EVOLUTION OF MOTOR AND VARIABLE FREQUENCY DRIVE TECHNOLOGY

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ABSTRACT

The purpose of this paper is not to describe in detail the operation and construction of variable frequency drives (VFD's) but to make the reader aware of specific market and product trends effecting the evolution and use of the motor drive combination. In addition, two specific application examples using standard AC drives in two different industries will be explored giving the reader a practical insight into energy conservation.

INTRODUCTION

Electric motors have long been and will continue to be the general workhorse of industry providing an efficient and reliable transfer of power for industrial and commercial applications. Specifically, the fixed speed three-phase squirrel cage induction motor has been defined as the general workhorse of industry. The motor speed depends solely on the number of stator poles and the frequency of the incoming voltage supply. In relation to the benefits of transferring electrical energy to mechanical energy the squirrel-cage induction motor is rugged and reliable requiring minimum maintenance at a very reasonable cost. Over the years a great many devices have been applied to change the speed of the motor through mechanical or electrical means. Until the advent of the AC variable frequency drive in the late 1950's, mechanical devices remained the predominant way to control the speed of the motor. But, early AC variable frequency drives (VFD) were bulky, unreliable in critical applications and very expensive compared to the alternatives at the time.

With the passage of the Energy Policy Act of 1992, there is an increasing need for energy conservation and efficient use of energy enabling commercial and industrial facilities to minimize production costs, increase profits and stay competitive. This energy act states specifically that *certain* motors *manufactured* after October 24, 1997 must meet the new energy standards found in the National Electrical Manufacturers Association (NEMA) standard MG-1-1987, Table 12-6C or Table 12-10 in MG-1-1993. *Certain* motors can be defined as any NEMA designed, general purpose, T frame squirrel-cage induction motor under NEMA Designs A and B, through 200 hp., single speed, foot mounted and polyphase operating at 230/460V at 60 HZ. Exempt from this legislation are DC motors and the special and definite purpose AC motors.

Technology has made great strides in improving the AC variable frequency drive to present day standards. Variable speed drives (VFD's) together with motors have emerged throughout industry as the popular approach to improve process control, product quality, reduce energy consumption and expand automation and diagnostics. Yet, energy efficiency motors and inverter duty motors are actually two separate product offerings serving two distinct applications. It is essential to understand these differences to insure a successful motor/VFD installation. This paper will attempt to introduce the reader to better understand the evolution of these products within the dynamics of an emerging energy conscious marketplace.

THE MARKET

Nationally, there are more than one billion motors in the U.S. with 40 million of these motors in industrial and manufacturing operations consuming 70% of the total electrical energy in a typical manufacturing facility. According to Paul Scheihing, Motor Challenge Program Manager for The Department Of Energy, "Nationally, U.S. industry spends more than $30 billion annually on motor *systems* energy cost."[1] Over the past fifteen years the use of VFD's with NEMA squirrel-cage induction motors has increased dramatically in the industrial and the commercial market segments. For example, during the mid eighties the petroleum and chemical industry critically viewed VFD's with a cautious eye. Today, this industry views the VFD as just another standard component within the system designers toolbox. Each year we see the effects of an increasing market as more and more industries realize the advantages to VFD's.

Figure 1 segments the use of electrical energy in the U.S. by application. From this chart we can conclude rather quickly which applications where one can achieve energy savings with a motor drive combination; the pumping, blowers/fans and the HVAC segments. As we discussed earlier, traditionally the motivating force to apply VFD's in the past was to obtain speed control comparable to a mechanical or DC drive. As the marketplace moves forward with regard to the aforementioned Energy Policy Act and we see the increased emphasis on energy conservation the use of higher performance AC standard drives will continue to grow exponentially. In fact, we see the standard AC drives market as a whole growing at a 10% annual compound growth rate from today to the year 2000. With the DC drive market declining at a 4% compound growth rate. The drives market shown in Figure 2 defines that 52% of the standard AC drives market is in the 7.5 through the 200 hp. motor relationship. Note, this is the bulk of the market that is also impacted by the EPACT legislation. While figure 3 takes the next step breaking out the AC standard drives market by specific application. Once again, we see the air moving and pump applications offering the largest application segments for the standard variable torque AC drive technology.

Variable torque applications like HVAC and pumping fit well with the analogy of an individual driving a car on an interstate at 60 miles per hour. Let's assume the engine under the hood is running at a constant RPM maintaining the 60 mph speed. Instead of the driver varying the pressure applied to the accelerator to change the speed of the vehicle, the driver in this analogy will slow the vehicle down by applying the brake pedal to create the desired resistance against the engine. As you could image this is a very inefficient approach, not only in energy consumption in miles per gallon but the accelerated wear on all of the component parts.

In a traditional commercial fan/blower application the rpm of the applied motor is fixed while the cubic feet per minute (cfm) is varied through the use of dampers. The damper is very similar to the brake pedal, creating the resistance against the output of the motor. For example, if we look at a typical applied HVAC system , 85% of the time the percent of air flow needed to operate a commercial system is between 40% and 85% of the air flow required. Maximum air flow or 100% of design air flow required for a system is only needed 2% of the time. In other words, 98% of the time the air flow can be varied through the use of a variable frequency drive while still maintaining system efficiency.(figure 4)[2]

With an energy efficient motor the user receives a premium motor manufactured specifically to lower energy consumption . Energy efficient motors commonly use low loss steel laminations along with a high degree of copper content thereby developing a motor with much lower thermal rise levels. The insulation system on an inverter grade motor has a more robust insulation system which usually consists of not only the energy efficiency motor construction attributes but other key features which includes insulated magnet wire, additional taping and/or lacing on the stator end turns as well as an improved stator insulation on end turns, slots and between phases. Plus extra cycles and/or additional coatings of varnish or VIP on the stator itself. Figure 5 clearly states that as industrial users applied standard motors in the past with 1,200 or above Hz PWM drives we have grown accustomed to a half life from a standard motor. Now with the increase of IGBT technology and increased KHz switching speed we can readily see the effects of insulation life of a standard motor compared to "Inverter Grade" motors. When retrofitting an existing system and upgrading to IGBT technology it is essential to consider the impact such drive technology will have on the life of the system.[3] We strongly feel our "Inverter Grade" motor demand will increase at a pace greater than the drive industry growth rate once the marketplace realizes the benefits of increased motor life through "Inverter Grade" motor construction.

AC DRIVE EVOLUTION

The VFD is used to create a controlled frequency AC wave form to the AC induction motor. By changing the frequency of the AC wave form the speed of the AC motor is changed. It is equally important to control the flux density in the motor to maintain torque producing capabilities throughout the speed range. The flux density is controlled by maintaining the volts/hertz ratio supplied to the motor. The torque is essentially proportional to the volts/hertz ratio squared. In other words, if the frequency or voltage is changed without changing the other , the torque characteristics change as a square function.

	Development	Drive Usage
1958	Solid state power devices develop known as SCR's.	DC drives become available.
Early 1960's	The cost effectiveness of SCR's improves.	DC SCR drives readily available for industrial applications. Performance and understanding of these applications improves.
Late 1960's	Analog control circuitry using digital control and firing circuitry.	Development of phase locked loops for synchronization improves line noise immunity allowing DC drives to operate better.
The 1970's	Development of large scale integrated circuit (LSI) technology.	Custom integrated circuitry improves the reliability and cost of current circuitry.
Pre 1985	SCR's/GTO's using six step technology. Drives are large, bulky and expensive.	Marginal acceptance a larger acceptance in certain industries like petro/chem and textile.

1985-..1989..	Bi-polar PWM technology , smaller more economical drives evolve.	A greater acceptance among users. There is still an issue with noise. Inverter grade motors in development along with field testing.
1987..89..1990 present	IGBT technology, smaller drive packages with micro drives for smaller hp motors. Switching frequency becomes ultrasonic.	A much larger acceptance. Micro drives have actually become commodities. Inverter grade motors are launched in 1990.
future....	Total motor drive compatibility. Systems sold as one. Energy efficiency across all industries and energy users. Motor development will parallel non-sinusoidal drive development.	The micro VFD will be mounted in the motor conduit box totally unexposed to the elements.

As you can see VFD technology has improved due to power devices and the microcomputer. Early VFD's used silicon controlled rectifiers (SCRs) or gate turn off thyristors (GTOs) and were either variable voltage inverter (VVI) or current source inverter (CSI) drives. As technology improved the pulse width modulated (PWM) drive was introduced. Originally the PWM drive used Darlington bi-polar transistors as power devices. However, with the introduction of the insulated gated bi-polar transistor (IGBT) in the late 1980's vast improvements in the design of AC VFD's resulted.

Vector controlled drives were also introduced around the time as IGBT's became more readily available. They are similar to the PWM VFD except they use a more sophisticated level of control logic. The basic principal is to model the motor's electrical performance inside the controller. This allows the controller to perfectly match the motor performance to the load requirement. Vector controlled drives provide higher dynamic performance. There are many types today with both direct and indirect methods of control. Some of them are stator-flux control, rotor-flux-oriented control, magnetizing-flux-oriented control and etc. Vector controlled drives are currently making an impact on the total DC drive market. By no means is the DC market dead nor will it be in the near future, but as the vector controlled drive becomes more accepted it will replace certain DC drive applications.

Costs of VFD's have come down dramatically primarily from the improved technology of power devices, micro computer advancements and improved manufacturing techniques. For example, a 10 horsepower drive manufactured in the early 1980's was large and bulky. Today that same drive can be held in the palm of your hand at approximately one third the cost.

APPLICATION CONSIDERATIONS

Probably the first question that should be asked is what type of application are you considering for a VFD. There are basically three types: constant torque, variable torque and constant horsepower applications. It must be pointed out that constant and variable torque loads are the dominate two types of applications.

A constant torque load is one in which the torque required is independent of the speed. The torque can be 100% throughout the speed range or vary. Examples of constant torque loads are conveyors, rotary lobe pumps, positive displacement pumps and compressors, punch presses, wire drawing machines, paper machines and printing presses. Considerations when applying VFD's to these type loads will be starting torque requirements, speed regulation, torque response and close loop capabilities.

Variable torque loads are applications where the torque required is proportional to the speed. This is where the basic affinity laws apply and as a result energy savings. The volume is directly proportional to speed, pressure is proportional to the square of the speed and power is proportional to the cube of the speed. Typical applications are most pumps, fans and specific HVAC applications which fall under the definition as centrifugal loads. When a VFD is applied to a centrifugal load the horsepower drawn from the AC lines very nearly follows the centrifugal load curve. Since the functional relationship of horsepower (or power) to speed is cubic, the energy required drops almost cubically as the speed is reduced. Most centrifugal loads today use some mechanical means to vary the volume, be it valves, dampers etc. The obvious reason to use a VFD for centrifugal loads is the potential energy to be saved. In the majority of most applications the energy saved will offset the initial cost and justify a suitable payback not to mention the ability to achieve precise control.

Constant horsepower loads are applications where torque varies inversely with speed. These types of loads require high torque at low speeds and low torque at high speeds. Typical applications are lathes and metal cutting tools operating over wide speed ranges. Some extruders, mixers and center driven winders can also be constant horsepower type applications.

ACTUAL APPLICATIONS

R.A. Miller Hardwood Company; North Tonawanda, N.Y.

R.A. Miller operates six kilns to dry out rough-cut lumber and to steam inject precise levels of moisture into the process wood to prevent splitting, cracking and checking. Prior to installing VFD's and energy efficient motors, R.A. Miller used three to five motors in each kiln to circulate air to dry the wood. The motors were controlled manually by turning individual circuit breakers on and off whenever the humidity levels were unsuitable and dampers were used to regulate the required air flow. As you could image, this resulted in uneven airflow, wasted energy, labor and wood.

An initial payback analysis was presented to R.A. Miller by the local utility and the VFD manufacturer. Initial estimates were as follows:

Installation Cost	\$ 46,286
Utility Rebate	\$(18,560)
Actual Cost	\$ 27,726
Projected Yearly Savings	\$ 29,088
Expected Simple Payback	11 months

Actual Results were:

First year energy savings exceeded $40,000
Increased operating hours
Reduced demand charges

Improved product quality due to tighter process control
A realized net waste reduction of 4%
A net realized payback each month

By applying VFD's and energy efficient motors R.A. Miller realized significant savings. For instance, at 90% speed (air flow) the energy consumed was 25% less than at full motor speed (100%) with damper control. At 60% speed (air flow) the VFD's consumed 20% to 25% of the energy compared to 67% energy consumption before at full speed with damper control. In conclusion, the total energy savings varied from 25% to 50% from the original control scheme which consisted of running the motors at a fixed speed and damper modulation.

In addition to the energy savings R.A. Miller realized real payback in improved product quality and a more precise flow pattern that resulted in much tighter quality control in the drying process. This enhancement in tighter control resulted in improved humidity control which inturn raised the quality of the produced hardwood. R.A. Miller realized less checking and splitting in their product for shipments. This is an excellent example where a customer has experienced the benefits we discussed earlier in the introduction of this paper, improved process control, increased product quality and a net realized reduction in energy consumption.

First Interstate Plaza: San Diego, Ca.

First Interstate is a multi- storied office building in the San Diego area. They are managed by the Compass Management and Leasing Company. The building has approximately 465,000 square feet of office and parking space. This retrofit project was proposed to the customer by the local utility company, a VFD manufacturer and a major chiller/air handler company.

This retrofit proposal included replacing the lighting fixtures throughout the building and applying VFD's to twenty-two air handlers, four garage fans and two 700 ton chillers. From the VFD standpoint the customer wanted to replace their conventional on/off air flow system with a constant air flow system. In addition, the VFD's on the garage fans would allow better removal of carbon monoxide from the underground parking area.

Estimated project cost for the mechanical portion (air handlers and chillers) was $478,000 with a rebate of $140,000 from the local utility. Payback for the mechanical portion is approximately three years. The expected annual dollar savings on this project is 30%. Estimated annual units of energy savings is 2.66 million kilowatts including replacing the lighting fixtures.

Even though actual savings have not been tabulated by the utility at the writing of this paper, savings were guaranteed at a minimum of 30%. With three separate companies cooperating together toward a common goal of realized savings the customer is seeing a substantial improvement in building operation. Just based on the conservative energy savings estimate the building owner will be able to reflect back to the tenants a lower rent which will in turn increase his overall building occupancy rate due to more competitive rates. Not to mention the unrealized benefit of less wear and tear on the mechanical equipment that will extend overall life expectancy.

CONCLUSION

Motor and VFD manufacturers are continually striving to improve overall performance of their products. This paper has attempted to give a survey of the past, present and future developments and trends in AC induction motors and VFD's. The three-phase squirrel-cage induction motor will remain the dominant machine for industrial drives. In the future the marketplace will see a distinct increase in vector controlled drives as well as a continued but a gradual decline for DC drives.

There is no doubt there will be a continuos search for new materials which will combine thermal conductivity, electrical insulation and mechanical strength to enhance the reliability of motors and drives in the future. This will result in a revolution in the packaging of integrated power modules providing a complete controller for micro drives. In the near future we feel the market will see an integration of power electronics into the motor. Such a compact design will provide industries with a complete motor and drive package as one unit. With regard to power electronic devices, the major area the market will see future development and expansion will be in the quantity produced and an increase in the power rating of the power modules. Power modules will range from multiple-device modules to smart devices to power integrated circuits or intelligent power modules. The continued trend of lower costs through improved manufacturability will significantly contribute to the future development of intelligent drive systems.

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U.S. ELECTRICAL ENERGY CONSUMPTION

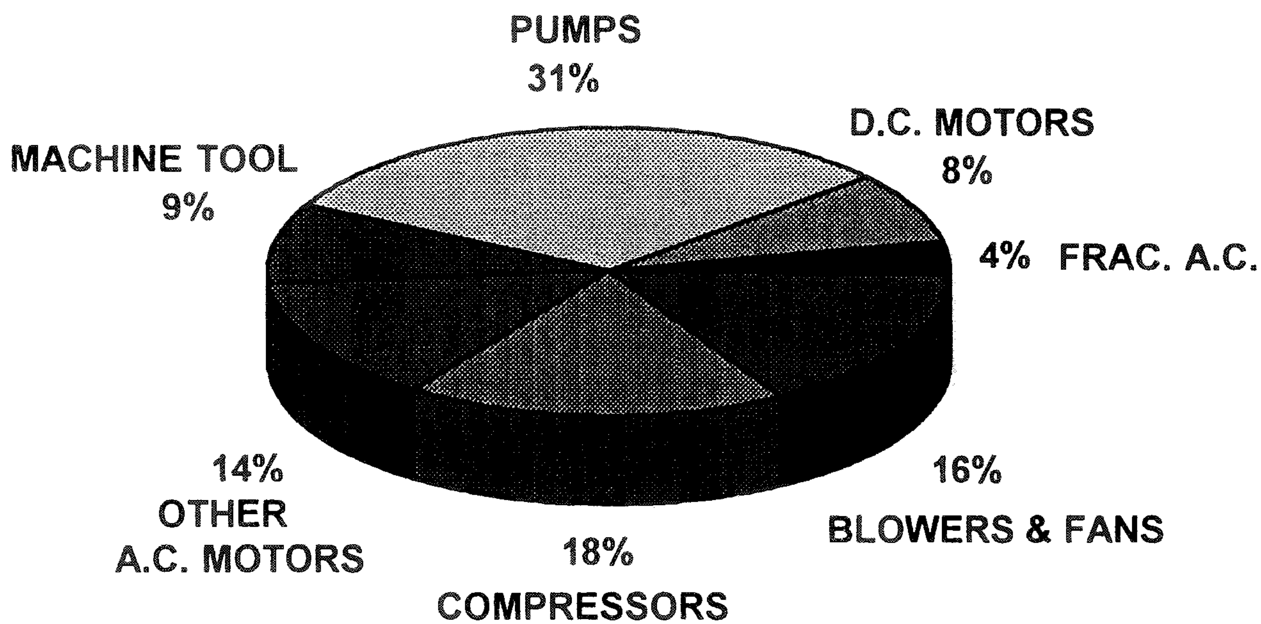


FIGURE 1

MARKET BY HP RATING
AC STANDARD DRIVES

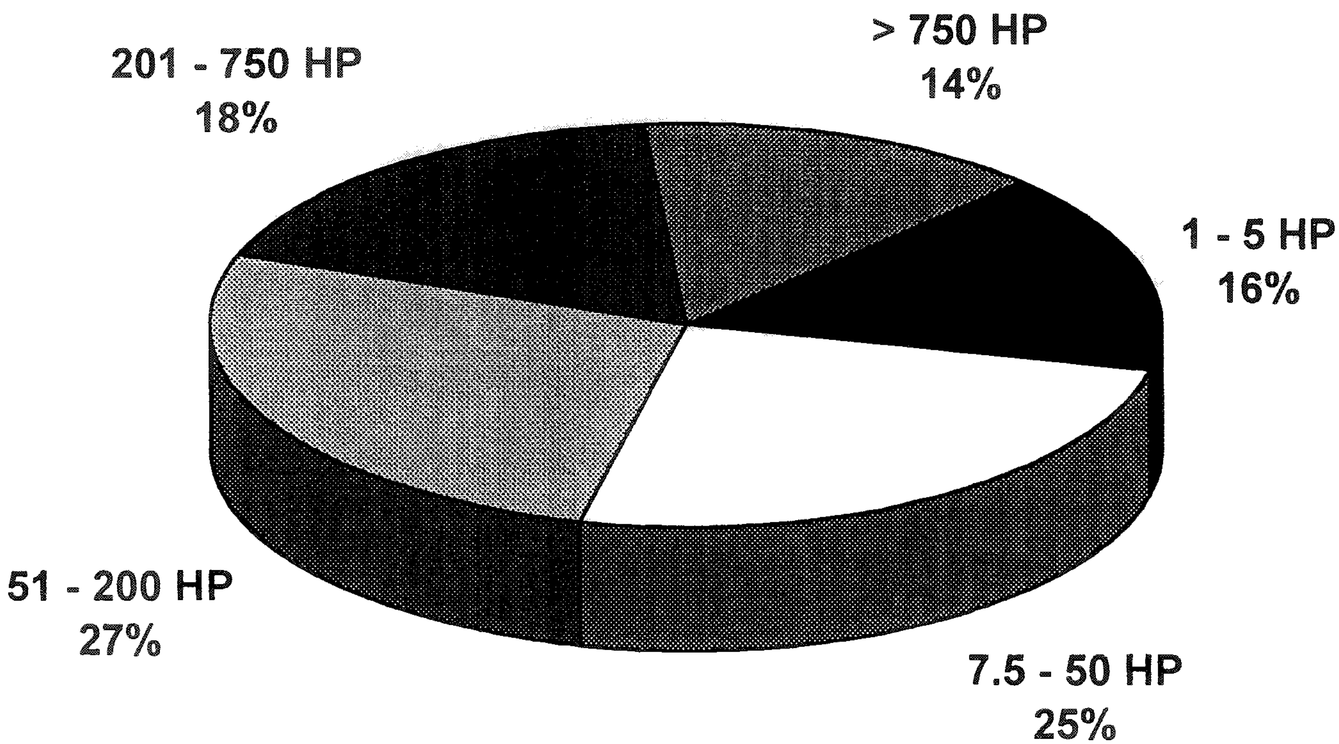


FIGURE 2

MARKET CHARACTERISTICS
AC STD APPLICATION PROFILE

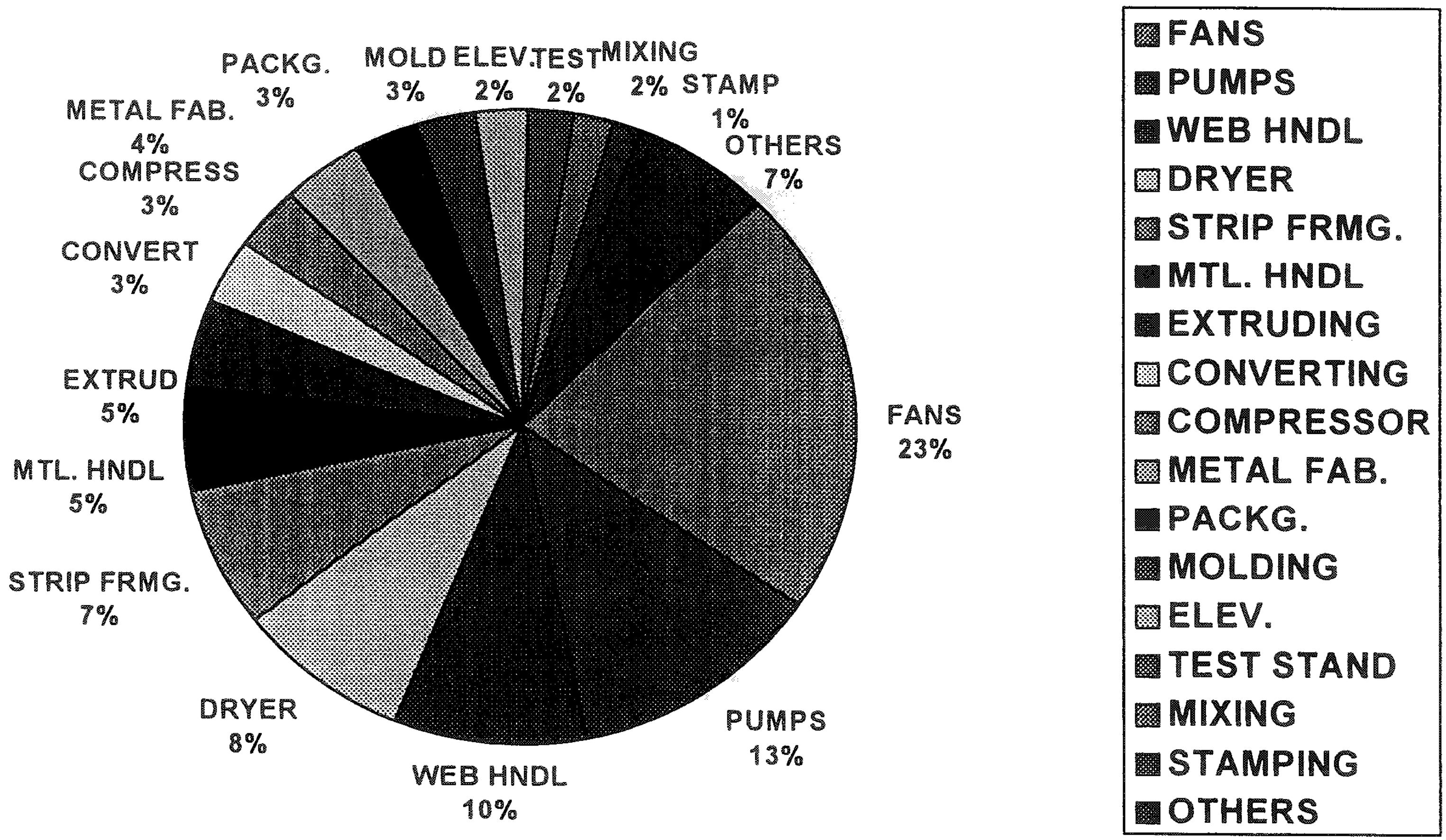
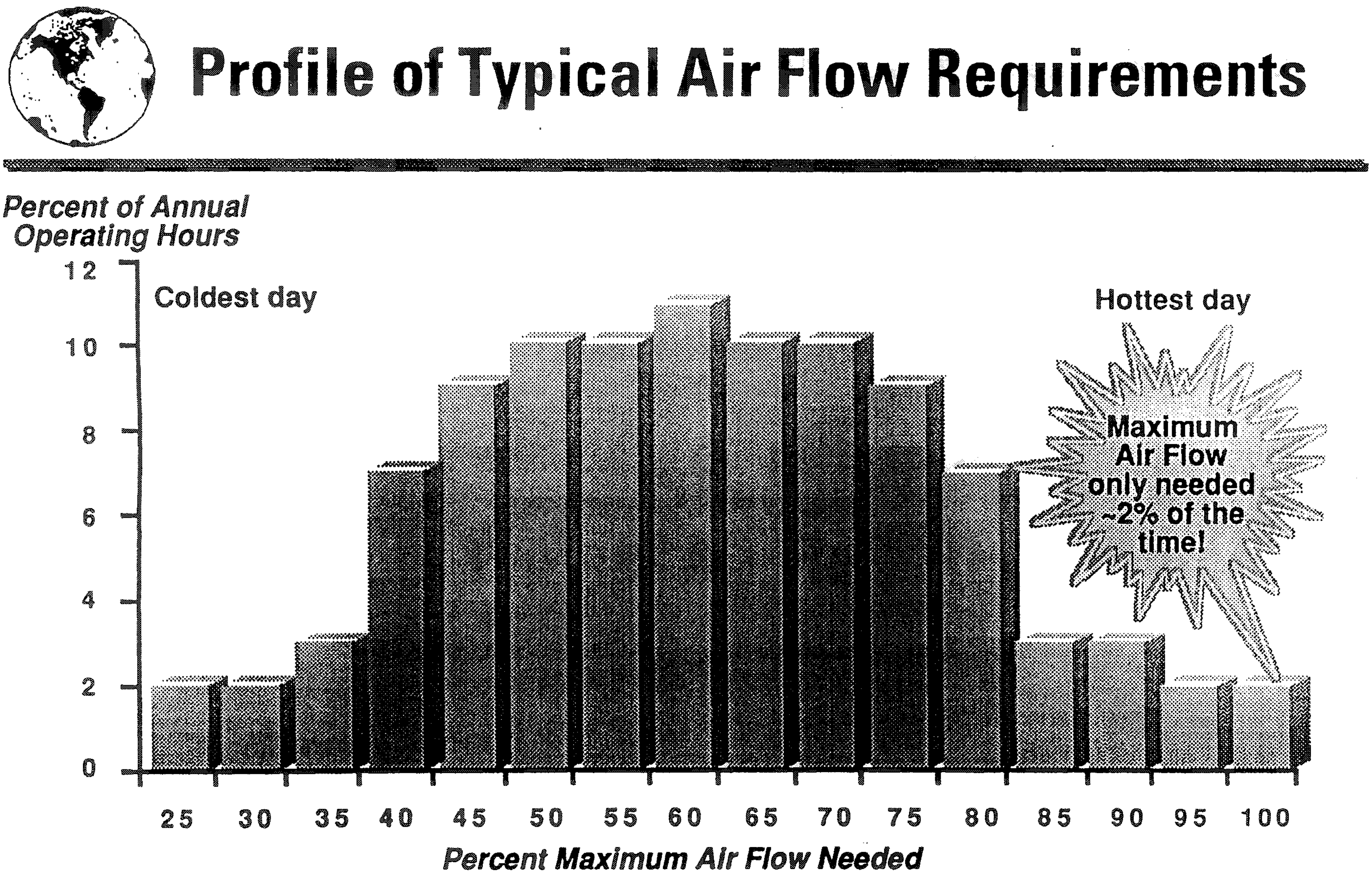


FIGURE 3



Source: York Applied Systems

FIGURE 4

SWITCHING FREQUENCY IMPACT

MAGNET WIRE LIFE vs SWITCHING FREQUENCY

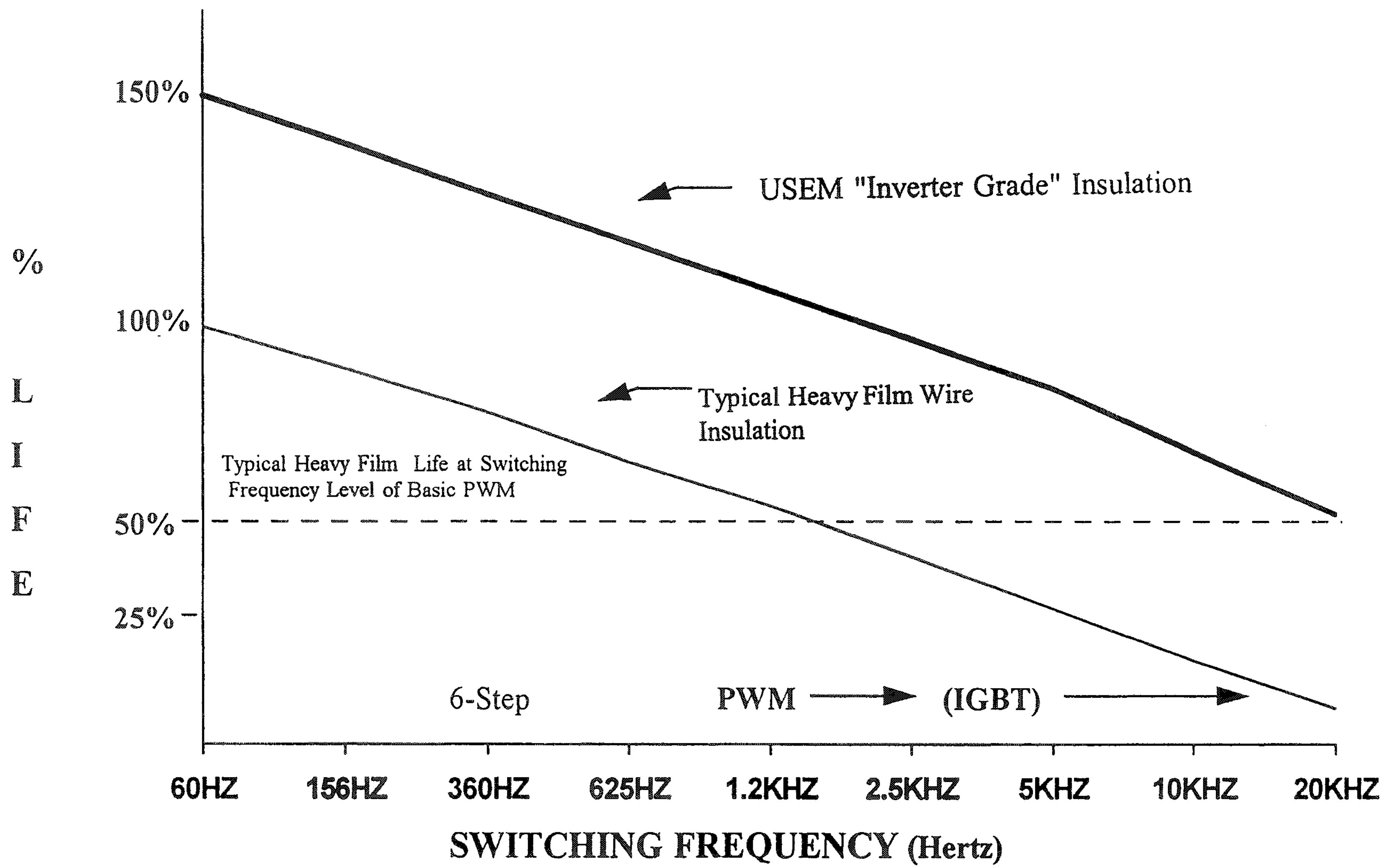


FIGURE 5

Based on test results of accelerated magnet wire testing in a 30°C ambient with a 1000V peak / 2000Vpeak to peak pulse waveform.

US Electrical Motors 1995