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Development of High-performance Power Supply Using Magnetic Energy Recovery Switch

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Abstract

High performance and efficiency of electrical appliances by the development of power electronics technology have brought rapid growth to the industry. This paper presents a new power supply named MERS (Magnetic Energy Recovery Switch), which enables power factor and variable frequency control to obtain further productivity and high quality of a products. Experimental results of motor applications that do not require variable speed operation and variable frequency induction heating using MERS are presented.

1. Introduction

The recent advancement of power electronics supported by dramatic improvement in the performance of power semiconductor devices has enhanced the performance of power control devices. The increase in the functionality of electric motors is described as an example: DC motors were the mainstream in the steel industry and other industries at first. Regarding converters for driving DC motors, although motor-generator (M-G) sets were mainly used in the 1960s, after thyristor devices appeared, the thyristor Leonard type went mainstream. DC motors have some disadvantages, for example, maintenance is not easy and increasing the capacity of a single unit is difficult. Against the background of the advancement of elemental technologies such as control and main circuit technologies, the use of AC drive systems that had overcome such problems began in the latter half of the 1980s.

Regarding AC drive systems, transistor inverters were used for medium- and small-capacity systems (e.g., for auxiliary drives) at first and cycloconverters were used for large-capacity systems (e.g., for main drives for rolling mill). As the performance of power semiconductor devices advanced after that, the application was gradually expanded. Currently, insulated gate bipolar transistor (IGBT) inverters are mainly used for medium- and small-capacity systems while voltage type inverters, such as gate commutated turn-off thyristors (GCTs) and injection enhanced gate transistors (IEGT) inverters, are mainly used for large-capacity systems.

In addition, industrial circles are paying attention to induction heating technologies[1)] from the aspect of global warming prevention. Currently, induction heating is a critical heating method because of the following reasons: It is a clean heat source because electricity is used for heating; the operability and controllability are excellent; and it can heat only a target spot locally. In large-capacity induction heating used in the steel industry and other industries, current type inverters used to be widely used because they had the advantage of achieving large capacity by a single unit: In the application to the low frequency (several kHz) range, inverters with thyristor devices used to be commonly used. However, recent improvement in the performance of power semiconductor devices brought voltage type inverters with IGBT devices into the mainstream. In the high-frequency (several ten kHz or more) range, voltage type inverters with IGBT and metal oxide semiconductor field effect transistors (MOSFETs) are used.

The steel industry has been enjoying such advancement of power electronics and it has been improving the functionality and efficiency of motors and other electrical appliances used at steelworks. We think that further efforts shown below are required to improve the productivity and to enhance the functionality and quality of steel products from the viewpoint of users while energy saving and CO_2 emissions reduction are further accelerated.

Firstly, regarding the motor sector, constant rate induction motors many of which are used at manufacturing sites always operate at a lagging power factor, so upper system transformers need to be large due to reactive power. On MW-class large-capacity units (e.g., sintering blowers), such loss cannot be ignored and often becomes a problem. To improve the lagging power factor, phase-advanced capacitors, thyristor controlled reactors (TCRs), and static synchronous compensators (STATCOMs) are used. However, all these types are installed onto network connection points to reduce received power and thereby they cannot improve the power factor after the

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connection points.

Secondly, in the induction heating sector, the power factor as a heating load is very low, so a fixed capacitor is connected in series or parallel to the load to place the loading side into the resonant state to reduce the capacity of the inverter power supply. However, the frequency of the heating current is determined only based on the impedance of the load, so when the shape and status of an object to be heated change, the impedance significantly changes: That makes it impossible to maintain the load's resonant state, which makes it impossible to secure an appropriate heat input. In the worst case, the voltage of the inverter power supply becomes too high, which causes power shut-off. To further enhance the heating controllability that is a characteristic of induction heating, a function for controlling heating current frequency that does not rely on the statuses of loads may be required, in addition to the control of the thermal amount based on the current magnitude.

The magnetic energy recovery switch (MERS)[2)] proposed in this paper is also a power converter with power electronics. Compared to conventional power converters, configuring and controlling it are easier. In a MERS, the load voltage can be controlled by controlling the power factor or the load current frequency can be controlled, depending on the control method. MERS is expected to be applied to more sectors as a measure to use energy effectively.

2. Effective Use of Energy

The steel industry consumes approximately 20% of the energy consumed in the entire manufacturing industry. Among which, the ratio of electric power to total energy consumption is approximately 40% or more. Thus, the steel industry consumes approximately 8% of the total electric energy consumed in the entire manufacturing industry. Efforts to save energy and improve the functionality and quality of steel products are required through the effective use of such enormous energy.

First, the necessity of power factor control and load frequency control as measures to use energy effectively in the steel industry is discussed.

2.1 Power factor control

An AC circuit includes reactance components such as inductive coils and capacitive capacitors, so there is a phase difference between the power supply voltage and load current. The product of the coordinate phase components of the voltage and current is called effective (electric) power. The product of the components for which the phase of the voltage is deviated from that of the current by $\pi/2$ is reactive power. Effective power refers to power that is supplied from a power supply and converted to kinetic energy and heat energy at the load to be consumed. On the other hand, reactive power refers to energy (power) that is supplied from the power supply and primarily accumulates as magnetic energy ($1/2 \cdot L \cdot i^2$) at the coil inductance (L) and as electrostatic energy ($1/2 \cdot C \cdot v^2$) at the capacitor (C), and that returns to the power supply again. Where, the power factor is defined by Formula (1).

Power factor

$$= \frac{\text{Effective power}}{\text{Apparent power}} = \frac{\textit{Effective power}}{\sqrt{\textit{Effective power}^2 + \textit{reactive power}^2}} \tag{1}$$

A power factor refers to the ratio between the effective power that the load actually consumes and the apparent power that is the product of the voltage and current supplied from the power supply. Apparent power is the product of the power supply's effective voltage value and the load's effective current value, indicating the power capacity that the power supply can supply. Reactive power is not converted to other types of energy and only moves between the power supply and load repeatedly, so the power factor is a value showing the effective use rate of the power supply. Therefore, if reactive power can be reduced by controlling the power factor, the transmission loss on a circuit can be reduced, which increases the power usage ratio.

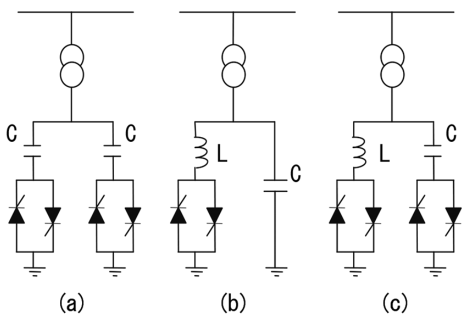


Fig. 1 Type of reactive power compensation

In an electric power system, when the power factor is poor, that is to say, when the reactive power increases, the power supply capacity increases and the system's voltage decreases, rendering the system unstable. Therefore, to control the power factor by maintaining the system voltage at the receiving ends of power from a power company, reactive power compensating devices are commonly used and they are inserted in parallel to the system at receiving ends. **Figure 1** illustrates typical variable impedance type reactive power compensating devices as examples. Figure 1 (a) is the capacitor control type, (b) is the reactor control type, and (c) is the capacitor/reactor control type. These reactive power compensating devices are connected in parallel to the system, so they cannot compensate the system's reactance after them and thereby they cannot control the power factors at loads at the ends of the system.

To control the power factors at loads at the ends of the system, devices that compensate the load impedance must be inserted in series to the loads. However, load impedance is not fixed. For example, the impedance when a device starts up is different from that in steady operation and even during steady operation, the impedance normally changes. Therefore, to control such power factors, power factor compensating devices with the variable impedance function need to be introduced.

2.2 Load frequency control

Induction heating is frequently used in the steel industry to heat steel plates and other materials. Induction heating with high controllability has various characteristics; for example, it does not use combustion gas and thereby it is a clean energy source and it can heat a target spot locally. Induction heating is highly anticipated to become a measure to prevent global warming because it emits less CO_2 and to improve the functionality and quality of steel products and the productivity thanks to the characteristics described above. Looking at induction heating as a heating method, induction heating is Joule heating caused by the current induced on an object to be heated by magnetic flux produced by the heating coil and the resistance of the object to be heated, so its power factor is very low.

Therefore, to reduce the power supply capacity, a load-resonant capacitor (power factor regulation capacitor) that compensates the reactive power of an object to be heated including the heating coil is installed in order to improve the load power factor. **Figure 2** shows the configuration of a general induction heating device.

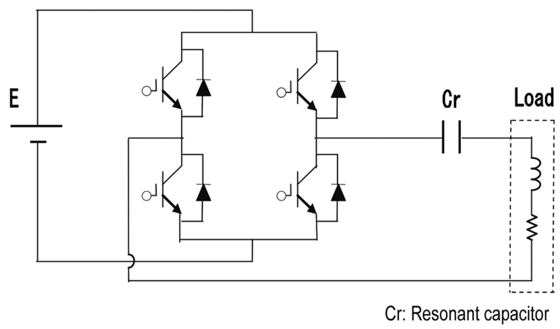


Fig. 2 Conventional induction heating circuit

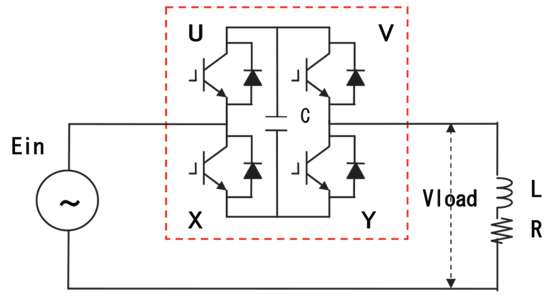


Fig. 3 Circuit configuration of MERS

However, a load-resonant capacitor is a fixed capacitor, so it cannot control the frequency dynamically. Example problems posed by such difficulty of dynamic frequency control are shown below using induction heating of steel plates as an example.

(1) Cannot cope with changes in the material quality and size of objects to be heated

When the material quality and size (thickness and width) change between steel plates, the physical properties also change, which changes the steel plate's impedance as a result. Therefore, changes in the resonance conditions with the load make stable induction heating difficult.

(2) Cannot resolve cyclic temperature deviation in the longitudinal direction of steel plates

When the temperature of an entire steel plate increases in a heating furnace, the temperature of the sections that are in contact with the rollers supporting the plate lowers compared to the other sections. This forms cyclic temperature deviation sections at intervals of approximately 10 m called skid marks longitudinally on the plates extracted from the heating furnace. As this temperature deviation occurs on the surface of steel plates, it is difficult for conventional heating power control to heat a plate uniformly in the thickness direction.

(3) Cannot heat the head and tail end sections in the longitudinal direction of a steel plate

When a steel plate is transported, only a part of the head or tail end section in the longitudinal direction presents between the upper and lower heating coils and the portion gradually changes, so the load impedance changes, making it impossible to secure appropriate heat input. In the worst case, the voltage of the inverter power supply becomes too high, which causes power shut-off. Therefore, uniform heating is impossible until the impedance stabilizes, which reduces the available percentage of steel plates.

To achieve dynamic frequency control, all capacity required for induction heating needs to be output from semiconductor converters without using conventional resonant capacitors or multiple power supplies need to be provided based on the variable control range of frequency. These methods increase the semiconductor capacity and device size when conventional circuit configuration is used, which possibly increases the cost as a result. This problem becomes obvious on large-capacity induction heating devices used in the steel industry, in particular. To date, no such induction heating technologies with a dynamic frequency control function have been realized yet.

Power factor control and load frequency control were discussed above as measures to use energy effectively. As a technology to achieve such control, MERS are available. The principle and configuration of a MERS are discussed in the next chapter.

3. Magnetic Energy Recovery Switch (MERS)[2)]

A magnetic energy recovery switch (MERS) is inserted between a power supply and load in series as shown in **Fig. 3**. It is a bidirectional current switch that recovers magnetic energy ($1/2Li^2$) accumulated at the load inductance to the built-in capacitor as electrostatic energy ($1/2Cv^2$). Reverse conductivity semiconductor switches (e.g., IGBT and MOSFET) are connected in full-bridge single-phase configuration: A capacitor with relatively small capacity is connected to the DC section and the AC side is connected in series to the circuit. This works as a variable series capacitor. As a characteristic of this circuit, a period during which the capacitor voltage becomes zero in each cycle is provided by installing a capacitor with a relatively small capacity to allow charge and discharge with the inductance on the AC side.

3.1 MERS operation mode

The basics of MERS behavior are to turn on and off a pair of devices located in a diagonal line. The upper and lower sections of the circuit are symmetrical, so the current can be controlled bidirectionally. **Figure 4** shows the relationship between the device statuses and current paths.

As initial conditions, the capacitor has been charged and devices V and X are on (at this time, devices U and Y are off).

(1) Because devices V and X are on (devices U and Y are off), the capacitor starts discharging. The current starts flowing in the direction shown in Fig. 4 (a).

(2) When the capacitor voltage becomes zero, the reverse diodes of devices U and Y are also turned on since the voltage across the diodes becomes zero, and the current flows in the two parallel paths as shown in Fig. 4 (b). Devices U and Y are turned on during this period.

(3) Next, with the capacitor voltage zero, when devices V and X are turned off as shown in Fig. 4 (c), the current flows via devices U and Y, charges the capacitor, and decreases to zero.

(4) Once the capacitor has been charged, because devices U and Y are on, the current starts discharging in the reverse direction as shown in Fig. 4 (d).

(5) When the capacitor voltage becomes zero, the reverse diodes of devices V and X are also turned on since the voltage across the diodes becomes zero, and the current flows in the two parallel paths as shown in Fig. 4 (e). Devices V and X are turned on during this period.

(6) Next, with the capacitor voltage zero, when devices U and Y are turned off as shown in Fig. 4 (f), the current flows via devices V and X, charges the capacitor, and decreases to zero.

At this time, the status of each device is the same as that in step (1) and after that the behavior in steps (1) to (6) is repeated.

When each device switches the status of the switch from on to

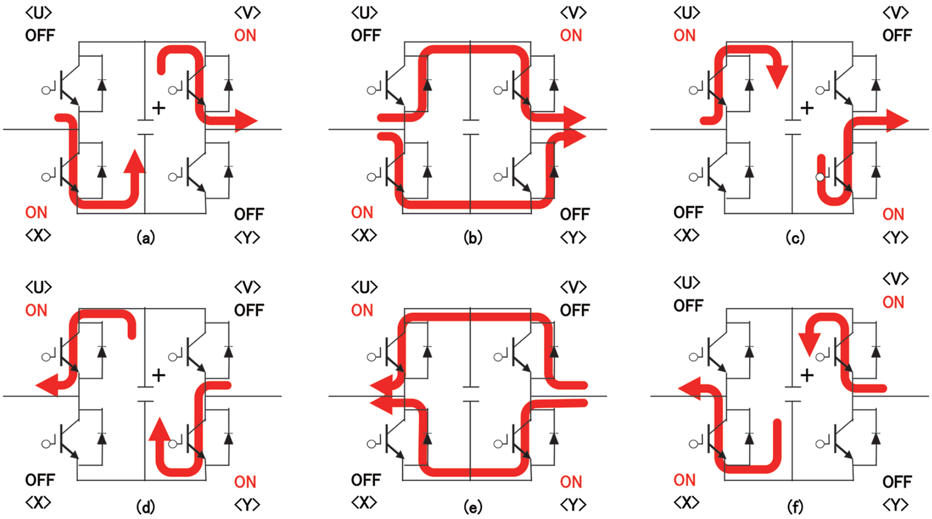


Fig. 4 Possible current paths of MERS

off, the voltage of each device is zero without exception, so each switching off is performed under zero voltage. In addition, the current starts flowing to each device when the status changes from (1) to (2) and from (4) to (5). The current starts flowing slowly, so switching on is performed under zero current and thereby the switching loss is very small.

3.2 Power factor control

This section describes the power factor control method using the MERS circuit. In the circuit configuration shown in Fig. 3, as shown in **Fig. 5**, the phase difference between the input voltage and input current (i.e., power factor control of the power supply) can be controlled by controlling the gate phase angle (α) (timing to turn on and off the device) of each semiconductor device for the zero-crossing point of the input power supply (Ein).

Figure 6(a) shows the relationship between the input voltage and input current when the gate phase angle (α) is smaller than $\pi/2$ ($\alpha<\pi/2$). Figure 6 (b) shows the situation when the gate phase angle (α) is equal to $\pi/2$ ($\alpha=\pi/2$). Figure 6 (c) shows the situation when the gate phase angle (α) is larger than $\pi/2$ ($\alpha>\pi/2$). Figure 6 (a) shows the lagging power factor ($\alpha=30°$). Figure 6 (b) shows a case where the power factor is 1 ($\alpha=\pi/2$). Figure 6 (c) shows the leading power factor ($\alpha=150°$).

Controlling the gate phase angles of the devices means controlling the charging and discharging timing of the capacitor in a MERS circuit. This determines the phase of the input current to the input voltage.

In the MERS circuit configuration in Fig. 3, the load voltage (Vload) is expressed using the formula below.

$$\mathrm{Vload} = \mathrm{Ein} + \mathrm{Vmers} \qquad (2)$$

Where, Ein is the input power supply voltage and Vmers is the voltage generated on the MERS circuit.

In addition, Vmers can be expressed by the formula below.

$$\mathrm{Vmers} = \mathrm{Ein} \cdot (\omega L/R \cdot \sin\alpha - \cos\alpha) \cdot e^{j\alpha} \qquad (3)$$

Where, L is the load inductance, R is the load resistance, α is the device's gate phase angle, and ω is the power supply's angular frequency.

Therefore, the load voltage (Vload) is expressed by the formula below.

$$\mathrm{Vload} = \mathrm{Ein} + \mathrm{Ein} \cdot (\omega L/R \cdot \sin\alpha - \cos\alpha) \cdot e^{j\alpha} \qquad (4)$$

The absolute value of the load voltage is expressed by the formula

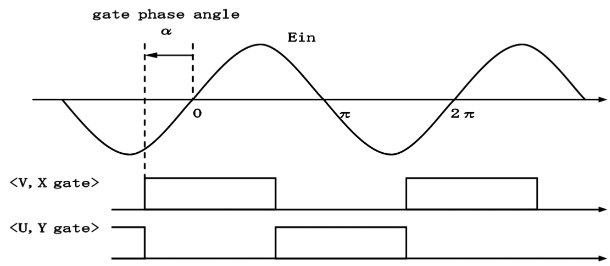


Fig. 5 Gate phase angle of MERS semi-conductor device

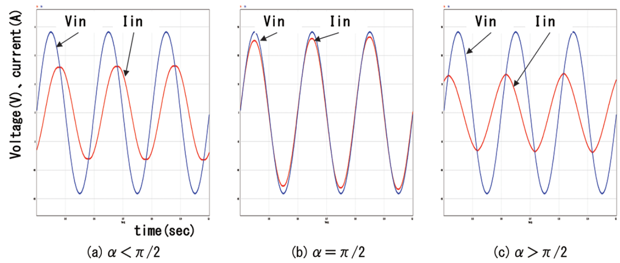


Fig. 6 Power factor control by the change of phase angle

below.

$$\mathrm{Vload\ (abs)} = \mathrm{Ein} \cdot \sin\alpha/\cos\theta \qquad (5)$$

Where, θ is the load power factor ($\tan^{-1}(\omega L/R)$).

Formula (5) shows that the magnitude of the load voltage can be controlled by the gate phase angle (α). This is no more than a variable impedance type reactive power compensating device that generates voltage by compensating the system's reactance voltage and that generated voltage compensates the voltage at the load end since the MERS circuit has been inserted in series to the load.

3.3 Frequency control

This section describes the frequency control method.

A MERS can be regarded from its circuit configuration as a series capacitor that is controlled by semiconductor switches. More specifically, controlling the timing to turn on and off the gates of the semiconductor switches makes it possible to control the capacitor's charge and discharge timing. When looking from the load side, the

MERS has a variable capacitor function. The load frequency can be controlled by controlling the timing to turn on and off the semiconductor switch gates in a MERS. The functions of a MERS as a voltage source where an AC power supply is connected to the MERS's AC terminals were described above. The voltage of a MERS capacitor is always in the straight polarity. Next, a dual circuit as a current source where a DC power supply is connected to both ends of a capacitor and an inductance load is connected to the AC terminals is discussed.

Figure 7 shows a dual circuit of the MERS in Fig. 3. The operation mode is the same as that specified in 3.1. Where, the frequency of the current flowing on the load can be controlled by controlling the frequency of gate signals when semiconductor switches U and Y are paired and V and X are paired. In addition, the capacitor voltage decreases to zero in every cycle, so the capacitor needs to be charged as a current source. It can be solved by connecting the capacitor to a thyristor bridge via a DC reactor (DCL) in current type DC link configuration as shown in Fig. 7.

3.3.1 Variable frequency range

This section describes a variable frequency range that can realize switching under zero voltage (zero-voltage switching) using a MERS circuit. **Figure 8** is example of MERS capacitor voltage waveforms. When the period during which the MERS capacitor voltage is zero is t_0, the formula below holds well.

$$t_0 = \frac{1}{2} \cdot \left(\frac{1}{fs} - \frac{1}{fres} \right) \tag{6}$$

Where, fs is the semiconductor switch's switching frequency and fres is the load resonance frequency.

Semiconductor switches U and Y and switches V and X perform switching when the MERS capacitor voltage is zero, so the following condition needs to be satisfied to realize zero-voltage switching.

$$fs \leq fres \tag{7}$$

Thus, to realize variable frequency in zero-voltage switching, the upper limit of the switching frequency should be the load resonance frequency. The lower limit of the frequency is described below.

A case where a load (resistance (R) is 200 mΩ and inductance (L) is 20 μH) is inductively heated at a frequency (fs) of 10 kHz is discussed here. The MERS capacitor (Cm) is 12 μF such that the resonance frequency (fres) becomes 10.3 kHz (> fs). The frequency (fs) is reduced at this constant. **Figure 9** shows the heating currents and MERS capacitor voltage waveforms in that case.

Figure 9 (a) shows waveforms when fs is 10 kHz. Figure 9 (b) shows those when fs is 6 kHz. Figure 9 (c) shows those when fs is 3 kHz. Figure 9 (a) and 9 (b) show that zero-voltage switching is performed as the frequency is equal to or lower than the upper limit frequency (resonance frequency).

However, during the zero-voltage periods, the heating current circulates between the load and MERS circuit as shown in Fig. 4 (b) and 4 (e) and decreases with a time constant of the load. When the decreased heating current falls below the input DC current, this DC current starts charging the MERS capacitor, so the voltage of the MERS capacitor is not zero at the time of switching off. Figure 9 (c) shows this behavior. Therefore, the lower limit frequency is frequency that satisfies the condition of "input DC current ≤ heating current."

3.3.2 Reduction of switching loss

In a MERS circuit, when the semiconductor devices are switched off, the voltage applied to them becomes zero, so the surge voltage at the time of switching is almost zero unlike the conventional method. Therefore, an excessive voltage rating is not required for the devices. In addition, when devices are switched on, the current starts flowing to the devices gradually (turn-on at zero current). Furthermore, the heating current circulates while the devices are off as shown in **Fig. 10** and it flows in parallel between the upper/lower semiconductor devices and load, so the cutoff current while the devices are off is approximately one half of the rating. Thus, the switching loss in a MERS circuit significantly decreases compared to the conventional method, which realizes a high-efficiency power

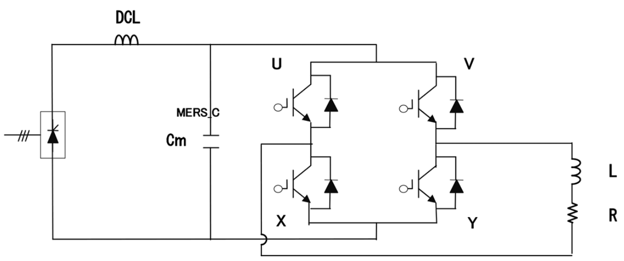


Fig. 7 Circuit configuration of variable frequency MERS

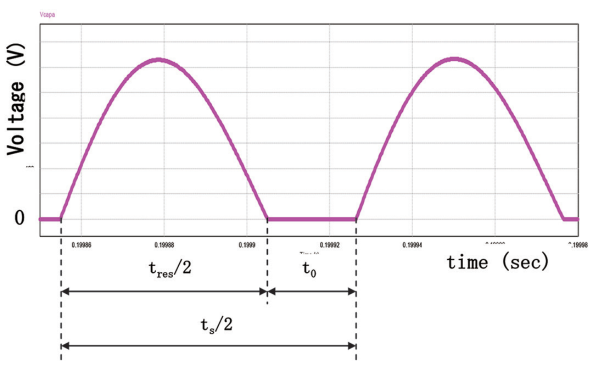


Fig. 8 Voltage waveform of MERS capacitor

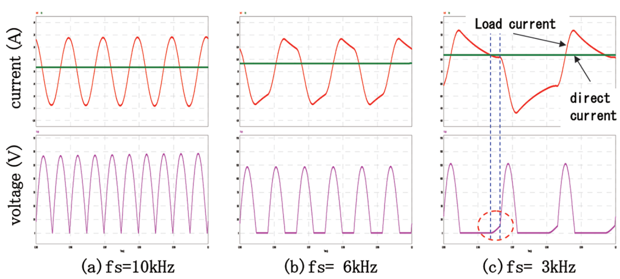


Fig. 9 Coil current and voltage waveform of MERS capacitor

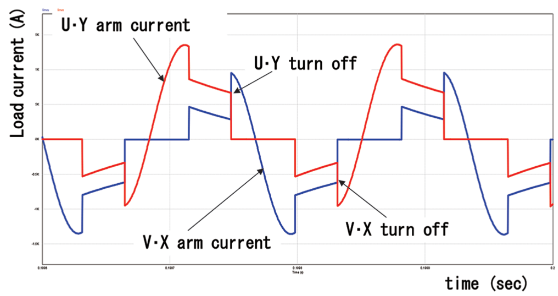


Fig. 10 U·Y (V·X) arm device current waveform at device turn off

supply.

4. Experiment Results

This chapter describes the results of the application of the MERS functions described in the previous chapter: (1) application of the power factor control to induction motors and (2) application of the frequency control to induction heating of steel plates.

4.1 Application to motor control[3)]

A MERS was applied to two induction motors that were operated in parallel and for which the full-voltage starting was 55 kW. Improved starting characteristics and improved power factor during operation are discussed below. **Figure 11** illustrates the test circuit configuration.

The motors are for water pumps and two units are always operating in parallel. Each three-phase motor is 400 V and 55 kW. A MERS circuit was applied to the main circuit on the Motor 2 side. Specifically, MERS's power factor control makes the current flowing on Motor 2 a leading phase and that offsets the lagging phase current of Motor 1 to realize operation where the power factor is 1 when viewed from the input power supply. The capacitor (Cm) of the MERS was determined as 1.6 mF such that the resonance conditions with Motor 2 inductance and the harmonic current would become the minimum. **Figure 12** shows the MERS control flow. The gate phase angle (α) is controlled by the fundamental wave component that was obtained by discrete Fourier transform (DFT) of MERS output voltage. **Figure 13** shows operation results where the power factor is 1. The figure shows that the input voltage (V_{in}) is in a coordinate phase with the input current (I_{in}), achieving operation where the power factor is 1.

In addition, in a MERS as shown in Formula (5), controlling the gate phase angle (α) of the semiconductor device allows the magnitude of the load voltage to be controlled, so another test in which the starting method of Motor 2 was changed to soft starting from full-voltage starting was also carried out. **Figure 14** shows operation results in soft starting. In Fig. 14 (b), V_{out} is the input voltage of Motor 2 and I_{out} is the input current. The capacitance of the MERS

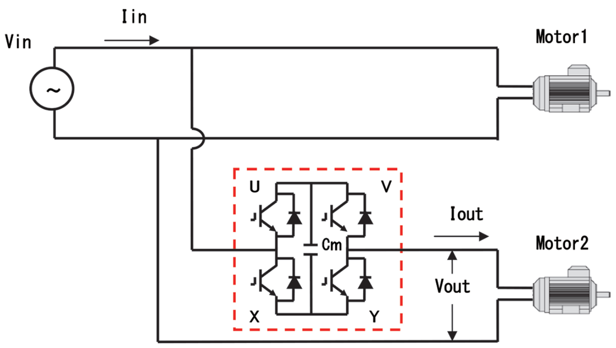


Fig. 11 System configuration of experimental induction motor

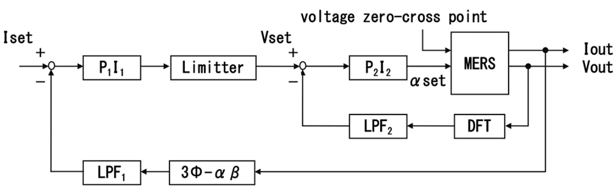


Fig. 12 Control block diagram of MERS

(X_{mers} (1/ω Cm)) was changed by controlling the gate phase angle (α) such that the starting current would not exceed 250 A to increase V_{out} gradually in order to achieve soft starting. Figure 14 (a) shows the starting current in conventional full-voltage starting.

Applying a MERS to one of the two induction motors operating in parallel realized operation where the power factor was 1, which could reduce the total power supply current of the two motors from 190 A to 148 A and can reduce the loss on the upper system transformer. In addition, the realization of soft starting reduces the starting current from approximately 7 times the rated current to 2.4 times (reduced by 65%), which can reduce the load to the motors at the time of starting.

4.2 Application to induction heating[4, 5)]

This section describes the experimental results of induction heating at the edge in the width direction of stainless steel plates using a MERS circuit. **Table 1** lists the specifications of the stainless steel plate to be heated. **Figure 15** illustrates the variable frequency type

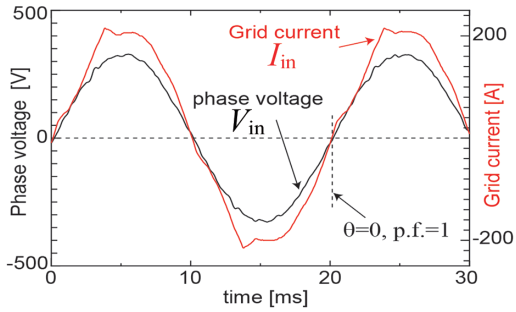
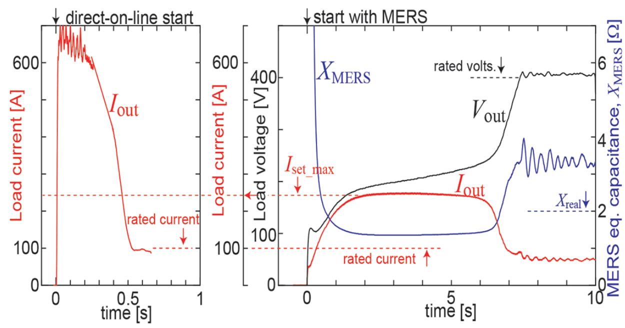


Fig. 13 Characteristics of steady state operation (power factor = 1)



(a) rush current (direct start)　(b) Motor current and voltage (soft-start)

Fig. 14 Stating characteristics of induction motor

Table 1 Specifications of stainless steel plate

Material	Items	Spec.	Items	Spec.
Stainless steel	Thickness (mm)	10	Electric conductivity	1.250×10^6
	Width (mm)	300	Permeability	1
	Threading-speed (mpm)	5	Steel density	7930
	Initial temp. (°C)	25	Thermal conductivity	13.51
	Room temp. (°C)	25	Heat-transfer coefficient	25.8

MERS circuit used for the experiment.

The capacity of the prototyped variable frequency type MERS power supply is 90 kVA (the output voltage is 900 V and the output current is 100 A): Its designed variable frequency range (fs) is 150 to 1 000 Hz. In the MERS circuit, a high impedance transformer (high leakage inductance) placed in the diode bridge's AC side is used instead of using DC reactor. In addition, on the primary side of the main transformer, a thyristor AC power regulator was installed to feed back the output current of the MERS circuit to regulate the voltage in order to control the load current.

Figure 16 shows the positional relationship between the heating coil that heats the edge of the stainless steel plate and the plate (material) to be heated. The inductance of the heating coil is 1.19 mH at load (3.06 mH at no load). The capacity of the MERS capacitor was determined as 7.5 μF from Formula (7) to realize zero-voltage switching at no load.

4.2.1 Heating test results

Figure 17 shows the heating current, effective power, and apparent power when the switching frequency was changed to 175, 475, and 1 000 Hz in stages during the heating with the loaded condition fixed. The figure shows that the current is maintained at constant regardless of the changes in the switching frequency: As the switching frequency increases, the load resistance also increases, and thereby the effective power increases.

Figure 18 shows the output voltage and current waveforms at the switching frequency values shown in the experimental results in Fig. 17. Figure 18 shows that the variable frequency at zero-voltage switching is achieved by changing the zero-voltage period of the output voltage.

Next, induction heating results of stainless steel plates using the prototyped variable frequency type MERS power supply is described.

First, **Fig. 19** shows the width direction temperature rise characteristics of the stainless steel plates when the frequency was dynamically changed to 175, 475, and 1 000 Hz during the induction heating with the heating current fixed at 75 A. Increasing the heating frequency makes it possible to control the temperature rise characteristics at the edges.

Secondly, the possibility of heating temperature distribution control based on heating frequency is discussed below. **Figure 20** shows the temperature rise distribution in the width direction when the switching frequency was controlled. The heating currents were 40 A at all the switching frequency values. The temperature rise is the amount increased from the temperature before the heating (uniform in the width direction) and the maximum temperature rise at 725 Hz was determined as 100% in the figure. As the switching frequency is higher, the edge is more concentratedly heated. As the switching frequency is lower, the plate is heated to its center in rather flat distribution. This shows that the temperature distribution in the width direction can be controlled by the switching frequency.

Thirdly, the temperature control results at the head section in the

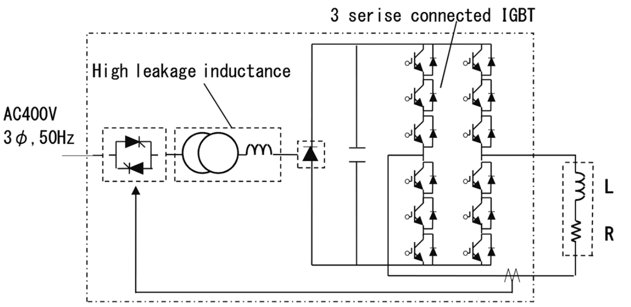


Fig. 15 System configuration of MERS experimental power supply[4)]

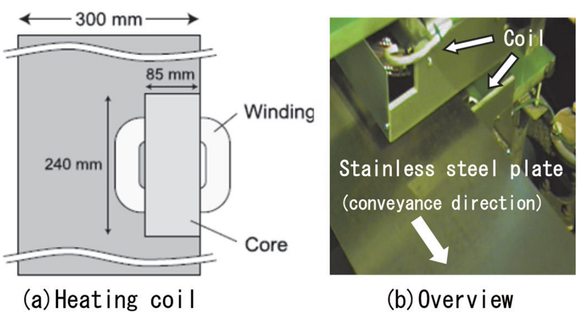


Fig. 16 Experimental facilities for stainless steel strip induction heating

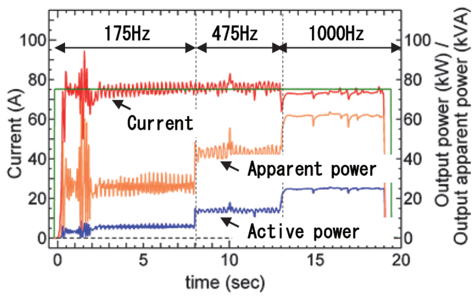


Fig. 17 Load current, coil input active power and apparent power while frequency was changed sequentially[4)]

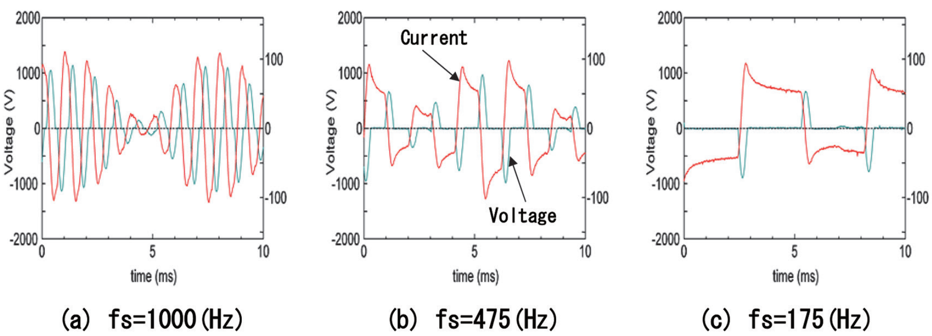


Fig. 18 Load voltage and current waveform at the time of frequency change[4)]

longitudinal direction of a stainless steel plate are described. With no stainless steel plate present between the upper and lower heating coils (at no load), a current of 725 Hz and 100 A was applied to the coils to start induction heating. **Figure 21** shows the result. At around 2.5 sec in Fig. 21, the tip of the material to be heated passed the center of the coils. The figure shows that the current was maintained at constant with the switching frequency maintained at 1 000 Hz from the no-load condition immediately after the operation began to the loaded condition: The current started flowing to the heating coil at the start of heating and when the stainless steel plate was put between the upper and lower heating coils, the induction heating was realized from the head section. In conventional induction heating in the resonance method with loads, whether a material to be heated presents between the upper and lower heating coils significantly changes the load impedance. Thereby, resonance conditions cannot be secured, which makes it impossible to supply a current from the power supply to the heating coil and induction heating is impossible at the head of a steel plate. On the other hand, it has been confirmed that the MERS method makes such induction heating possible because it does not involve resonance methods with materials to be heated.

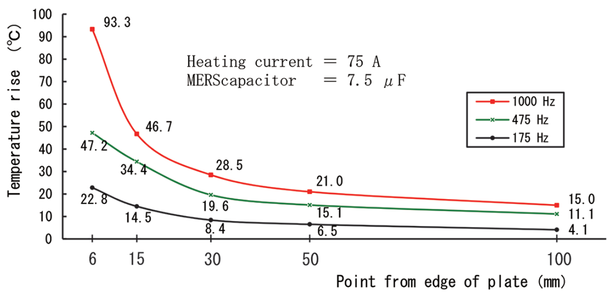


Fig. 19 Temperature rise along width direction of stainless steel strip[5)]

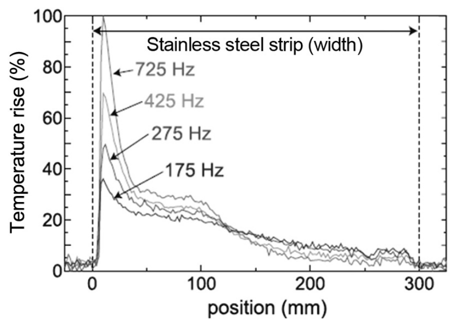


Fig. 20 Temperature rise distribution along width direction of the stainless steel strip with several frequencies[4)]

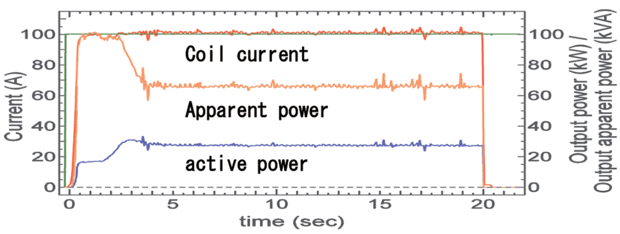


Fig. 21 Coil current, coil input active power and apparent power with fixed set-point of frequency and current[5)]

From the results above, we have learned the following items by using a variable frequency type MERS power supply as an induction heating power supply.

(1) Improvement in the heating efficiency by reduced loss on the power supply
(2) Realization of the control of heating temperature distribution in the width and thickness directions
(3) Realization of uniform heating throughout the length and width of materials to be heated

The heating controllability, which is a characteristic of induction heating, can be further improved and the induction heating method that used to be impossible can be realized. However, no resonant capacitor is provided on the load side in the variable frequency method, so all load current flows to the MERS power supply, which increases the semiconductor capacity. Dramatic improvement in the performance of semiconductor devices has made it possible to obtain high-performance devices rather easily, but to expand the application at manufacturing sites, the capacity of power supplies needs to be decreased.

4.2.2 Reduction of the capacity of MERS power supplies

Providing a pseudo-resonant capacitor on the load side reduces the reactance component of the load when viewed from the MERS power supply, which in turn can reduce the capacity of the power supply. As an example, a 200-kW MERS power supply for which the frequency can be changed from 10 to 8 kHz is studied below for a heating load with the resistance (R) of 200 mΩ and inductance (L) of 20 μH. **Figure 22** illustrates the circuit configuration of a variable frequency MERS power supply with reduced capacity. The capacity of the pseudo-resonant capacitor was determined as 30 μF and that of the MERS capacitor was determined as 20 μF such that zero-voltage switching is enabled in the range of 8 to 10 kHz. As shown in **Table 2**, the MERS power supply capacity can be reduced by 40% at 10 kHz and by 60% at 8 kHz. In both cases, the zero-voltage switching function was maintained as shown in **Fig. 23**, so a low-loss power supply is available.

5. Conclusions

This paper described MERS power supply circuits with a function for controlling the power factor of systems and the load current

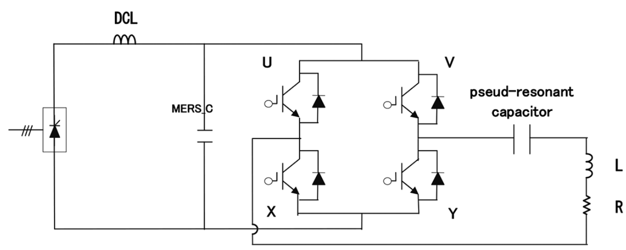


Fig. 22 Circuit configuration with pseudo-resonant capacitor

Table 2 Simulation result of capacity reduction

Frequency (kHz)	MERS		MERS with pseud-resonant C	
	Load current (A)	Capacity (kVA)	Load current (A)	Capacity (kVA)
10	1 000	1 270	1 000	750
8	1 155	1 380	1 155	540

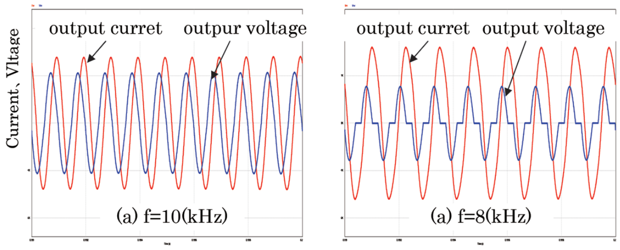


Fig. 23 Current and voltage waveform of MERS at the time of frequency change

frequency as high-functionality power supplies. The performance of the proposed MERS power supply was assessed in a test. The results showed that the energy of induction motors could be reduced by the power factor control and the heating controllability could be improved in an efficient way by controlling the frequency of induction heating power supplies.

With the advancement of power electronics as a background, the MERS technology is expected to improve the quality of products thanks to its high controllability and could be actively used in industrial circles as a technology to further improve the quality in addition to saving energy and reducing environmental stress.

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