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HIGH-FREQUENCY INVERTERS FOR INDUCTION HEATING

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1. FOREWORD

Induction heating system is widely utilized because of its merits as high efficiency, automatic operation, energy saving, easy temperature control, and improvements of working environment as well as many others. Also, through various frequencies and output powers are required due to the difference in heating conditions and heating capacities of the system, depending on the quality, form, heating temperature, temperature distribution of the heating material, this requirement is satisfied through adoption of high-frequency inverter using semiconductor elements that enable to obtain any frequencies at will.

Up to now, the mainstream of such systems was the thyristor HF inverter being applied, mainly, to the frequency range of about 500 Hz to 10 kHz, and its practical limit was more or less 20 kHz. However, in recent years, high-frequency inverters using new power devices such as power transistor, MOSFET, etc. were developed and it was made possible to answer the demand for the frequency range of 10 kHz to several hundreds kHz. Fuji Electric has now standardized its products for the frequency region inferior to 50 kHz, with thyristor HF inverters and transistor HF inverters.

This paper introduces the standard specifications and features of thyristor HF inverters and transistor HF inverters, as well as operating characteristics of transistor HF inverters that have been standardized recently and applications of high-frequency inverters.

2. SPECIFICATIONS AND FEATURES

2.1 Thyristor HF inverter

2.1.1 Standard types and specifications

Table 1 shows standard types and specifications of

Table 1 Thyristor inverters — standard types and specifications

Input	Three-phase, frequency 50 Hz/60Hz ±5%, voltage variation ±10%, input voltage varies depending on output capacity.							
Output frequency (kHz)	0.5		1		3		10	
Output	Output (kW)	Output voltage (V)	Output (kW)	Output voltage (V)	Output (kW)	Output voltage (V)	Output (kW)	Output voltage (V)
	190	600	150	600	80	600		
	450	600	350	600	210	600	60	400
	900	1,200	700	1,200	420	1,200	120	800
	1,600	1,200	1,260	1,200	760	1,200	340	800
	2,400	1,200	2,000	1,200	1,140	1,200	–	–
	3,000	1,800	–	–	–	–	–	–
	4,000	1,800	–	–	–	–	–	–
Output control range	5~100%							
Output control	Voltage control							
Frequency control	Self-controlled							
Cooling system	Water cooled (pure water circulating system)							
Cooling water temperature	5~35°C							
Type	Current-type inverter							

Note: Tye topmost column of "Output" is for air cooled type.

thyristor HF inverters. Fuji Electric has a wide experience of manufacturing various types of inverters as from air cooling small capacity inverters to water cooling large capacity inverter up to 4,000 kW, and completed a wide range of standarized series.

2.1 Features

Fig. 1 shows the basic circuit diagram of thyristorized HF inverter.

(1) High Efficiency

Thanks to proper selection of thyristor elements and their optimum use as well as bus-bar wiring structures matching to high frequencies, the frequency-conversion efficiency is as high as 97% (1 kHz).

(2) Stable Operation in wide range

It is a self-controlled inverter operating in synchronization with resonant frequency of the load circuit, and a stable operation is possible even when there is a large variation in the load impedance due to change in temperature and shapes of heating materials.

(3) Abundant Output Control Functions

As for the output control functions, output voltage control with current limiter is the standard practice, however constant power control and heating temperature control are also possible. In addition to that, programmable operation, automatic impedance matching system can also be incorporated.

(4) Easy Maintenance

The component equipment are made compact through adoption of unit system. For cooling system, that of pure water circulation method using a deionizer resine is adopted, so that their maintenance and inspection are extremely easy.

2.2 Transistor HF inverter

2.2.1 Standard types and specifications

Fig. 1 Thyristorized HF inverter basic circuit diagram

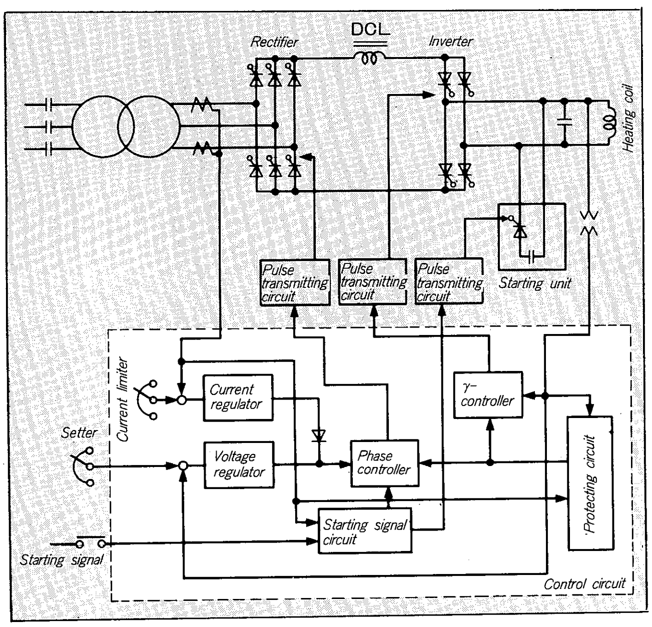


Table 2 shows the standard types of Transistor HF Inverters and their specifications.

2.2.2 Features

Fig. 2 shows a skelton diagram of the transistor HF inverter. Besides the high efficiency, wide-range stable operation and abundant output control function, this inverter has the following features.

Table 2 Transistor HF inverter — standard types and specifications

Input	Voltage	200 V, 220 V ±10%						
	Number of phases	3						
	Frequency	50/60 Hz ±5%						
Output	Frequency (kHz) / Output	1	3	5	10	20	30	50
	*3	O	O	O	O	O	O	O
	*5	O	O	O	O	O	O	O
	10	O	O	O	O	O	O	O
	20	O	O	O	O	O	O	O
	30	O	O	O	O	O	O	O
	50	O	O	O	O	O	O	O
	100	O	O	O	O	O	O	–
	200	O	O	O	O	O	–	–
	300	O	O	O	O	–	–	–
Output voltage	135 V or 270 V, square wave (with input of 200 V)							
Output control range	5 ~ 100%							
Output control	Power control or current control							
Frequency control	Self-controlled							
Cooling system	Water cooled							
Cooling water temperature	5 ~ 35°C							
Type	Voltage type inverter							

*Air cooled.

Fig. 2 Transistor HF inverter — skelton diagram

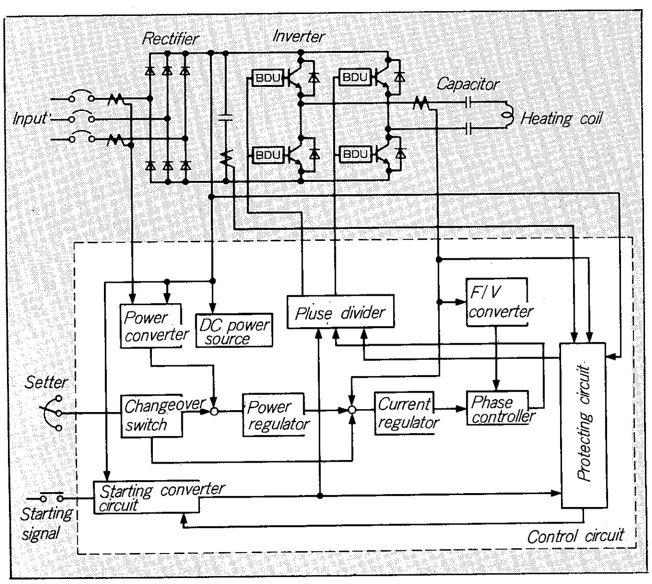


Fig. 3 Transistor HF inverter – output current waveform as starting

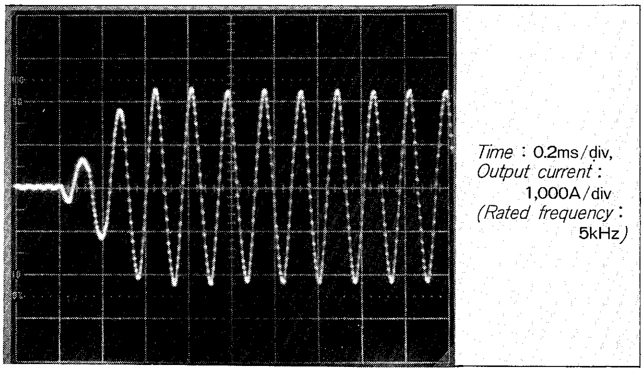
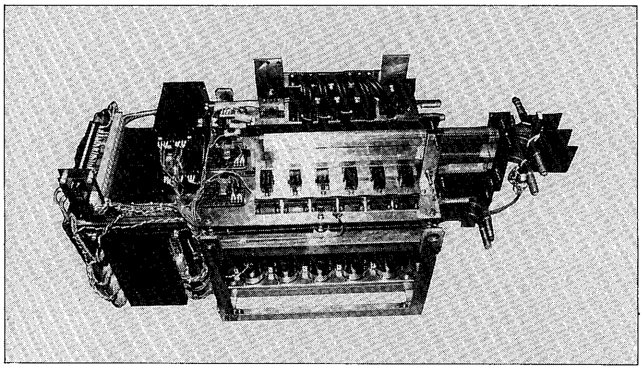


Fig. 4 Transistor stack



(1) Quick response

Fig. 3 shows the output current waveform, and as it is known from this figure, the waveform setting time is short and starting and stopping are frequently made, so that the equipment can cope with the diversification of heating mode, amplifying the field of its application.

(2) Protection against short circuit

This inverter equipment is protected from short-circuit by interrupting instantaneously the transistor base current by suppressing the abrupt rise of short-circuit current and by detecting the short-circuit current using its detecting CT, when an arm short-circuit and/or output short-circuit are produced.

(3) Compactness

The main circuit and control circuit consistute a single unit so that the construction of this inverter is compact. (*Fig. 4* shows its outer view.)

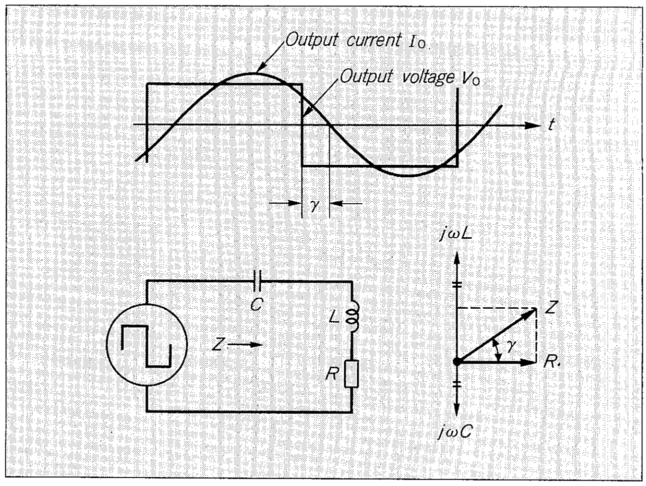
Within this unit system, many power transistors are parallel-connected, but as a bus-bar wiring so structured as that the current will be well balanced is adopted, there occurs little current unbalance between each element.

3. OPERATING CHARACTERISTICS OF TRANSISTOR HF INVERTER

3.1 Principle of operation

The high-frequency voltage tuned to series resonance-frequency of the load (L, C) is fed to the load through the inverter circuit. High-frequency power control is carried out by changing the phase angle γ of the inverter output voltage V_0 and output current I_0. *Fig. 5* shows the principle of operation, and the power supply will be turned to rectangular waveform output with the constant-voltage variable-frequency power source made out by the inverter and C is the substitution of series resonance condenser, while L-R is the substitution of heating coil by series equivalent inductance and resistance. The impedance Z of the load circuit is expressed by the following formula:

Fig. 5 Transistor HF inverter, principle of operation



$$|Z| = \sqrt{R^2 + (\omega L - \frac{1}{\omega C})^2} \quad \ldots\ldots (1)$$

and the real part R of Z is

$$R = |Z| \cdot \cos\gamma \quad \ldots\ldots (2)$$

And by substituting $V_0 = |Z| \cdot I_0$ to formula (2), we have:

$$I_0 = V_0 \cdot \cos\gamma / R \quad \ldots\ldots (3)$$

and the high-frequency power P_0 can be expressed by the following formula:

$$P_0 = I_0{}^2 \cdot R = V_0{}^2 \cos^2\gamma / R \quad \ldots\ldots (4)$$

Thus, by changing γ, P_0 can be controlled.

3.2 Operating characteristics

When the above formula (2) is transformed, we obtain:

$$\cos\gamma = R/|Z| = R/\sqrt{R^2 + (\omega L - \frac{1}{\omega C})^2} \quad \ldots\ldots (5)$$

When we change γ from the formula (5) above, if R, L and C are of a determined value, ω will be changed. The variation of ω, with variation of γ, and $\omega_0 = 1/\sqrt{LC}$ (resonant angular frequency), is obtained by the following formula:

$$\frac{\omega}{\omega_0} = \frac{\tan\gamma}{2Q} + \sqrt{\frac{\tan^2\gamma}{4Q^2} + 1} \quad \dots\dots\dots\dots\dots\dots (6)$$

whereas, $Q = \omega_0 L/R$

Fig. 6 shows the change of ω, when Q of the formula (6) is set as the parameter. In case of induction heating, it becomes evident that the Q of the heating coil is usually more than 2, and even by changing γ, the frequency change due to the change of resonance frequency is little.

In series resonance transistor HF inverter, when γ becomes negative, that is, the leading current, unstable operation is caused in the region of high frequencies of rapid reverse recovery charge of diode. In order that the stable operation be possible, the inverter controls γ to be normally positive, that is, I_0 should be lag current. And, when we substitute formula (5) to (4), we have:

$$P_0 = \frac{V_0^2 \cdot R}{R^2 + (\omega L - \frac{1}{\omega C})^2} \quad \dots\dots\dots\dots\dots\dots (7)$$

so that, even when there is a change in frequency, control of P_0 is possible; however, in case of those changing the resonance conditions in a large scale, as shown in *Fig. 7*, there is a risk that the inverter would enter momentarily into unstable region, not being able to obtain enough wide operating range. Thus, this system in which γ is controlled, the necessary operating range is obtained with sufficient margin, has an advnatage of being able to construct the stable operating range.

4. APPLICATION

Fuji Electric has used many HF inverters destined to various applications beginning from HF induction melting furnace, iron billet heater, induction heater for hardening and annealing and thin plate heater. The examples are introduced in the following.

4.1 High-frequency induction melting furnace

For high-frequency induction melting furnace, mainly thyristor inverters are used. Thyristore inverters are suitable for large capacities and Fuji Electric has already a record of manufacturing 340 units. *Fig. 8* shows an outer view of 500 Hz, 4,000 kW Inverter Cubicle.

4.2 Induction iron-billet heater for forging

Fig. 9 shows an outer view of Transistor Inverter-Adopted Billet Heater F180H, and *Fig. 10*, a dimensional comparison with a conventional type Billet Heater.

As this Heater is designed to have a higher efficiency, it has a heating efficiency so high that no products of other firms could attin: it attained an energy saving of about 15%, as compared with the conventional ones (330 kWH/T with heating to 1250°C).

4.3 Induction heater for hardening

As the transistor inverters have a good control re-

Fig. 7 Operating range of transistor HF inverter

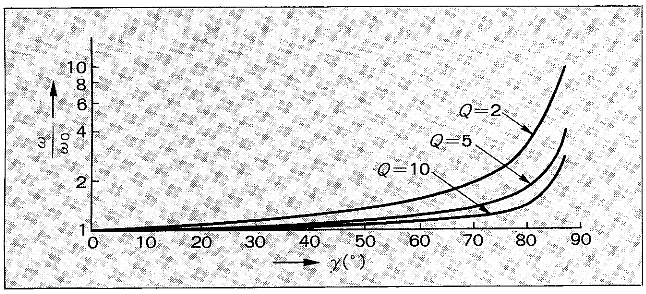


Fig. 6 Frequency variation vs. changes in γ

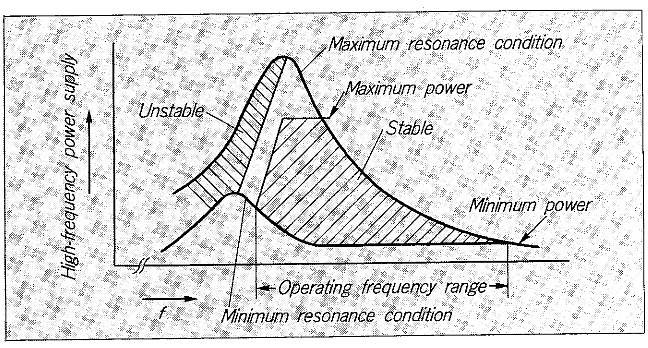


Fig. 8 Outer view of 500Hz 4,000kW inverter cubicle

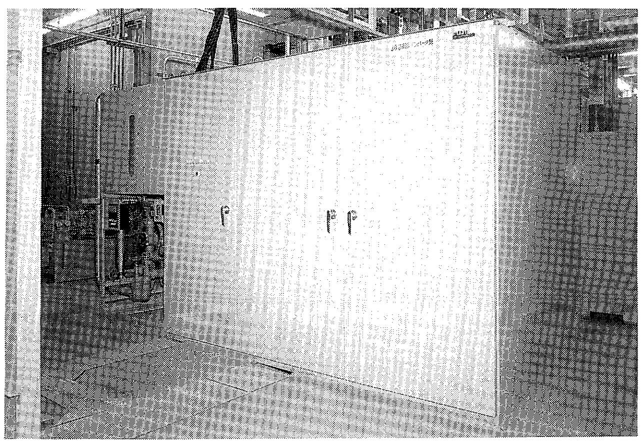


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Fig. 9 Outer view of billet heater F180H

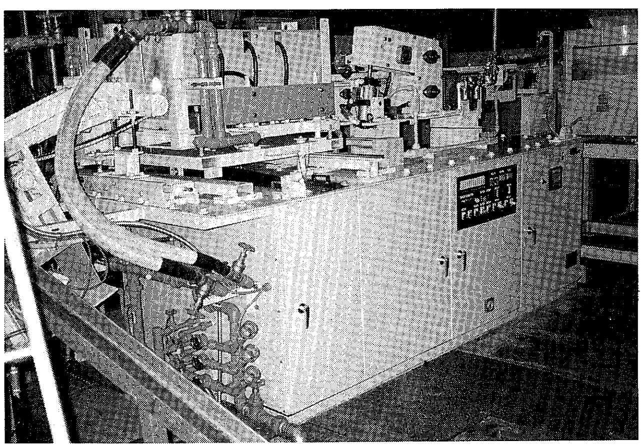

Fig. 10 Dimensional comparison with a conventional type billet heater

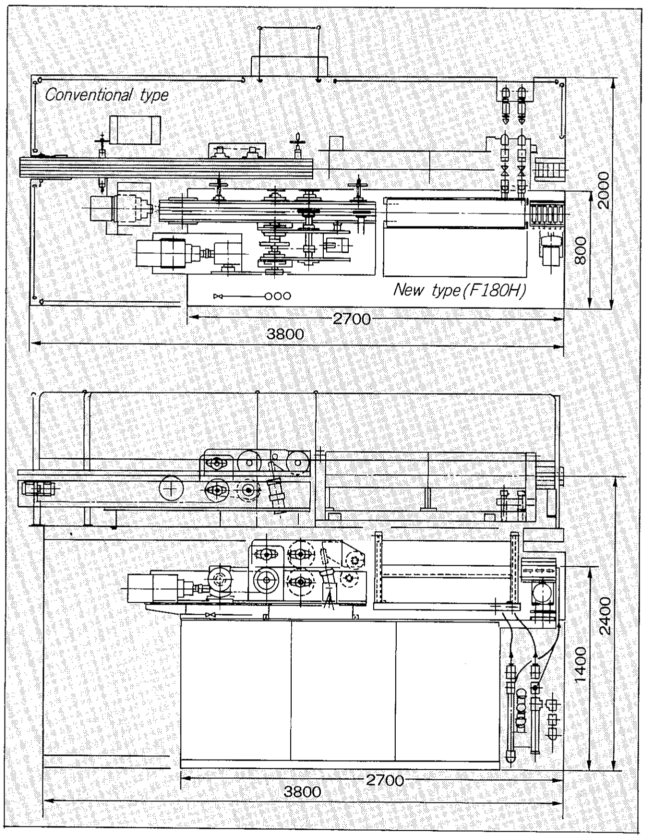

Fig. 11 Outline of double frequency inverter

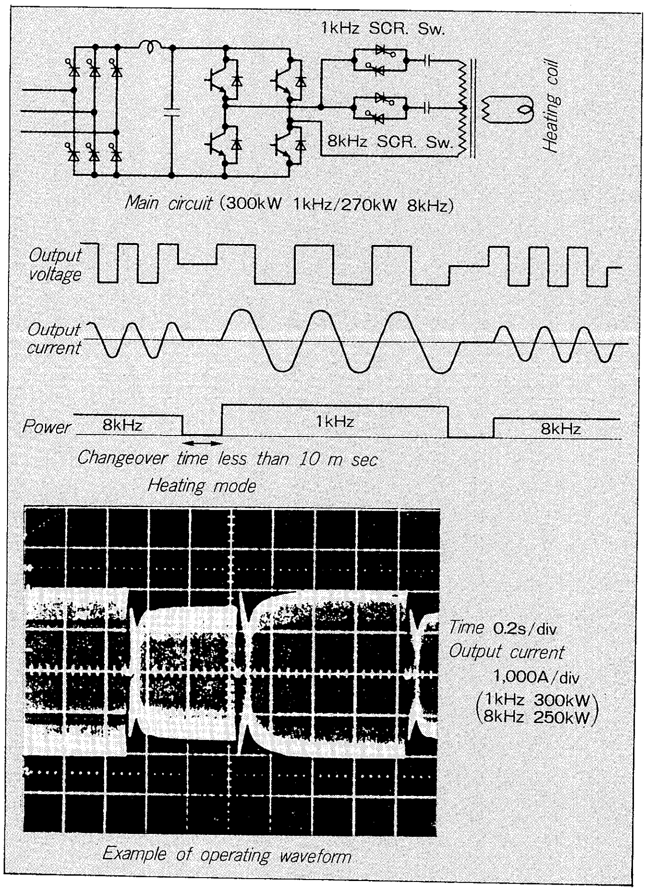

Fig. 12 Outline of high-power induction cooking range

sponse, and starting and stopping can be effectuated moment-aneously and frequently, they can cope with the diversification of heating modes, and process the heating of complicated shape metals within a short time. *Fig. 11* shows the outline of double frequency inverter (1 kHz, 300 kW/8 kHz, 270 kW) that has been set to practical use for the first time in this sector of industries. The inverter carries out time sharing operation through instantaneous changeover of frequencies from 1 kHz to 8 kHz or vice versa. (Patent pending)

4.4 Induction cooking ranges

Fig. 12 shows an outline of high-power induction cooking range. It is mainly used for business. The units are available with rated input voltage of 200 V, single or three-phase, and in two standard versions with rated output of 3 kW and 5 kW.

5. CONCLUSION

This paper introduced the high-frequency inverter for induction heating and described the examples of its application to other products. It is believed from now on, that making inverters higher in frequency will be steadily advanced, thanks to development of high frequency devices, while making intelligent of the induction heating system will be promoted still further for automatization and energy saving. We Fuji Electric intend to epand through adoption of power MOSFET, the machine types to be used for 100 kW to more than several 100 kHz class and, at the same time, will propel further digitalization of products in order to cope with the more and more diversifying demands for more of multifunction.

Also, as the high-frequency inverters for induction heating at present are mainly for large-capacity installation, the influence from harmonics of power source cannot be neglected. At present, we take up measures for the matter through use of 12-pulse rectifiers and L-C filters, however, it is our urgent task to develop harmonic decaying inverter including low-cost active filters.