic energy also in this circuit. Consequently the full-bridge inverter supplies only losses.

Fig. 6 shows schematic waveforms of generated current and voltage of the capacitor of the MERS. The current flowing through the coil is decreased by the MERS and it becomes zero. The magnetic energy of the current is absorbed to the capacitor, and then used to raise opposite direction current. The inverter supplies the maximum power when the inverter are controlled so that forward current flows when it outputs positive voltage and reverse current flows when it outputs negative voltage. The shifted time t_{a} to realize that condition is give by

$$t_{\mathrm{a}} = \frac{\pi}{2}\sqrt{LC}. \tag{4}$$

I_{p} and V_{p} are given by (2) and (3) respectively.

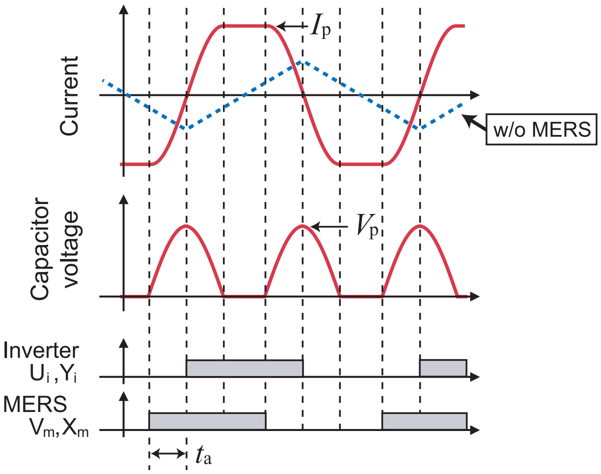


Fig. 6. Schematic waveforms of generated current i and capacitor voltage v_{c} by the circuit of Fig.5. Gate signals to $\mathrm{U_i}$ and $\mathrm{Y_i}$ of the full-bridge inverter and $\mathrm{V_m}$ and $\mathrm{X_m}$ of the MERS are also shown. Gate signals of MERS are shifted by t_{a} to those of the inverter. Current waveform shown as dotted line indicates schematic current waveform when the MERS is not used.

C. Voltage rating reduction of power supplies

Required DC voltage to raise current by a conventional voltage source type power supply E_{norm} is given by

$$E_{\mathrm{norm}} = L\frac{I_{\mathrm{p}}}{T_{\mathrm{r}}}, \tag{5}$$

where L is the inductance of the coil and I_{p} is peak current and T_{r} is requested time to raise the current. On the other hand, from (2), required DC voltage with a power supply with MERS is given by

$$E_{\mathrm{mers}} = I_{\mathrm{p}}R, \tag{6}$$

while R is the resistance of the circuit. From (5) and (6), voltage reduction rate δ is given by

$$\delta = \frac{E_{\mathrm{mers}}}{E_{\mathrm{norm}}} = \frac{T_{\mathrm{r}}}{\tau_{\mathrm{c}}}, \tag{7}$$

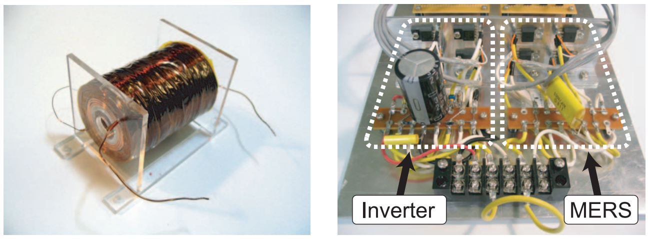
where τ_{c} is the time constant given by L/R. This means that the voltage rating reduction is achieved more effectively in the condition that the time constant is much longer than the requested time to raise the current. Usually power supplies for high frequency current control are under this condition.

Using MERS can reduce voltage rating and capacity of power supply. However, total capacity of semi-conductor devices can not be reduced since MERS also consists of semi-conductor devices. The most important point of the voltage rating reduction is that DC capacitors of the power supply can be reduced by using MERS. Large DC capacitors whose size are determined by the voltage rating and the current rating of the power supply are connected in parallel to voltage source. Therefore, voltage rating reduction causes decreasing of the DC capacitors. In general, the DC capacitors occupy large part of the power supply in volume. The DC capacitors store energy as large as several times energy of one cycle in order to maintain the voltage within the range of several percent. On the other hand, the capacitor of MERS only stored the energy of one cycle. Therefore, total size of capacitors is reduced by using MERS.

TABLE I

MAIN CHARACTERISTICS OF MOSFETS OF THE EXPERIMENTAL DEVICE

	Inverter	MERS
Voltage rating V_{DS}	250 V	600 V
Current rating I_{D}	14 A	20 A
On-state Resistance $R_{\mathrm{DS(on)}}$	0.22 Ω	0.16 Ω
Diode forward on-voltage V_{SD}	1 V	1 V



(a) Test coil (b) Experimental device

Fig. 7. Photos of the experimental setup. (a)Test coil is air-core coil made from polyester enameled copper wire of 0.7 mm in diameter. (b)Experimental device which have a inverter and a MERS with a small capacitor.

IV. EXPERIMENTS

Some experiments are carried out to comfirm operations of the power supply. A laboratory pilot device for alternating magnetic field coils is made. Circuit configuration is same as Fig. 5. Main characteristics of MOSFETs of the inverter and the MERS are shown in Table I. Voltage rating of MOSFETs of the MERS should be larger than the voltage generated in the capacitor of the MERS. Fig. 7 are photos of experimental setup. A DC power supply which can generate variable DC voltage was used as DC voltage source. Table II shows parameters of the test coil used for the experiments. Time constants τ_{c} are including resistance of the power supply circuit estimated by Table I.

Target condition was set to 4 A with 30 μs rising time which is much shorter than the time constant of the coil. By using conventional power supply, required voltage E_{norm} to achieve that condition is 206.7 V from (5). From (7), δ is estimated at 0.0489 and consequently the required voltage E_{mers} will be reduced to about 10 V by using MERS. The capacitor of MERS is determined at 0.2 μF to meet that condition from (1). In that condition, the maximum voltage of the capacitor will be 357 V from (3).

Forward and reverse currents of 4 A were raised alternately at 5 kHz repetition rate. Experimental results comfirmed that required voltage was reduced most effectively when the gate shift time t_{a} is 30 μs calculated by (4). Fig. 8 shows waveforms of current and applied voltage when t_{a} is 30 μs. It was also confirmed that required DC voltage was reduced to 13.4 V extremely. The MERS generated about 360 V and controlled current by applying that voltage.

TABLE II

EXPERIMENTAL PARAMETERS

Inductance L	1.550 mH
Resistance R	1.676 Ω
Time constant τ_{c}	613.6 μs

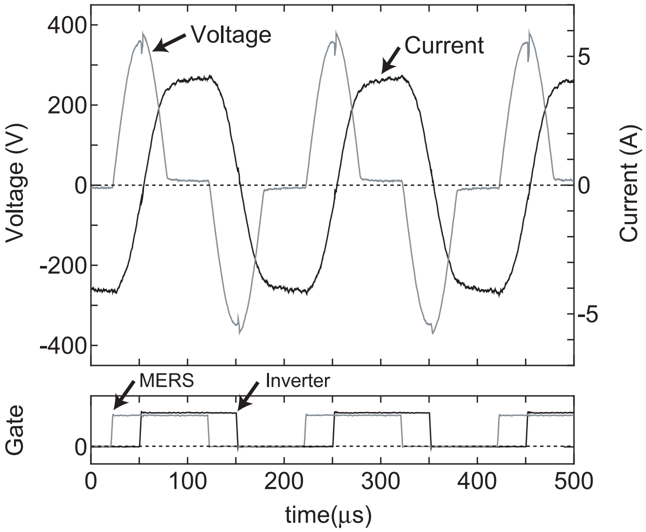


Fig. 8. Waveforms of current and voltage applied to the coil when t_{a} is 30 μs. MERS generated about 360 V and applied it to the coil alternately. The current was controlled fast by that voltage.

V. CONCLUSION

This paper discussed the fusion supplies such as the active control of tokamak plasma using MERS. The power supplies can reduce their voltage ratings regardless of frequency by forced LC resonance. MERS can not reduce total semiconductor capacity but total amount of DC capacitors which occupy large part of power supplies. Therefore, by using MERS, comparatively small scale fusion power supplies can be designed.

Voltage rating reduction rate is discribed by coil parameters and target condition. Large time constant and fast rising time can realize more effective voltage rating reduction. This indicates that fusion power supplies for large scale coils which has large time constant are suitable applications. Experiments by the laboratory pilot device comfirm operations of this power supply and voltage rating reduction.

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