History of Power Electronics for Motor Drives in Japan

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Abstract—**Power electronics today is one of a wide range of well defined technologies. The object of this paper is to review the 50-year history of motor drives in three major application fields, which are the industrial field, the railway, and the elevator in Japan. Furthermore, the progress of power semiconductors and cooling systems, which are prerequisites for power electronics, are summarized in historical order. Important inventions from overseas and their impact on Japanese industries are also introduced.**

Keywords—**History, Power electronics, motor drive, Japan**

I. INTRODUCTION

Power electronics today is one of a wide range of well defined technologies. It has a key role in the transformation and adaptation of electrical energy between the supplier and the user. As the motor drive is one of major application fields of power electronics, a lot of developments have been achieved and evolutional systems have been produced for motor drives in Japan. The emergence of many kinds of power semiconductors and the digital control technology such as the use of microprocessor, made it possible to realize epoch-making products.

In this paper, the 50-year history of power electronics for drive systems in Japan is summarized. In the first place the developments of power semiconductor devices and cooling systems are stated. Afterwards various converters and their control methods are sorted out and classified with historical events. Finally the developments in three application fields, which are the industrial field, the railway, and the elevator, are presented with the introduction of major products.

II. POWER SEMICONDUCTTOR DEVICES

The invention of the transistor in 1948 revolutionized the electronics industry. Semiconductor devices were first used in low power level applications for communications, information processing, and computers. In 1958, General Electric developed the first Tyristor, which was at that time called SCR [1]. With the arrival of Thyristors, the era of power electronics began. The progress of power semiconductor devices is summarized in Fig. 1. Since the production of the 400 V 80 A Thyristor with the wafer of 20 mm's in diameter in 1961 in Japan, development work led to a constant improvement in the semiconductor components and the assorted circuit technology, resulting in rapid development and the extension of the classical converter technology in Japan as well as in the USA and Western Europe. Since then, a steady growth in the ratings of the Thyristors and their operating frequency has enabled extension of their application to motor control. The increase in current ratings of the Thyristors has been possible by the availability of larger-diameter silicon wafers. Single devices are now manufactured with wafers of 6 inches in diameter. The high voltage blocking capability of the Thyristors has been achieved by the ability to produce very uniformly doped high-resistivity N-type silicon by Neutron Transmutation Doping (NTD) since the 70s. As the NTD process allows the conversion of a silicon isotope into phosphorus by the absorption of a thermal neutron, a very uniform doping can be produced throughout the wafer. Especially the large investment in the Japanese steel industry in the 70s gave impetus to the development of the Thyristors of higher ratings. The 2500 V Thyristor and the 4000 V Thyristor were respectively developed for the 750 V DC motor in 1967 and the 1200 V DC motor in 1976. The 8000 V 3500 A light-triggered Thyristors with 6 inch wafers were used for the DC power transmission system in Kii channel of Japan in 2000.

Since around 1975, more turn-off power semi-conductor elements were developed and implemented during the next 20 years, which have vastly improved modern electronics. Included here are improved bipolar transistors (with fine structure, also with shorter switching times), Field Effects Transistors (MOSFETs), Gate Turn-off Thyristors (GTOs) and Insulated Gate Bipolar Transistors (IGBTs).

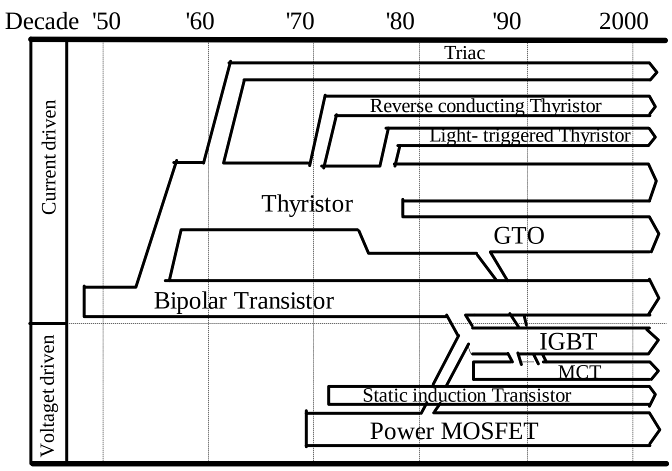


Fig. 1. Progress of power semiconductor devices.

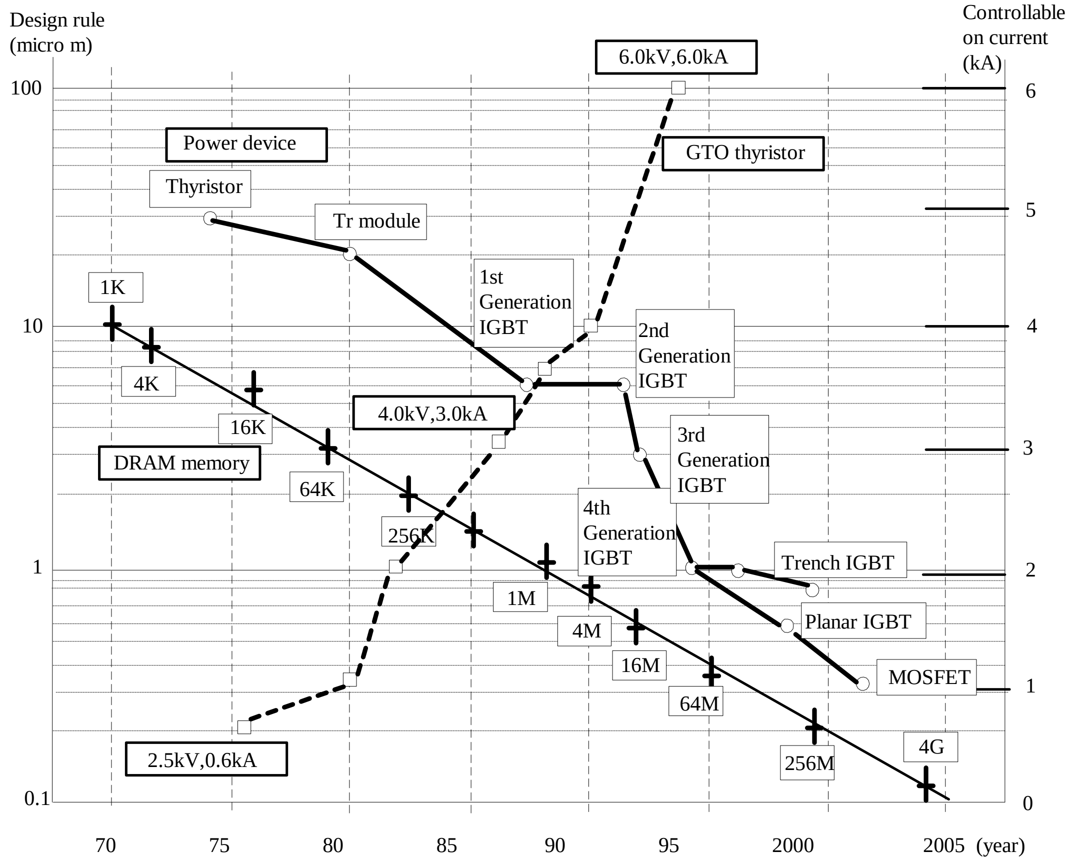


Fig. 2. Historical review on devices and their design rules.

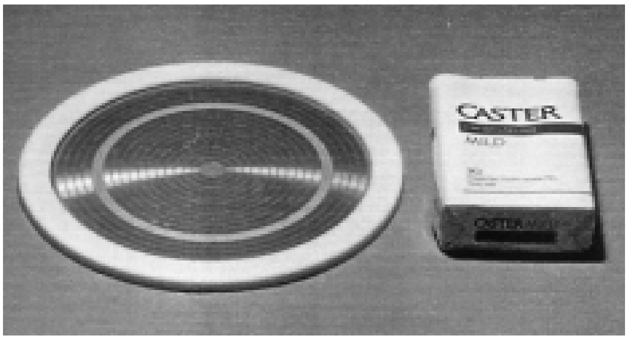


Fig. 3. 6000 V 6000 A GTO element with a 6 inch wafer.

The development of the GTO was the key to extending the power rating of many systems to megawatt range. It has found widespread application to traction drives. The growth in blocking voltage capability of GTOs with their controllable currents is shown in Fig. 2. Devices have been developed to that with capability for 6000 V and switching 6000 A, using the 6 inch wafer as shown in Fig. 3.

The power MOSFET, which was developed in the 70s using the Metal-Oxide-Semiconductor (MOS) technology originally developed for CMOS integrated circuits, has been used for low-voltage, high-frequency applications. Although the power bipolar transistors had been .extensively used for motor applications in the 70s and the 80s, bulky and expensive control circuits were needed, as the bipolar transistor is a current-driven device. For this reason, the power bipolar transistor was replaced by the IGBT in the 90s. The introduction of IGBT in 1982 in the USA was aimed at providing a superior device for the medium-power applications by attempting to combine the best features of the power bipolar transistor and the power MOSFET. In Japan, the 600 V and 1200 V IGBTs (so-called first generation) were developed respectively for the 200V inverters and the 400V inverters in 1986. Afterwards the alternation of generations took place until the 5th generation today and the improvement to attain shorter switching times and lower switching losses, has been constantly achieved. The power loss of 5th generation IGBT is reduced to a fifth of that of 1st generation IGBT at the inverter operation and an IGBT-based Intelligent Power Module (IPM) rated at 6500 V 600 A (shown in Fig. 4) has been developed recently in Japan.

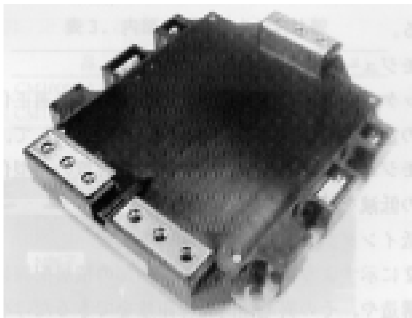


Fig. 4. 6500 V 600 A IGBT module.

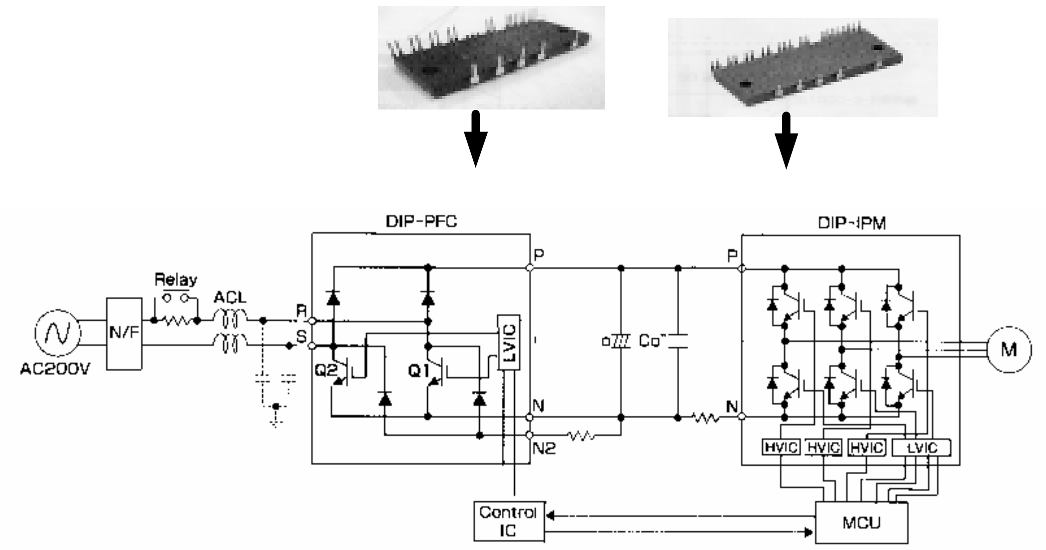


Fig. 5. Configuration of an inverter for an air conditioner and 600V 20A Dual In-line IPM.

The IPM includes gate drive circuits and protective functions that shut down the gate drive to the IGBT and provide a fault output signal when achieved. For home appliances such as air conditioners, refrigerators and washing machines, the 600 V Dual In-line Package IPM (DIP-IPM) which houses IGBTs and High Voltage ICs (HVICs) in the molded module. As the HVIC holds the isolation ability between circuits of high voltage level and circuits of low voltage level on a monolithic chip, this IPM can be controlled directly by a microprocessor of 3 V signal level as shown in Fig. 5.

In the 70s, devices called Static Induction Transistor (SIT) and the Static Induction Thyristor (SITH) were introduced by Prof. J. Nishizawa in Japan.

It’s important to fabricate devices with fine structure to improve their switching speed. Fig 2 also shows the design rules for DRAM memories and power semiconductor devices, and the latter can be seen behind the former around 10 years. Although basic principles of almost all power semiconductor devices were invented in the USA, Japan has been playing an important role in improving devices’ characteristics and realizing devices for practical use with synthetic technologies.

III. COOLING SYSTEMS

As power electronics handles large power, it is important to transfer the heat which is generated by power devices efficiently. In some cases, the loss over a few kW is dissipated by one device. Fig. 6 shows types of cooling systems. Natural convection cooling or forced cooling by air was widely used for its simplicity. In higher power ratings, water or oil cooling has been used to further improve the thermal conduction. Water or oil flows thorough aluminum heat sinks of can type to transfer the heat.

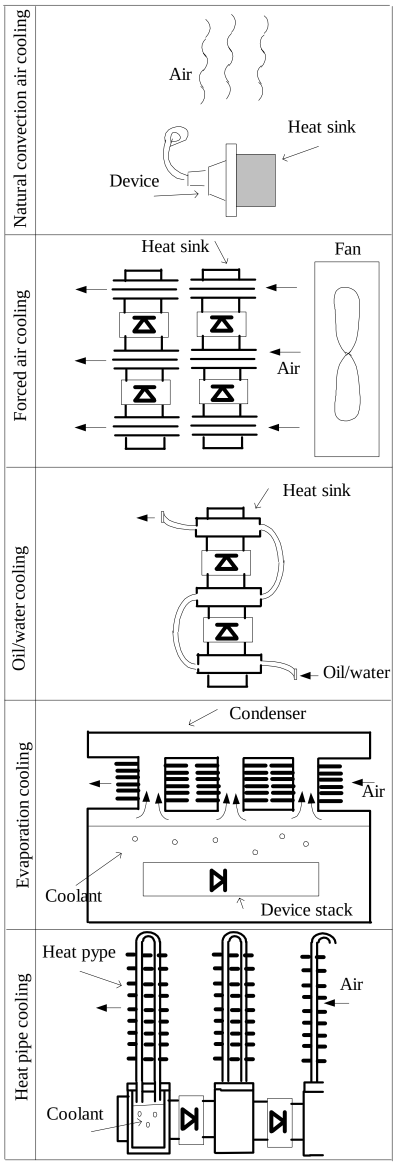


Fig. 6. Types of cooling systems.

Immersed oil cooling, which means that device stacks are placed in the closed oil tank and are cooled by oil, was also popular for the good insulation property of the mineral oil.

In 1968, the diode rectifier of 1200 kW 660 V ratings was installed as a power supply for electrolysis service in Japan [2]. In this equipment, evaporation cooling with Freon R113 was used for the first time in the world for large equipments. Evaporation cooling has a very high heat transfer density and needs no pumps. The final heat exchange to the ambient air takes place in separate coolers mounted on top of the vessel. Fig. 7 shows the boiling state in the vessel. During the 70s and the 80s, evaporation cooling had been widely used for equipments of rolling stocks and rectifiers of railway substations. Freon R113 was replaced in the 90s by PFC (par-fluoro-carbon, C6F14), which has no chlorine, due to the environmental considerations. PFC was also included in the list of restricted material for the global warming at the Kyoto protocol in 1997, and evaporation cooling with pure water was also adopted in the 2000s.

Cooling system using heat pipes was developed and adopted in the 90s. As condensed coolant (pure water) returns with the capillary phenomenon of wicks inside of heat pipes, easy fabrication between cooling fins and heat sources can be realized.

As water offers the best cooling properties and causes no environmental problems, water has been playing the leading role in spite of the appearance of many substitutes.

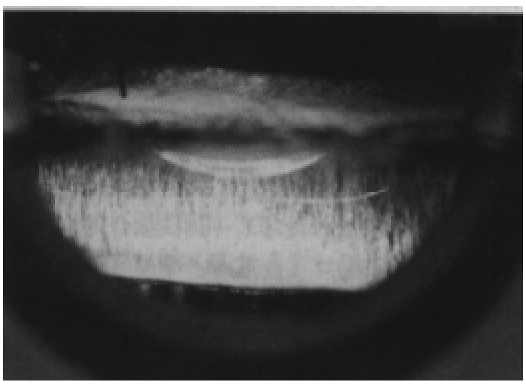


Fig. 7. Freon evaporation cooling.

IV. CONVERTERS AND CONTROL FOR DRIVES

Fig. 8 shows general trends of driving systems, although the years of the adoption are considerably different in each application fields. As AC motor drive systems have many features such as high performance, maintenance free, smaller size, and light weight, AC motor drive systems replaced DC motor drive systems in the 80s and the 90s almost in all application fields. DC motors disappeared except replacements.

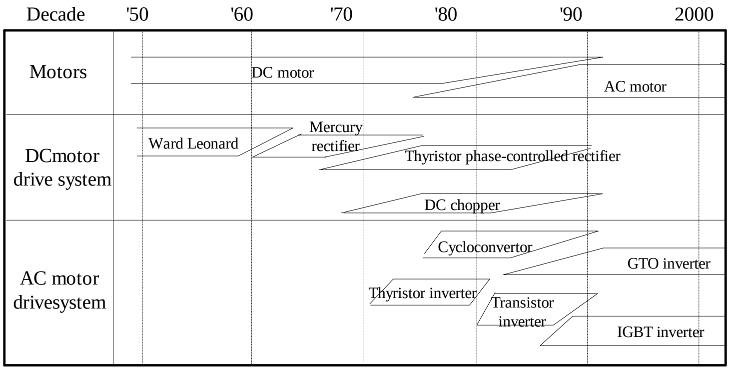


Fig. 8. History of motors and their drive systems.

A. Converters for DC motor drive systems

The phase-controlled rectifier so called Thyristor Leonard has been widely used with the AC power source, while the DC chopper has been used with the DC power source such as that in the railway system. The phase-controlled rectifier is found as an input converter topology for the AC motor drive system today.

B. Converters for AC motor drive systems

The idea of using a variable-frequency supply to control the AC motors was old, and rotating frequency converters had been employed for many years before the 80s. These were used principally in multi-motor mill drives and in special applications where a high operating frequency was chosen in order to permit the use of compact AC motors. Since the 60s, the rotating machine methods had been supplanted by static conversion methods.

According to Prof. R. G. Hoft, University Missouri-Columbia, “The Bibliography on Electronic Power Converters,” published by AIEE in February/1950 contains a chronological list of references, and it listed that the first inverter paper was published in 1925 [3]. In subsequent years, inverter equipments were developed, using the controlled electronic valve of that era – the grid controlled, gas-filled tube. In addition to the limitations of the available valves, circuit configurations themselves had problems for the stable operations.

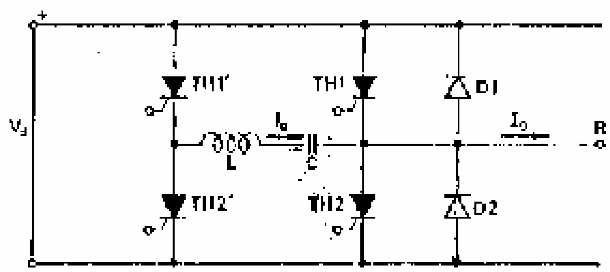


Fig. 9. One leg of a bridge inverter employing the McMurray commutation method.

The McMurray-Bedford circuit and the McMurray circuit (shown in Fig. 9) were introduced respectively in

1961 and in 1963 in the USA [4], [5]. In these circuits, the inductive load current continues to flow through feedback diode D2 in Fig. 9, when Thyristor TH1 is turned off. The feedback diodes improve the stability of operations remarkably and the basic configuration has been adopted as a standard voltage source inverter.

The development of simple and efficient methods of obtaining forced-commutation was the main problem in the Thyristor inverter, and many circuits were proposed in Japan as well. Among them, the CT feedback circuit, which was invented by E. Ohno and M. Akamatsu in 1964, could permit the return of the trapped energy to the DC supply with current transformers and improved total efficiency remarkably [6]. For higher power ratings, series connection of inverter units is the preferred technique. High-voltage, low current systems cause lower current losses and it can produce the voltage of quasi-sinusoidal wave form. In 1976, the 8.5 MVA inverter, which consisted of 6 units in series, was manufactured by Mitsubishi Electric Corp. as the 50/60 Hz power supply for testing pump induction motors [7].

Pulse Width Modulation (PWM) technology enabled elimination of harmonics from the inverter output voltage, allowing quasi-sinusoidal machine waveforms and eliminating torque pulsations. The subharmonic control method (presented by A. Schonung and H. Stemmler of BBC in 1964 [8]) was the simple modulation, where the switching instants are determined as the intersections between the reference signal and triangular carrier signals having the constant frequency. This subharmonic PWM has been a standard technique thereafter. The output voltage waveform of the PWM inverter contains miscellaneous harmonics and its precious analysis was reported by K. Takahashi and S. Miyairi in 1975 [9]. In 1983, the space vector modulation was introduced by Y. Murai and Y. Tsunehiro and has been applied to the analysis of the magnetic flux and to actual implementations as well [10].

Since around 1975, more turn-off power semiconductor elements such as bipolar transistors and GTOs were developed and implemented during the next 20 years. As the PWM inverters using turn-off elements have the simple circuit configuration as shown in Fig. 10 and can improve their operating efficiencies a great deal, they gradually replaced Thyristor inverters with forced-commutating circuits.

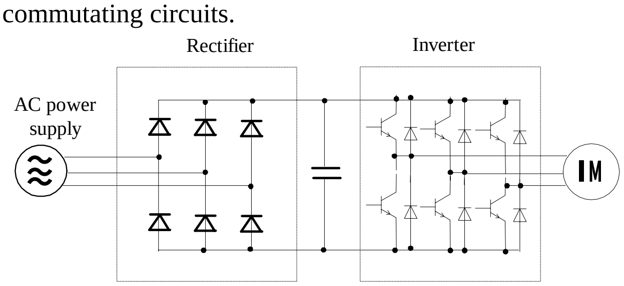


Fig. 10. Composite AC-DC-AC converter.

The visit of Exxon Co. to Japan in 1979 made a great impact in Japanese manufacturers as so called Exxon shock. Exxon Co. intended to find manufactures of small and compact inverters for versatile use as licensees of the patent of R. H. Baker. R. H. Baker invented a 3-level inverter as shown in Fig. 11 and the concept of multi-level inverters was also presented [11]. With this as a trigger, a lot of efforts were given to the development of small and compact inverters in Japan. As a result, a versatile inverter went on market in 1980 and has been widely accepted in various applications. The versatile inverter was constructed with transistor modules and was of box type instead of conventional cubicle type, although it was made of a standard 2-level inverter circuit.

As for the 3-level inverter, its detailed analysis was presented by A. Nabae, I. Takahashi, and H. Akagi in 1980 [21], and it has been adopted in drives for railway traction and steel rolling mills since 1992 in Japan.

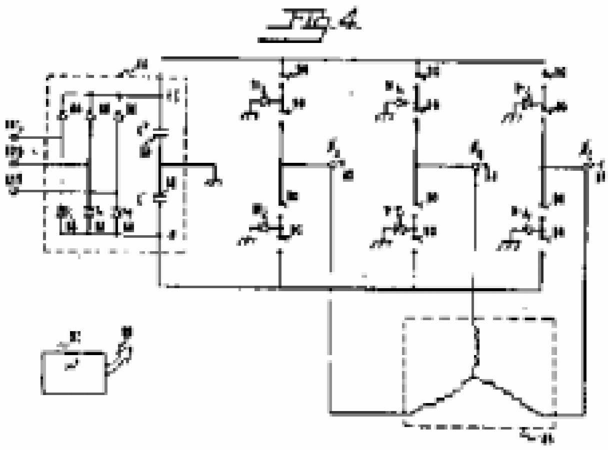


Fig. 11. A 3-level inverter (Baker).

With an AC power source, the AC drive system consists of the composite AC-DC-AC converter as shown in Fig. 10. Recently the PWM rectifier has been replacing the diode rectifier and the Thyristor phase controlled rectifier in order to improve the input power factor and to get the sinusoidal wave form of the input current. Furthermore many improved circuits such as DIP-PFC (shown in Fig. 5) have been developed and Fig. 11 shows the input current of an inverter with a DIP-PFC for an air conditioner.

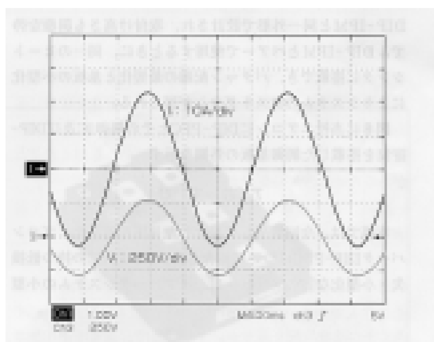
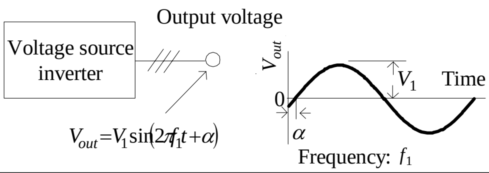


Fig. 12 Wave forms of input voltage and current of an inverter for an air conditioner.

In a cycloconverter, the alternating voltage at supply frequency is converted directly to a lower frequency without any intermediate DC stage. The operating principles were developed in the 30s when the grid-controlled mercury-arc rectifier became available. The advent of the Thyristor of large capacity led to many installations of cycloconverters for the drives of steel rolling mills in the 80s in Japan. However, as the naturally commutated cycloconverter has a limitation on the maximum output frequency by the supply frequency of the AC bus and shows low power factor in the AC source, the voltage source inverter using turn-off devices took place of the cycloconverters in the 90s.

C. Control for AC Motor Drives

A static converter which delivers variable-frequency power to a motor must also vary the terminal voltage as a function of frequency in order to maintain the proper magnetic conditions in the core. The applied voltage/frequency ratio must be constant in order to maintain constant flux, and this mode of operation is known as constant V/f. This open-loop operation of an induction motor at variable frequency provides a satisfactory variable-speed drive when the motor is required to operate at steady speeds for long periods. When the drive requirements include rapid acceleration and deceleration, an open-loop system is unsatisfactory, since the supply frequency cannot be varied very quickly. When a fast dynamic response is necessary, closed-loop feedback methods are essential.



Variables	V/f control	Slip freq. control	Vector control
Amplitude: V_1	Frequency dependent	Controllable	Controllable
Angle: α	Non-controllable	Non-controllable	Controllable
Frequency: f_1	Controllable without feedback	Controllable with feedback	Controllable with feedback

Fig. 13. Voltage source inverter and its controllable variables.

Fig. 13 shows three typical methods and their controllable variables of the output voltage [13]. In the slip frequency control, the demanding slip frequency is added to, or subtracted from, the measured rotating frequency, in order to determine the inverter frequency. The demanding slip frequency can be modified with the output signal of the motor current controller, and the slip frequency can then be controlled so that operations always occurs at small slip, thereby yielding high torque at high power factor with low losses. Thus, the system could be designed to maintain constant torque over a wide speed range and constant-horsepower output as well, and the slip frequency control was widely adopted for railway traction drives in the 80s and the 90s in Japan.

The vector control or the field-oriented control was one of the important innovations in AC motor drives. The field orientation concept implies that the current components supplied to the machines should be oriented in phases (flux component) and in quadrature (torque component) to the rotor flux vector. This is achieved by controlling not only the magnitude and the frequency of the inverter output voltage but also its phase angle (shown in Fig.13), thus the instantaneous position of the rotor flux. In Germany, the basic concept of the indirect vector control without flux measurement was proposed by K. Hasse in 1968 [14], and the direct vector control, which uses direct flux measurement to find the actual magnitude and position of the rotor flux (shown in Fig. 14), was developed by F. Blaschke in 1971 [15]. Although these publications started long before, the subsequent use of vector control had been fully developed in the 80s in Japan, using sophisticated digital control units such as 32 bit microprocessors.

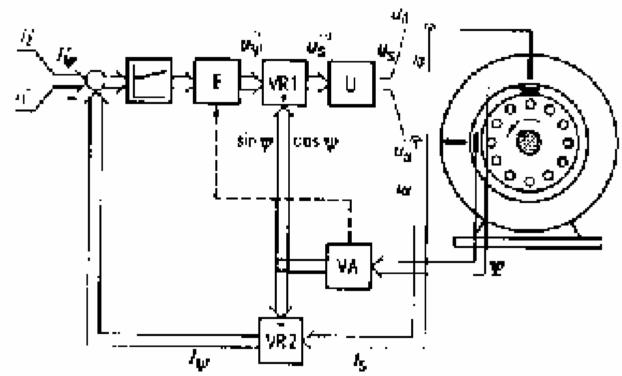


Fig. 14. Direct vector control of an induction motor. (Blaschke)

In 1980, S. Yamamura proposed another torque control called the field acceleration method [16]. He showed that the d-q equations can be solved in closed form without coordinate conversion, assuming the rotor frequency is constant in a short period, and that the stator current is controlled instantly. The field acceleration method can change the phase angle of the inverter output voltage like the vector control, and has similar transient torque response as that of the vector control.

V. MOTOR DRIVES FOR INDUSTRIAL APPLICATIONS

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A. Motor Drives for Metal Mills

The power supply for DC motor drives for metal mills was the major application field of the mercury arc rectifier at that time and large Thyristor phase-controlled rectifiers and many small auxiliary drives were put into practical use in the USA in the 60s [17]. In Japan, a 2800 kW 2x750 V rectifier was installed for the aluminum hot strip mill in 1987, and large equipments such as a 4500 kW 750 V rectifier for a steel ingot mill and an 11200 kW 750 V rectifier for a steel slab mill were produced thereafter. By the large investment in the Japanese steel industry in the 70s, many types of equipment were produced and digital control systems using microprocessors were realized by Japanese manufacturers from the late 70s to the 80s ahead of the world [18].

In the 80s, AC motor drive systems using the vector control were extensively realized in Japan. In 1981, a 2500 kW 0~8/16 Hz cycloconverter for a synchronous motor of a hot reversing mill and 2 sets of 7500 kW 0~6.9/13.7 Hz cycloconverters for induction motors of steel slab mills were made respectively in 1981 and in 1985. In 1994, a composite large AC-DC-AC converter, which consists of a GTO inverter and a GTO rectifier in the line side (shown in Fig. 15) in order to improve the input power factor and to get the sinusoidal current, was developed for the metal mill [19].

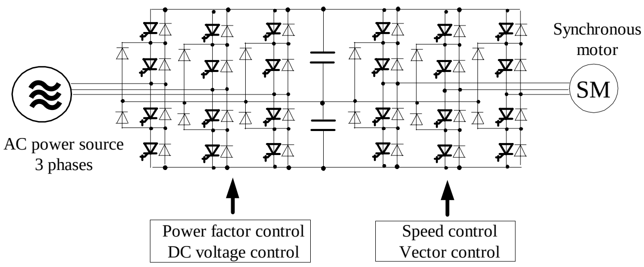


Fig.15. 10MVA 3-level GTO/GCT inverter system for the steel mill.

B. Versatile Inverters

The versatile inverters were developed aiming for factory automation at the first stage, but their application fields have been expanding for general use. Fig. 16 shows the series of general purpose inverters. The first generation of general purpose inverters appeared in early 80s using power transistor modules with 8 bit microprocessors as control chips. In the 90s, IGBTs and IPMs were introduced and realized tremendous minimization of the equipments as shown in Fig. 17.


Fig.16. Versatile inverter series.

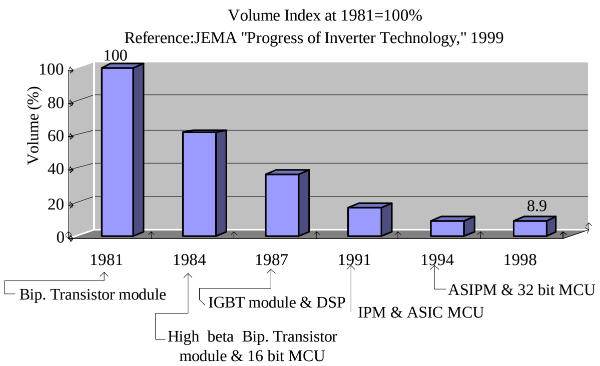


Fig. 17. Miniaturization progress of versatile inverters.

C. Home Appliances

An inverter air conditioner is the representative example of application of AC drives to home appliances. The inverter air conditioner appeared in 1978 in Japan and improved both comfortableness and energy consumption by the variable speed drive of the compressor. A robust and low cost induction motor was generally used as a driving motor at first place, but a higher efficiency permanent magnet synchronous motor has been beginning to take place of an induction motor to realize higher energy savings. Fig. 5 shows one example of the configuration of an inverter for an air conditioner using IPMs and AC drive systems of almost same configurations are adopted for refrigerators and washing machines.

V. MOTOR DRIVES FOR RAILWAY APPLICATIONS

For many years DC motors with series field windings had been used as main traction motors of electric railways. Japanese railways have the DC feeding system for private railways and most of JRs (originally parts of Japanese National Railway), and the AC feeding system for Shinkansen and parts of JRs from historical reasons.

The first application of power electronics to the electric train control began with the control of DC motors with the chopper for the DC feeding system and with the phase-controlled rectifier for the AC feeding system both in the latter half of 60s. The chopper control was used mainly in the subways. The development of inverter controlled AC motors for traction motors started almost ten years later and the commercial service began in the middle of 80s in subways as well as suburban railways. Presently, AC motor drives have many advantages and occupy the main positions from city trams to Shinkansen.

A. Drives with DC Feeding Systems

The application of power electronics to the electric train control started with DC choppers because the DC motors were used for main drives with DC power feeding lines. The first practical application in Japan was with the field chopper in 1969, and with the armature chopper without regeneration in 1970 both in Hanshin railways. In 1971, the mass transit chopper cars with regenerative braking started commercial operation in Chiyoda line of Teito Rapid Transit Authority (now Tokyo subways), six years after the first test vehicle with the armature chopper ran successfully in 1965 [20].

Improved types followed, among them were Automatic Variable Field (AVF) chopper, which could weaken and strengthen the motor field current automatically in respect to the pulse width of the main chopper to improve the braking characteristics from high speed region. The Four Quadrant (4Q) chopper was developed to achieve smooth operation in four modes, combinations of powering/braking and forwards /backwards.

In Japan, the first induction motors were used for traction drives of light rail vehicles in Kumamoto city in 1982. In the 90s, induction motors occupied the dominant position in traction drives such as the adoption of induction motors for Series 300 Shinkansen.

Fig. 18 shows the appearance of electric cars for Kumamoto municipal transportation bureau and the 300 kVA inverter using reverse-conducting thyristors was adopted for drives of two 120 kW 2~ 73 Hz induction motors [21]. The slip frequency control, which was developed by this system, had been adopted during many years as the typical control system of induction motor drives for traction applications [13].

In the latter half of the 90s, the vector control was realized with sophisticated control technology and had been gradually adopted in the industrial field. In 1995, the German made inverter with first vector control was installed for Series E501 trains of East Japan Railway Company. Nowadays the vector control is applied for almost all of newly made AC propulsion trains in Japan.

Fig. 18. Appearance of AC propulsion electric cars for Kumamoto municipal transportation bureau.

B. Drives with AC Feeding Systems

In 1963, the ED75 AC locomotive using the silicon diode rectifier was made and many ED75 locomotives were used. In 1966, the ED75501 locomotive using the 2200 kW 1100 V Thyristor rectifier, which consists of 4 hybrid bridge circuits connected in series in order to reduce harmonic current in the feeder line, was made. In 1968, the ED76501 locomotive with Thyristor switches for the arc-less tap-changer and the ED78 locomotive with regenerative braking were developed. As for electric cars, the 726kW 600V Thyristor rectifier was made for Series 711 suburban AC trains in 1967.

As for Shinkansen rapid trains, the 1627 kW 1660 V diode rectifier with the tap-changer was made for DC motors in 1964. The Thyristor phase-control rectifier was developed for the prototype train of Tohoku and Johetsu lines in 1978. Since 1984, the development of PWM rectifies and inverters for induction motors had been done with GTOs, and in 1990 this system was applied to the Series 300 Nozomi train (shown in Fig. 19). In 1999, the composite configuration of three-level PWM rectifies and inverters using IGBTs (shown in Fig. 20) was adopted by the Series 700 Nozomi train. The vector control was applied to the Series 700 trains and realized excellent adhesion characteristics. Table 1 shows the historical review on driving systems for Shinkansen trains and individual specifications prove that the weight and size of the motor was reduced remarkably in years [22].

Fig. 19. Series 300 Shinkansen (Nozomi).

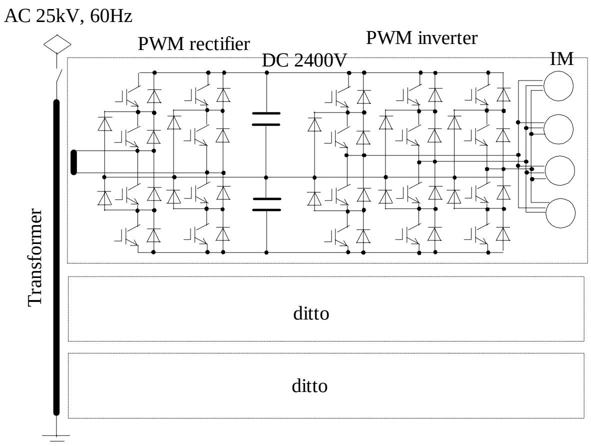


Fig. 20. Schematic diagram of the Series 700 Shinkansen.

Table 1.Historical review on driving systems for Shinkansen rapid trains.

	Type (Series)	0 Series	100 Series	300 Series	500 Series	700 Series
Train	No. of cars	16M	12M4T	10M6T	16M	12M4T
	Maximum speed (km/Hr)	220	230	270	300	285
Controller	Controller (Power device)	Tap-changer + Rectifier (Diode)	Phase-controlled rectifier (Thyristor)	PWM rectifier + Inverter (GTO)	PWM rectifier + Inverter (GTO)	PWM rectifier + Inverter (IGBT)
Motor	Type	DC motor	DC motor	Induction motor	Induction motor	Induction motor
	Output (kW)	185	230	300	275	275
	Weight (kg)	876	825	396	379	391
	Volum (m^3)	0.196	0.206	0.0965	0.086	0.0956
	Weight to Output ratio (kg/kW)	4.74	3.59	1.32	1.38	1.42
First year of operation		1964-10	1985-3	1990-3	1997-3	1999-3

VI. MOTOR DRIVES FOR ELEVATORS

In Japan, the engineers have applied from early stage many new technologies for elevators, such as Variable Voltage Variable Frequency (VVVF) inverters, rare-earth Permanent Magnet (PM) motors and hybrid drives using Ni-MH battery. The history of the motor drives for traction elevators and the energy saving is shown in Fig. 21 [23]. High-speed elevators (v>=2 m/s) are equipped with gearless traction machine and are used in high buildings and hotels. The low-speed elevators (v<1.75 m/s) use geared traction machines and are installed in mid and low buildings and apartment houses. However, with the advent of Machine-Room-Less (MRL) elevators the low-speed elevators are equipped with gearless traction machines with PM motors.

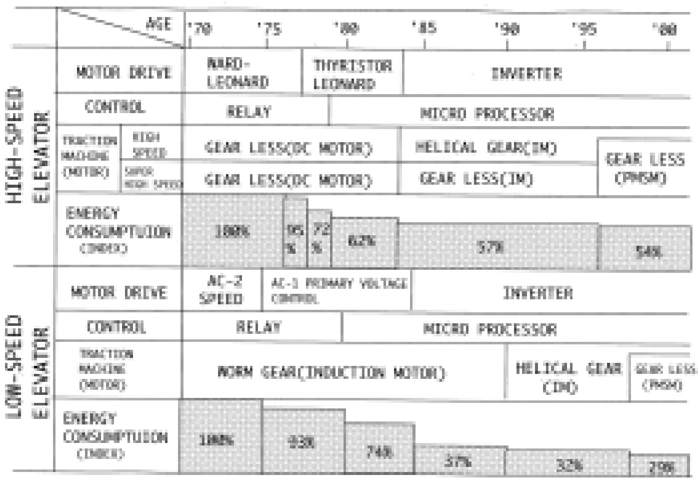


Fig. 21. History of motor drives for traction elevators

A. Thyristor Drive Systems

In case of high-speed elevators Thyristor-Leonard drive system replaced the Ward-Leonard in the second half of the 70s. On the same trend in the middle of 70s, low-speed elevators with induction motors were equipped with thyristor based primary voltage control, replacing the classical method of changing the number of poles. Moreover, in this period the control circuit evolved from relay logic to microprocessor based control. As a result, the energy consumption of high-speed elevators was reduced by about 40 %, compared with classical Ward-Leonard drives.

B. Inverter Drive Systems

In 1983, the inverter drive systems were applied for high-speed elevators and in the next year were extended to low-speed elevators as well. Therefore, in case of low-speed elevators approximately 50 % energy saving was obtained and their ride quality is comparable with that of high-class elevators.

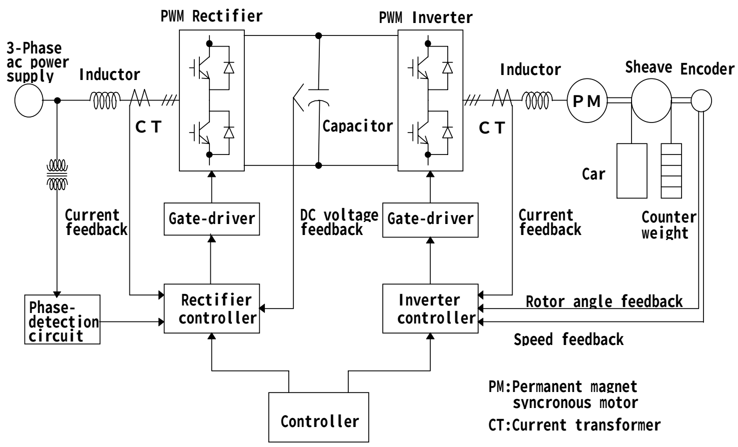


Fig. 22. Motor drive system for a high-speed elevator.

The highest speed elevator in current world (v=12.5 m/s) was installed at Yokohama Landmark Tower in 1993 [24]. As the inverter system has to drive a 120 kW motor by power transistors, the output of three transistors connected in parallel are combined using an inductance.

For the first time, high-speed elevators were equipped with 40 kW PM motors in 1996. The latest motor drive system (shown in Fig. 22) uses a PWM rectifier with power factor control and a PWM inverter. Due to power factor control the power equipment capacity has been reduced by approximately 25 % compared with Thyristor-Leonard drive and the ratios of current-harmonics on power source side are below 5 %.

Currently, the world highest speed elevator (v_{up}=16.8 m/s, v_{down}=10 m/s) is under installation at Taipei Financial Center. This elevator uses a 170 kW PM motor, which has two windings and is driven by a two-inverter system [25].

C. Machine-room-less Elevators and Permanent Magnet Motors

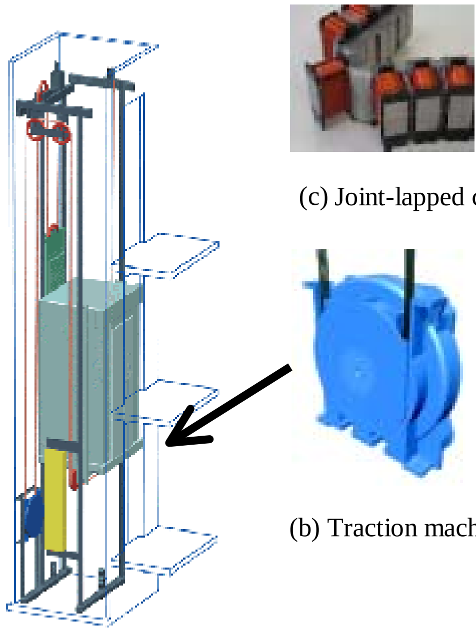
Machine-room-less elevators in low-speed range represent the latest innovation in elevator technology. In Japan, elevators without machine-rooms have been used as home elevators since 1988 and as linear motor elevators since 1989. In Europe, in 1996 MRL for low-speed standard elevator was developed, and in Japan, MRL has been applied since 1998.

A MRL elevator installed in 2001 is shown in Fig. 23 (a). The traction machine is placed in the lower part of the elevator shaft to reduce the height of the shaft. The gearless traction machine (shown in Fig.23 (b)) with the permanent magnet motor is preferred due to its small size and reduced noise level. The motor has concentrated windings and a joint-lapped iron core (shown in Fig. 23 (c)), which is opened during automatic winding. Torque ripples are reduced by careful design such as the proper combination of number of poles and slots, and the adequate shape of the stator teeth and the permanent magnet.

D. Hybrid Drive Systems Using Ni-MH Batteries

Low-speed elevators use diode rectifiers instead of PWM rectifiers due to the difficulties of regenerative braking (especially in small buildings). Therefore, during braking, the generated power is dissipated on the resistor.

As hybrid automobiles have been more and more popular in recent years, Ni-MH battery technology progressed significantly. The hybrid drive system for MRL elevators (shown in Fig. 24) has been developed and has been applied since 2001. Approximately 20 % of energy saving is obtained and low speed operation is achieved during about 10 minutes when AC. power source fails [26].



(c) Joint-lapped core

(b) Traction machine

(a) Machine-room-less elevator Elepaq-i

Fig.23. Machine-room-less elevator.

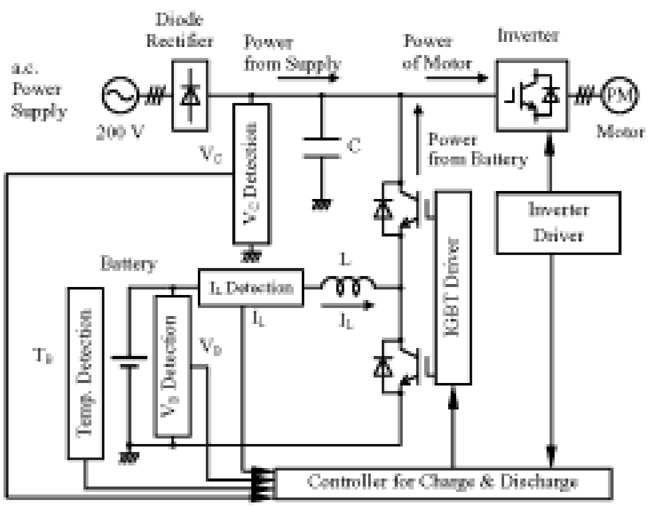


Fig.24. Hybrid drive system using Ni-MH battery.

VII. CONCLUSION

The 50-year history of power electronics for motor drives in Japan was stated. Although many important technologies and basic principles were introduced from overseas, power electronics for motor drives in Japan has been thriving with our further efforts and ideas. Power electronics will be expected to play an important role in our future society.

REFERENCES

[1] F. W. Gutzwiller et al. *GE Silicon Controlled Rectifier Manual*, Liverpool, New York, General Electric Co., 1960.

[2] T. Matsumoto, A. Ishikawa, and Y. Noji, “The Freon Cooled Silicon Rectifier Equipment for Shinkosha K.K.,” (in Japanese), Fuji-jihou, 43, 2, pp.175- 179, 1969.
[3] R .G. Hoft, “Power Electronics: Historical Review, Present Status and Future Prospects,” IPEC-Tokyo ’93, pp.6-18, 1983.
[4] W. McMurray and D. P. Shattuck, “A Silicon Controlled Rectifier Inverter with Improved Commutation,” Trans. AIEE, Part1, Vol. 80, p.531, 1961.
[5] W. McMurray, “SCR Inverter Commutated by an Auxiliary Impulse,” IEEE Trans. Communication and Electronics, Vol. 83, p.824, 1964.
[6] E. Ohno and M. Akamatsu, “Speed Control of AC Motors with SCR Variable Frequency Inverters,” (in Japanese), Mitsubishi-Denki-Giho, Vol. 38-6, p. 97, 1964.
[7] I. Hosono, T. Kawabata, S. Yano, “Large Capacity 8500 kVA Self Commutated Inverter,” (in Japanese), Mitsubishi-Denki-Giho, Vol.51, 7, pp.491-496, 1977.
[8] A. Shonng, and H. Stemmler, “Static Frequency Changers with “Subharmonic” Control in Conjunction with Reversible Variable-Speed A.C. Drives,” The Brown Boveri Review, Vol. 51, August/September, pp. 555-577, 1964.
[9] K. Takahashi and S. Miyairi, “Relation between the Output Voltage Waveform of the PWM Inverter and its Gate Control Signals,” (in Japanese), IEE of Japan Trans. B, Vol.95-2, pp.25-32, 1976.
[10] Y. Murai and Y. Tunehiro, “Improved PWM Method for Induction Motor Drive Inverters,” IPEC-Tokyo ’83, pp. 407-417, 1983.
[11] R. H. Baker, “Bridge Converter Circuit,” United States Patent, 4270163, May 26, 1981.
[12] .A. Nabae, I. Takahashi, and H. Akagi, "A New Neutral-Point-Clamped PWM Inverter," IEEE IAS Annual Meeting Record, Vol.2, pp.761-766, 1980.
[13] M. Yano and M. Iwahori, “Transition from Slip-Frequency Control to Vector Control for Induction Motor Drives for Traction Applications in Japan,” Proceedings of PEDS2003, pp.1246-1251, 2003.
[14] K. Hasse, “Zum Dynamischen Verhalten der Asynchronmachine bei Betrieb mit variable Standerfrequenz und Standerspannung,” ETZ-A, Bd.89, H.4, pp.77-81, 1968.
[15] F. Blaschke, “Das Prizip der Feldorientierung , Die Grundlage fur die TRNSVEKTOR-Regelung von Asynchnmachinen,” Siemens Zeitschrift, 45, p.757, 1971.
[16] S. Yamamura and S. Nakagawa, “Transient Phenomena and Control of an AC Servomotor (IM) – Proposal of Field Acceleration Control,” (in Japanese), Trans. B, IEE of Japan, Vol. 101-B, p.557, 1980.
[17] L. F. Stringer and E. T. Schonholzer, “hyristor Drive Systems for Metal Mill Application,” Iron and Steel Engineer, March pp.75-90, 1967.
[18] T.Konishi, K. Kamiyama, and T. Ohmae,"A Performance Analysis of Microprocessor-Based Control Systems Applied to Adjustable Speed Motor Drives," IEEE Trans. Ind. Appl. vol.IA-16, No.3, pp.378-387, 1980.
[19] M. Honbu et al, “A Large GTO Inverter Drive System,” (in Japanese), Hitachi Hyoron, Vol.65, No.4, p.289, 1984.
[20] T. Katta, “Thyristor Chopper-Controlled Electric Cars in Japan,” Japanese Railway Engineering, Vol.20, No.2, pp.3-10. 1980.
[21] M. Ohta, A. Kaga, M. Muneyuki, and E. Akagawa, “AC Propulsion System for Kumamoto Municipal Transportation Bureau,” IPEC-Tokyo ‘83, pp.1375-1586, 1983.
[22] Itoh, “Series 700 Shinkansen,” (in Japanese), Tetsudo Sharyo to Gijutu, February, 1999.
[23] S. Abe and E .Watanebe, "History of Elevators and Related Research," (in Japanese), Papers Tech. Meeting IEE Japan, HEE-03-13, pp.1-8, 2003.
[24] E. Watanabe, H. Kamaike, T.Tanahashi, and H.Araki, "Drive Control Equipment for 750 m/min (12.5 m/sec) Elevators," Elevator Technology 5, pp.163-172, 1993.
[25] T. Munakata, H .Kohara, K. Takai, Y. Sekimoto, R. Ootsubo, and S. Nakagaki, "The World's Fastest (1010 m/min) Elevator," Elevator Technology 12, pp.217-225, 2002.
[26] S. Tominaga, I. Suga, H. Araki, H. Ikejima, M. Kusuma, and K. Kobayashi, “Development of Energy-Saving Elevator Using Regenerated Power Storage System,” IEEE Proc. of the Power Conversion Conference-Osaka (PCC-Osaka), Vol.2, No.D7-8, pp.890-895, 2002.