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**Japanese Power Electronics
Inverter Technology and Its
Impact on the American Air
Conditioning Industry**

August 1990

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JAPANESE POWER ELECTRONICS INVERTER
TECHNOLOGY AND ITS IMPACT ON THE
AMERICAN AIR CONDITIONING INDUSTRY

Kenji Ushimaru
Energy International, Inc.
Bellevue, Washington

G. L. Wilfert, PNL Task Manager

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ABSTRACT

Since 1983, technological advances and market growth of inverter-driven variable-speed heat pumps in Japan have been dramatic. The high level of market penetration was promoted by a combination of political, economic, and trade policies in Japan. A unique environment was created in which the leading domestic industries--microprocessor manufacturing, compressors for air conditioning and refrigerators, and power electronics devices--were able to direct the development and market success of inverter-driven heat pumps. As a result, leading U.S. variable-speed heat pump manufacturers should expect a challenge from the Japanese producers of power devices and microprocessors. Because of the vertically-integrated production structure in Japan, in contrast to the out-sourcing culture of the United States, price competition at the component level (such as inverters, sensors, and controls) may impact the structure of the industry more severely than final product sales.

EXECUTIVE SUMMARY

An inverter is an electronic power controller consisting of transistors connected as switching devices. These power transistors switch on and off rapidly to modulate the power flowing in a circuit; and on a time-average sense, near-sinusoidal voltage and current waves are synthesized at controlled frequency. Conventional heat pumps achieve capacity control by intermittent operation--cycling on and off to match the load--while inverter-driven variable-speed heat pumps are capable of modulating the compressor speed in response to building heating or cooling loads and outside temperatures. Variable-speed heat pumps can provide significant energy efficiency. By controlling the compressor speed to meet building space conditioning loads more precisely, energy savings at 15% to 40% over the conventional equipment can be achieved on a seasonal basis.

Technological advances and market growth of inverter-driven variable-speed heat pumps in Japan have been dramatic since 1983. For example, of the 4.5 million pieces of air conditioning equipment sold in the Japanese domestic market in 1988, over 60% were heat pumps (as opposed to cooling-only equipment) and slightly over 50% of the heat pumps were inverter-driven. This indicates that inverter-driven residential heat pump sales total 1.5 million units per year and are still growing. The success of residential split-type heat pumps with variable-speed capability has been supported by increasing consumer awareness and demand for enhanced comfort, high seasonal efficiency, and technical innovations. The latter have been designed to surmount intrinsic constraints in Japanese residential electrical services.

While sales of inverter-driven heat pumps in Japan continue to grow, the future of variable-speed heat pumps in the United States remains uncertain. The disparity between the level of inverter sales causes concern that the U.S. air conditioning and heat pump industry may be adversely impacted by the aggressive marketing strategy of the leading Japanese manufacturers when they decide to penetrate the U.S. market. The residential application can be a foundation for large production volume and may become a driver for further cost reduction in manufacturing. If Japan continues to manufacture and sell, and the United States does not, then Japan will continue to be the cost and technology driver for variable-speed components, and will be in a position to expand at the expense of competing companies in the United States.

This report was initiated to evaluate Japanese power electronics inverter technology and its impact on the worldwide heating, ventilation, and air conditioning (HVAC) industry. The reasons for, and future projections of, the continuing success of inverter technology and its impact on related industries in Japan were analyzed. To attain these objectives, this report provides the following set of discussions:

- a brief description of historical trends in heat pump market growth and economic conditions in Japan
- an inverter technology description and application know-how to provide a basic understanding of key design features
- an examination of key component technologies such as power electronic switching devices, micro-processor control, competing technology comparison, and the future of emerging innovations
- an examination of the complex interaction among individual successes in seemingly unrelated industries that contributed to the mutual support of inverter applications in the HVAC industry.

From a technical perspective, inverter technology is based on solid-state power switching devices, micro-processor control, and other associated electronic components. Japanese design of variable-speed heat pumps

is based upon taking the best advantage of inverter capability. This report examines the relationship between technical innovations in low-cost microprocessor manufacturing, small-capacity refrigerant compressor development, and power electronic devices for low-horsepower induction motors.

The Japanese central government played a subtle, but significant, role in establishing the foundation for the new generation heat pump developed for the residential and commercial air conditioning industry. Following two major oil crises, the Japanese central government published the "Decree of Energy Conservation" in June 1979. The decree, "Laws Governing the Rationalization of Energy Utilization," included several subsections covering the minimum energy consumption standards for space conditioning equipment, as well as a policy announcement regarding the thermal efficiency of a building envelope. Specifically, control of infiltration, zoned heating and cooling equipment, and improvement of seasonal energy efficiency were pointed out as the "energy conservation directive."

Aided by a national policy promoting the development of new generation air conditioning and heat pump equipment, the leading Japanese manufacturers began to produce rolling piston compressors and electronic controls and components for the air conditioning industry. The same manufacturers were also focused on building a volume production base for computer memory devices and microprocessors.

These developments occurred simultaneously in the late 1970s and early 1980s, and are interrelated in a manner unique to the Japanese industry-government infrastructure. A major conclusion of this report is that the political, economic, and trade policies of Japan created a singular environment in which the leading domestic industries--microprocessor manufacturing, compressors for air conditioning and refrigerators, and power electronics devices--were able to direct the development and marketing success of inverter-driven heat pumps.

The major concern of this work is the aggressive production and pricing policies Japanese manufacturers employ to build an infrastructure of overproduction. When domestic demand of key ingredients in inverter-driven heat pumps was finally outpaced by the increase in production capacity of those components, low-cost inverters were applied to add another dimension to the residential heat pump market. The Japanese conglomerates (who are vertically integrated manufacturers of critical components as well as final products) expanded the production capacities of HVAC- and electronics-related components. As a result, prices of critical components decreased dramatically because of the economy of scale established in the process. This enabled the conglomerates to package a new heat pump system, which uses volume-produced, low-cost components. The development of inverter-driven heat pumps was a consequence of production increases in certain areas of the business in Japan. Contrary to popular belief, the success of inverter-driven heat pumps was not driven by technology advances, but rather by the consistent production policy and pricing policy of Japanese conglomerates who, in effect, found a new market for their components. In fact, the inverter was the catalyst for the dramatic expansion of new application markets for microprocessors, power devices, and over-supply of rotary compressors.

In terms of future competition in the United States HVAC market, leading U.S. variable-speed heat pump manufacturers should expect a challenge from the Japanese producers of power devices and microprocessors. Because of the vertically-integrated production structure in Japan, in contrast to the out-sourcing culture of the United States, price competition at the component level may impact the structure of the industry more severely than final product sales.

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GLOSSARY

ASD	adjustable speed drive
BJT	bipolar junction transistor
BPM	brushless permanent magnet motor
BV	breakdown voltage
CAMs	continuous air monitors
COP	coefficient of performance
COMFET	conductivity modulated field effect transistor
CSI	current source inverter
EER	energy efficiency ratio
ECM	electronically-commutated motor
emf	electromotive force
EMI	electromagnetic interference
FET	field effect transistor
FOC	field orientation control
GTO	gate turnoff (thyristors)
HVICs	high-voltage integrated circuits
ICs	integrated chips
IGBT	insulated gate bipolar transistor
IGT	insulated gate transistor
IOT	instantaneous overcurrent trip
JFET	junction field effect transistor
JIS	Japanese Industrial Standards
LSI	large-scale integrated
MMF	magneto motive force
MOS	metal oxide semiconductor
MOSFET	metal oxide semiconductor field effect transistor
MOSThyristors	MOSFET-controlled thyristors
PAM	pulse amplitude modulation
PIC	power integrated circuit
PWM	pulse width modulated
RAM	random access memory
RBSOA	reverse bias safe operating area
ROM	read only memory
SCR	silicon-controlled rectifier (or thyristor)
SEER	seasonal energy efficiency ratio
SIRET	static induction recessed emitter transistor
SIT	static induction transistor
SIThy	static induction thyristor
SWM	sine wave modulator
UPS	uninterruptible power supply
VSI	voltage source inverter
VLSI	very large-scale integrated circuits
VVVF	variable voltage, variable frequency

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1.0 INTRODUCTION

This report focuses on the technology developments and market trends of Japanese variable-speed heat pumps utilizing advanced power electronics inverters. An inverter is an electronic power controller consisting of power transistors connected as switching devices. These power transistors switch on and off rapidly to modulate the power flowing in a circuit; and on a time-average sense, near-sinusoidal voltage and current waves are synthesized at controlled frequency. As the power of alternating current from the inverter is delivered to the compressor motor at varying frequency, the rotational speed of the motor follows the modulated frequency. Rather than the on-off control of fixed-speed air conditioners, the inverter can provide proportional control of the output to match the house load over a wide range of operating conditions, thereby achieving improved operating efficiency on a seasonal basis.

Since 1983, the technological advances and market growth of inverter-driven variable-speed heat pumps in Japan have been dramatic. The level of success attained by residential split-type heat pumps with variable-speed capability has been supported by increasing consumer awareness and demand in terms of enhanced comfort, high seasonal efficiency, and technical innovations designed to overcome inherent constraints in residential electric services in Japan.

The purpose of this report is to evaluate Japanese power electronics inverter technology and its impact on the worldwide heating, ventilation, and air conditioning (HVAC) industry. In the early 1980s, the Japanese HVAC industry advanced from a mechanically driven, small-capacity air conditioning equipment industry to undisputed leaders in the area of microprocessor-controlled, power electronics inverter manufacturing. The present work analyzes this transformation to determine the reasons for--and future projections of--the continuing success of inverter technology and its impact on related industries in Japan.

The basic thesis of this work was to determine the relationship between the technical innovations in low-cost microprocessor manufacturing, small capacity refrigerant compressor development, and power electronic devices for low horsepower induction motors. These innovations occurred simultaneously in the late 1970s and early 1980s. The developments are interrelated in a way that is unique to the Japanese industry-government infrastructure. One of the major conclusions of this report is that the political, economic, and trade policies of Japan created a unique environment in which the leading domestic industries--microprocessor manufacturing, compressors for air conditioning and refrigerators, and power electronics devices--were able to direct the development and market success of inverter-driven heat pumps.

In any residential appliance market, the development of a market-viable technology is greatly influenced by regional culture, lifestyle, economic conditions, climate, and competing equipment. While Japan and the United States constitute the world's largest air conditioning and heat pump markets, the difference between the two countries is significant. In the present study, an effort is made to clearly identify the background environment relative to design load conditions, economic parameters, customer preference, and design philosophy.

The content of this report is divided into the following sections:

- The first section (Chapter 1) provides a brief description of the historical trends in heat pump market growth and economic conditions in Japan.
- The second section (Chapters 2 and 3) discusses basic inverter technology and application know-how to provide the reader with a basic understanding of the key design features.

- The third section (Chapters 4 and 5) describes key component technologies, such as power electronics switching devices, microprocessor control, competing technology comparison, and a future outlook of emerging innovations.
- The next section (Chapter 6) examines the complex interaction among individual successes of seemingly unrelated industries which contributed to the mutual support of inverter applications in the HVAC industry.
- The final section (Chapter 7) concludes with an assessment of how advanced inverter technology may influence the air conditioning equipment industry in the United States and its trade allies.

Because each of the study areas is a broad field in itself, it is not the objective of this report to provide complete technical information in each specific discipline. Readers with a desire to gain detailed knowledge in motor control technology or heat pump design and testing should refer to reference materials as necessary. Instead, it is the intention of the research project to address the relevant issues and consolidate basic information on heat pump performance, motor control techniques, and inverter technology. The consolidation of overview technical information is designed to serve as a foundation for a study to determine how the success of Japanese variable-speed heat pumps was motivated and supported and how the export-oriented Japanese industries may impact the U.S. air conditioning industry in the near future.

2.0 TRENDS IN THE JAPANESE RESIDENTIAL HVAC MARKET

The analysis presented in this report is motivated by the remarkable penetration of inverter-driven heat pumps in the Japanese residential HVAC market during the 1980s and a need to examine its potential impact on the air conditioning equipment market in the United States. Inverter technology has been developed and applied in industrial equipment, machinery, and instruments since the 1950s. What is remarkable about the market acceptance of inverter technology in Japan in the 1980s is:

- the dramatic growth of inverter-driven heat pumps, which rapidly expanded the scale of the basic component manufacturing process
- the ability of the inverter--technology-intensive, expensive, previously limited to use in industrial and commercial machinery--to penetrate the residential market in a significant way.

The examination of inverter technology begins by analyzing the residential air conditioning market trends in Japan.

2.1 MARKET TRENDS

The Japanese HVAC market has experienced two stages of growth. The trend in shipments of residential air conditioning equipment for domestic consumption between 1975 and 1987 is illustrated in Figure 2.1. The vertical axis in the figure shows domestic sales of residential air conditioning equipment below 2.5 tons in millions. The lower half of the figure shows sales of room air conditioners (cooling only) between 1975 and 1987. The upper half of the figure shows sales of heat pump equipment with hatched bars representing sales of fixed-speed heat pumps and solid bars representing sales of inverter-driven variable-speed units.

The first stage of growth occurred between 1975 and 1979, primarily for cooling-only room air conditioners. Aided by steady increases in the standard of living and housing starts, shipments of

Figure 2.1. Shipments of Residential Air Conditioning Equipment in Japan 1975-1987

residential room air conditioners (cooling only) increased from 1.63 million units in 1975 to 2.87 million units in 1979; this represented a 75% increase. During the same period, the heat pump market grew from 0.35 million units to 0.54 million units--a 54% increase. Industry experts attributed the dramatic increase in the domestic demand for air conditioning and heat pump equipment to the increase in the industrial and economic strength of Japan in the worldwide export market, which brought a higher standard of living to the average Japanese home. During the first growth period, the demand for cooling-only air conditioning equipment dominated the residential market; sales of heat pump air conditioning equipment were still less than 600,000 units per year.

The Japanese air conditioning equipment market collapsed, along with many other appliance markets, during the worldwide recession from 1980 to 1983. Housing starts fell to a low level and Japan experienced record-setting cool summers.

Shipments for the cooling-only air conditioning equipment fell from 2.87 million units in 1979 to 1.25 million units in 1982; this represented a 56% decline. Despite the unfavorable economic and cooling load conditions, heat pump air conditioning equipment showed remarkable strength. Stimulated by advances in heat pump technology and efficient production know-how, Japanese manufacturers steadily shifted their price and performance competition in heat pump air conditioners to compete more effectively against kerosene and gas heaters in winter and room air conditioners in summer. The growth picture indicates an increase from 0.51 million units of heat pump equipment shipped in 1980 to 1.16 million units in 1983; the market more than doubled in the recession-prone 4-year period.

Coming out of the worldwide economic recession around 1983, the air conditioning equipment market entered the second stage of dramatic growth. Aided by the advent of the variable-speed heat pump and increased consumer awareness of high-efficiency residential appliances, the Japanese residential air conditioning market moved from the dominance of cooling-only equipment to the dramatic growth of heat pump equipment. In fact, the total heat pump market increased from 1.16 million units in 1983 to an estimated high of 2.2 million units in 1987, a 90% increase over a 5-year period. Even more remarkable is the increase in demand for variable-speed heat pumps. Since its introduction, the heat pump market share increased from newcomer status to that of a strong contender for the lead in domestic air conditioning equipment at over 1.1 million units in 1987. In 1987, domestic shipments for residential air conditioning equipment reached 3.9 million units [Japan Air Conditioning, Heating and Refrigeration News (JARN 1988)].

The Japan Refrigeration and Air Conditioning Industries Association (JRAIA) provided the following breakdown of residential equipment demand.^(a)

^(a) Private communication with JRAIA, Tokyo, August 1987.

JRAIA reported 1986 sales of 2.23 million heat pumps in Japan, of which:

- 1.1 million units were single-room heat pumps with a variable-speed compressor (49% of the total residential heat pump market)
- 1.0 million units were single-room heat pumps with a fixed-speed compressor (45% of the total)
- 30,000 units were multi-room heat pumps with a variable-speed compressor (1% of the total)
- 100,000 units were multi-room heat pumps with a fixed-speed compressor (4% of the total).

Clearly, the Japanese air conditioning equipment market successfully transformed from cooling-only to heat pump equipment in the early 1980s. Furthermore, the heat pump market rapidly evolved to where half of the heat pumps sold in Japan in 1987 were of the variable-speed type.

Technological advances are numerous in the areas of compressors, inverter drives, controls, and system integration techniques. The Japanese manufacturers committed their resources to research and development, manufacturing facilities, and marketing promotion. Incremental cost increases associated with advances in heat pump technology will be paid back over the cooling and heating cycle throughout the year, accelerating the payback period significantly compared to cooling-only equipment.

2.2 TECHNOLOGY TRENDS

Technological trends in heat pump equipment efficiency are explained in the following subsections.

2.2.1 Definition of Efficiency of Heat Pump Equipment

There are several common ways of expressing the "efficiency" of heat pump equipment. The energy balance of the first law of thermodynamics allows analysis and design of individual system

components. The first law performance parameter for refrigeration systems is the coefficient of performance (COP). COP represents the ratio of the rate of useful heat output delivered by the complete heat pump unit (exclusive of supplementary heating) to the corresponding rate of energy input, in consistent units and prescribed operating conditions.

In addition to the system coefficient of performance, another common measure of steady-state efficiency, especially for the cooling mode operation, is the energy efficiency ratio (EER). The EER is defined as the ratio of total cooling capacity to the power input in watts at any given set of rating conditions. In English units, the EER is expressed in Btu/hour of cooling capacity per watt of input power. In metric units, the EER is expressed in kcal of cooling capacity per watt of input power.

A measure of equipment performance on an annual basis is the seasonal energy efficiency ratio (SEER). The SEER for a heat pump or a central air conditioner is an expression of the total cooling output on a seasonal basis divided by the total electrical energy input in watt-hours during the same period. In English units, the SEER is expressed in Btu/hour of cooling per watt-hour of input energy. In metric units, the SEER is expressed in kcal of cooling output per watt-hour of input energy. Whereas the EER can be measured under prescribed conditions for any equipment, the measurement of the SEER for given equipment under varying loads is quite complex. Consequently, the SEER of given equipment must be determined by using an industry-accepted test procedure, which combines both steady-state ratings at several data points and computational estimates of equipment behavior over a range of prescribed load conditions.

2.2.2 Trend of Steady-State Efficiency Improvements for Japanese Heat Pumps

The growth in equipment technology, measured in terms of the cooling EER for Japanese heat pump units, is presented. Figure 2.2 shows the trend of these improvements (in metric EER, kcal/watt = 1.25 Btu/watt) for split-type, wall-mounted

Figure 2.2. Energy Efficiency Ratio of Air Conditioners in Japan (split-type, wall-mounted) [Source: Japan Refrigeration and Air Conditioning Industries Association (JRAIA)]

indoor units with a cooling capacity of 2,240 kcal/hr (8,888 Btu/hr or 0.74 ton) at 60 Hz. The data presented here is the shipment-weighted average EER for heat pump units having the capacity of 0.74 tons with the shipment-weighted average EER in English units (Btu/hour per watt) given along the vertical axis. The data was recorded between 1973 and 1985. As can be observed in the figure, the average EER of Japanese residential heat pumps increased from 7.4 in 1973 to 11.2 in 1985; this represents an increase of 50%. It should be noted here that the advantage of inverter application is not necessarily reflected in this figure. It is because the greatest benefit of inverter application for air conditioning equipment is energy savings on the seasonal basis. Figure 2.2 shows EER at a single, steady-state (rated) condition, and it is essentially an indication of steady-state efficiencies for motors, compressor, and heat exchangers. The benefit of inverter application of the seasonal basis will be explained in the following section.

Data such as this and other descriptions of the dramatic growth in the steady-state efficiencies of Japanese heat pumps reported by manufacturers (e.g., Umezumi and Suma 1984; Nakashima et al. 1985; Itoh 1986; and Muñozorio et al. 1986) warrant careful analysis. A heat pump is a complex

thermodynamics system. Every component interacts with the rest of the system, affecting capacity, efficiency, power consumption, etc. Usually, a change in one component must be accompanied by design modifications in other components to improve system efficiency, reduce impact on manufacturing cost, and maintain high reliability.

Each incremental improvement in steady-state efficiency is evidenced by manufacturer reports, particularly from Japan, attributed to the "key technical breakthrough," such as the rolling piston compressor, microprocessor controller, solid-state relays, etc. One must be careful, however, not to blindly accept a manufacturer's assertion that the benefits of some change are attributable to a single-component improvement. Usually, the Japanese manufacturers make several improvements or changes between models and then attribute most or all of the benefits to the feature they wish to emphasize for marketing reasons. Thus, in analyzing state-of-the-art heat pump technology, it is important to keep in mind that technical papers and reports can be used for marketing purposes as well.

2.2.3 Benefits of Capacity Modulation on Seasonal Efficiency for Heat Pumps

The inverter-driven heat pump, first introduced by Toshiba in 1982, is the highlight of the developments in the Japanese heat pump market. Rather than having only the on-off control, modulation of cooling capacity to match the required load can conceivably generate energy-efficiency benefits. Regulation of the refrigerant mass flow rate is the most common method of capacity control in air conditioning systems, and an ideal flow modulation scheme should include 1) full-load efficiency unaffected by the mechanisms, 2) continuous adjustment to load, 3) good part-load efficiencies, 4) reduced starting torques, 5) unchanged compressor reliability, 6) no reduction of compressor operating range, and 7) no increase in compressor vibration and sound levels at part-load operation (Bahel and Zubair 1989). It is noted that not all benefits can be realized simultaneously by any single-capacity control technique.

Continuous variable compressor speed appears to offer the best means of capacity control and also meets most of the criteria mentioned here. With such a method, a compressor operates only as fast as is necessary to meet the building load. However, until recently this capacity control approach has been restricted to large systems by high initial costs. Now increased power rating of solid-state devices has become available on a mass-production basis. These devices enable higher-power inverter circuit designs to be achieved, thus encouraging manufacturers to seriously consider application of variable-speed electric motors for air conditioning and heat pump compressors.

A number of attractive features of inverter-driven variable-speed heat pumps have been reported (Bahel and Zubair 1989; Miller 1988; Lannus 1988; and Mohan and Ramsey 1986). In terms of seasonal energy efficiency, inverter-driven heat pumps can lessen energy consumption in a building by 1) lower start-stop (cycling) losses, 2) improved refrigerant cycle performance because of decreased compression ratios and reduced heat exchanger loading during low speed operation, and 3) lower fan power requirements through variation of air flow rates. The findings of Hori et al. (1985), Iida et al. (1982), Marquand et al. (1984), Mills (1987), Tassou et al. (1983), and Umezu and Suma (1984) show inverter-driven heat pumps can achieve seasonal energy savings of 15% to 40%.

Another attractive feature of a modulated system is the ability to operate in a low-capacity, load-following mode during periods of peak electrical demand. A number of electric utility companies in the United States have indicated interest in temporary air-conditioning curtailment during high-demand periods to shed peak electrical loads. In such situations, inverter-driven heat pumps can be restricted to low-capacity operations. This would result in retaining some cooling during high-demand periods, and at the same time produce a substantial reduction in utility peak demands. Thus, variable-speed heat pumps and air conditioners are expected to facilitate load management by the utilities and possibly operate the unit in a manner predetermined by such factors as the

previous day's environmental data or forecasts provided by the utilities (Bahel and Zubair 1989).

2.3 JAPANESE SPACE CONDITIONING OPERATING ENVIRONMENT

Any analysis of space conditioning equipment, whether technically or market oriented, can be misleading unless the design load condition is described. To give the proper perspective to how Japanese variable heat pump technology evolved in the last 5 years, it is important to understand the definition of Japanese space conditioning operating conditions, as well as the similarities and differences between typical Japanese and North American design philosophies.

The average low-temperature range in Japan is 0°C to -10°C (32°F to 14°F), except for extremely cold regions such as Hokkaido Prefecture (the northernmost island of Japan). In summer, the average high temperature range in the Tokyo-Osaka corridor is 25°C to 35°C (77°F to 95°F) with relative humidity above 80%. Under these conditions, an air-source heat pump room air conditioner is useful and viable. Over 60% of the country's population lives in the corridor between Tokyo and Osaka. Therefore, it makes sense that competition for the greatest share of the popular space conditioning equipment market occurs in this region.

The market for central space-conditioning systems (i.e., with central air ducts or hydronic systems) comprises approximately 2% of the Japanese residential market in most population centers, except Hokkaido, where the central type is quite common. The Hokkaido is served by types of heating equipment similar to typical U.S. central-style heating equipment in cold climate regions (regions defined by the U.S. Department of Energy (DOE) as between 4,000 to 5,500 heating degree days).

Figure 2.3 shows the average low temperature in January. In Tokyo, the average low temperature is 0°C (32°F). Heat pumps are usually installed in living rooms. The average floor area of a Japanese

Figure 2.3. Average Low Temperature in Winter in Japan

living room is $13\text{--}17\text{ m}^2$ ($140\text{--}183\text{ ft}^2$). Most Japanese construction is wood, except for concrete apartments, and heating loads are represented by the values specified by the Japanese Industrial Standards (JIS). Table 2.1 shows the heating load specified by JIS. The set temperatures for calculation of the heating capacity are 21°C (70°F) indoor and 0°C (32°F) outdoor, resulting in a heating load of $3.03\text{--}4.95\text{ kW}$ ($10,350\text{--}16,900\text{ Btu/hr}$) for the range of floor space.

The cooling load is estimated to be 260 kW ($8,890\text{ Btu/hr}$) for an average-size room. Thus, the required ratio of heating-to-cooling capacities would be in the range of 1.2 to 1.9. It is the goal of Japanese heat pump manufacturers to develop a product that can attain this required ratio with good efficiency; that is, without the use of auxiliary heating systems.

For comparison of equipment size and performance, the preceding description of operating conditions and environment form the basis for the task of residential heat pump design in Japan. With this backdrop, the dramatic market penetration of variable-speed heat pumps in the vast Japanese residential market is examined. The market remains strong for split-type room air conditioners and heat pumps under 2.5 tons, with about 3.9 million units

Table 2.1. Heating Load Per Unit Floor Area (Japanese Industrial Standards, C9612)

Room Conditions			Heat load per unit floor area (W/m ²)	Ventilation times (times/h)	Window <u>area</u> floor area (%)	Occupants per 10 m ²	Light W/m ²
Wooden house	Japanese style	face to south	291	1.5	40	3	0
		face to north	279	1.5	20	3	10
	European American style	face to south	279	1	30	3	0
		face to east	279	1	30	3	0
		Concrete Apartment		up stairs	262	1	30
middle stairs	233			1	30	3	10

(a) The heat load is enough to keep the room temperature at 21°C (70°F) with an outdoor temperature at 0°C (32°F).

sold in 1987 and 4.5 million units sold in 1988. In terms of the constant annualized growth rate, the residential inverter-driven heat pumps grew at a rate of 85% per year. Considering the history of inverter technology for motor speed control, the dramatic increase in inverter-driven equipment warrants a close examination and an assessment of

its impact on other application areas. It is clear that the market demand for inverters and its rapid growth rate will continue to drive the system cost downward. As inverters become less expensive, they should become more affordable in other application areas, possibly impacting other industries, markets, and trade partners.

its impact on other organizations. It is clear that the same does not hold for all organizations. Growth rates with different patterns of growth are observed. As a result, the growth rates of individual organizations are not the same. They are determined by the growth rates of the organizations that they are associated with. The growth rates of the organizations that they are associated with are determined by the growth rates of the organizations that they are associated with.

It is clear that the growth rates of the organizations that they are associated with are determined by the growth rates of the organizations that they are associated with. The growth rates of the organizations that they are associated with are determined by the growth rates of the organizations that they are associated with. The growth rates of the organizations that they are associated with are determined by the growth rates of the organizations that they are associated with.

3.0 FUNDAMENTALS OF MOTOR-SPEED CONTROL

The fundamentals of motor-speed control are discussed in this section.

3.1 SIGNIFICANCE AND MOTIVATION FOR THE ANALYSIS

Increased industrial productivity and energy efficiency have been associated with increased utilization of electrotechnologies. New power switching devices are one of the key developments in this area. These devices offer cost-effective methods for controlling motor speed to precisely match the load torque or load shaft speed. In the motor application industry, these devices are referred to as adjustable speed drives (ASDs).

Proper application of the technology offers increased energy efficiency through motor-speed control in applications where the load varies during operation, such as in the case of space conditioning. In principle, ASDs afford improvements in many industrial, commercial, and residential energy utilization processes. Several device designs and circuit topologies are available in ASD technology. Specific device selection requires a careful analysis of the application, motor characteristics, and mode of operation.

The aggressive pricing and manufacturing policies employed by the leading Japanese corporations contributed to driving the cost of ASDs and custom integrated chips (ICs) low enough to be applied in a wide variety of residential and commercial equipment.

Currently, over 50% of the residential heat pumps sold in Japan use inverters for capacity modulation through compressor speed control. Competition among major HVAC equipment manufacturers continues to provide incremental changes and new features for inverter-driven heat pumps. The Japanese residential market accepted the premium cost placed on inverter-driven heat pumps because the equipment met the requirements of:

- quiet operation at low speed (less than 60 Hz)
- enhanced comfort (small indoor temperature fluctuation and unimpaired comfort during defrosting)
- improved seasonal energy efficiency ratio (SEER)
- development of special convenience features derived from additional electronic controls and unique load modulation capability.

While the Japanese residential and commercial heat pump market is rapidly accepting inverter-driven equipment, market penetration is low in the United States, and future penetration of the American market is uncertain. The most popular U.S. heat pump size is in the range of 2.5 to 4 tons; the inverter capacity is in the range of 3 to 5 hp. With the use of medium power electronics components (such as the power Darlingtons devices), the capacity range of 3 to 5 hp requires a significantly higher level of technical development compared with the 1-hp range popular in Japanese equipment.

Inverter technology in the medium power range is challenged by:

- initial cost - driven by the cost of protection circuits and other auxiliary components
- electrical noise [electromagnetic interference (EMI)] - from high-frequency power electronic switching
- reliability - higher power requires larger heat sinks, and innovative ways to dissipate heat arising from electronic components.

In light of growing ASD applications in the residential HVAC market sector, it is important to assess the direction of the technology development and evaluate opportunities to gain value-added business (derived from improvements in efficient

HVAC equipment technology through proper use of ASD equipment). This section describes low horsepower inverter technology from past, present, and future perspectives. Based on a systematic analysis of ASD technology, this report is designed to communicate 1) state-of-the-art motor control methods, 2) emerging technology developments, and 3) impending changes in the motor drive industry. These topics are important to the U.S. industry, which is challenged by the rapid advances achieved by Japanese HVAC equipment manufacturers, many of whom also manufacture other ASD systems and critical components.

In this section, the areas of emphasis include:

- inverter technology (Section 3.2)
- state-of-the-art induction motor control technology (Section 3.3)
- state-of-the-art brushless dc motor control technology (Section 3.3).

Throughout this report, the following definitions are used to describe power electronics equipment:

- rectifier - equipment for transforming ac to dc
- inverter - equipment for transforming dc to ac
- converter - equipment for transforming ac to ac
- dc converter - equipment for transforming dc to dc
- cycloconverter - equipment for transforming a higher frequency ac to a lower frequency without a dc power connection.

3.2 SYNOPSIS OF INVERTER TECHNOLOGY

While various forms of mechanical inverters have been available for over 75 years, the development of the silicon-controlled rectifier (SCR) (or thyristor) made possible the controlled rectification

of alternating current power (utility ac power) into direct current (dc) power by a solid-state switching device. It also made possible the inverting of the rectified dc back into ac.

In many motor applications, the optimum value of voltage is not available from the primary power source. In such instances, dc-dc "converters" or dc-ac "inverters" may be used to provide the desired value of voltage. An inverter is used to transform dc power to ac power at controlled frequency (of the alternating current). If the ac output is rectified and filtered to provide dc again, the overall circuit is referred to as a converter (see for example, RCA 1975).

Power conversion circuits, both inverters and converters, consist basically of some type of "chopper." Figure 3.1 shows a simple chopper circuit. In this circuit, a switch S is connected between the load and a dc voltage source E. If the switch is alternately closed and opened, the output voltage across the load will be as shown in Figure 3.2. If the

Figure 3.1. Simple Chopper Circuit

Figure 3.2. Sample Trace of the Output Voltage Across the Chopper Circuit

on-off intervals are equal, the average voltage across the load is equal to $E/2$. The average voltage across the load can be varied by varying the ratio of the on-to-off time of the switch, by periodically varying the repetition rate, or by a combination of these factors. If a filter is added between the switch and the load, the fluctuations in the output can be suppressed, and the circuit becomes a dc-dc step-down converter (the output voltage is lower than the line voltage) (RCA 1975).

Figure 3.3 illustrates the basic concept where the utility input is converted into dc by means of either a controlled or an uncontrolled rectifier and then inverted to provide variable voltage, variable frequency power to the motor. All continuous adjustable speed ac motor drives in the horsepower range under consideration here employ dc link inverters.

The presently available systems can be classified into three basic inverter types:

1. square wave, voltage source inverter (VSI)
2. square wave, current source inverter (CSI)
3. pulse-width-modulated (PWM), voltage source inverter.

These inverter types and features pertinent to their heat pump applications are discussed in later sections.

To derive performance and cost benefits from the capacity modulation of heat pumps requires an efficient and inexpensive "inverter." Out of the various drives considered previously (EPRI 1981), the

solid-state inverter drives are unique in terms of their high efficiency. Various types of solid-state switching devices can be applied in the voltage-reversing process for a dc-ac inverter.

For application in heat pumps, the overall ASD system consists of three distinct parts: an inverter to condition the utility input to yield adjustable frequency and voltage output, a hermetic motor, and a compressor. The inverter acts as an interface between the utility input and the motor. To accomplish a wide capacity range, the motor and the compressor should be capable of operating at reduced speeds, resulting in decreased cooling and lubrication. In addition, the inverter must satisfy the following basic requirements (Mohan and Ramsey 1986):

- ability to adjust its output frequency in proportion to the desired output speed (which in a heat pump is dictated by the heating/cooling load)
- ability to adjust the output voltage to maintain an essentially constant volts/Hertz ratio over the desired speed range, keeping the output torque capability constant
- ability to supply rated current at any frequency within the desired speed range, keeping the output torque capability constant.

Providing an efficient adjustable speed operation of induction or synchronous motors requires adjustment of both frequency and voltage. Frequency adjustment allows variation of the motor speed while voltage adjustment permits controlling the torque to drive the compressor.

Figure 3.3. Inverter-Type Adjustable Speed Drive

Of the three inverter types mentioned, each has its own inherent advantages and disadvantages with associated variations of equipment costs. The aim of the following sections is to analyze state-of-the-art induction and synchronous motor control techniques for determining how the popular Japanese technology evolved and how it compares with U.S. inverter development.

3.3 STATE-OF-THE-ART INDUCTION MOTOR DRIVES

The performance of induction motors is explained in the following text and figures.

3.3.1 Overview

ASDs accomplish motor speed control by adjusting the speed of the rotating field (flux wave) in the motor stator. The motor produces torque by an interaction of the flux wave and the magnetic field of the current-carrying conductors in the rotor.

A generalized set of torque speed curves for an induction motor, illustrating the effect of varying the frequency of the applied voltage while maintaining a constant volts/Hertz ratio, is shown in Figure 3.4. If this motor happens to be driving a constant torque load, also shown in Figure 3.4, then the

Figure 3.4. Torque-Speed Curves for an Induction Motor at Various Frequencies Keeping Volts/Hertz Constant ($f_{e5} > f_{e4} > \dots > f_{e1}$) (Source: Mohan and Ramsey 1986)

motor would operate at speeds a_1, a_2, a_3 , etc., depending on the frequency. Another property revealed by these curves is that the breakdown or the maximum torque capability remains the same at all frequencies.

These curves clearly show the nearly ideal speed control which can be accomplished by frequency variation, the torque speed control which can be accomplished by frequency variation (the torque speed performance being essentially the same as at the rated motor frequency). It should be noted that in Figure 3.4, the breakdown torque is the maximum instantaneous torque the motor is capable of developing. The rated torque at which a motor can operate continuously is much less (generally 50% of the maximum torque) than the breakdown torque and depends on the motor design.

In actual heat pump applications, it may be beneficial to operate a unit at higher than its rated speed to deliver greater cooling (or heating). This can be accomplished by increasing the inverter output frequency beyond the rated frequency (f_{rated}) of the motor. Since the inverter output voltage is designed to reach its maximum value at f_{rated} , for $f > f_{rated}$, the voltage is held constant at its maximum value and the volts/Hertz ratio (which dictates the flux in a motor) decreases. Therefore, for $f > f_{rated}$, a motor can operate at its rated horsepower but not at its rated torque in a continuous manner. Figure 3.5 shows the torque which a motor is capable of developing on a continuous basis without overheating. In the constant power region, the torque varies as $(1/\text{speed})$. At very low speeds, the stator resistance can no longer be neglected in comparison to other motor loss parameters. Thus, the motor volts/Hertz ratio must be raised, as shown by the dotted line, to maintain a constant torque.

3.3.2 Performance of a Three-Phase, Single-Speed Induction Motor

Figure 3.6 shows a three-phase induction motor where the phase windings are displaced in space by 120 degrees with respect to each other. Three-phase motors are typically 2 to 3 percentage points higher in efficiency in comparison with single-phase

Figure 3.5. Induction Motor Continuous Capability Above and Below the Rated Speed

Figure 3.6. Three-Phase Induction Motor

motors due to the balanced magnetic field created by three equally spaced windings.

Figure 3.7 shows typical operating characteristics of a three-phase, 5-hp induction motor (Mohan and Ramsey 1986). It had a breakdown torque which is 2.15 times the rated torque. The starting torque is approximately 95% of the breakdown torque, which is typical for motors in this design class. The locked rotor ampere rating was measured to be 106 A, whereas the rated current for this motor was 20 A. The motor power factor decreases rapidly for low load conditions with torque of less than 10 ft-lbs.

Figure 3.7. Performance Characteristics of a Three-Phase, 5hp, 230-V Induction Motor (Source: Mohan and Ramsey 1986)

In comparison to the single-phase induction motors, three-phase motors typically exhibit higher efficiencies and much higher starting torque capability. Three-phase motors, therefore, have improved startup performance during low voltage conditions. However, use of such line-fed three-phase motors for residential applications is not possible unless the three-phase power supply is available to the house. This limitation is overcome by adjustable speed inverter drives, which can convert single-phase ac input voltage to a three-phase output with controlled voltage and frequency.

3.3.3 Basic Inverter Configurations for Adjustable Frequency Drives

To effectively utilize an induction motor over a wide frequency range, it is necessary to provide both frequency and voltage control in the power converter. While frequency control is achieved through controlling the fundamental switching rate of the main power switches in the inverter, voltage

control is accomplished in a variety of ways--depending on the inverter type and the requirements of the specific application.

There are two basic power circuit configurations in use, the voltage source inverter (VSI) and the current source inverter (CSI). An important variation of the VSI configuration is the pulse width modulated inverter (PWM) which incorporates voltage control and variable frequency operation in the basic inverter power circuit.

Square Wave, Voltage Source Inverter (VSI)

Figure 3.8 shows the circuit diagram for a VSI where a single-phase utility input is assumed. If a three-phase input is available, a three-phase-controlled rectifier bridge would be used. The phase-controlled rectifier consists of SCRs converts ac input into a dc voltage across the capacitor C_d . The inverter, by sequential switching of the six switches, produces a three-phase ac voltage at a desired frequency. Ideally, when a switch is closed, it allows the current to flow in a direction indicated by the arrow without any resistance; otherwise, it represents an open circuit. Either power transistors, Darlington's, metal oxide semiconductor field

effect transistors (MOSFETs), or gate-turnoff thyristors (GTOs) can be used as a switch. It is also possible to use SCRs but the need for an external commutation circuit precludes their usage in low power application (<10-hp) under consideration here.

As shown in Figure 3.8, the VSI is characterized by the presence of reverse connected diodes across each main switch. These "feedback" or "reactive" diodes provide reverse current paths such that when a particular power switch is turned on, one input dc-terminal and one output ac-terminal are connected regardless of the direction of the load current.

The VSI is also characterized by the dc link capacitor shown in Figure 3.8. This capacitor is required to allow momentary reverse currents in the dc link.

In a VSI, each switch is closed for 180° , with three switches in the "ON" state at all times as shown in Figure 3.9a. The feedback or reactive diodes connected in antiparallel with the switches provide reverse current paths. When a particular switch is closed, and the other switch in the same leg is opened, the corresponding phase terminal remains connected to one dc bus (positive or negative) regardless of the direction of load current in that phase.

The idealized output voltage waveforms are shown in Figure 3.9b. As can be observed, their magnitude depends on the dc link voltage V_d , which is controlled by the rectifier to yield a constant volts/Hertz.

VSI efficiency is typically very high (over 90%). Therefore, it is difficult to measure this efficiency accurately by measuring the input and output power flows unless power measuring equipment which responds accurately in the presence of large amounts of harmonics is available. The VSI efficiency was calculated and measured by Mohan and Ramsey (1986). This work reported that depending on the design and the components selected, the VSI

- a,b,c = three-phase output
- L = inductor
- V = voltage
- T = thyristors
- C = capacitor.

Figure 3.8. Square-Wave VSI (Source: Mohan and Ramsey 1986)

Figure 3.9a. Thyristor Gating Sequence for VSI Operation

Figure 3.9b. Idealized Voltage Waveforms for VSI Operation

efficiency can be estimated for most applications to range from 94% to 96% at full load.

Square Wave, Current Source Inverter (CSI)

Figure 3.10 shows the circuit diagram for a CSI where a three-phase input is assumed. The inverter for a CSI consists of six SCRs, and the diodes and the capacitors are used to provide current commutation from one SCR to the next. The phase-controlled rectifier bridge converts the ac input into a dc current through a relatively large dc link

a,b,c = three-phase output
L = inductor
T = thyristors

Figure 3.10. CSI Circuit Design (Source: Mohan and Ramsey 1986)

inductor, L_d . By sequential switching of the SCRs in the inverter, three-phase output currents are produced at a desired frequency.

In a CSI, neglecting the commutation intervals, each SCR conducts for 120 degrees with two SCRs conducting at any given instant of time as shown in Figure 3.11a, along with the idealized output current waveforms in Figure 3.11b.

The energy efficiency of a CSI is considerably lower than a VSI due to the following additional losses:

- losses associated with a relatively large dc link inductor, L_d
- conduction losses in the inverter, which requires a current path through 2 SCRs and 2 diodes in series as compared to two transistors in their saturated state in a VSI. It is estimated that a CSI efficiency in small size drives (<10-hp) would be less than 90% at full load (Mohan and Ramsey 1986).

The input power factor of a CSI operation varies with the motor speed (and the motor load), becoming very poor at low speeds, even worse than a VSI. CSI has a considerably lower efficiency compared to a VSI in the horsepower range of residential heat pump applications. Moreover, the cost of such a system would be high, the result of the

Figure 3.11a. Thyristor Gating Sequence for CSI Operation

Figure 3.11b. Idealized Current Waveform for CSI Operation

requirements of a feedback control loop and a large dc link inductor. It begins to compete in larger horsepower ranges (<50 hp) where the use of SCRs becomes economical regardless of the inverter type because of large voltage and current capacities. For these reasons, the CSI is not a good candidate in less than the 10-hp range.

Pulse-Width-Modulated (PWM) Voltage Source Inverter

Figure 3.12 shows the circuit diagram for a PWM inverter, where a single-phase utility input is assumed. If a three-phase input is available, a three-phase, full-wave diode rectifier bridge is used. Unlike a VSI where the inverter controls only the

a,b,c = three-phase output
L = inductor
V = voltage
T = thyristors
C = capacitor

Figure 3.12. PWM Circuit Diagram

frequency, in a PWM system the inverter controls both the frequency and the magnitude of the output voltage, with the rectifier bridge left uncontrolled.

Various modulation techniques are described in literature, but the sine wave modulation (SWM) is by far the most commonly used technique. Here a fixed-amplitude triangular carrier voltage, V_{tri} (at a high carrier frequency) is compared against a sinusoidal reference voltage, V_a^{ref} , whose amplitude and frequency determine the inverter output voltage. This is illustrated in Figure 3.13. When V_{tri} is less than V_a^{ref} for phase a, the switch A+ is closed and A- is opened. Otherwise, the opposite is true. The voltage V_{aN} of the inverter terminal "a" with respect to the negative dc bus, is shown in Figure 3.13. For phases b and c, the same triangular wave is compared with the reference voltage waves displaced by 120 degrees in time with respect to V_a^{ref} . The voltage, V_{bN} , and the phase-phase voltage, V_{a-b} , are also shown in Figure 3.13. A lower amplitude of the reference waves would result in notches of longer duration in the output voltage waveforms, thus allowing the volts/Hertz ratio to be kept constant.

Similar to a VSI, either power transistors, Darlington, MOSFETs or GTOs can be used as

Figure 3.13. Sine-Wave-Modulation and the PWM Inverter Waveforms

inverter switches. However, they must have a fast switching response for their application in a PWM inverter.

It should be noted that as the amplitude of the reference waves becomes higher than that of the triangular wave, a PWM begins to approach a square-wave VSI inverter with only a few notches per fundamental cycle.

The energy efficiency of a PWM inverter is estimated to be high (over 90%) at full-load, similar to a VSI, on the following basis:

- The filter inductor, L_f , in a PWM inverter is either nonexistent or is much smaller compared with a VSI, resulting in lower inductor losses.
- The uncontrollable rectifier in a PWM inverter will have lower losses compared to a phase-controlled rectifier in a VSI system, since the PWM uses diodes instead of switching devices.

- In a PWM inverter, the switching losses compared to the conduction losses cannot be neglected because of many switching operations per fundamental cycle. Therefore, it is important to use a fast switching device that would keep the switching losses to a minimum.

In Japan, PWM is the circuit of choice for residential heat pumps (less than 2.5 tons). The voltage source PWM-type for the single quadrant application (forward speed and accelerating torque only) has the simplest inverter topology; it is also the most inexpensive to build.

3.3.4 Induction Motor Drive Control

In general terms, ac drive control techniques can be subdivided into two classes: frequency-controlled and torque-controlled drives. While both systems provide variable-frequency, variable-voltage excitation to the ac motor, the control strategy and the response to load and set point variations are quite different. The response time and the final steady-state operating point (flux level, slip frequency, etc.) are also quite different for the two types of systems. A brief summary of the basic control concepts for each system is presented in this section.

Frequency-Controlled AC Drives

The basic, frequency-controlled ac drive is essentially an open-loop controlled system in which the output voltage and frequency are directly determined by the reference input. An ac motor will operate in exactly the same way from this system as it does when supplied from a 60-Hz power line, except that the voltage and frequency are adjustable and the current capacity is very limited compared to a typical power line. Since all ac motors operate at or near synchronous speed, the frequency-controlled ac drive is inherently an adjustable speed system. Induction motors will operate with the same type of torque-speed characteristic as conventional 60-Hz excitation. The difference is that the synchronous speed is adjustable and the limited current capacity restricts operation to the "small slip" region near synchronous speed. Motor

starting must be accomplished by beginning with a very low frequency and "ramping up" the frequency slowly enough that the motor can follow the change without excessive slip. The ramp rate is adjusted to meet varying starting torque and load inertia conditions. Voltage-to-frequency coordination (constant volts/Hertz) is provided by an open loop control with an adjustable low frequency voltage boost to overcome stator resistance effects at low speeds.

Although the basic frequency-controlled ac drive is an open loop system, a variety of internal feedback loops are often introduced to overcome inherent limitations. Examples include current limiting loops to avoid unnecessary shutdown by reducing frequency and voltage if the current reaches the preset limit, IR drop compensation to improve speed regulation, and compensators to improve low frequency stability.

In many applications, frequency-controlled operation with normal induction motor speed regulation of 2-5% is sufficient to achieve adequate steady-state performance. This is especially true when the drive is inside an outer control loop. A good example is a setpoint pressure control for a variable air volume fan in an HVAC installation. Here, the motor speed determines air flow, which is sensed and controlled by the external pressure loop.

In applications where precise speed control is required, a synchronous motor can be used to provide zero-speed regulation and exact-speed match with the drive frequency. This method provides accurate speed control but is more expensive because of the higher cost of the synchronous motor. The alternative to a frequency-controlled induction motor drive is a tachometer and a speed control loop.

VSI and PWM Drives

Figure 3.14 is a block diagram of a typical, open-loop, variable-frequency drive controller. There are many variations of this type of controller. Most systems provide rated frequency at nominal supply voltage to match standard motors. Adjustments for

Figure 3.14. Typical Open-Loop Control System for a VSI

low frequency voltage boost and base speed volts/Hertz trim are normally provided. A voltage regulator to handle fluctuations in the supply voltage is typical; extended output frequency to about twice rated-frequency at constant voltage for constant horsepower operation is often provided. Because of the limited overcurrent capability of the power switches, an instantaneous overcurrent trip (IOT) is always provided, and many (but not all) systems have an internal current limit loop which reduces the voltage and frequency when necessary to avoid unnecessary IOT shutdowns. All these control parameters must be in residence in a microprocessor controller of inverter-driven heat pumps.

The primary differences between PWM systems and the simplest variable frequency drive (a six-step) relate to harmonics. The voltage harmonics present in the output wave create harmonic motor currents, additional losses and torque pulsations.

The harmonic currents are primarily limited by the machine leakage reactance; therefore, higher leakage machines are preferred. Oversized machines may cause excessive harmonics and high peak currents, even when operated at light load.

In the six-step drive, the harmonics and low-speed torque pulsations are unavoidable. PWM drives offer reduced low-order harmonics and small pulsation torques at the expense of generally increased inverter switching losses. A major problem with PWM is increased motor acoustic noise, though primarily with large fan/blower machines.

3.4 STATE-OF-THE-ART DIRECT CURRENT MOTOR CONTROL TECHNOLOGY

State-of-the-art dc motor control technology information is explained in the following subsections.

3.4.1 Direct Current Motor Drive Family

Although the focus of this discussion is on the recent development of a permanent magnet brushless dc motor, it is important to present the fundamentals of dc motor control. Direct Current (dc) motor drives can be relegated to essentially two

generic types; these types are categorized by their sources as shown in Figure 3.15. The first class contains systems in which the source is dc.

The oldest of such configurations utilizes a tapped resistor, in which the current to the dc motor is adjusted (in its traditional form) by means of continuous air monitors (CAMs). When the field winding is connected in series with the armature, such systems comprise the traditional traction drive for powering trams, subway cars, and so forth. This type of system has been almost entirely replaced by the chopper-controlled dc motor in which the voltage adjustment is accomplished by means of one or more solid-state switches.

The second class of dc drives contains systems in which the source is ac; these are of primary interest in this study. In the classical Ward-Leonard drive, the most common system, the dc motor is supplied from a dc generator which is, in turn, driven by an induction or synchronous motor. The Ward-Leonard system has been the industry workhorse for over eight decades. However, this system has largely been supplanted by modern, solid-state systems, primarily line-commutated thyristor converter drives and drives employing a diode rectifier/chopper arrangement. In addition, force-commutated rectifiers employing internal commutating circuits, power transistors or GTOs (gate

Figure 3.15. Classification of dc Drive Types

turnoff thyristors) have emerged and will be used increasingly in the future. This section briefly describes the operating principles of speed-controlled dc drives and presents recent developments in brushless dc motors.

3.4.2 Direct Current Machine Design Features

From the viewpoint of the power electronics engineer, the mechanical commutator is a remarkable device (Figure 3.16). In the figure, the main field poles and commutation interpoles are omitted for simplicity. In general, a commutator with n segments can be thought of as an n -phase winding, with the n phases connected in a delta form. As the dc armature rotates, the brushes switch the currents in the phase coils undergoing switching or "commutation."

This continuous switching process gives the commutator the following properties:

1. All phase coils, other than those being switched, carry full current and are fully utilized.

Figure 3.16. Simplified Diagram of a dc Motor

2. The resultant square spatial waveform of the armature magnetomotive force (MMF) is optimum for interaction with the (ideal) square-field flux waveform. These two waves are always held in the correct relative relationship so the greatest torque per watt of losses is achieved.
3. Full four-quadrant operation occurs without any special control signals or other provisions as operating conditions are changed.
4. Torque ripple with shaft rotation is low because of the large number of phases employed in a typical dc motor.
5. The commutator is relatively inexpensive, representing (in a large machine) about 15% of the total cost.

Mechanical commutators, however, have several disadvantages which make these machines less than ideal. These include:

1. Periodic maintenance and overhaul are needed, with attendant reliability concerns.
2. The arcing with mechanical commutation limits machine size to a $\text{kW} \times \text{rpm}$ product of 2 to 3×10^6 .
3. Arcing with mechanical commutation is disadvantageous in a hermetic system because it breaks down refrigerants.
4. Centrifugal forces on the commutator bars limit machines of normal design to 1500 rpm at 1 MW, 5000 rpm at 50 kW and 10,000 rpm at a few kW.
5. Sparking brushes cause electromagnetic interference.
6. Reliable operation is difficult in corrosive, dusty, damp, liquid-immersed, evacuated or explosive atmospheres.

In smaller sizes (below 5 hp), the discrete-wound dc field has been largely supplanted by permanent magnets. Such machines are widely used in computer peripherals, the machine tool industry, thermal imaging, robotics, actuators for aircraft applications and a wide range of general industrial needs. New types of permanent magnet materials, such as neodymium-ferri-te-boron (Nd-Fe-B) magnets, are largely replacing samarium-cobalt (Sm-Co) designs for all but high temperature applications. However, in spite of its relatively small remnant flux density, ferrites remain the magnet of choice for cost-sensitive applications.

3.4.3 Electronically-Commutated Motors with a Permanent Magnet Field

In sizes in excess of 1,000 hp, it becomes economical to use CSI-synchronous motor drives for adjustable speed applications. These are commonly called the load-commutated inverter drives. Such synchronous motors have field poles on the rotor excited by a dc current. In smaller horsepower, it is possible to use a permanent magnet field on the rotor and supply the motor with a voltage source-type inverter (VSI or PWM). Commonly used terms for such systems are electronically-commutated motors (ECMs), brushless permanent magnet motors (BPMs) "brushless" dc motors, and synchronous motor drives. Interest in these systems in the HVAC industry is strong from high efficiencies of the permanent magnet motors. In a permanent magnet motor drive, the inverter consists of self-commutating switches, such as power transistors.

Unlike an induction motor, a synchronous motor operates exactly at its synchronous speed which is dictated by the frequency of the applied excitation to its ac winding located on the stator. The electromagnetic torque produced is proportional to the applied stator voltage " V ", the back emf (electromotive force) " E " generated due to the rotating magnetic field produced by the permanent magnets on the rotor, and the sine of the torque angle between these two phases. For a voltage-fed synchronous motor, its torque capability as a function of speed is shown in Figure 3.17.

Figure 3.17. Torque Capability of a Synchronous Motor as a Function of Speed

Operation Below the Rated Speed

In this region, also called the constant torque region, the inverter is controlled to yield a constant volts/Hertz ratio. This is shown by the linearly increasing voltage with speed (or frequency) except at very low speeds where the voltage is slightly raised to compensate for the drop across the ac winding resistances. Similar to an induction motor, maintaining a constant volts/Hertz ratio ensures the capability to develop maximum torque, as shown by the maximum torque envelope. At a given frequency of operation, the motor current and the torque angle will change accordingly to deliver the necessary torque, such that it does not exceed the maximum capability.

Operation Above the Rated Speed

A synchronous motor can also be operated in this region, called the constant power region. The magnitude of the applied voltage is kept constant, having reached its maximum, and the field current is reduced to keep the back emf, E , from going up as speed goes beyond its rated value. However, this presents difficulty in terms of a permanent magnet motor operation where the designed dc field cannot be controlled. Therefore, a permanent magnet synchronous motor drive must be designed with rated speed equal to the maximum speed.

3.4.4 Basic Control Techniques

In an open loop control, the inverter sets the frequency of the output voltage based upon an external command. In addition, it maintains a constant volts/Hertz ratio. Such a system in a block diagram form is shown in Figure 3.18 (Mohan and Ramsey 1986). To produce a starting torque, a squirrel-cage winding must be present on the rotor in addition to the permanent magnets. The generated field in the winding brings the rotor and stator into synchronism.

Under a closed loop control as shown in Figure 3.19, the rotor position is sensed and the appropriate switches within the inverter are turned ON and OFF. The speed can be increased or decreased by advancing or retarding in time the inverter switching operations with respect to the rotor position. In a similar manner, knowing the rotor position allows a starting torque to be developed without the need for a squirrel-cage winding on the rotor. Again, the volts/Hertz ratio is kept constant.

3.4.5 Feasibility of Permanent Magnet Motors for Heat Pump Applications

An ECM with permanent magnets can easily provide a continuous capacity modulation in a speed range of six-to-one. A low-cost PWM

Figure 3.18. Open Loop Control of an Electronically-Commutated Motor (Source: Mohan and Ramsey 1986)

Figure 3.19. Closed Loop Control of an Electronically-Commutated Motor (ECM) (Source: Mohan and Ramsey 1986)

inverter may be used with a back emf sensor to control the synchronous speeds of the motor. The motor speed, however, cannot exceed its rated speed, which may impose a penalty in terms of oversizing the motor and the inverter. For example, if a conventional compressor is to be operated at 50% higher than its rated speed in case of very low outside temperature, an induction motor drive can easily accomplish this because the power demand remains less than its rated value. In case of an ECM with permanent magnets, the motor and the inverter must be rated at this 50% higher speed. Therefore, both will be oversized compared to an induction motor drive.

In spite of the inherent technical challenges of ECM technology, two leading U.S. motor manufacturers have successfully introduced a series of permanent magnet motors for applications in heat pumps, warm air furnaces, and central air conditioners with capacity modulation. Technology selection between an induction motor with a VSI or PWM inverter, and the choice between induction motors and ECMs, will be discussed in Chapter 5.

4.0 IMPACT OF NEW SEMICONDUCTOR DEVICES ON INVERTER TECHNOLOGY

The impact of new semiconductor devices on inverter technology is discussed in this section.

4.1 OVERVIEW

The solid-state switching device is the essential ingredient of an efficient, high performance inverter. Energy loss of an inverter can be traced back to how well the power switching devices perform in a given circuit topology, and the reliability of the system can be attributed to operation ruggedness and the heat dissipation characteristics of the solid-state devices.

More importantly, the world's leading inverter manufacturers (either for general purpose or application-specific design) are also manufacturers of solid-state switching devices, as well as micro-processor control modules. This suggests that a close examination of the impact of electronics devices is required to analyze the influence some device manufacturers exert on technology development, product design, and marketing.

The objective of this section is to present a reference guide on state-of-the-art and emerging power semiconductor devices. While the discussion addresses performance parameters of power electronics devices, the primary objective of Section 4 is to provide application engineers with insight into the performance of high power semiconductor devices and their impact on inverter design, inverter-aided system integration, and an outlook of how the advanced technology base is being developed in the United States and Japan.

Since the invention of the bipolar transistor in the 1940s and the SCR in the 1950s, the industrialized world has seen a great deal of progress in power semiconductor devices. A dramatic growth in power electronics production and application is currently under way. In 1982, the device market in the U.S. was estimated at \$2 billion, including a variety of power conditioning applications with

increasing power levels (Baliga 1984). Furthermore, EPRI estimated that the domestic market for power electronic devices increased to \$12 billion in 1986, with the potential of doubling the revenue by 1990. Device cost is only a part of the total cost in the power electronics equipment market, which was estimated at \$60 billion annually (EPRI 1985).

4.2 THYRISTOR TECHNOLOGY

Of the mature power electronics device technologies, the SCRs, or thyristors, are firmly entrenched in the industry and have been applied to increasing operating loads. Circuit design engineers and applications engineers have demanded advanced devices with higher blocking voltages, higher current carrying capabilities, higher tolerance against dV/dt and dI/dt , shorter turnoff times, lower gate-driver power requirements, and lower power dissipation. The development of new devices, on the other hand, promoted the development of new circuits and new applications of power electronics. The most desired combination of characteristics for a power switching device are the blocking, firing, and conducting capabilities of a standard thyristor, together with the turnoff capability of a power transistor.

Thus, the application requirements established an environment in which new self-turnoff devices were invented. These self-commutated power switching devices are used in a variety of applications. The advent of GTO thyristors and static induction thyristors (SITHys) for use in power conditioning have contributed not only to increasing the overall efficiencies of power switching devices, but also to providing new opportunities to realize significant benefits for utility, industrial, commercial, residential, and transportation users. With the recent progress made in the mass production of high quality, large-capacity, reliable power switching devices, the users of power equipment and control systems have converted to solid-state power

electronics. The key ingredients in the success of the devices have been circuit control and application.

A significant developmental incubation period is required for a given power electronics device technology or application innovation to mature from a concept to a commercial technology. For example, it took GTO technology nearly 20 years from its invention by General Electric's Corporate R&D group (Goldey et al. 1961) to full commercialization by the Toshiba Power Systems Division (Seki et al. 1980).

In the early stages of the GTO commercialization, there was a certain degree of over-expectation towards the potential performance attributes of the device. Many engineers were led to believe that GTOs would have the high blocking, easy-triggering, and low-loss conducting capabilities of an SCR, combined with a turnoff capability and the small gate input typically required for a power transistor. Over the years, many different types of GTOs have been developed. But, as is common in power semiconductor technology, an improvement in one performance parameter is only possible with a compromise of other device attributes. For example, the increased switching speed afforded by gold diffusion or gamma-ray irradiation (which reduces carrier lifetime in the N-layer) results in an increase in the forward voltage drop in the ON state, essentially reducing the conduction efficiency of the device. The typical trade-off relationship between forward voltage drop and turnoff time is illustrated in Figure 4.1.

Through theoretical analysis and practical experience, device engineers and application specialists realized that the performance attributes available in GTOs are dependent on the application. The performance requirements of a given application create important technical challenges and trade-offs of performance parameters for the GTO device. After GTO devices were tested, destroyed, improved, and retested, the technology matured to the level of wide application.

Figure 4.1. Typical Trade-Off Relationship between Forward Drop and Turnoff Time of Power Thyristors (Source: Schlegel 1976)

Before commercially available GTOs were accepted in power electronics applications, many design objectives had to be met. By taking advantage of the GTO's attributes (high voltage blocking capability and fast turnoff without the use of forced commutation circuits), manufacturers made significant progress in improving the high current turnoff capability and increasing the reverse bias safe operating area (RBSOA) to enhance the acceptability of the device in the marketplace. The success of GTO-based power electronics products is evident from the cumulative sales figure of one of the world's leading manufacturers (Figure 4.2). As the sales figure indicates, the cumulative total capacity of GTO-based products increased tenfold every 3 years between 1978 and 1985. Overall trends in

Figure 4.2. Cumulative Total Capacity of GTO-Based Products Sold by Toshiba Corporation between 1977 and 1985 (Source: Seki et al. 1980)

device rating also indicate a dramatic growth in device development (Figure 4.3).

Thyristors are found in a variety of applications, including electrical power and frequency conversion, power regulation and control, and switching. Thyristor-based inverters provide portable (for example, for marine use) power supplies. Variable-frequency thyristor inverters provide induction motor speed control. Higher frequency converters are used in induction heating and melting and ultrasonic cleaning. Thyristor choppers are used to provide speed or position control of dc motors and regulation of dc generators. Thyristors also find

Thyristor Voltage Rating by Year of Production

Current Rating at 1,200V (460V AC > 1,000V DC)

GTO Gate Turnoff Thyristor
 BJT Bipolar Junction Transistor
 IGT Insulated Gate Transistor
 MOSFET Metal Oxide Semiconductor Field Effect Transistor

Figure 4.3. Trends in Device Technology Development [Source: Adler et al. 1984 (©1984 IEEE)]

applications in high voltage ac/dc and dc/ac conversion for dc transmission.

Today, we stand in the midst of new advances in power electronics technology. The state-of-the-art development of power electronics has been based on countless device innovations, process

improvements, and developments in the physical understanding of solid-state switching. It is evident that power switching devices will see wider application opportunities and further technological challenges in the years to come.

4.3 COMPARISON OF POWER SEMICONDUCTOR DEVICES

Many different power semiconductor devices are used in ASDs. Almost all are used in a switching mode where they switch between ON and OFF states, commutating current between different parts of the circuit. From a circuit perspective, these power switches fall into two different classifications: passive (or uncontrolled) switches like diodes, and active (or controlled) switches like transistors and thyristors. Both kinds of devices are used in every inverter, but diodes usually do not get as much attention because they are less expensive and less critical than the active switches. However, a good understanding of diode operation is necessary to understand thyristor and transistor operation. After a brief survey of diode operating principles, most of this section will be concerned with active switches.

The SCR has been the primary example of a power semiconductor switch. It is used in traditional dc motor drives and cycloconverters. However, for ac and brushless dc motor drives, the SCR has been replaced by switches which can be easily turned OFF as well as ON. Several different power semiconductor devices are commonly used, and new types (with claims of superior performance) are constantly introduced. Each of these switches operates in a different manner and often has widely different characteristics and costs, complicating the choice of switch type.

4.3.1 Classification by Injection Level

All power switches used in ASDs are considered high-voltage devices compared to the 5 V- to 15 V-level used for information processing. From a semiconductor material perspective, any blocking voltage above 50 V is considered high voltage,

requiring a relatively light doping level in the semiconductor to keep the internal electric fields low enough to avoid breakdown. Yet, when the doping level is light, the carriers available for conduction are few and the effective series resistance is high. To obtain a low ON resistance in a power semiconductor switch, either the active area of the device must be very large or additional carriers must be externally injected into the lightly doped blocking region. In this section, the different power semiconductor switches are classified in three groups based on the mechanism used to achieve conduction in the forward bias or ON state. These three groups are: 1) double injection devices in which both holes and electrons are injected for conduction, 2) single injection devices in which only one carrier type is injected to enhance conduction, and 3) bulk conduction devices where no injection occurs. This classification provides a fundamental framework for comparing different devices. Within each group, the basic conduction process is the same, but the various device types use different methods to control the turn-off and turn-on process.

The large research and development effort in very large scale integrated circuits (VLSI) products continues to provide technology improvements that can be applied to power devices. For example, as smaller integrated circuit technology becomes available, power device designers also use this technology to make the control electrodes in power devices smaller. With smaller electrodes, adjacent regions can be spaced closer together to produce faster devices.

In the following sections, a simple sketch of each device type is shown and discussed to explain the principles. Next, the relative state of technological development type is compared to assess the future of each device type. Finally, power-integrated circuit technology is also reviewed as a candidate to be utilized in future inverter development.

Double-Injection Devices

Cross sections of four commonly used double injection devices are provided in Figure 4.4. The

Figure 4.4. Double-Injection Power Devices

simplest is the common power diode, which has the P- ν -N structure. Here, P stands for heavily doped P-type material, N for heavily doped N-type, and ν for very lightly doped N-type. The ν region is called the base region of a diode or thyristor, and is the region in which the depletion layer forms in the reverse bias state. Since the high electric field needed for blocking crosses the ν region, its width must be proportional to the breakdown voltage the diode is designed to withstand.

Under forward bias, the few carriers available from the ν region are insignificant for conduction. Instead, huge quantities of holes and electrons are injected from the top and bottom of N and P regions to fill the ν region with conduction carriers. Since the concentration of these carriers is orders of magnitude above that of the light background doping level, the concentration of holes must be equal to the electrons in the ν region to avoid a buildup of electric charge.

When the diode is reverse biased, these injected carriers must be removed before blocking can begin. The diode storage and switching time represent the amount of time necessary to remove these

injected carriers. The higher the breakdown voltage, the wider the ν region and the longer the reverse recovery time. "Fast" high-voltage diodes are made by reducing the carrier lifetime in the ν region, thus restricting the buildup of injected carriers. Since this also limits the number of carriers available for conduction, faster diodes will have relatively higher forward voltage drops.

Thyristors are double-injection devices in which additional P and N regions are added for control electrodes. Thyristors operate identically to a diode in both the reverse blocking and forward conducting states. However, an additional P-gate region in the SCR enables it to have a forward blocking state when the P- ν and P-N (gate-cathode) junctions are reverse biased. The ν region supports the electric field in the blocking state, and the N-type cathode and P-type anode inject holes and electrons for conduction under forward bias. During conduction, the injection levels can be so high that the P-gate and ν regions become insignificant. A major advantage of thyristors as power switches is their ability to withstand large overcurrent stress. Since they function like diodes at high currents, an overcurrent turns them ON even harder and prevents a turn-OFF which would destroy a device. The SCR shown in Figure 4.4 is the simplest example of a thyristor. Conduction in the forward direction cannot begin until the gate-cathode P-N junction is forward biased, enabling injection of electrons from the cathode across the narrow P region and into the ν region. Once conduction starts, the gate loses control and the SCR turns OFF exactly as a diode does when reverse voltage is applied.

Fast SCRs are constructed by making the cathode and gate control regions close together, using interdigitated geometries. The carrier lifetime in the ν region can be reduced only slightly as this reduction interferes with the turn-ON process.

The GTO thyristor shown in Figure 4.4 is constructed similarly to an SCR, except the interdigitated cathode fingers are made so narrow between the gate regions that a reverse-bias gate current pulse can turn the GTO OFF. The closely interdigitated structure gives the gate electrode

control of the entire P region surrounding the cathode. With a large reverse current pulse on the gate, all the holes are pulled out near the cathode. Then, the N-type cathode is forced to stop injecting electrons and the GTO turns OFF.

Although GTOs have been available for 25 years, high-voltage, high-current GTOs have only been available in the last 10 years. They are subject to a failure mode known as second breakdown; this is marked by an abrupt decrease in device voltage with a simultaneous internal constriction of current. The second breakdown phenomenon was first reported by Thornton and Simmons (1958), and has been studied extensively in power transistors (Schafft 1967; and Klein 1968). The mechanism for the second breakdown in the GTO has only been understood in the last 10 years.

For high-power semiconductors, the device must be operated within a certain safe region so that permanent damage caused by the second breakdown can be avoided. The avalanche breakdown (first breakdown) occurs when the applied emitter-gate voltage reaches the limit given by the well-known current-voltage relationship in a device. As the voltage increases, the second breakdown occurs. The experimental results can generally be treated as consisting of four stages:

- the first stage leads to instability of current-carrying capacity at the breakover voltage
- the second to switching from the high- to low-voltage blocking capability
- the third to the low-voltage, high-current range
- the fourth stage to destruction.

The third thyristor (Figure 4.4) is the static induction thyristor (SITh). This device is also called the field-controlled diode since it has a basic P- ν -N diode structure with a P-type grid structure inserted at the cathode end of the ν region. In the forward blocking mode, the grid P- ν diode is reverse biased, and the depletion layer formed in the

ν region terminates the electric field in the ν region. Thus, injection of electrons from the cathode is prevented and forward conduction is blocked. Forward biasing the gate junction enables conduction to begin, and hole injection from the anode keeps it conducting without additional gate bias. The SITh can be turned OFF by biasing the gate with a reverse current pulse. This pulse removes all the holes from the gate region--preventing them from being injected into the cathode. Without hole injection into the cathode, the regenerative process is stopped, electron injection from the cathode ceases and the device turns OFF.

The SITh is a controversial power device. Spectacular speed and power performance capabilities for ASD applications have been claimed and demonstrated. However, the devices are made by a small Japanese manufacturer, Toyo Electric, and are often difficult to obtain. They are reputed to be much faster than a GTO. However, the grid construction requires an extremely fine scale and high precision in fabrication. Later studies have shown that if a GTO gate is constructed with the same fine scale, equivalent performance is obtained in a GTO. This is not surprising since the turnoff mechanisms are practically identical in the two devices. Currently, GTOs are not constructed with such a fine gate structure, because with present technology the cost would be too high and reliability might be sacrificed.

Single-Injection Devices

Power semiconductors that operate by single injection also have the lightly doped N-type ν region necessary for high-voltage operation. Outside the ν region, the more heavily doped regions have an N-P-N or a P-N-P structure. During forward conduction, holes and electrons together (in approximately equal concentrations) are injected from one side of the ν region. Also, the conduction current is carried by only one carrier-type, electrons for the N-P-N structure and holes for the P-N-P structure. The concentration of the holes and electrons tends to drop because of recombination as one moves away from the side from which they were injected. For these reasons, the conductivity in the

ν region is not as good as with the double-injection devices, and at high current densities these devices tend to have a slightly higher forward voltage drop.

Since injection occurs only from one side, these devices can be turned OFF and ON faster and more easily than the double-injection devices. Unlike the thyristors, these devices do not latch, and a small bias current or voltage must continuously be applied to hold the devices ON.

The most common single-injection power device is the bipolar junction transistor (BJT) whose structure is shown in Figure 4.5. This is the familiar N-P-N transistor, which conducts current by injection of electrons from the emitter across the P-type base and ν regions, which are collected by the collector. The flow of current is controlled by forward or reverse biasing the base emitter junction. For the transistor to remain ON, the base must be forward biased to inject holes into the ν region and

neutralize the electric charge of the conduction electrons. For turn-OFF the base current is reversed, first pulling holes out of the ν region and then reverse biasing the base emitter junction. Although injection occurs from only one side, at turn-OFF, the carriers are removed from both sides: electrons by the collector and holes by the base.

The second device shown in Figure 4.5 is the static induction recessed emitter transistor (SIRET), a BJT with a large number of extremely small emitters. With such a fine structure, this device must be made with advanced integrated circuit technology. We show it as a separate device because its advanced technology provides spectacularly improved performance. Compared to the conventional BJT, it switches faster and avoids the second breakdown failure mode to which conventional BJTs are subject. However, both the switch and the circuit must be protected from a tendency to turn ON too fast.

The next device shown in Figure 4.5 is the static induction transistor (SIT). It is constructed with a P-type grid similar to the static induction thyristor, except the P-type anode is replaced by an N-type drain region, thus preventing injection of holes into the ν region under normal positive bias.

For bipolar mode, the SIT is designed with a very close spacing between adjacent P-type grid regions, and for a low ON resistance, injection of holes is required to raise the electron concentration throughout the ν region. In the bipolar mode, operation is similar to a BJT. Turn-ON and turn-OFF of the SIT in the bipolar mode is identical to that of the BJT. Since the gate region is constructed with a very fine structure, the SIT has many of the performance features of the SIRET.

When operated in the field-controlled mode, no injection occurs and the SIT operates as a bulk conduction device. This mode will be discussed in the next section with other bulk conduction devices.

The final double injection device considered is the Insulated Gate Bipolar Transistor (IGBT) (Figure 4.5). This device combines a P-N-P BJT and a

Figure 4.5. Single-Injection Transistors

power MOSFET to give the low ON resistance of the BJT and the convenient insulated gate control of the MOSFET. Manufacturers have sold this device under other names -- including the Insulated Gate Transistor (IGT) and the Conductivity Modulated FET or COMFET.

In the IGBT, the source electrode is connected across N and P source regions. Thus, this P-N junction always remains zero biased. Placing a positive bias on the gate electrode induces a channel of electrons along the surface connecting the N source and the ν regions. With a positive bias on the drain, these electrons flow across the ν region and forward bias the drain junction. The P-type drain injects holes into the ν region which are collected by the P-type source region. The drain acts as the emitter and the source as the collector of a P-N-P transistor whose base current is provided by the electrons flowing into the ν region from the channel along the surface. Most of the current is carried by the holes injected from the drain. When the gate is biased negatively, the surface channel and the electrons are turned OFF, thus forcing the drain P- ν junction OFF. Unlike the BJT, no way exists to reverse the electron "base" current at turn-OFF to pull the control electrons out of the ν region. Instead, one must wait for these carriers to recombine. Usually the carrier lifetime is reduced in the ν region to provide for faster recombination.

The IGBT operates like a slow power MOSFET with exceptionally low ON resistance at high currents. It is particularly useful at blocking voltages above 500 V where a conventional MOSFET must have a relatively high ON resistance.

Bulk-Conduction Devices

Power devices, which operate in the bulk conduction mode, must have the lightly doped ν region to support the electric field required for a high breakdown voltage device. However, for conduction, these devices must rely on the small number of electrons associated with the doping atoms. To compensate for their poor conductivity, devices need large cross-sectional areas to keep their

ON-state resistance low. Compared to injection-type devices, the larger active area makes these devices more expensive for the same current handling capability as explained in the previous section.

As the design breakdown voltage (BV) of a device is increased, the width of the ν region must increase and its doping decrease. Both of these factors combine to increase the ON resistance R_{on} which follows the approximate relationship $R_{on} \sim 2.5 (BV)$. The resistance becomes too high to make usable bulk conduction devices to operate above 1 kV breakdown voltage. However, with no injected charge in the conducting region to sweep out, these devices are very fast switches. Switching power supplies are currently under development where such switches operate at 1 MHz rates. Research papers have been presented on 10 MHz converters.

Common power semiconductors which operate by bulk conduction are shown in Figure 4.6.

Figure 4.6. Bulk Conduction Power Devices

The most common is the N-channel power MOSFET shown. This device is constructed in the same manner as the IGBT of Figure 4.5 except the drain is of N-type material. Again, the source electrode is connected to both N and P source regions, keeping this P-N junction always at zero bias. Placing a positive bias on the gate electrode induces a channel of electrons along the surface connecting the N source with the ν region. All the current must be carried by electrons crossing the ν region. Since the drain is N-type, no injection occurs from the drain. When the gate is biased negatively, the surface channel is turned off, the P- ν junction becomes reverse biased and the MOSFET turns OFF. The diagram of the MOSFET in Figure 4.6 shows the source and gate structure enlarged for clarity. Actually, the source, gate, and channel regions are made up of a large number of small cells. In today's volume manufacturing processes (employed by such industry giants as Motorola and International Rectifier), power MOSFETs are made with integrated circuit technology. In fact, during the last 10 years, virtually all significant technology advances in the manufacture of MOSFETs were originated in the microelectronics industry. Future advances in the combination of power electronics (from the bipolar devices) and microelectronics should be monitored.

The second bulk conduction device (Figure 4.6) is a Schottky diode. This is a metal semiconductor diode (in contrast to a P-N junction diode) where an electric potential barrier exists between the metal cathode contact and the lightly doped N-type or ν region beneath. When a forward bias is placed on the cathode, electrons from the metal can cross the barrier into the ν region. Under reverse bias, the potential barrier increases and a depletion layer spreads into the ν region. Since no injection occurs under forward bias, these diodes have negligible reverse recovery times. Also, the height of the metal semiconductor barrier can be adjusted by varying the surface treatment or composition of the metal to give a lower forward voltage drop than possible with a P-N junction diode. The P-type guard ring shown in Figure 4.6 is needed to prevent fringing of the electric field at the edges, giving the Schottky diode a P-N junction-type breakdown

characteristic. However, practical Schottky diodes cannot be made with breakdown voltages above 120 V.

Schottky diodes are the choice for power converters that require fast switching speed. Diodes with forward voltage drops as low as 0.3 V are commonly used in low voltage converters. An SIT is the third device shown in Figure 4.6. It is identical to the SIT shown in Figure 4.5 except the spacing between the grid elements in the gate is somewhat larger to provide better conduction in the ν region past the gate. In the ON state, voltage across the gate and the source is zero and bulk conduction occurs through the ν region by electrons flowing from source to drain. In the OFF state, the gate is reverse biased so the depletion region connects the grid elements and conduction across the ν region is blocked. Since no carriers are injected, switching occurs very rapidly. This device also can be operated in the bipolar mode to lower the ON state resistance.

The SIT is essentially a power junction field effect transistor (JFET). Its overall performance is similar to that of the power MOSFET which is less expensive to construct. The field-controlled SIT is unique as a "normally ON" device, since the device is ON with zero bias on the control electrode. For most applications, this characteristic is a disadvantage for safety considerations. Most designers prefer that power switches be automatically OFF when no control power is present for their safety concerns; thus, these devices are not commonly used.

Power Integrated Circuits

Since 1984, a number of integrated circuit manufacturers have been developing special integrated circuits that are able to block high voltages and permit currents of up to 30 A. These circuits are becoming commercially available, and ASD electronics will be greatly affected by these devices when they become inexpensive and readily available. These integrated circuits are called power integrated circuits (PICs) or "smart power" circuits.

A typical PIC silicon chip contains the following functions:

- sensing circuits that monitor output voltage and current
- reference voltage circuits
- control discrimination and logic circuits that produce the properly timed pulses needed to drive the power switches
- medium-power driver transistors that can themselves either drive a small motor or directly drive discrete high-power switches
- safety and protection circuits - for example: integrated sensors for over-current and over-temperature can limit component stress and provide protection against known failure modes.

Widespread availability of relatively inexpensive PICs will significantly lower the price of high performance or intelligent motor drives. Another application of PIC technology is to improve the performance of a basic power semiconductor switch. For example, the sensitive gate SCR has an extra, low-power SCR built in to the main SCR semiconductor chip. In operation, a relatively low-current external pulse is all that is required to turn ON the low power SCR, which then triggers the main, high-current SCR. These sensitive gate SCRs represent one of the first applications of PIC technology. A variety of these devices is under development. They include MOSFET-controlled GTOs (called MOSThristors), SCRs that automatically turn ON when they are stressed, and power MOSFETs that automatically turn-OFF when stressed. Such applications of PIC technology to existing devices can be expected to improve the performance of all existing power device types.

Comparison of Devices

Many competing device types are available for a given application. Manufacturers specializing in one type of device often claim that their type is superior.

Figure 4.7 places the various device types discussed on a plot with injection level on one axis and the approximate scale of technology employed on the other axis. The traditional power semiconductors (diodes, BJTs, SCRs) appear at the top of this chart while newer devices (SITHys, IGBTs, MOSFETs), which require more advanced technology, appear at the bottom.

4.4 PERFORMANCE RATINGS RELEVANT TO ADJUSTABLE SPEED DRIVES

Figure 4.8 plots the volt-ampere rating available for a single device-type versus its usable operating frequency. Power handling capability drops at a rate slightly faster than $1/\text{frequency}$. This decrease in power handling capability with frequency is based on the fundamental physical principle that faster devices must have shorter carrier transit times and narrower internal active base regions. With narrower active regions, heat removal becomes more difficult, thus causing a drop in power capability. Some of the new device types require a fine-structured technology, which is difficult to replicate over a large cross-sectional area. Figure 4.8 indicates that thyristors perform better than transistors (BJTs and IGBTs) around 50 kHz. Such a comparison is misleading since thyristors are used differently at these frequencies than transistors. Thyristors are limited to use in resonant converter circuits, whereas transistors can be used in switching mode PWM circuits, which are preferable for ASDs.

4.4.1 Voltage Current Power Ratings

The performance criteria for a power semiconductor switch include: the amount of voltage it can block, the amount of current it can interrupt, and the amount of current (average, rms, peak, surge) it can conduct. These voltage and current ratings determine the maximum volt-ampere or apparent power that a single switch can control in a

Figure 4.7. Relationship of Scale of Technology with Speed and Current Density of Power Electronic Devices (Source: Ushimaru and Lauritzen 1988)

Figure 4.8. Maximum Volt-Ampere Ratings Versus Time for Typical Device Types (Source: Ushimaru and Lauritzen 1988)

single-phase circuit. These limitations form an approximate measure of the power handling capability of the switches available for ASDs.

For reliability, the operating voltage and current levels must be derated somewhat from the maximum values. Most three-phase ASDs use a minimum of six active switches (two for each phase) in each controller. The switches can be connected in parallel to increase their current ratings or placed in series to increase their voltage ratings. Reliability and instability problems discourage most designers from paralleling devices. Device manufacturers are in a much better position to select, match and package devices for paralleling, and they frequently sell packaged modules of paralleled devices with current ratings equal to that of four or more single devices.

4.4.2 Fast-Switching Speed Criticality for Pulse-Width-Modulated Drives

The next most important criteria is the speed with which a semiconductor device can switch. This parameter is important for three reasons: 1) minimum power dissipation, 2) maximum inverter efficiency, and 3) the requirement of fast switching for the PWM mode. The peak power dissipation and the maximum stress on the switch occur during the switching interval. The more quickly a switch can internally change from a conducting to a nonconducting state, the less energy needs to be dissipated by the switch, and the inverter itself can be made more efficient. Generally, devices with faster switching times enable the use of those ASD inverter circuits that offer more flexible performance features.

Inverters that operate in a PWM mode require devices that switch in 10 ms or less, since carrier wave switching must occur at a rate at least 20 times the output frequency. In the PWM mode, power is converted to an intermediate frequency of 1 kHz to 20 kHz or higher before down-converting to the frequency required by the motor. The faster PWM inverters can provide more precise control of the output waveform enabling near-sinusoidal output waveforms to be obtained.

The most desirable ASD inverter utilizes a PWM mode with a modulation frequency of at least 20 kHz. At this frequency, the switching noise in motors and inductors is above the audio range. Thus, to human ears the drive is silent, without the unpleasant acoustic noise apparent in lower-frequency PWM drives. However, a 20 kHz PWM inverter requires devices with switching times less than 0.5 ms.

Generally, the faster switching devices (transistors and fast GTOs) have lower voltage and current ratings than the slower devices (SCRs and slow GTOs). Thus, there is a trade-off between high power capability and the improved waveform and power factor control, which can be possible with a faster PWM inverter.

4.4.3 Forward Conduction Drop

No semiconductor device offers a perfect zero resistance switch in its ON state. The total power dissipated in each device is the sum of the dissipated energy over the forward voltage drop in the ON state plus the switching losses discussed in the previous section. The power dissipated by the reverse leakage current in the blocking state and the power needed to drive the switch are usually negligible in comparison.

Devices, which use double injection (holes and electrons injected from both sides of the junction-like diodes and thyristors), generally have the lowest forward voltage drop. Devices that operate by single injection (most BJTs) have a slightly higher voltage drop; devices that operate by bulk conduction (MOSFETs) have the highest forward voltage drop. Devices having the highest levels of carrier injection must also wait the longest for the conduction carriers to clear when switching to the blocking state. Thus, a switching speed versus forward drop trade-off exists. This is shown in chart form in Figure 4.7.

4.4.4 Modes of Control

Four different drive modes are used in controlling power semiconductor switches:

Natural Commutation or Uncontrolled Turnoff

The switch, usually an SCR, opens when the current in an ac circuit goes through zero each half cycle. Only the instant of switch closing can be independently controlled.

Forced Commutation

A large commutation capacitor is discharged across an SCR to momentarily force the current through it to reverse and turn the SCR OFF.

Current Injection

Current must be injected across a P-N junction to turn a power device ON or OFF. With a BJT,

the current must flow continuously to maintain the ON state, while with a GTO the current need only flow for brief periods to provide for turn-ON or turn-OFF. Turn-ON in an SCR is by current injection.

Insulated Gate Drive

An insulated gate or a reversed biased P-N junction gate is used to modulate the number of carriers in the conducting region. Since this is the easiest and fastest mode of drive to control, it has become very popular and has promoted interest in power MOSFET applications, as well as in static induction transistors and thyristors.

A great deal of research is aimed at developing insulated gate drives for GTO and BJT structures. The goal is to combine the high speed and ease of drive of the insulated gate with the high current and voltage handling capabilities of the GTO. Natural commutation is still used with SCR drives, primarily in cycloconverters and traditional dc motor drives. Forced commutation in high current ASDs is no longer necessary because of the availability of high-current GTOs. Of course, a trade-off exists between ease of drive and switch current and voltage capability. However, improvements in device technology may eventually make the insulated gate drive available for all types of power switches.

4.4.5 Ruggedness and Reliability

Any device used in a high power ASD must be reliable, because failures result in expensive down time and possible damage to property or life. The introduction of devices using new technology is usually followed by the discovery of new failure modes that are unique to that technology. Many years are often required to study and understand failure modes well enough to make the design changes necessary to prevent the failures. Twenty years were required for the second breakdown in BJTs and GTOs to be understood so that device design could be changed to minimize the effect. Power MOSFETs were claimed to be free of the second breakdown for 7 years, until 1987 when such

failure modes were identified and understood. Now, specific circuit design approaches are recommended to minimize second breakdown in MOSFETs used in ASD applications.

The two present trends in power device development are: 1) smart power, which involves integration of control circuits with power devices on the same chip, and 2) the use of smaller-scale control electrodes on discrete power devices. These techniques have been motivated by the most recent trend in power devices, which is to utilize VLSI technology to create a whole new generation of integrated power devices. This started with the power metal oxide semiconductor (MOS) transistor in the late 1970s (Temple and Love 1978) and has evolved toward totally new devices such as the MOS-gated thyristor (Plummer and Scharf 1980; and Pshaenich 1982) and the IGT (Baliga et al. 1983). This latter device combines the best features of the MOSFET and the bipolar transistor in a device that conducts more current in a unit area than either types. In addition to the new discrete devices, monolithic high-voltage integrated circuits (HVICs) that combine power and signal circuitry on a chip have come on the scene. These devices are a dramatic extension of the trend towards mixed technologies in the IC industry, and for the first time, allow the cost efficiencies of integrated circuitry to be applied in the power electronics field. The initial application areas have been in telecommunications (Shackle et al. 1980), power supplies (Ruggles and Fay 1982), high-voltage displays (Fujii et al. 1981), and power circuits (Shackle and Pospisil 1983); and (Wildi and Chow 1984).

Other significant byproducts of integrated circuit technology, as applied in the discrete power device area, include static induction devices and annular BJTs. These devices require elaborate structures with very fine-line resolution similar to that required for advanced digital integrated circuits. Although the performance of some of these new power devices may be spectacular, their reliability is expected to be lower than devices with the same power rating but with more conservatively designed structures.

4.4.6 Cost

The cost of power semiconductor devices varies. Mature device technologies are relatively inexpensive (e.g., SCRs with 20 kVA ratings cost about \$15 each). The latest GTO with an equivalent rating may cost a factor of 10 or more. Generally, prices drop as technologies mature. Most medium- to high-capacity ASDs are not manufactured in high enough volume to obtain the large price drops that high-volume commercial products obtain. However, in the case of 1-hp inverters for heat pump applications in Japan, the rapid expansion of the market demand created a price trend for inverters which nearly paralleled that of microelectronic devices (computers).

In the future, one can expect the cost of power semiconductors and ASDs to drop as these technologies mature, particularly if PICs become available to take over the sensing and control portions of the ASD.

4.5 FUTURE TECHNOLOGIES

What improvements in power devices can be expected in the future? For discrete devices, significant improvements can continue to be expected for all device types.

Improvements in materials processing techniques, such as crystal growing and device fabrication technology, can be expected to lead to larger area (higher current) and more uniform (higher voltage) crystals. In conventional devices, the increased area leads to higher current capability and the more uniform crystals lead to higher voltage capability.

Improvements in integrated circuit technology contribute to the ability to make power devices with finer structures and high performance features. The new area of PICs can be expected to lead to great simplification in the drive circuits for high-power semiconductor switches. They can also be expected to provide power switches with intelligence or "smarts." For example, a number of

laboratories are developing power switches with built-in protection circuits to automatically turn a power switch OFF (for a power MOSFET) or ON (for a thyristor or BJT) when a stressful condition begins to occur. The device automatically switches to a safe condition without waiting for an external control circuit. If the switch is protected by turning ON, then the overcurrent must be interrupted by a fuse or circuit breaker before the converter can be restarted. However, expensive replacement of the semiconductor switch is avoided, thus significantly reducing the maintenance cost to the user.

Will the price of power semiconductors and their associated control electronics drop so low that every electric motor will have an integrated ASD? When the first microprocessor chips were invented 15 years ago, who would have forecast that in 1987 almost every medium-sized home appliance would contain a microprocessor? (And every new automobile would contain several microprocessors?)

We stand at a turning point in technological advances. It is envisioned that the changes in electrotechnology occurring in the next 15 years will bring about a greater impact on the U.S. motor-drive industry than those we experienced in the last 15 years. There are three major reasons for the anticipated changes:

1. Advances in new solid-state devices will continue to impact the equipment market (motors, drives, induction heaters, etc.) at an accelerated rate.
2. The parallel advances in microelectronics and power electronics fields are converging to result in revolutionary new products.
3. U.S. industry, more than ever before, is influenced strongly by foreign competition. The significant level of success demonstrated by inverter-driven heat pumps in the Japanese residential HVAC market leads to the question: will the economy of scale and application know-how accumulated from the inverter business in the HVAC market threaten the domestic producer of similar products in the United States?

4.6 IMPACT OF NEW POWER DEVICES ON INVERTER BUSINESS

The primary factors determining a power device's suitability for a given application are its power handling capability, efficiency, ruggedness, availability, support circuit complexity, and price. The complicated interactions among these factors change with each generation of devices.

The price of semiconductors, both power and digital, has historically followed what is known as the semiconductor experience curve. The price of semiconductor devices has decreased by a factor of approximately 30% (in constant dollars) whenever the cumulative unit volume for that device doubles. As a result, new devices show rapid decreases in price during their early market years. Older devices show a continuing decrease in price at a slower and slower rate.

"Moore's Law," which carries the name of Intel Corporation's President Gordon Moore, states that the complexity of integrated circuits (in terms of the number of devices or gates per chip) approximately doubles every year. This trend has remained valid throughout most of the 1960s and 1970s. Whether this trend continues into the early 1990s, or the rate of advance will slow the trend, is uncertain. However, the significant market success enjoyed by the leading Japanese HVAC systems manufacturers, who are also leading developers of BJTs and microprocessors, will most likely exert downward pricing pressure on the world semiconductor business. This hypothesis will be examined in detail in Section 5 of this report.

4.7 IMPACT OF FOREIGN COMPETITION

The United States faces a strong task of international competition. In the 1980s, the United States has encountered the greatest magnitude of international trade competition. In the field of ASD products, however, U.S. companies are holding their own, but offshore manufacturers' influence is growing.

Examining the market areas in which U.S. concerns lost ground in international competition, we find:

- microprocessors for personal computers, i.e., microchips for volume production and volume sales
- low power (less than 5 hp) induction motor controllers
- Darlington power transistors for volume production and volume sales
- self turnoff devices for high-power applications, such as the GTO.

On the other hand, the United States still appears to lead in the fields of:

- custom ICs
- integrated power devices, such as MOSFETs
- fundamental innovations.

During the late 1970s and early 1980s, U.S. monetary policy, fiscal policy, deregulation in various industries, economic recession, and other factors contributed to maintain the value of the U.S. dollar unreasonably high in the overseas currency market. The result was a mixed blessing. Inflation was fought back and foreign capital generously flowed into the United States--fueling robust economic expansion. On the other hand, U.S. companies opted to move 20% of their total manufacturing capacity overseas, and research and development funds were cut back to cope in the recessionary environment.

As a result, the United States was unable to compete in the consumer electronics market on the basis of quality-for-price on products. In the electronics field, personal computers are being sold as a consumer electronics product. Mass-produced microprocessor chips are being installed on a wide variety of products from automobiles to TV and VCR sets. Continuing loss of the computer-chip

market share in the world compelled the U.S. chip manufacturers to claim illegal dumping practice by the Japanese, for which the U.S. federal government agreed to assess a substantial tariff penalty. Furthermore, in the area of Darlington power transistors and low-horsepower inverters, a significant change is taking place. Figure 4.9 shows the estimated cost of an ac variable-speed drive from fractional to 220 hp in constant 1980 dollars. This prediction was made in 1981 by Masher and Smith (see reference). They stated, "A major limit on the penetration of (ac variable-speed) drives is the minimum cost. Even in the year 2000, the minimum cost for fractional horsepower units is estimated at about \$400." Today, ac inverter drives, at 1 hp, using a Darlington power bridge with a PWM adjustable speed range of 30 to 180 Hz, are available at approximately \$120 in Japan for application in residential variable-capacity heat pumps. Toshiba introduced the first residential variable-capacity heat pumps in 1983 when less than 100,000 units were sold. The market grew explosively to 1.1 million units sold in 1987. If we put this trend in the context of the semiconductor experience curve, we expect the price of the inverter module to have dropped in price by a factor of four. It was clearly

demonstrated in Japan that low-horsepower inverters for residential and commercial applications are market viable, and the more they are sold, the lower the price. The influence from foreign manufacturers has certainly changed the tone of previous predictions.

U.S. manufacturers are not far behind. In 1989, two major air-conditioning equipment companies were expected to introduce their own ECM-driven adjustable-capacity heat pumps for residential applications. These units will use IGTs on their power units with capabilities up to 5 hp.

As we have pointed out, device manufacture know-how can only be gained from an iterative design process between devices and driven equipment. Devices need to be stressed, field tested, destroyed, and improved many times before they can be considered market-ready. At least in the area of high-voltage application, Japanese and European manufacturers have accumulated an extensive body of experience and knowledge using the advanced high-voltage circuits and advanced induction motors for popular applications.

Figure 4.9. SRI Estimated ac Variable-Speed Drive Costs (Source: Masher and Smith 1981)

5.0 STATUS OF THE POWER ELECTRONICS INVERTER APPLICATION IN JAPANESE HVAC INDUSTRY

The status of the power electronics inverter application in the Japanese HVAC industry is described in the following subsections.

5.1 OVERVIEW

Although the energy conservation benefit of inverter application in the HVAC industry is well known, only recently have inverter technology and digital control modules advanced to the point of being small, lightweight, and cost-competitive for implementation in residential applications. It is important to note that the success of inverter-driven space conditioning equipment occurred first in the Japanese HVAC market. Whereas similar technology was tried in the United States for use in the residential unitary heat pump market in the late 1970s, the variable-speed equipment did not (and has not) become popular in the United States. The success of inverter technology penetration into the Japanese HVAC market has been attributed to significant advances in power electronics, rotary compressor, and microcircuitry technology. Although inverter technology was widely available in industrial applications, size and cost were problems from the 1960s to the late 1970s. In the early 1980s, however, advances in technology and volume-based production of rotary compressors, power electronics devices, and microprocessors took place simultaneously in Japan; all of which contributed to the timely development of a low-cost, lightweight, solid-state inverter for residential HVAC application (Tsuji and Hamaguchi 1987).

In this section, state-of-the-market inverter technology, heat pump control strategy, and new motor technology are reviewed.

5.2 INVERTER DESIGN FOR AN HVAC APPLICATION

The function of an inverter is to modulate and control the available power from the local utility to

provide a variable voltage, variable frequency power source to the motor. The ultimate control parameter of a motor is its torque production, but the speed of an induction motor is expressed as:

$$N(\text{rpm}) = 120 f(1-s)/p$$

where f = frequency of the alternating current source

s = slip

p = the number of poles.

The speed of an induction motor is controlled by the frequency of the ac source. Furthermore, the magnetic flux Φ of the rotor can be expressed approximately as

$$\Phi = kV/f$$

where k = the proportionality constant of the given rotor

V = source voltage

f = the frequency of the ac source.

For induction motors, the magnetic flux is limited by a certain maximum value above which the rotor current reaches the saturation point. Above the saturation point, the rotor current increases rapidly to cause damage to the rotor windings. One requirement of the inverter during low-speed (low f) operations is to control voltage to maintain constant V/f or volts/Hertz (Figure 5.1). The method of voltage and frequency control is commonly referred to in Japan as the variable voltage, variable frequency (VVVF) control. The V/f pattern is selected for each motor type and load profile (Tsuji and Hamaguchi 1987).

Both the VSI and CSI can provide constant V/f induction-motor control, but usually the current

Figure 5.1. A Typical V/f Pattern

source-type inverter is used only when high-speed response to transient-load conditions is required. The VSI is already in use for industrial, commercial, and residential applications because of its simple topology and low cost.

A schematic of a VSI is illustrated in Figure 5.2. The ac source is rectified to dc voltage E_d in the converter section, and is inverted to synthesized sinusoidal waveform at controlled frequency in the inverter section. Converter section can be built from either diodes or thyristors. For application voltage below 900V, power transistors are commonly used in the inverter section.

To provide variable-voltage output at a controlled frequency, either the pulse amplitude modulation (PAM) or the PWM method is used. Here, we present factors that affect the technology selection in the residential heat pump application.

5.2.1 Efficiency

The PWM inverter takes advantage of high-frequency power switching to synthesize variable-frequency sinusoidal waveform. Switching speeds are usually on the order of 1-2 kHz. The loss mechanisms of solid-state inverters in this application include forward conduction loss and switching loss. Due to this high-speed switching requirement, the PWM inverter has slightly higher

R, S, and T comprise the three-phase power input into the converter.
 E_d is the voltage across the converter section.
 U, V, and W comprise the three-phase power output from the inverter.

Figure 5.2. Circuit Diagram of PWM Inverter (Source: Ushimaru et al. 1987)

losses than a similarly sized PAM inverter. Furthermore, a PWM inverter contains large, low-frequency harmonics distortion in its synthesized waveform. This distortion can cause torque pulsation in the rotor section of the induction motor causing a reduction in mechanical efficiency of the system, whereas output from a PAM inverter can be filtered out to maintain reasonable system efficiency.

However, a total system loss due to inverter use, consisting of forward conduction loss, switching loss, and mechanical loss from torque pulsation, is nearly constant at all speeds. Thus, the combined losses at low-speed operations can amount to a few percentage points. It follows that the seasonal efficiency gain of a heat pump from inverter use must be based on an optimum match between load variation and compressor sizing.

5.2.2 Audible Noise

PWM-type inverters require high-frequency switching to synthesize variable-frequency sinusoidal waveform over the entire range of operation. Thus, even at low-motor-speed operation, the device switching continues at the carrier frequency of 1-2 kHz. On the other hand, PAM-type inverters tend to have lower audible noise at low-frequency operation (Tsuji and Hamaguchi 1987).

5.2.3 Mechanical Vibration

Generally, mechanical vibration for a variable-speed system is attributed to harmonic power distortion for the PWM-type and torque ripple for the PAM-type. Furthermore, over the range of motor speeds, the mechanical system will undergo certain periods of resonant vibration at various characteristic frequencies. Increased mechanical vibration, due to inverter use, is inherent to the concept of variable-speed motor operation. Sound engineering should be exercised to reduce harmonics, improve current source torque ripple, and avoid operation around resonant frequencies in the product design stage.

5.2.4 Cost

Cost is the most critical selection factor for small-capacity inverter drives for residential HVAC applications in Japan. Whereas the PWM-type can be built from a converter section using inexpensive diodes and the inverter section using power transistors, the PAM-type requires power transistor switching devices in both the converter and the inverter section. Thus, the PAM inverter is more expensive to build than the PWM inverter. As a result, all inverter-driven heat pumps in Japan use the PWM-type inverter (Tsuji and Hamaguchi 1987).

5.3 FIRST INVERTER-DRIVEN HEAT PUMP IN THE JAPANESE RESIDENTIAL MARKET

Toshiba Corporation announced its introduction of an inverter-driven heat pump for residential applications in 1982 (Cohen 1982). The introductory product used a power-transistor-based PWM inverter for a 0.75-ton cooling capacity at 60 Hz with a control range of 30 to 90 Hz. The rated heating capacity was obtained at 75 Hz.

The initial unit used a 4-bit microprocessor to control inverter frequency for the appropriate heating or cooling, according to an algorithm based on measured temperature of the ambient condition around the unit and the set temperature. Digital data needed to synthesize the inverter waveform is stored in a read only memory (ROM) for 1.25-Hz steps. For each frequency, the data gives the on-time for six successive 30-degree increments during a half cycle of alternating current.

Digital circuits replicate the remainder of the three-phase voltage from the data for a half cycle. The other two phases are obtained by shifting the first phase. Three pairs of power transistor switching devices, one for each phase of the motor, connect the corresponding phase lead of the motor to the positive or negative terminal of the power supply during the time that it receives either a positive or negative pulse to its base terminal.

Another feature important in Japan is constant capacity at different line frequencies. The inverter's power source is direct current, obtained by rectifying and filtering the commercial power source. The air conditioner will provide the same output in the part of Japan with 50-Hz power as it does in the region with 60-Hz power, or in different countries with different line frequencies. Similarly, the unit may be adjusted to work in regions with slightly different voltages, abrogating the need for different motor design.

At the time of introduction, the price of the Toshiba inverter-driven heat pump was set at \$1,372, and was only 13% higher than a fixed-speed heat pump of similar capacity and features (Cohen 1982).

In the first 16 months after the introduction, Toshiba sold 20,000 units. During this time period, the downturn in economy and record-setting cool summers in Japan caused a severe recession in the air conditioning business. Despite the unfavorable business conditions, Toshiba achieved some 40% increase in sales of inverter-driven heat pumps from 1983 to 1984. The 1984 model sold for \$1,204, down from \$1,372 of the 1983 model, and only \$182 more than conventional fixed-speed models of similar capacity. Toshiba claimed an average operating cost savings of \$36 per year with the average simple payback of 5 years. Toshiba's product announcement in 1982 was followed by announcements from Hitachi and Sharp in 1983 and by Mitsubishi Electric, Sanyo, and Matsushita in 1984.

During the first 2 years of product marketing, Toshiba incorporated a number of significant product design changes. The most notable improvement resulted from the development of a large-scale integrated (LSI) chip for inverter control. One LSI chip was claimed to have replaced ten integrated circuits formerly needed in the waveform synthesizer. Furthermore, the rectifier bridge was used to boost the source voltage from 100 V (the line voltage in Japan) to 200 V into the inverter section. The combined benefit of higher voltage source and high-speed operation above 60-Hz line frequency was a 25% reduction in the weight of the compres-

sor from 4.5 to 3.5 kilograms (Berger 1983). Actually, a smaller compressor was used at higher speed and torque production capability to provide the same performance at lower cost through the use of the inverter. Thus began the dramatic growth of residential inverter-driven heat pumps in Japan.

5.4 CURRENT TECHNOLOGY LEVEL OF JAPANESE INVERTER-DRIVEN RESIDENTIAL HEAT PUMPS

A typical Japanese heat pump inverter, inverter components, and system efficiency are explained in the following subsections.

5.4.1 Inverter

The state-of-the-market inverter technology available in Japan for residential heat pumps (less than 2.5 tons) is PWM-type. Figure 5.3 shows the key features of a typical heat pump inverter, and its approximate performance ratings are described in the following.

Typical residential inverter power rating is 100-V, 25-A, single-phase ac input. The ac input from the standard residential electric service is at 50 Hz in the Tokyo area (the Eastern region), and 60 Hz in the Osaka area (the Western region). The single-phase ac input goes through a dc-link (an ac-dc converter) with maximum dc voltage of approximately 300 V. The dc output from the dc link module is fed into a dc-ac inverter. All Japanese heat pump inverters are of the PWM-type for frequency and voltage control. The PWM inverter requires the least number of solid-state switching devices (six devices for three-phase output as compared to at least 12 devices for a PAM inverter). For the particular type of torque-frequency required for the operation of a variable-speed compressor (nearly constant torque and a linear power increase with the speed), the PWM has been selected on the basis of low manufacturing cost and reliable performance.

State-of-the-market inverter technology in Japan consists of a Darlington-type power

Figure 5.3. Key Features of a Typical Heat Pump Inverter (Source: Ushimaru 1988)

transistor bridge with ratings of 0-300 V. The frequency range of commercial inverters is 35-115 Hz for medium-size heat pumps (1.5-2.5 tons) to 30-180 Hz for the popular 0.75-ton units. The control module for inverter frequency selection is quite complex and is usually unique to each manufacturer. The low-voltage signal path is located in the indoor fan unit, which interprets performance and ambient parameters from various sensors. These parameters are fed into a microprocessor system controller, which selects the appropriate frequency. With today's technology, the frequency (and voltage) selection is a preset data access into an 8-bit memory chip for PWM input.

To illustrate the rapid pace of technology development, Figure 5.4 is included to present the comparison of residential 1.5-kVA-rated inverter for heat pump application. The unit on the right is the inverter used in the 1983 model, and the unit on the left is the inverter used from the 1987 model (Ide

and Kanazawa 1987). It is immediately noticeable that the new inverter has fewer parts--principally because of integration of microprocessor chips and associated protection capacitors into a single LSI chip. Also, the modular design allowed much cleaner wiring in the new unit. It is suspected that the power transistors have lower conduction loss and lower switching loss, thereby allowing the heat sinks to shrink down to a compact size. The result of the development--in only four years--is reduction in size and weight of the inverter unit by approximately a factor of two.

5.4.2 Microprocessors

Perhaps the most rapid development pace in Japanese inverter components was achieved by integrated chips. The 1983 model used approximately ten individual 4-bit processors as well as ROM chips to operate the system. By 1987, most individual processors had been integrated into a

Figure 5.4. Comparison of 1983 and 1987 Inverter Units (Source: Ide and Kanazawa 1987)

single LSI chip. Today's LSI for inverter-driven heat pumps contains logic circuits for data analysis, digital processing, and protection, as well as a ROM wave synthesizer control on a single chip (Tanaka et al. 1987). The current LSI can be characterized as "single access voltage and frequency selection;" i.e., once a set frequency is selected, the corresponding value of voltage (to follow the constant V/f pattern) is automatically read out from the ROM. Its arithmetic speed is not demanding by today's performance standard, and it is easy to interface with digital and analogue sensors to provide adequate performance over the range of operation.

However, the single-access frequency voltage selection can have limited performance capability for off-design conditions because the ROM contains preset values of voltage versus frequency over the entire range of operation (Tanaka et al. 1987). Depending on the preset design condition, performance of a PWM inverter using a single access V/f logic can suffer reduction in efficiency, increased harmonics, and poor power factor at extreme low- and high-speed operations. To improve inverter performance and maintain high efficiency and low harmonics over the entire range of inverter operation, an effort is under way to develop a high-speed digital processor to actually compute the optimized PWM switching in real time. If the PWM

carrier wave frequency is on the order of 1-2 kHz, real time operation of the PWM optimization arithmetic would have to proceed at less than 500 microseconds. This would be a demanding requirement even for today's fast chips.

5.4.3 Pattern Control Scheme

System efficiency of an inverter-driven motor can be improved even without the super-fast arithmetic chip. One compromise is that of the pattern control scheme described below.

Residential HVAC application is not a demanding engineering task for induction motor control engineering. It requires single quadrant motor operation with a nearly constant motor torque requirement over the range of operating speeds. Furthermore, the transient time constant involved in

the refrigeration cycle is much greater than the response time constant of the electric system. Thus, the mechanical system stays stable during transient control situations. As a result, one can select a simple V/f profile that matches the range of expected heat pump operation adequately, providing reasonably good efficiency and motor response between say, 30 to 150 Hz.

On the other hand, one can also apply other V/f patterns that may give better performance at the low and high ends of the speed regime. Figure 5.5 illustrates such an example. The figure shows three distinct patterns of V/f. Conventional PWM control, with the LSI ROM, used a single pattern V/f (pattern B in the figure) to cover the entire range of operation. This method, though simple and easy to implement, suffers when source voltage is unstable or the motor load fluctuates rapidly.

Figure 5.5. V/f Pattern Control Scheme (Source: Ide and Kanazawa 1987)

The pattern control scheme provides flexibility in the pattern selection from any of the three V/f curves that are all resident in the LSI ROM. Instead of carrying out a real-time calculation of PWM optimization algorithm, the logic circuit of the LSI can select the best V/f pattern from the three shown. For example, when the system begins its operation by the V/f profile of pattern B, the LSI can quickly shift the control logic to pattern A when the source voltage drops by a certain value or the motor load increases by a predetermined amount. Prior to introduction of inexpensive dedicated chips for PWM optimization calculation, the leading manufacturers will continue to implement the pattern control scheme for the PWM inverter.

5.4.4 Motor Technology

Motor technology is another area of technical evolution. The HVAC industry is concerned with the cost and performance of the system, for which motor selection is a critical factor. The trend in the Japanese HVAC industry is to use an inverter-driven, three-phase induction motor for cost reduction and to use an inverter-driven, brushless dc motor for efficiency improvement. The proper selection, however, is quite complex, and there is no clear winner in today's market.

When operated with variable-frequency excitation, the induction motor has a capability curve very much like that of a dc motor. Below base frequency, the motor is operated at constant volts/Hertz and provides constant torque capability at constant current and slip frequency.

The less demanding performance requirements of an appliance drive and the overriding importance of cost has led to a good deal of developmental work on low-cost versions of brushless dc motors [or ECM (Electrically Commutated Motor) in American technical literature]. ECM systems are beginning to replace induction motors in compressor drives and appliances in the United States. In terms of motor efficiency, brushless dc motors have inherently higher efficiencies because of the elimination of magnetizing current necessary to run a

motor. Developments in switching devices and/or any price reductions in components or permanent magnet materials could have a dramatic impact on the appearance of ECMs in a wide variety of low power applications.

In terms of cost, however, induction motors have a definite advantage. Induction motors have a well-known reliability record and are generally accepted in the industry as the low-cost motor technology of choice. Whereas ECMs require a temperature-sensitive magnetization process during manufacturing, induction motors have been incorporated into appliance manufacturing and assembly processes with heat setting, lamination, and other processes that require high temperature conditions. In order to properly magnetize an ECM and hermetically package it into a compressor housing, significant portions of the equipment assembly process may have to be changed. This would add to the manufacturing cost of ECM equipment. A company that can overcome this hurdle, the low-cost manufacturing process that integrates a magnetizing process with hermetic sealing of the motor-compressor assembly, will certainly have an advantage in the race for the development of an inexpensive, reliable, high-efficiency motor.

In terms of the parts count, the traditional belief that ECMs have inherently fewer parts is disputed. While ECMs can be designed with no physical shaft encoder/decoder, they still require an inverter drive. In terms of electronic components, today's PWM inverter with an induction machine is competitive against the ECM inverter with a back-emf position sensor. Both motor technologies require a PWM inverter and auxiliary circuits for control and protection. Thus, the assessment of emerging motor technology for HVAC applications will incorporate an evaluation of the impact of motor choice on system performance and cost.

The following describes the only dc motor-driven heat pump manufactured in Japan, and the technique for controlling the amount of current used.

Direct Current Inverter Heat Pump

Hitachi Ltd., who introduced a variable-speed residential heat pump with a brushless dc motor in 1984, continues to be the only Japanese manufacturer offering the dc motor-driven heat pumps. Figures 5.6a and b show the rotor and the stator of Hitachi's 1-hp brushless dc motor (Serizawa et al. 1987). Figure 5.6a depicts the outside appearance of the rotor on the right and the stator on the left. The stator section is similar to that of a conventional induction motor, and can be produced in large quantity by the same motor winding process. The rotor consists of the iron core, ferrite permanent magnets, metallic cover, and the diecast material for balance and protection (Figure 5.6b). Zinc alloy was used as the diecast material for strength and high specific gravity. By using this material as the diecast base and integrating the rotor section, a better balance for high speed rotation is achieved (Serizawa et al. 1987).

Hitachi's claim is illustrated in Figure 5.7, which shows the measured efficiency comparison between a dc motor and a similarly rated induction motor for the heat pump application. As we would expect, the brushless dc motor is about 10% more efficient than a conventional induction motor at the low speed range. The immediate merit of the brushless dc motor is the elimination of the copper wattage loss in the rotor windings. At high speed operations, the induction motor's typical V/f profile gives good performance. The difference in motor efficiency at 6,000 rpm is four percentage points between the two motor types. Figure 5.8 explains the loss mechanism of the induction motor (left) and brushless dc motor (right) (Serizawa et al. 1987). This figure compares the proportion of motor loss by taking the typical induction motor loss as 100% and computing the relative merit of the brushless dc motor as a fraction. Although the published data only compare motor performance in generality, it is interesting to note Hitachi's motivation for the development.

Current Control Strategy

The fundamental difference in performance between induction motors and ECMs is motor efficiency. The induction motor requires current to flow into two branches: the magnetizing branch

Figure 5.6a. Rotor and Stator Sections of Hitachi's Brushless dc Motor (Source: Serizawa et al. 1987)

- ① : Iron Core
- ② : Ferrite Permanent Magnets
- ③ : Metallic Cover
- ④ : Diecast Material

Figure 5.6b. Rotor Schematic of Hitachi's Brushless dc Motor (Source: Serizawa et al. 1987)

Figure 5.7. Efficiency of Typical Induction Motor Versus Brushless dc Motor (Source: Serizawa et al. 1987)

EFF : Efficiency
 $W_{CU1,2}$: Copper Wattage Loss
 BL : Brushless Motor
 IM : Induction Motor (conventional type)
 W_{FE} : Ferrous Wattage Loss

Figure 5.8. Comparison of Motor Energy Loss Between a Typical Induction Motor and a Brushless dc Motor (Source: Serizawa et al. 1987)

(stator) and the work branch (rotor). ECMs essentially replace the magnetizing branch with a permanent magnet to provide a continuous magnetic field. At off-design conditions, the current requirement for an induction motor to magnetize the rotor reach 10% to 30% of total current consumption. The current flow in the magnetizing branch does no work except to consume current in the process of generating the magnetic field. By eliminating the magnetizing current requirement, ECMs can have an inherent efficiency advantage over the induction motor.

However, a technique to control the amount of current flowing into the magnetizing branch of an induction motor has recently been developed. The original design was developed in West Germany. It is called "field orientation control" (FOC) in European and Japanese literature and is often referred to as "vector control" in the U.S. In this strategy, either a shaft-mounted encoder or a Hall Effect sensor serves to detect the position of the rotor shaft. This information is used to control torque in induction motors in basically the same way as in dc drives. The function of the dc motor commutator to maintain a fixed spatial angle between the interacting magnetic field is accomplished by electronic means. Electronic sensor information and phase control, based on the physical orientation of the rotor shaft, enables the current to be controlled for both magnitude and phase. The ac currents used to obtain the values of flux and torque are directly related to the rotor position information from the motor shaft. Torque is controlled with a close-loop feedback system between the inverter power supply, rotor flux, and shaft encoder.

Encoder-based, torque-controlled drives can be regarded as controlled current, slip-regulated drives. By proper coordination of the stator current amplitude and slip frequency, the rotor flux and output torque are independently controlled. This technique enables the slip frequency to be selected regardless of motor speeds (i.e., independent control of slip for torque control). As a result, the induction motor can be operated by controlling slip for maximum torque (high starting torque for

compressors) or for maximum efficiency (load following operation).

The vector-controlled ASD systems are appearing in the building equipment market; for example, elevators, escalators, and high-speed elevators with greater than 300 m/min-rise rate (Sakai et al. 1988).

Costs of electronic components are expected to come down as new devices are manufactured in significant quantities. As new and faster micro-processors are being developed, it will be possible to make an induction motor behave like a dc motor and vice versa through electronics control. The control strategy choices are between:

- the use of a moderate efficiency inverter with high efficiency dc motor, and
- the use of a moderate efficiency induction motor with vector control.

5.4.5 Harmonics Problems

Poor power quality refers to any deviation from sinusoidal, constant amplitude, constant frequency voltage to a utility customer. Common power quality problems are classified as:

- surges or momentary overvoltage spikes
- dips or momentary drops in voltage
- outages or interruptions in the power
- waveform distortion resulting from the presence of harmonic voltages on the line.

The increasing use of inverters should have a beneficial impact on surges and dips, because inverters enable motor loads to be gradually applied and disconnected from the power system. However, the electronic switches in inverters can cause large currents to be drawn from the power system at harmonic frequencies. Since power systems have high source impedances at non-fundamental frequencies, they are not able to supply large harmonic currents. Therefore, the system voltage waveform

distorts to suppress the harmonic currents in the system. Usually, some combination of harmonic voltage (waveform distortion) and harmonic currents results. Other utility customers (or other appliances on the same service line) are affected by the waveform distortion.

In terms of the adverse impact of harmonic distortion on the electric utility system, there are several issues which will be of increasing concern. The direct and indirect effects of harmonics distortion on our daily lives include:

- Harmonics distortions are known to cause torque pulsation in the rotor shaft. To varying degrees, this affects the mechanical components. If the resulting torque pulsation is serious, the equipment noise and vibration will be significant and the life of the mechanical component may be shortened. This effect will then undo all perceived benefits of an inverter, i.e., efficiency will decrease, mechanical components will be under higher stresses, and the system will have higher audible noise.
- Electrical noise [electromagnetic interference (EMI)] may interrupt other nearby appliances and computers. As more and more inverters come into service, they will be operating near computers and other sensitive data processing equipment. For many business owners, this effect will be a serious detriment to the use of inverter-driven heat pumps. By using inverters, they may encounter frequent problems with computers and other valuable equipment operation.

Undoubtedly, the growing use of electronic switching devices will begin to impact our daily lives in the near future. At present, we are only beginning to see implications of the widespread application of inverters. There is a great deal to learn in this area. Utility and equipment manufacturers will have to work closely to keep problems manageable. Institute of Electrical and Electronics Engineers (IEEE) Standard No. 519-1981, "Harmonic Control and Reactive Compensation of Static Power Converters," represents the engineering

profession's policy on power quality. This is being revised and updated.

In Japan, the tremendous number of inverters sold with heat pumps is mostly under the fractional horsepower range. Because harmonic distortion is proportional to the magnitude of output power from the inverter, the magnitude of the distortion is quite small; enough to be attenuated within the household electrical circuit. Fortunately, harmonic distortion has not been recognized as a major issue in residential electric service at the small inverter capacity.

However, with the increasing affluence of Japanese consumer economy and the increasing market needs in large capacity heat pumps, the Japanese manufacturers are beginning to address the issue of harmonics elimination strategy (Hiyoshi 1988). There are several ways to accomplish harmonics reduction. They include:

- increasing the inverter carrier wave frequency and incorporating a fast microprocessor chip to compute the optimum PWM strategy for high efficiency. This requires a switching device capable of fast switching (up to 20 kHz) and a microprocessor capable of real time calculation (in the range of 8 MHz). The increase in the cost of equipment resulting from the improved inverter will be added to the equipment cost as a premium.
- developing harmonics elimination equipment as optional equipment. For medium- to large-capacity heat pumps, the manufacturer may offer harmonics elimination equipment at additional cost. There are different techniques for designing such equipment, but all will add to the cost of the system as a premium.
- a local utility preferring to install a large-scale harmonics filter on a service grid. This will ensure that the utility delivers high-quality power to all customers. However, this approach will increase the cost of power available to all consumers.

Resolution of harmonics problems is technically possible. The major hurdle is the cost. Equipment manufacturers most likely will not add any more to the cost premium of an inverter by adding a harmonics compensation device because it would adversely impact the lucrative inverter market. By the same token, utility companies most likely will not bear the cost of electric service unless they see a positive return on their investment. The choice depends in part on whether inverter technology is actually saving more energy by being efficient, or is being more wasteful by creating too much electrical noise and power drainage. Technical resolution is available, but economic justification is uncertain.

6.0 ASSESSMENT OF INVERTER TECHNOLOGY DEVELOPMENT ON THE RESIDENTIAL HVAC MARKET

This report focuses on the evolution of motor control technology and its application in the HVAC industry in Japan. The design philosophy of present equipment has been described in particular detail. It has been shown that the rapid pace of technology improvement in power electronics, microprocessors, and rotary compressors was stimulated by rapid increases in market demand. The eventual success of inverter-driven heat pumps parallels successes in automobile and precision machinery industries.

In retrospect, it was not a coincidence that Toshiba Corporation introduced the residential inverter-driven heat pump in 1982. The Japanese conglomerates (who are vertically integrated manufacturers of critical components as well as final products) steadily expanded the production capacities of HVAC- and electronics-related components since the late 1970s. As a result, prices of critical components decreased dramatically from the economy of scale established in the process, thus enabling the conglomerates to package a new heat pump system using volume-produced, low-cost components.

Thus, the development of inverter-driven heat pumps was a consequence of production increases in certain areas of the business. Contrary to popular belief, the success of inverter-driven heat pumps was not promoted by technological advances, but rather by the consistent production and pricing policies of Japanese conglomerates who, in effect, found a new market for their components. Their strategy of rapid production increases and persistent cost reductions will undoubtedly stimulate new technology innovations. We documented published data to confirm this thesis and provided technical insight into why the HVAC industry was targeted and what direction inverter technology will take in the future.

This section is divided into subsections for ease in discussing relationships the Japanese HVAC industry has with the market and the Japanese government.

Section 6.1 Japanese Industry Motivations Behind the Development of Inverter-Driven Heat Pumps

Section 6.2 Situational Analysis of Rotary Compressor Production in the Early 1980s

Section 6.3 Situational Analysis of Power Electronics Device Production in the Early 1980s

Section 6.4 Situational Analysis of Microprocessor Production in the Early 1980s

Section 6.5 Conclusion

6.1 JAPANESE INDUSTRY MOTIVATIONS BEHIND THE DEVELOPMENT OF INVERTER- DRIVEN HEAT PUMPS

Several publications point to the timely development of component technology, government policy for energy conservation, and the oil crises of the 1970s as the primary motivations for development of inverter-driven heat pumps (Ide and Kanazawa 1987; Toyonaka 1986; Tanaka et al. 1987; and Endo et al. 1988).

Perhaps Toyonaka of Environmental System Engineering Co., Ltd. most effectively describes the brief history of energy policy and fossil fuel crises. Most precisely, Toyonaka explained that during the first oil crisis of 1973 (the Arab Oil Embargo), the

Japanese government, industry, and consumers at large became aware of the world's limited energy supply and the vulnerability Japan faces as a country having few natural resources. During the 1970s, the Japanese public began emphasizing the "value" of comfort-building appliances and energy efficiency (Toyonaka 1986).

Following two major oil crises, the Japanese central government published the "Decree of Energy Conservation" in June 1979. The decree entitled, "Laws Governing the Rationalization of Energy Utilization," included several subsections covering the minimum energy consumption standards for space conditioning equipment, as well as a policy announcement regarding the thermal efficiency of a building envelope. The law further provided guidance on construction material, promotion of better insulation material use, a waste heat recovery system, and the importance of energy conservation in space conditioning. Specifically, control of infiltration, zoned heating and cooling equipment, and improvement of seasonal energy efficiency were outlined in the "energy conservation directive" (Toyonaka 1986).

The government law emphasized energy efficiency in the commercial building sector. Thus, in the commercial space conditioning market, a shift in architectural philosophy to design a building envelope based on low running (energy) cost became the prime mover for significant increases in multi-zone, air-source heat pumps in the early 1980s.

The rapid developments of digital microprocessors, small rotary compressors, and power transistors, which occurred simultaneously between 1978 to 1983, were motivated to a great extent by the government decree of 1979 for energy conservation (Ide and Kanazawa 1987; and Endo et al. 1988). Thus, an environment was established in which energy-efficient equipment was highly promoted. But inverter technology had been well known and available for medium to large horsepower motors since the 1950s. The HVAC industry had to wait until 1983 for the market to open up for

variable-speed equipment. This, we believe, occurred as a result of two seemingly unrelated reasons:

- Japanese conglomerates set the production and pricing policies to dramatically reduce the price of critical components.
- The HVAC application for inverters was a relatively easy motor control technique to implement, resulting in a potentially large seasonal energy-saving benefit.

The key to relating these two reasons is because the initial manufacturers of inverter-driven heat pumps (Toshiba, Hitachi, and Mitsubishi Electric) were themselves the major manufacturers of power electronics, microprocessors, and rotary compressors. Hence, their aggressive production and pricing policies pushed the price of these components low enough to allow introducing low-cost inverters for the residential market. In fact, a simple voltage source PWM inverter with a few microprocessor chips can control the HVAC application for compressor drives. These initial market leaders produced key components as well as the final heat pump product in a vertically integrated fashion.

Customers were already educated by the central government's decree in promoting energy-efficient equipment. The manufacturers had to wait only until the price of key components declined enough to justify the package. In fact, there is some evidence that manufacturers actually "created" a new product for the HVAC market to dispose of overproduced components in the related areas, as analyzed in the next subsection.

6.2 SITUATIONAL ANALYSIS OF ROTARY COMPRESSOR PRODUCTION IN THE EARLY 1980s

Japanese compressor manufacturers significantly increased the capital expansion of automated production facilities for small-capacity rotary compressors in the late 1970s (Ushimaru 1986). These aggressive production policies resulted in dramatic increases in the total production and export of

rotary compressors between 1982 and 1987 (Figure 6.1). Although the domestic consumption of compressors (principally for residential air conditioners, refrigerators, and automobile air conditioners) increased during the same period, export production outpaced domestic demand.

This pattern of dramatic increases in production capacity to drive the cost down until the price of the product becomes attractive for export is a fundamental strategy employed by Japanese corporations (Abegglen and Stalk 1985). When demand is strong, Japanese corporations tend toward "doubling strategies," by which capacity and output are doubled within a short planning period of 2 to 4 years. These strategies can result in growth rates of 50% or more per year. Today these "growth biases" can be found in Japanese producers of video cassette recorders, compact disk drivers, personal computers, magnetic tapes and disk drives, personal radios, robots, facsimile machines, word processors, and even inverters.

Rather than cutting back when demand is weak, Japanese corporations, characterized as having a growth bias, typically step up their levels of investment in production. Product variety is increased, prices are cut, and distribution is expanded. In the face of stagnant or falling demand, Japanese manufacturers of trucks, refrigerators, audio equipment, and air conditioning equipment have all dramatically increased their

Figure 6.1. Increase in Production Capacity of Rotary Compressors in Japan

product variety and expanded distribution (Abegglen and Stalk 1985).

The next section examines a similar trend in power electronics device production.

6.3 SITUATIONAL ANALYSIS OF POWER ELECTRONIC DEVICE PRODUCTION IN THE EARLY 1980s

The growth of high power GTO devices was shown in Figure 4.2. Although these high power devices (GTOs) are not currently used in residential applications of 460V or less, they are an indication that the production capacity of power switching devices is growing rapidly in Japan.

In the early 1980s, General Electric, Westinghouse, and Mitsubishi Electric entered into a joint venture with the aim of re-establishing their lead in power devices. The joint venture corporation, located in Youngwood, Pennsylvania, was named "Powerex." In the early stages of Powerex, the American market for uninterruptible power supply (UPS) was targeted as the growing market sector. The GTOs were to be used in solid-state power conditioning to provide utility-grade power from the direct-current (dc) battery supply. In this market, leading Japanese manufacturers were offering equipment using GTOs for high-capacity units (over 600 kVA) and power transistors for low- to medium-capacity units. Of the growing UPS market, Powerex recognized that the U.S. manufacturers had almost 100% of the domestic U.S. market share in 1980, but their position was steadily challenged by foreign competition (Hunt 1987).

While the U.S. manufacturers were losing the market share as a percentage of the total market, the market itself was growing rapidly, thus creating an illusion that domestic manufacturers were competing effectively. However, as the domestic UPS manufacturers reviewed the pattern of component sourcing, they realized the real danger of their

market position in this important segment of the U.S. economy. They recognized, in 1986, that although 85% of the UPS systems (including circuits, end-user control, and packaging) sold in the United States were assembled by domestic manufacturers, 85% of power devices (the heart of a UPS system) were imported from offshore manufacturers (Hunt 1987).

In Japan, the production capacities of power devices increased according to the production and pricing policies set by leading manufacturers. This was not the case in the United States. Production policies are established and carried out to meet pricing policies. Leading Japanese electronic component manufacturers' growth bias trend includes the expectations of continued growth, decisions and plans formulated to produce growth, and the unfaltering pursuit of growth, unless the very life of the organization is threatened (Abegglen and Stalk 1985). Companies with a bias toward growth add physical and human capacity ahead of demand. Prices are set not at the level the market will bear, but as low as necessary to expand the market to fit the available production capacity. Costs are programmed to come down to support pricing policies, and investments are made in anticipation of increased demand.

This trend is evidenced by leading Japanese manufacturers of air conditioning systems (who also manufacture rotary compressors, power devices, and microprocessors). These manufacturers accelerated plant expansion rather than cut back production to save capital expenditures after facing lagging demand in the air conditioning market during the late 1970s. As a result, production capacities of key ingredients in inverter-driven heat pumps increased significantly, further driving the cost to the level considered affordable by the residential market.

The trend of putting production ahead of market demand is more prominent in microprocessor manufacturing, which is reviewed next.

6.4 SITUATIONAL ANALYSIS OF MICROPROCESSOR PRODUCTION IN THE EARLY 1980s

Prior to the controversial trade dispute surrounding possible dumping of 64K-bit Random Access Memory (64K-RAM) devices by Japanese manufacturers, the pocket calculator industry was the precursor to intense competition in memory devices. The Japanese pocket calculator industry has gone through a typical growth cycle—extremely high growth for many years and related rapid price reductions—followed by low growth as the market demand was satisfied (Figure 6.2). From 1967 to 1973, output of pocket calculators grew at an annual rate of 133%. The initial pioneers of the product were quickly followed by a great number of new entrants who exited from the business as the

Figure 6.2. Production of Electronic Calculators, 1965-1983 (Source: Adapted from Japan Ministry of International Trade and Industry, 1983 Year Book of Machinery Statistics)

industry matured. These included substantial companies like Sony, which could not (or chose not to) stay in the race.

Recent data on memory device (RAM) investment reveals a similar pattern. All of Japan's major semiconductor producers announced capital investment increases in 1984 of more than 53% over 1983 (Abegglen and Stalk 1985). Several, including Matsushita Electric Industries, announced a 150% increase in microprocessor capital investment. Yet even Matsushita's total budget is only half of the budgets announced by the two leaders in the field, Hitachi and NEC, each of which intended to invest \$400 million in the microprocessor area in 1984 (Abegglen and Stalk 1985).

This commitment was supported by the production and pricing policies of leading Japanese producers of memory devices. Between July 1981 and August 1982, Japanese capacity for production of 64K RAMs increased from 9 million devices per year to 66 million (Verner et al. 1983). As a result, Japanese producers took 65% of the world market (Figure 6.3). The cumulative change in the memory device market also shows the change in leadership from the United States to Japan in this critical market (Figure 6.4).

Moreover, the Japanese are displacing not only the U.S. microchip industry, but also the critically important equipment and materials manufacturers who supply it. Because advances in semiconductor technology are closely linked to equipment and materials capabilities, the decline of these suppliers means that the United States is not only suffering production losses, but actually losing its ability to stay at the leading edge. In addition, it is becoming dependent on Japan for the technology critical for its entire manufacturing base (Prestowitz 1988). Prestowitz further cautions that U.S.-based firms of semiconductor manufacturing equipment are losing ground to Japanese-based firms who compete in the world market (Figure 6.5). This trend is also true

Figure 6.3. Memory Products: World Market Share (Percentage of World Shipments) (Source: Prestowitz 1988)

for precision machining equipment, which is the key to volume production of high-precision machinery, such as rotary compressors and scroll compressors.

Aggressive production and pricing policies demonstrated by leading Japanese manufacturers serve as a built-in mechanism to overproduce key components. The residential HVAC market, with a projected demand of 4 million units of air conditioning equipment per year by the mid-1980s, turned out to be a good arena in which leading manufacturers were able to:

- cultivate new application markets for power switching devices
- expand market demand for microprocessors

Figure 6.4. Cumulative Change in World Semiconductor Market Share since 1978 (Percentage Points) (Source: Prestowitz 1988)

- stimulate the stagnant rotary compressor market (by accelerating the product life cycle and introducing new products at a rapid pace).

Figure 6.5. Semiconductor Manufacturing Equipment World Market Share (Percentage of World Shipments) (Source: Prestowitz 1988)

All of these objectives were achieved, and the catalyst for the dramatic expansion of new application markets for microprocessors, power devices, and oversupply of rotary compressors was the inverter.

7.0 CONCLUSIONS

This report covered technical issues relative to inverter-driven heat pump technology and policy issues surrounding the implicit motivation for the technology.

Of the 4.5 million air conditioning units sold in the Japanese domestic market in 1988, over 60% were heat pumps (as opposed to cooling-only equipment) and slightly over 50% of the heat pumps were inverter-driven. In 1988, inverter-driven residential heat pump sales totaled 1.5 million units and are still growing.

The Japanese residential market still revolves around the 0.75-ton inverter-driven heat pump; this is their most competitive and popular market. The evolution of technical advances in the small-capacity heat pump market can be characterized as:

- The basic structure of the inverter is ac PWM with Darling-ton-type power transistors.
- The popular motor choice is a low-cost induction motor.
- Production sources for inverters, controllers, and mechanical equipment are all internal, thus creating the important vertical integration environment.

On the other hand, the U.S. technology base has revolved around the following component technologies:

- Strong emphasis on motor efficiency, especially in the HVAC applications, provided an impetus for developing an efficient brushless dc motor in the 3- to 5-hp range.
- Component purchasing from a variety of vendors is common--some components are purchased from domestic suppliers and others from overseas. However, consolidation in the HVAC and other industries through mergers and

acquisitions resulted in virtual sole-source integration structure within some manufacturers.

The key difference between the technology bases in Japan and the United States is the size of the market and the focus of the market segment. In Japan, the most important market segment is the 0.75- to 1-ton split-type equipment market, whereas in the U.S. it is the 2- to 4-ton unitary market. Because of the unique economics and performance trade-off issues based on a critical difference in equipment sizing, it is not appropriate to conclude whose technology base is more advanced. It is more meaningful to analyze what technology base will be the most economically beneficial for the future market.

The major concern this work has identified is the aggressive production and pricing policies Japanese manufacturers employ to build an infrastructure of overproduction. When domestic demand of key ingredients in inverter-driven heat pumps was finally outpaced by increases in production capacities of those components, low-cost inverters were applied to add another dimension in the residential heat pump market. In terms of future competition in the U.S. HVAC market, leading U.S. variable-speed heat pump manufacturers should be cautioned to expect a challenge from the Japanese producers of power devices and microprocessors. Because of the vertically integrated production structure in Japan, as opposed to the outsourcing practice of the United States, price competition at the component level may impact the structure of the industry more severely than final product sales.

From a market perspective, it is anticipated that Japanese consumers will continue to move toward larger size equipment and U.S. manufacturers will be driven to improve equipment efficiency. Facing the effective date of new appliance efficiency standards [the National Appliance Energy Conservation Act of 1987 (NAECA)] in the early 1990s, U.S.

manufacturers are gearing up their equipment designs based on inverter application. The Japanese manufacturers will be designing new inverter concepts for medium-size equipment. In this size range, we should anticipate keen competition between the world's top two HVAC industries.

In conclusion, the successful advent of residential inverter-driven heat pumps in Japan appears to be fueled more by the desire to find a new market for low-cost power devices and dedicated microprocessors than to advance the technology of air conditioning equipment. Inverter-driven heat pumps were developed by taking advantage of the following:

- The increasingly sophisticated perception of Japanese customers, who had experienced hardship in the two major oil crises of the 1970s, began appreciating the "value" of HVAC equipment rather than following simple economics.
- Government guidelines for building system selection, construction practice, and the energy conservation law laid the groundwork for manufacturers to educate the public about high-efficiency equipment. Customer education was promoted and guided by the central government. This prompted manufacturers to sell products based on high seasonal efficiency (such as the inverter-driven products).
- Producers' business climate in the early 1980s was such that production lines were expanded for rotary compressors, microprocessors, and power devices. When the worldwide recession hit Japan, the Japanese air conditioning equipment producers were additionally impacted by record-setting cool summers. They had an oversupply of rotary compressors, and the same companies who manufactured compressors also produced microprocessors and power devices. Thus, inverters emerged to form a new market application in residential heat pumps.

Today, in the backdrop of Japan's financial security and increasing affluence, the outlook for variable-speed heat pump technology development is characterized by continuing efforts to 1) develop high-performance, low-cost inverters for unitary-size (3- to 5-ton range) equipment, 2) improve the efficiency of PWM inverters, 3) develop the technology base and low-cost production strategies for scroll compressors, and 4) further improve the system economics.

Regardless of other new developments, the trend of market and technology competition among major heat pump manufacturers (both Japanese and the U.S.) will continue to create an innovation-rich environment in which technology development and low-cost production capability will be the basis for future HVAC business worldwide. The responsibility of the U.S. manufacturing-base gatekeepers will be to anticipate challenges by leading Japanese manufacturers to corner the inverter market by their production capacities, application innovations, and growth-biased way of business. Certainly, a challenge exists in low-cost component production for the HVAC industry and other important segments of the U.S. economy. Because of the vertically-integrated production structure in Japan, which guarantees a large captive market of key components to reduce production costs, price competition at the component level will impact the structure of the U.S. HVAC industry more severely than competition of final product sales.

Japanese conglomerates are capable of manufacturing products as diverse as microprocessors and refrigerant compressors, and tapping more markets than most American companies. As a result, research and development costs and risks are spread over several markets; American manufacturers typically incur comparable costs to reach one or two markets. However, the American HVAC industry need not concede its market to foreign competition. U.S. manufacturers have the advantage of a large-volume domestic production base offering

low-cost units that compete effectively worldwide. If the HVAC industry maintains customer satisfaction by providing reliable equipment and utilizing

its technological innovations, it can regain its leadership role in engineering excellence of HVAC products.

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