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High-Performance Adjustable AC Drive Systems

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Abstract:

We described the characteristics and introduction of cyclo-converters, GTO (gate turn-off thyristor) inverters, and IGBT (insulated-gate bipolar transistor) inverters as high-performance adjustable AC drive systems. High-performance adjustable AC drive systems were first introduced practically for vector control applications in the 1980s and are now applied as substitutes for conventional DC drive systems. With the development and commercialization of GTO inverters in recent years, the high-performance adjustable AC drive systems have come to be employed in small- to large-capacity and low- to high-peed uses.

1. Introduction

High-performance adjustable AC drive systems could not have been established without the development of larger-capacity, higher-speed and lower-loss power semiconductor devices and the realization of vector control and PWM (pulse width modulation) control by high-performance microcomputers. Highly rated for their control performance, the high-performance adjustable AC drive systems have been introduced into continuous annealing and processing lines (CAPLs) and continuous galvanizing lines (CGLs) constructed in recent years, and are being substituted for conventional DC drive systems when replacing old hot and cold strip mill drives.

The advantages of adopting the high-performance adjustable AC drive systems can be considered as follows. Besides the benefits derived from the high accuracy (speed control accuracy and torque control accuracy) of controllers, the use of AC motors offers the following benefits as well:

1) AC motors provide a large unit capacity (space savings).

2) The absence of a commutator enables a structure with good maintainability and excellent environmental resistance.

3) A large rate of change of current (di/dt) raises response.

The introduction of a high-performance adjustable AC drive system improves not only maintainability but also response and speed matching. These characteristics greatly improve the yield by improving the accuracy of automatic gage control (AGC) on rolling lines, and stabilizing strip tension and preventing slip marks on processing lines.

2. Applicable Scope and Trends of Adjustable AC Drive Systems

At present, high-performance adjustable AC drive systems come in three types: cyclo-converters, GTO (gate turn-off thyristor) inverters, and IGBT (insulated-gate bipolar transistor) inverters. Their applicable scope corresponds to the speed and output of motors or loads, as shown in **Fig. 1**[1].

The trends of high-performance adjustable AC drive systems in recent years are briefly summarized below:

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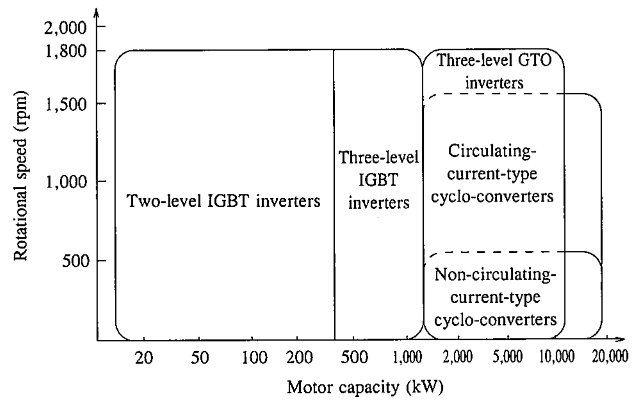


Fig. 1 Applicable scope of adjustable AC drive systems

Transistor inverters

(1) The switching devices of transistor inverters have advanced from power transistors to insulated-gate bipolar transistors (IGBTs) with low loss and high speed. The applicable scope of transistor inverters has expanded with the commercialization of three-level inverters or neutral point-clamped (NPC) inverters.

GTO inverters

(2) GTO inverters, developed to fill the intermediate capacity range between the transistor inverters and the cyclo-converters, have made steady progress and now occupy a position in the market for high-performance adjustable AC drive systems.

Cyclo-converters

(3) The use of light trigger thyristors developed for power purposes has made it possible to employ cyclo-converters in larger-capacity applications.

3. Characteristics and Introduction of Adjustable AC Drive Systems

Traditionally, cyclo-converters were used for large-capacity motors like hot strip mill motors, and transistor inverters were used for small-capacity motors like those installed on processing lines. In the absence of appropriate systems for medium-capacity motors installed as main drive motors for cold strip mills and processing lines, old DC drive systems and expensive cyclo-converters had to be adopted in these applications. Against this background, the GTO thyristors initially adopted for the "Nozomi" Shinkansen trains were improved and applied as GTO inverters. GTO inverters are now delivered in increasing numbers for medium- and large-capacity motors.

This chapter describes the characteristics and introduction of cyclo-converters, GTO inverters, and transistor inverters (IGBT inverters) applied as high-performance adjustable AC drive systems for the steel rolling and processing lines noted above.

3.1 Cyclo-converters

3.1.1 Characteristics of cyclo-converters

The thyristors employed as the switching devices in cyclo-converters have a higher thermal capacity than other semiconductor devices. The thyristors are low in switching speed but can be connected both in parallel and in series. This characteristic makes it possible to increase the output voltage and current-carrying capacity. The cyclo-converter can be regarded as an adjustable AC drive system that can easily accommodate loads of large capacity and overload rate. Cyclo-converters composed of light trigger thyristors are available to a maximum capacity of 15 MVA.

Cyclo-converters can be classified into the circulating-current type and the non-circulating-current type according to the AC waveform output. These two types are compared in **Table 1**. The non-circulating-current type has a dead time of 1 to 3 ms for switching between forward current and reverse current. This dead time results in a higher torque ripple compared with that obtained with the circulating current type. The maximum output frequency is held low under this constraint. Since the forward and reverse converters are not used at the same time, the power transformer can be shared and used after switching, and the amount of wiring work can also be reduced. As a result, the non-circulating-current type provides a less expensive system than the circulating-current type.

The large torque ripple of the non-circulating-current type precluded its adoption in steel processing lines that emphasize product quality (as represented by surface defects) (refer to "10. Examples of application at Nippon Steel" in **Table 1**). Since the non-circulating-current type is widely used in foreign countries, it is expected to find increasing usage in Japan as well. The circulating-current type offers the advantage of simplifying the reactive power compensator by controlling the circulating current. The type of cyclo-converter to adopt is selected by considering these factors.

3.1.2 Introduction of cyclo-converters

Cyclo-converters are operated with a lagging power factor via the phase control of the thyristors and have a high harmonic content. Measures to improve the power factor and reduce the harmonic content are required. **Table 2** shows the calculated effectiveness of measures to improve the power factor of a 72-arm circulating current-type cyclo-converter at the No. 4 cold strip mill of Nippon Steel's Yawata Works[2].

The targeted power factor is set at a high value to avoid increases in the primary power capacity. If the power supply capacity is greater than required, there is no need to set the targeted factor at such a high value. The results of calculation showed that when an existing synchronous motor was used as a synchronous phase modifier, the total required capacity of the power-factor-improving capacitors and harmonic filters was still 29 MVA. The space required to install these devices was estimated at 150 m^2. The values given in **Table 2** change with the impedance of the power supply system and existing load-carrying capacity, among other factors. They should be used as reference values only.

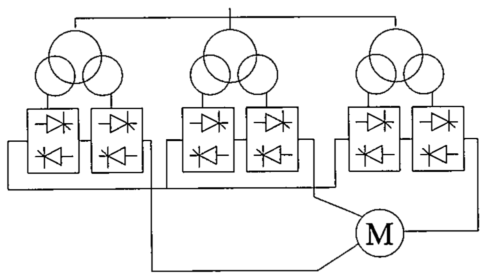
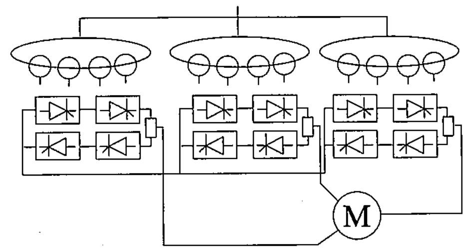
At the Yawata No. 4 cold strip mill had small load variations, small-capacity power-factor-improving capacitors sufficed. When a cyclo-converter is applied to a line with large load variations such as a hot strip mill, a static var controller/compensator (SVC) or static var generator (SVG) is required as the reactive power compensator. Although the SVC is inexpensive and frequently used, it generates harmonics due to the use of thyristors as the switching devices. Some measure must be taken against the harmonics, including those generated by the thyristors. Since SVG uses GTO thyristors as the switching devices, the harmonic components are small enough to be ignored. Being expensive, the use of the SVG is often restricted to applications where a high response is demanded.

3.2 GTO inverters

3.2.1 Characteristics of GTO inverters

Partly due to the increased diameter of the component device of GTO inverters, these inverters can be applied to large-capacity

Table 1 Performance and application examples of cyclo-converters

	Cyclo-converter	
	Non-circulating-current-type cyclo-converter	Circulating-current-type cyclo-converter
1. System configuration		
2. Maximum capacity/set	•72 arms: 9.4 MVA (17.5 MVA for light trigger thyristors) • 36 arms: 4.7 MVA (devices connected in parallel for larger capacity)	• 72 arms: 8.26 MVA (15.4 MVA for light trigger thyristors) • 36 arms: 4.13 MVA (devices connected in parallel for larger capacity)
3. Output voltage	• 72 arms: 3.3 kV (5 kV for light trigger thyristors) • 36 arms: 1.5-1.65 kV	• 72 arms: 3.3 kV (5 kV for light trigger thyristors) • 36 arms: 1.5-1.65 kV
4. Output frequency	1/3 of commercial input	4/5 of commercial input
5. Field weakening range	1 : 3	1 : 6
6. Response speed : Speed control : Torque control	40 rad/s 600 rad/s	60 rad/s 800 rad/s
7. Torque ripple	• 72 arms: 2.0% for IM*1 and 2.0% for SM*2 • 36 arms: 2.0% for IM*1 and 7.5% for SM*2	• 72 arms: Almost 0% for IM*1 and 0.7% for SM*2 • 36 arms: Almost 0% for IM*1 and 0.7% for SM*2
8. Converter efficiency	99%	98.5%
9. Effect on power supply : Power factor : Harmonics	• SM*2 : 0.65-0.85 • IM*1 : 0.6-0.7 (72 arms) 0.45-0.55 (36 arms) • $f_H = (*6n \pm 1)f_s \pm 6mf_0$ m,n:1,2,3,···· where f_H = harmonic frequency; f_S = power supply frequency; f_0 = output frequency; and * = 12n for 12-pulse type	• SM*2 : 0.65-0.75 • IM*1 : 0.6-0.65 (72 arms) 0.4-0.5 (36 arms) • $f_H = (*6n \pm 1)f_s \pm 6mf_0$ m,n:1,2,3,···· where f_H = harmonic frequency; f_S = power supply frequency; f_0 = output frequency; and * = 12n for 12-pulse type
10. Examples of application at Nippon Steel	*Nagoya roughing mill 10,000 kW *Oita sizing mill 6,100 kW *Oita hot strip mill flying shear 2×1,480 kW	*Kimitsu hot strip mill finishing train (SM drive) 11,250 kW *Oita hot strip mill finishing train (SM drive: light trigger thyristors) 12,000 kW *Yawata new cold strip mill (IM drive) 7,400 kW *Hirohata No. 1 cold strip mill (IM drive) 4,500 kW *Hikari No. 1 cold strip mill 5,000 kW
11. Amount of electrical work	• Extensive wiring work is required, but it does not exceed the wiring work required for the circulating-current type • Field assembly and test of transformer	• Greatest amount of wiring work is required between the transformer and cyclo-converter • Field assembly and test of transformer
12. Auxiliary equipment	Example of 22-kV power supply at Nagoya • Reactive power compensator and harmonic filter are required	• Depending on size of power supply, harmonic filter and reactive power compensator (static capacitor + circulating current control) are required

*1 IM: Squirrel-cage inductor motor, *2 SM: Synchronous motor

Table 2 Results of calculation of measures for improving power factor of cyclo-converter at Yawata No. 4 cold strip mill

Item	Description
Total load carrying capacity of cyclo-converter	25.8MW
Aim power factor	99.5%
Power factor improving capacity	38.5MVA — Power factor improving capacitor : 20MVA — Harmonic filter : 9MVA — Synchronous phase modifier (SM) : 9.5MVA
Reactive power compensation	Circulating current ΔQ:10VA

loads. They now compete with cyclo-converters in the capacity region of 10 MVA or less. Their characteristics are as follows:

(1) GTO thyristors, which are self-switching devices, are adopted in the AC/DC converter section to permit operation with a power factor of unity, resulting in the increased utilization factor of the power supply equipment. High-speed switching produces a waveform closer to the sinusoidal waveform, making it possible to reduce the harmonic content of the power supply. These advantages eliminate the need for measures against the harmonics and reduce costs for the power supply equipment.

(2) Since a high output frequency is obtained, a motor with a higher speed and lower torque can be used for the same capacity. As a result, the cost for the unit motor can be reduced.

(3) The construction of power transformers is simpler than that of cyclo-converters, field assembly work is eliminated, and cable installation between the transformer and the converter is simplified.

GTO inverters have the above advantages, but call for auxiliary equipment such as pure water coolers to remove the heat generated by the switching loss and snubber loss characteristic of GTO devices. The converter efficiency of GTO inverters, including the converter section, is about 96%. This low efficiency is one of the factors compelling the development of lower-loss devices to replace the GTO devices. This loss occurs even under no load, which means that the GTO inverter is an adjustable AC drive system suited for lines continuously running at high speed. When the GTO inverter is to be applied to an intermittent load, an appropriately designed no-load control method is desirable (the switching frequency should be lowered or the switching should be turned off).

The performance data and application examples of the GTO inverters are listed in **Table 3**, together with those of the IGBT inverters to be described later.

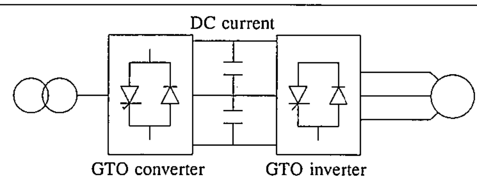
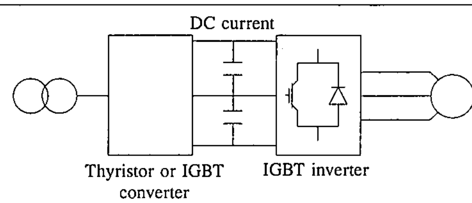
3.2.2 Introduction of GTO inverters

The introduction of a GTO inverter at the Yawata No. 4 cold strip mill is described as the first application of the GTO inverter. The installation of a 72-arm circulating current-type cyclo-converter was initially planned at the Yawata No. 4 cold strip mill, but a GTO inverter was adopted instead for the following reasons. First, the GTO inverter matched the motor capacity required; second, operation with a unified power factor was attractive at the No. 4 cold strip mill, where the power supply capacity was limited; and third, the GTO inverter was judged to be the best system for high-speed rolling of the light-gage strip in the future.

The torque ripple was a maximum of 0.5% (refer to **Table 3**), which caused apprehensions about surface defects on the product. These apprehensions were allayed, however, by the results of a survey conducted at the Kimitsu No. 2 cold strip mill and at the Yawata No. 4 cold strip mill and new cold strip mill. These results eliminated uncertain factors about GTO inverters and enabled the introduction of a GTO inverter at the Yawata No. 4 cold strip mill.

The results showed that the torque ripple of 0.5% was not large enough to affect product quality. When the torque ripple was measured after the introduction of the GTO inverter at the Yawata

Table 3 Performance and application examples of three-level NPC inverters

	Three-level NPC inverter	
	GTO inverter	IGBT inverter
1. System configuration		
2. Maximum capacity/set	4,000 or 10,000 kVA (Units are connected in parallel for larger capacity.)	1,500 kVA (Units are connected in parallel for larger capacity.)
3. Output voltage	4,000kVA : 2,400V 10,000kVA : 3,300V	840V
4. Output frequency	60Hz	60Hz
5. Field weakening range	1 :6	1 :6
6. Response speed: Speed control : Torque control	80 rad/s 1,000 rad/s	80 rad/s 1,000 rad/s
7. Torque ripple	≤ 0.5%	≤ 0.5%
8. Converter efficiency	• 0.98 for inverter and 0.96 for combination of converter and inverter Loss is unchanged under no load.	• 0.98 or more for inverter Loss is unchanged under no load.
9. Effect on power supply: Power factor : Harmonics	• Operation with power factor of almost 1.0 is possible with adoption of GTO converter. • Generally, no measures are required against harmonics, but it should be noted that communication interference may be caused by many higher-order harmonics.	• Since IGBT inverters are small in capacity, thyristor converters are generally adopted, and the power factor is comparable to that of DC motors. • Generally, no measures are required against harmonics.
10. Examples of application at Nippon Steel	*Yawata No. 4 cold strip mill (IM*1 drive) 5,700 kW *Kamaishi high-speed wire rod mill 1,300 kW	*Yawata rail and shape V4 mill 2,000 kW
11. Amount of electrical work	• While only a small amount of wiring work is required, pure water stainless steel piping work is needed.	• Only a small amount of wiring work is required.
12. Auxiliary equipment	• Pure water circulation unit for converter cooling • Industrial water cooling and feed pumps if necessary • Measures against harmonics, depending on size of power supply	• No particular equipment (power quality with use of thyristor converter is comparable to that of DC drive system, air cooled)

*1 IM: Squirrel-cage inductor motor

Table 4 Improvement in gage accuracy

	Steady-state portion	Acceleration and deceleration portion
Old DC motors ($\omega_c \fallingdotseq 6$ rad/s)	Base	Base
New AC motors + PC*1 function enhancement	△50% improvement on base	△80% improvement on base

*1PC : Programmable logic controller

Table 5 Performance data of representative IGBT inverter

		Devices (converter/inverter)	Thyristors/IGBTs (2 levels)
		Rated output	-400 kVA (double 800 kVA)
Input		Converter input voltage	AC600V
		Permissible variations (voltage/frequency)	±10%/±5%
		Common power supply system	Reverse parallel thyristor system
		Converter drive system	DC output voltage controlled constant (DC 600 V)
Output		Output voltage	AC420V
		Maximum frequency	90Hz
		Overload	150%×60s
Inverter control		Modulation system	PWM*1
		Control system	• Speed control, torque control, and speed control with droop • Speed control with automatic field weakening (option/sensorless system)
	Switching (inverter)	Frequency	1.5kHz
		Synchronous/asynchronous	Asynchronous
Control performance		Speed control accuracy	±0.01% (±0.5% for sensorless system)
		Speed control range	0.5-100% (2-100% for sensorless system)
		Speed control response	ω_c = 60 rad/s (20 rad/s for sensorless system)
		Torque control accuracy (linearity)	±5%
		Torque control range	1 : 10
		Field weakening range	1:3 (1:5 for option)
Regeneration system			Power supply regeneration system

*1PWM : Pulse width modulation

No. 4 cold strip mill, it was as low as 0.2%[3]. The GTO inverter system essentially requires no measures against power supply harmonics. Since the GTO inverter served multiple loads (six stands and tension reels), the phases of the respective power transformers were combined into a 12-phase equivalent circuit to reduce the amount of lower-order harmonics produced.

The introduction of the GTO inverter at the Yawata No. 4 cold strip mill improved the strip gage accuracy in comparison with the old DC drive system, as shown in **Table 4**[3]. (This improvement in the gage accuracy includes the advantage of simultaneous modification of the thickness-gage-sampling circuit.)

3.3 IGBT inverters

3.3.1 Characteristics of IGBT inverters

Thyristors were initially used as inverter elements. The commercialization of inexpensive power transistors (bipolar transistors) promoted the trend toward low-capacity AC motors. This method has been introduced into the continuous annealing and processing lines (CAPLs) and continuous galvanizing lines (CGLs) constructed in recent years. At present, voltage-sourced-type insulated-gate bipolar transistors (IGBTs) with low loss are used to improve the converter efficiency. Transistor inverters were originally intended for low-capacity motors, but were later enhanced for rail, shape, and bar mill drive motors as the capacities of devices expanded and the three-level inverters were commercialized. (Refer to "10. Examples of application at Nippon Steel" in **Table 3**.)

Table 5 lists the performance data of a representative IGBT inverter. Thyristors or IGBTs are used in the converter section. Operation at a unified power factor is slightly advantageous for low-capacity loads like steel processing lines. In this type of application, a common power supply using thyristors is often employed. Since the IGBTs are devices capable of switching at high speed, the inverter can run at a high carrier frequency of 1.5 to 3 kHz, and the output current waveform is close to the sinusoidal waveform. As a result, a nearly ideal drive system can be realized with little torque ripple. (In reality, the carrier frequency is determined by considering the switching loss, among other factors.)

3.3.2 Introduction of IGBT inverters

IGBT inverters have been introduced at many steel plants and have encountered few performance problems. Following is a description of the sensorless vector control system introduced at the Yawata No. 1 continuous annealing line (CAL) when its old motors were replaced.

The old motors used in the Yawata No. 1 CAL were small in capacity and all fell within the applicable scope of IGBT inverters. In replacing them, it was decided to emphasize equipment and installation costs and to introduce a sensorless vector control system for helper groups. The sensorless system can be introduced with greater advantage into steel processing lines where many small-capacity motors are installed. As in the case of the CAL, the drive systems of steel processing lines with furnaces require highly accurate torque control and speed control to prevent heat buckles, walking, and product defects. The accuracy of the sensorless system is inferior to that of the sensor system in both speed control and torque control (refer to **Table 5**). For this reason, the introduction of sensorless vector control systems was limited to steel processing lines with little possibility of defects occurring: for example, an electrical steel processing line using carbon rolls.

We were not sufficiently confident when we decided to introduce a sensorless vector control system into the Yawata No. 1 CAL. Since helper drive control is usually provided with drooping characteristics, we judged that some degree of speed error was permissible. The motors were constructed for later retrofitting of sensors. The configuration of the Yawata No. 1 CAL is shown in **Fig. 2**. For line drive control, tension control is performed by the tension-setting device (TD) after the No. 3 bridle roll unit (BR), and speed control is performed by the No. 4 bridle roll unit. Forty-five motors, ranging from 3.7 to 11 kW in capacity, are installed for the helper drives in the heating zone, soaking zone, slow-cooling zone, and rapid-cooling zone between the tension-setting device and the No. 4 bridle roll unit. All of these motors are of the sensorless type.

In the adjustment stage, it was confirmed that there were no large errors in roll peripheral speed and speed estimate. In the strip-threading test stage, the CAL was adjusted, starting with a relatively large droop rate of 5%, by considering the possible occurrence of roll and strip defects. After the CAL was started up, the strip processed through the CAL was inspected for detects at the inspection line. The inspection results were equal or superior to those obtained before the installation of the sensorless vector control system. Now that the sensorless system has proved effective in the Yawata No. 1 CAL, it is expected to find additional applications in CAPLs and other steel processing lines.

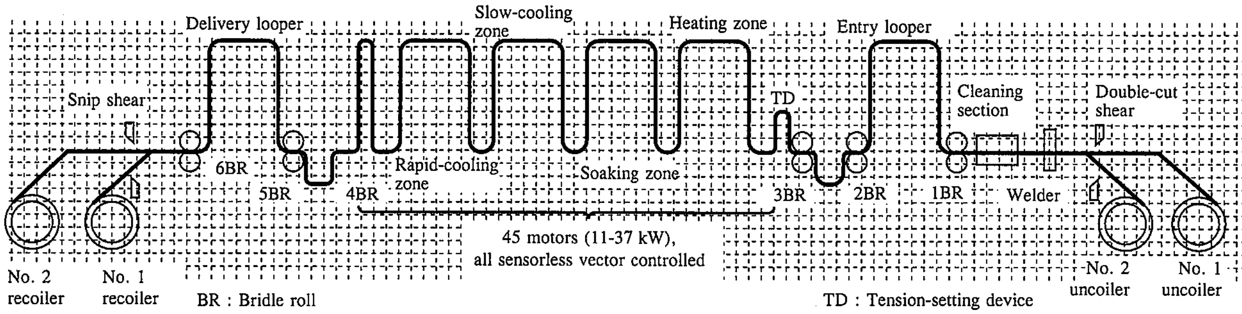


Fig. 2 Configuration of Yawata No. 1 CAL

4. Conclusions

The characteristics and introduction of cyclo-converters, GTO inverters, and IGBT inverters, which are high-performance adjustable AC drive systems, have been described. Cyclo-converters and GTO inverters, both designed for large-capacity motors, have similar applications. Drive systems must be selected by considering their respective characteristics. The main factors are measures to improve the power quality for cyclo-converters, and converter loss and auxiliary cooling equipment for GTO inverters. The conditions of electric power and water available at project sites and other relevant factors applicable there must be comprehensively evaluated. The introduction of a sensorless vector control system has been discussed with respect to IGBT inverters. Since the sensorless system provides cost savings and improves system reliability, we are convinced that it will find increasing usage in steel processing lines.

At present, advanced functions, including shaft torsional vibration suppression, are prepared as auxiliary control functions for high-performance adjustable AC drive systems. Simplification of adjustment and maintenance will call for enhancement of the automatic tuning function and development of a failure analysis system.

References

1) Mitsubishi Electric catalog MELVEC-1200
2) Hakata, H. et al.: Application Strategies for AC Rolling Mill Drives. IEEJ Technical Meeting on Industrial Application, August 25 1992, p. 148
3) Terasaki, et al. : Technical Meeting on Metal industries Div., IEEJ July 27 1995,