URBAN CONSORTIUM

The Urban Consortium (UC) is a special network of the nation's largest cities and urban counties brought together by PTI to find new solutions to their common concerns. The UC provides a creative forum where elected and appointed officials can identify, test, and validate practical ways to improve the provision of public services while generating new revenue opportunities.

With staff, management and business services provided by PTI, the Consortium addresses the critical needs of large local governments through its three task forces: Energy, Environment, and Telecommunications and Information. The task forces act as laboratories to develop and test solutions and share the resulting products or management approaches with the wider audience of both large and small local governments.

THE URBAN CONSORTIUM ENERGY TASK FORCE

The main objective of the Urban Consortium Energy Task Force (UCETF) is to improve urban energy management decision-making through applied research and technology transfer. With a core membership of technical and management professionals from over 20 large cities and counties, the UCETF mission is to assist cities and counties in developing and implementing sustainable energy policies and programs through applied research, development, commercialization, and technology cooperation efforts.

While the UCETF annual workplan shows the common agendas of the Urban Consortium, it addresses priority areas of urban energy policy such as:

- transportation
- linkage among energy, environment, and economic/social development issues
- energy efficient facilities
- technology transfer.

One of the elements of the UCETF work program is to carry out applied research and technical assistance with partial funding provided by the USDOE. Proposals to meet the specific objectives of these annual work programs are solicited from large urban jurisdictions. Projects based on these proposals are then selected by an evaluation committee for direct conduct and management by staff of city and county governments. Projects selected for each year's program are organized in thematic units to assure effective management and ongoing peer-to-peer experience exchange, with results documented at the end of each program year.

This approach for the definition of priorities and the selection, conduct and documentation of applied research projects by staff from participating local governments is a unique strength of the UCETF -- a "user-driven" focus to assure that projects conducted by city and county staff will produce results that effectively meet energy management needs critical to local governments.

The research and studies described in this report were made possible by grants from the United

States Department of Energy through the UC Energy Task Force.

The statements and conclusions contained herein are those of the grantees and do not necessarily represent the official position or policy of the US Government in general or USDOE in particular.

PUBLIC TECHNOLOGY, INC.

PTI is the nonprofit, research, development and commercialization arm of the National League of Cities, the National Association of Counties and the International City/County Management Association. PTI's members are among the most progressive and entrepreneurial city and county governments in North America.

With its members PTI explores new ways to harness technology to better serve citizens, while creating new revenues for cities and counties. Under the leadership of its three parent organizations, PTI has pioneered a new program emphasis -- Public Enterprise.

Public Enterprise helps local governments use their assets wisely and offer services with a bottom-line, business-like orientation. Cities and counties have many valuable assets including rights-of-way, recyclables, information and telecommunications; Public Enterprise helps local officials use these and other assets in new, creative and profitable ways.

To ensure that programs and research have the widest possible benefit, PTI is guided by a strategic plan that emphasizes partnerships with private industry, expertise in multi-disciplinary technologies, training in the art of change management, and participation in the international arena of local government to broaden the search for technological and management solutions.

Member cities and counties provide PTI's core financial support. Grants and contracts from foundations, Federal agencies, and corporations also support PTI activities which are carried out from offices located in Washington, DC. PTI's President is Dr. Costis Toregas.

October 1991

**VARIABLE FREQUENCY DRIVE
APPLICATIONS GUIDE**

Energy Task Force
of the Urban Consortium
for Technology Initiatives

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CITY OF PHOENIX

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MASTER

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PREFACE

1991 URBAN CONSORTIUM ENERGY TASK FORCE RESEARCH

THE URBAN CONSORTIUM (UC) is a special network of the Nation's largest cities and urban counties brought together by PTI to find new solutions to their common concerns. The UC provides a creative forum where elected and appointed officials can identify, test, and validate practical ways to improve the provision of public services while generating new revenue opportunities. With staff, management, and business services provided by PTI, the UC addresses the critical needs of large local governments through its three task forces: Energy, Environment, and Telecommunications and Information.

The Urban Consortium Energy Task (UCETF) has 20 members and was established to improve urban energy management and decision-making through applied research and technology transfer. The UCETF focuses on developing and sharing new approaches and innovative solutions to energy management problems with local governments. Projects are organized in thematic units and co-managed by a member of the Task Force.

A description of the 1991 program Units and projects are:

ALTERNATIVE VEHICLE FUELS AND TECHNOLOGIES (AVF)

Alternative vehicle fuels offer a very strong potential to aid in the reduction of U.S. dependence on foreign oil supplies, with the resulting benefits of decreased air pollution in urban areas. Local governments can play an instrumental role in realizing this potential through practical applied research and highly visible demonstrations of alternative fuels and technologies. Issues addressed this year include identifying (a) intensive and credible market development efforts based on an applied research and demonstration program that combines reliable technology with experience-tested applications, (b) environmental and energy diversity benefits, and (c) institutional and infrastructure barriers. The 1991 AVF unit consists of:

Broward County, FL -- *Dual-Fuel Conversion Demonstration and Technology Transfer Project*

New York City, NY -- *Alternative Fuel Vehicle: Financing Issues*

Denver, CO -- *Technical and Market Comparison Between H₂/CNG (Hythane), Electric Hybrid, and CNG Fueled Vehicles*

Denver, CO -- *An Alternative Fuels Fleet Evaluation System -- A Transfer Project*

Detroit, MI -- *Analysis of Institutional and International Limitations for Alternative Fuel Vehicles*

Washington, DC -- *Comparison of Energy Consumption, Energy Savings, and Environmental Effects of EV/PV vs. Conventional Gasoline Vehicle*

ELECTRICITY MANAGEMENT

Urban interests for electricity management focus on means to maintain stable, secure and reasonably priced supplies of electric energy. Approaches include procedures for better demand management, application of "least cost" planning concepts, appropriate use of decentralized and/or small power production facilities, improved end-use efficiency, and developing sound structures for cooperative action among municipalities and energy utilities. Urban strategies include support for decentralized "small" power production, along with better demand management and improved end-use energy efficiency. The successful development and implementation of such strategies will require close cooperation with the utility industry and will address topics in areas of institutional relations, source flexibility, and demand-side management. The 1991 Electricity Management Unit consists of:

Albuquerque, NM -- *Alternatives to Traditional Rate Setting*

Chicago, IL -- *Integrating Innovative Supply and Efficiency Techniques*

Chicago, IL -- *The Chicago Energy Management Cooperative*

Dade County, FL -- *Energy Cost Reduction Through Resource Recovery*

Detroit, MI -- Hydraulic Waste Energy Recovery (Phase II) City of Detroit Water Distribution System

San Jose, CA -- Utility/Local Government Partnership to Increase Energy Conservation in New Construction

ENERGY EFFICIENT FACILITIES

Activities involving energy efficient facilities are at present, part of a national effort to achieve maximum cost-effective energy productivity in the building sector. There exists a need for collaboration between local government officials responsible for energy and environmental programs and other local government officials responsible for facilities, as well as the Federal officials and private sector groups, e.g. utilities. New technologies and management/administration practices to advance energy efficiency in facilities require major partnership efforts and transfer programs. Multi-family housing that has a large concentration of low-income families presents a unique challenge to lowering energy costs and maintaining energy efficient facilities. Projects in this unit are:

Boston, MA -- Neighborhood Energy Efficiency Outreach Partnership

Columbus, OH -- Energy Efficiency and Indoor Air Quality: Solutions for Fire Stations

Louisville, KY -- Partnership Approach to Energy Efficiency in Non-Profit Facilities

Montgomery County, MD -- Technology Transfer of Building Energy Design Guidelines

New Orleans, LA -- Residential Utility Costs Comparative Study

Phoenix, AZ -- Variable Frequency Drive Applications Guide

Portland, OR -- Energy Savings Through Operation and Maintenance Training in the Low-Income Multi-Family Sector

Washington, DC -- Comparison of Two Techniques for Identifying Energy Conservation Measures in Low Income Homes

ENERGY, ENVIRONMENT and ECONOMIC DEVELOPMENT

This an area that has both visionary and immediate practical emphases on the definition and evaluation of realistic strategies and actions to support energy-sustainable and

environmentally responsible communities. Emphases include uses for renewable energy, practical domestic supply and conservation alternatives, and the synthesis of energy concerns with wider local government interests in economic development, environmental quality, and internal cost control. Urban strategies to improve energy-sustainability require attention to both broad based institutional changes, as well as specific projects designed to encourage the application of appropriate technology and community development practices. The "Sustainable Communities" project has involved three municipalities with State agency, Lawrence Berkeley National Laboratory, and a formal advisory committee with broad national representation. Projects under this unit are:

Austin, TX -- Energy Star Sustainable Rating Program

Phoenix, AZ -- Impact of Heat Island on Cooling and Environment: A Demonstration Project

Pima County, AZ -- Tucson Solar Village - Project Management

Portland, OR -- Sustainable City Transfer Project

San Francisco, CA -- Neighborhood Energy/Economic Development at South Bayshore

San Francisco, CA -- Sustainable City Transfer Project

San Jose, CA -- Sustainable City Transfer Project

Seattle, WA -- Coordination of Energy and Air Quality (CEAM)

Seattle, WA -- Bicycle Program -- Urban Trails System

Tucson, AZ -- Local Government Involvement in Long Term Resource Planning for Community Energy Services

Reports from each of these research projects, including this report, are specifically designed to aid the transfer of proven experience to other local governments. Readers interested in obtaining any additional reports or further information about the Urban Consortium Energy Task Force and the Urban Consortium should contact:

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CHAPTER 1 - OVERVIEW

ABSTRACT

While electricity costs have been steadily rising over the last decade, the City of Phoenix has been conserving energy while saving energy dollars through the use of Variable Frequency Drives. Applying variable frequency drive technology to Alternating Current (AC) induction motors, in air handling and fluid handling applications, has allowed the City of Phoenix to operate a variety of equipment at higher overall system efficiencies. The AC induction motor is the main form of energy conversion in the United States of America. It is the major converter of electrical energy into other usable forms. It is estimated that two thirds of the electrical energy produced in this country is applied to electrical motors. Much of the power that is consumed by AC motors goes into the operation of centrifugal fans, blowers and pumps. Approximately one half of the motors in operation today are used for these types of loads. These particular loads - fans, blowers and pumps, present the greatest opportunity for energy savings.

Traditionally, fans and pumps have been designed to be capable of handling the maximum demand of the system in which they are installed. However, quite often the actual demand can vary and it can be much lower than the original design capacity. These situations have been corrected in the past through additions of outlet dampers to fans or throttling valves to pumps. While these can be effective and simple controls they severely affect the efficiency of the system.

Variable frequency (speed) is the most efficient means of capacity control. The most cost effective method of achieving variable speed capacity control is using AC adjustable frequency drives. AC adjustable frequency controls convert any fixed speed AC motor into an adjustable speed device. Adjusting the speed of a motor, by controlling the frequency of the AC power to that motor, reduces its horsepower requirements. According to pump and fan laws, capacity is proportional to speed while horsepower is proportional to the cube of the speed. Therefore, by reducing the speed of an AC motor by 20 percent the horsepower requirement is reduced by nearly 50 percent. Reduced speed through variable frequency control allows for flexibility of meeting changing weather and comfort requirements without operating costly equipment at full capacity.

PROJECT PURPOSE

The purpose of this project is to demonstrate that older, inefficient systems as well as new ones with improved efficiencies can benefit from Variable Frequency Drive control. It is also the intent of this project to provide information that can be used at the design stages of new projects, so that variable speed control can be part of the original system design. The specific objectives are as follows:

1. Investigate existing technology of variable frequency drives and outline the different types.
2. Establish criteria for site and equipment selection based on system requirements.

3. Demonstrate the feasibility of retrofitting AC motors in various air and fluid handling applications.
4. Provide guidance material for other jurisdictions wishing to apply variable frequency drive controls.

REPORT ORGANIZATION

Five main chapters and two appendices comprise this report. The major sections are organized as follows:

Chapter 1 -- an abstract and overview of the document.

Chapter 2 -- the technical background of variable frequency drive operation and the related operational savings will allow the reader to comprehend the concepts presented in the text.

Chapter 3 -- details the various projects the City of Phoenix has successfully participated in over the last decade.

Chapter 4 -- details purchasing procedures and specifications in dealing with the various suppliers.

Chapter 5 -- outlines installation procedures for successful project completion, and includes lessons learned from these projects.

Appendices -- consist of a detailed bibliography and a typical VAV system power calculation comparison.

CHAPTER 2 - TECHNICAL INTRODUCTION

INTRODUCTION

This chapter is intended to provide technical background information for understanding the basic terminology and theory associated with Variable Frequency Drives also known by their acronym as VFD's. If additional information is required, which can not be found in this publication, refer to the Bibliography in Appendix A which contains several references for further research. Included in this chapter is a list of definitions covering most of the terms for easy comprehension. This is followed by technical information on the operation of AC motors and the application of variable speed control to air handling and fluid handling systems. This chapter also addresses the issue of energy savings which can be expected when variable frequency drives are applied correctly.

DEFINITION OF IMPORTANT TERMS

Adjustable Speed. The concept of varying the speed of a motor, either manually or electrically.

Drive Controller. (Variable Speed Drive) An electronic device that can control the speed, torque, horsepower and direction of an AC or DC motor.

Duty Cycle. The relationship between the operating and rest times or repeatable operation at different loads.

Efficiency. Ratio of mechanical output to electrical input indicated by a percent. In motors, it is the effectiveness with which a motor converts electrical energy into mechanical energy.

Head. A measurement of pressure, usually in feet of water. A 10 foot head is the pressure equivalent to the pressure found at the base of a column of water 10 feet high.

Horsepower. A measure of the amount of work that a motor can perform in a given period of time.

Induction Motor. An alternating current (AC) motor in which the primary winding on one member (usually the stator) is connected to the power source. A secondary winding on the other member (usually the rotor) carries the induced current. There is no physical electrical connection to the secondary winding, thus its current is induced.

Inverter. A term commonly used for an AC variable frequency drive. An inverter is also a term used to describe a particular section of an AC drive. This section uses the DC voltage from a previous circuit stage (Intermediate DC Circuit) to produce an AC current or voltage having the desired frequency.

Multispeed Motor. An induction motor that can obtain two, three or four discrete (fixed) speeds by the selection of various stator winding configurations.

NEC. The National Electrical Code is a recommendation of the National Fire Protection Association and is revised every three years. City or state regulations may differ from code

regulations and take precedence over NEC rules.

NEMA. The National Electrical Manufacturers Association specifies standards such as HP ratings, speeds, frame sizes and dimensions, torques and enclosures.

PWM. A type of AC adjustable frequency drive that accomplishes frequency and voltage control at the output section (inverter) of the drive. The drive's output voltage is always a constant amplitude and by "chopping" (pulse width modulating) the average voltage is controlled.

Speed Regulation. The numerical measure in percent, of how accurately the motor speed can be maintained. It is the percentage of change in speed between full load and no load.

Surge Protection. The process of absorbing and clipping voltage transients on an incoming AC line or control circuit.

Synchronous Speed. The speed of an AC induction motor's rotating magnetic field. It is determined by the frequency applied to the stator and the number of magnetic poles present in each phase of the stator windings.

Torque. A turning force applied to a shaft, tending to cause rotation. Torque is normally measured in ounce-inches or pound-feet and is equal to the force applied, times the radius through which it acts.

Transducer. A device that converts one energy source to another (e.g. mechanical to electrical). Also, a device that when actuated by signals from one or more systems or media, can supply related signals to one or more other systems or media.

Transient. A momentary deviation in an electrical or mechanical system.

Transistor. A solid state three terminal device that allows amplification of signals and can be used for switching and control.

VVI. A type of AC adjustable frequency drive that controls the voltage and frequency to the motor to produce variable speed operation. A VVI type drive controls the voltage in a section other than the output section where frequency generation takes place. The frequency control is accomplished by an output bridge circuit which switches the variable voltage to the motor at the desired frequency.

Work. A force moving an object over a distance.

BASICS OF VARIABLE FREQUENCY DRIVES

A variable frequency drive is an electronic device that controls the speed, torque, horsepower and direction of an AC or DC motor. These drives serve processing needs and numerous industrial applications such as fans, pumps and conveyors in a variety of industries. This guide will concentrate its effort in presenting alternating current (AC) motor control, since the majority of applications within the Energy Task Force member jurisdiction fall under this category.

Variable Frequency Drives are able to change the 60 Hertz commercial power to direct current power and then electronically change it back to alternating current of a frequency capable of variation. This variable frequency AC is

then able to drive induction motors at various frequencies and consequently at various speeds. Variable Frequency Drives are able to control motors with infinite number of speeds within the range of operation (usually between 100 percent and zero percent speed). They are constructed of solid state electronic components making them useful for variable speed motor drives since they are reliable and losses are relatively minimal.

The frequency of the applied power to an AC motor determines the motor speed and is based on the following equation:

$$N = (120 f / P)$$

where: N = speed (RPM)
 f = frequency (Hz)
 P = number of poles

With the unit conversion factor of 120 being fixed, along with the number of poles of a given motor, it is apparent that the motor speed will vary proportionately with the frequency of the AC current supply. The AC variable frequency drive controls the frequency (f) and voltage applied to the motor. The speed (N) of the motor is then proportional to this applied frequency. With a variable frequency drive this is simply accomplished through adjustment of a control potentiometer, or an automatic adjustment from a process controller by changing the value of a 4 - 20 mA or 0 - 10 VDC control signal. To maintain constant motor torque, the drive controller automatically maintains the voltage and frequency output at a constant relationship for any motor speed. This constant is called the "Volts per Hertz" ratio (V/Hz). By maintaining this ratio, an induction motor can be operated over a wide speed range and still deliver the rated torque. This "Volts per Hertz" ratio is maintained throughout the

operating speed range in order to prevent excessive losses and motor heating.

Variable or adjustable frequency drives are also commonly known as "Inverters". They are available in a range of horsepower from fractional to 1,000 HP. Since they are designed to operate standard induction motors they can be easily added to an existing system. There are three major types of variable frequency drive designs available today. These are known as Current Source Inverters (CSI), Variable Voltage Inverters (VVI), and Pulse Width Modulated Inverters (PWM). These different types of variable speed drives will be analyzed later in this chapter.

FAN OPERATION AND ENERGY SAVINGS

The most common fan is the centrifugal fan which imparts energy in to the air by centrifugal force. This results in an increase in pressure which produces air flow at the outlet of the fan. These types of fans are used in a wide variety of applications in commercial and industrial systems.

System curves and fan curves are used in the design of air distribution systems. The system curve shows the requirements of the air system that the fan is used on. It shows how much pressure is required from the fan to overcome system losses and produce the desired air flow. The fan curve is a plot of fan capability independent of the system. The intersection of these two curves is the natural operating point of the system. It shows the actual pressure and air flow that will occur at the fan outlet when the system is in operation. Without the introduction of external influences the system will operate at this point only. Many systems however require operation at a

wide variety of points. Figure 1 shows a profile of flow variations experienced in a typical air distribution system. Several methods have been used in the past to vary the flow (CFM) of an air distribution system to achieve the optimum operating points. These include the use of outlet dampers, variable inlet vanes, and variable frequency drives. Each of these three methods of control affect either the system curve or the fan curve in order to produce a different natural operating point. In doing so, they also may change the fan's efficiency and the horsepower requirements.

Figure 1 - Typical Fan Operation

Outlet Dampers. These are control louvers or dampers that are installed at the outlet of a fan. In order to control air flow, they are turned to restrict the outlet which reduces the air flow. The outlet dampers affect the system curve by increasing the resistance to air flow. Figure 2 shows different system curves indicating different outlet damper positions, while Figure 3 shows horsepower requirements for this type of operation.

Figure 2
Outlet Damper-System Curves

Figure 3
Outlet Damper-HP requirements

Figure 3 indicates that the horsepower decreases gradually as the flow is decreased.

Variable Inlet Vanes. They modify the physical characteristics of the air inlet, so as to modify the fan operating curve which changes the air flow. This method modifies the fan curve so that it intersects the system curve at a different point. Figure 4 is a representation of the changes in the fan curve for different inlet vane settings.

Figure 4
Variable Inlet Vane Settings

Figure 5
Variable Inlet Vane -
HP Requirements

Figure 5, in the previous page, shows that the horsepower required by this method drops to an even greater extent in comparison to the outlet damper method.

Variable Frequency Drives. They change the actual fan RPM which changes the performance of the fan producing a different airflow. This method takes advantage of the change in the fan curve that occurs when the speed of the fan is changed. These changes are presented in the following set of formulas known as the affinity laws.

$$\begin{aligned}Q_2/Q_1 &= N_2/N_1 \\P_2/P_1 &= (N_2/N_1)^2 \\HP_2/HP_1 &= (N_2/N_1)^3\end{aligned}$$

where: N = Fan Speed (RPM)
 Q = Flow (CFM)
 P = Pressure (Static Inches of Water)
 HP = Horsepower

The above formulas indicate that capacity (CFM) is directly proportional to speed (RPM), and horsepower is proportional to the cube of the speed as well as to the cube of the capacity. When the flow and pressure laws are combined the result is a formula that matches the system curve formula.

$$P = K \times (CFM)^2 \quad \text{System Curve Formula}$$

where: P = Pressure
 K = system constant

therefore: $P_2 = P_1 \times (N_2/N_1)^2$

$$Q_2/Q_1 = N_2/N_1, \quad (Q_2/Q_1)^2 = (N_2/N_1)^2$$

substituting $(Q_2/Q_1)^2$ in the above equation for $(N_2/N_1)^2$ results in:

$$P_2 = P_1 \times (Q_2/Q_1)^2 \quad \text{or}$$

$$P_2 = [(P_1/Q_1)^2] \times (Q_2)^2$$

The quantity $P_1/(Q_1)^2$ coincides with the system constant, K. This indicates that the fan will follow the system curve when its speed is changed. Figure 6 below represents the variable speed method, while Figure 7 shows the significant reduction in HP achieved by variable speed control.

Figure 6
Variable Speed Method

Figure 7
Variable Speed - HP requirements

Utilizing the variable speed method allows the fan to produce the desired results with the minimum of input horsepower. The

outlet dampers and variable inlet vanes modify some system parameter which generally results in fan efficiency reduction, which in turn requires greater horsepower than the variable speed method.

Energy Savings. The energy savings potential when comparing constant speed operation to variable speed operation is impressive. Energy savings are directly related to horsepower reduction. Referring to Figure 1, typical fan operation, it is not difficult to realize that variable system loads allow for variable speed operation. The percentage of design airflow (CFM) is concentrated for the most part in the 40 percent to 80 percent range. The time of operation in the 80 percent to 100 percent range is minimal. Therefore savings can be realized when variable speed control is applied. In the earlier analysis of fan operation it is mentioned that capacity (CFM) is directly proportional to speed (RPM), while horsepower (HP) is proportional to the cube of the speed (RPM).

A typical 100 HP fan motor is analyzed below in order to evaluate the energy savings. Three motor speeds will be considered; 100% as the original design speed, 80% and 60% as the speeds controlled by a variable frequency drive.

1. Constant Speed:	$100 \text{ HP} \times (100\%) =$
	$100 \text{ HP} \times (1.0)^3 = 100 \text{ HP}$

2. VFD Control (80%)	$100 \text{ HP} \times (80\%)^3 =$
	$100 \text{ HP} \times (0.8)^3 = 51.2 \text{ HP}$

$$100 \text{ HP} - 51.2 \text{ HP} = 48.8 \text{ HP saved}$$

$$\begin{aligned}
 3. \text{ VFD Control (60\%)} \quad & 100 \text{ HP} \times (60\%)^3 = \\
 & 100 \text{ HP} \times (0.6)^3 = 21.6 \text{ HP}
 \end{aligned}$$

$$100 \text{ HP} - 21.6 \text{ HP} = 78.4 \text{ HP saved}$$

As this typical example indicates great horsepower reduction can be achieved through the use of VFD's. To determine the KWH's saved in a month, multiply the horsepower saved by 0.746 KW/HP and then by the number of operational hours per month at that speed. This figure can then be multiplied by the cost of electricity to determine the energy dollars saved.

A simple formula is listed below:

$$\text{HP saved} \times 0.746 \text{ KW/HP} \times \text{Hrs/mo.} \times \$/\text{KWH} = \$/\text{month}$$

This example is a basic representation of energy savings taking into account only the operation of the fan motor. In reality the motor efficiency and the drive efficiency should also be taken into account. These efficiencies are application specific and could vary depending on the operational parameters. A more detailed energy analysis can be performed by any VFD manufacturer in order to obtain the correct energy savings, once a specific application has been identified.

PUMP OPERATION AND ENERGY SAVINGS

Pumps are typically grouped into two basic categories; positive displacement pumps and dynamic (centrifugal) pumps. Positive displacement pumps use mechanical means to vary the size of the fluid chamber in order to cause fluid to flow. Dynamic pumps impart a momentum into the fluid by rotating impellers immersed in the fluid. The momentum produces an increase in pressure or flow at the pump outlet. The majority of pumps used today are of the dynamic or centrifugal type. For this reason only the centrifugal pumps will be considered for analysis in this guide.

In order to gain good understanding in pump operations one must be familiar with certain terms. Therefore, in addition to terms defined earlier in this chapter, more definitions are presented below:

Head. A measurement of pressure, usually in feet of water. A 10 FT head is the pressure equivalent to the pressure found at the base of a column of water 10 feet high (at standard temperature and pressure).

Static Head. The pressure required to overcome an elevation change in the system.

Dynamic Head (Friction Head). Pressure losses within the pipe or pipe system due to flow. The dynamic head of a system usually increases proportionally to the square of the flow rate, Q.

$$\text{HEAD} = K \times (Q)^2$$

System Head. The curve of the head required to satisfy both the static head and the dynamic head for a range of flows on a given system.

Pump Head. The pressure the pump produces at its outlet. Centrifugal pump heads can vary depending on the flow through the pump with the impeller speed also being a factor.

Pump Curve. A characteristic curve of a pump showing the head-flow relationship of the pump.

Net Positive Suction Head. This is a characteristic requirement of a pump in order to maintain optimum operation. It is a requirement for external pressure at the inlet of the pump. If the inlet pressure is less than the net positive suction head, the fluid inside the pump can transform into a vapor and cause "cavitation". This is an undesirable effect which can cause great damage.

Water Horsepower. The energy output of the pump derived directly from the outlet parameters.

$$\text{WATER HP} = \text{FLOW} \times \text{HEAD} / 3960 \quad (\text{For water of 1.0 spec. gravity})$$

Brake Horsepower. The horsepower required to operate the pump at a specific point.

$$\text{BRAKE HP} = \text{WATER HP} / \text{PUMP EFFICIENCY}$$

A set of formulas, also presented in the fan operation section of this chapter, known as affinity laws can be used to predict the operation of a centrifugal pump. These laws are listed on the next page.

$$Q_2/Q_1 = N_2/N_1$$

$$P_2/P_1 = (N_2/N_1)^2$$

$$HP_2/HP_1 = (N_2/N_1)^3$$

where: N = Pump Speed
 Q = Flow (CFM)
 P = Pressure (Feet of Head)
 HP = Horsepower

Flow Control. In pump system operations two distinctive curves are used to define the operating point. They are the pump curve and the system curve. The point of where these two curves intersect is called the natural operating point. That is where the pump pressure matches the system losses and everything is balanced.

Figure 8, below, shows a typical set of pump and system curves as well as the natural operating point.

Figure 8
 Pump and System Curves

In order to maintain a stable system operation, system balance should only occur at one point. If this point does not occur but at least comes close to the desired point of operation, then the system is considered acceptable. However, if this point does not come close enough, certain modifications must take place. Either the pump or the system's physical configuration has to be modified in order to achieve the desired operating point.

If the system is part of a process that changes often or continuously, then some method of continuously altering the pump characteristic or the system parameters is needed. Two general methods have been widely used to accomplish continuously varying flow objectives. One method is throttling which changes the system curve by the use of a control or a throttling valve. The other method is variable speed control of the pump which modifies the pump curve.

Throttling System. Figure 9, shown on the next page, is an example of a typical throttling system. Two different conditions of the system curve are shown. One is shown with the valve open, and the other is shown with the valve throttled or partially closed. It can clearly be seen in Figure 9, that when the flow in the system is decreased the pump head increases.

Figure 9 - Throttling System Conditions

Variable Speed Operation. The variable speed method takes advantage of the change in the pump characteristics that occur when the pump impeller speed is changed. The new pump characteristics can be predicted from the affinity laws stated earlier. With the variable speed method the pump head decreases as the flow decreases. Figure 10, on the next page, shows a typical system operated by a variable speed pump.

Figure 10 - Variable Speed Pump Control

Energy Savings. To show the actual difference between 100 percent speed, throttling, and variable speed control, a typical example is given below:

Parameter: A pump, 25 HP, is to operate a system requiring 63 FT head at a flow rate of 1200 GPM. This example does not account for static head. Flow rates of 100%, 80%, 60%, and 40% are required at various times.

1. 100% Speed:

GPM	1200
% FLOW	100
BRAKE HP	25

2. Throttling Operation:

GPM	1200	960	720	480
% FLOW	100	80	60	40
BRAKE HP	25	23	21	19

3. Variable Speed Operation:

GPM	1200	960	720	480
% FLOW	100	80	60	40
% SPEED	100	80	60	40
BRAKE HP	25	12.8	5.4	1.6

The above figures were obtained using the given parameter and the pump curve. It is clearly evident that the variable speed operation achieves the greatest reduction in HP requirements. Figure 11, below, is a comparison of the horsepower requirements versus the percentage of flow for the throttling as well as the variable speed methods.

Figure 11
Horsepower Requirements vs. % of Flow

The difference in the above curves, at any point, indicate the possible energy savings by operating by the variable speed method instead of the throttling method. In actual practice, the efficiency of the motor and the drive must be taken into

account in order to obtain more accurate savings. The actual energy savings will also depend on the amount of time that the motor operates at each reduced speed point. Operating at the 60 percent load point for the majority of the time will result in greater savings than operating at the 80 percent load point the majority of the time.

Energy Savings with Static Head. The example presented previously did not incorporate any static head. A system with static head changes the system curve and the horsepower requirements. The affinity laws can not directly derive the answer for the operating points for a variable speed system with static head. It is still possible to calculate the horsepower curve, but precise knowledge of the pump curve and the system curve is required. Then a detailed analysis with the aid of an appropriate computer program is advisable.

To illustrate the changes that can take place when static head is present Figure 12, below, shows the horsepower requirements for three different static head percentages.

Figure 12
System Horsepower Requirements

Note in Figure 12 that the dynamic operation of the throttling system does not change with static head. The static head actually performs part of the work of the throttling valve. However, the horsepower requirement for this method remains above that of the variable speed method.

New design considerations. Variable Frequency Drives have gained wide acceptance in the heating, ventilating and air conditioning industry. They are incorporated into designs in order to reduce energy consumption and costs. While there is no doubt that variable speed drives save energy, a life cycle cost analysis is recommended for new projects. Different alternatives should be studied for each application. For water pumping, a single speed pump, multiple pumps and variable speed pumps should be analyzed to determine the system with the lowest economic cost.

In order to determine the most cost effective system for a particular application, it is necessary to analyze operating costs in detail. As the demand on a pump decreases it follows the curve to deliver the lower flow rate. If, as is normally the case, the pumps are selected for highest efficiency at design flow, there will be a reduction in pump efficiency as the demand decreases. In addition, as the load on a motor decreases (below 85 percent full load at which point a typical motor is most efficient) the motor efficiency decreases. The ratio of WATTS/GPM flow increases as the flow through the pump decreases. This exact fact is the reasoning for multiple pump systems. By turning certain pumps OFF, it is possible to maintain a relatively low WATTS/GPM ratio and a low operating cost.

To illustrate this theory, a typical pumping system with design conditions of 250 GPM at 50 feet of head is presented in Table 1. The pumping systems considered are a constant speed 5 HP pump, a combination of two 3 HP pumps, and a variable speed 5 HP pump.

The demand profile for this project is considered to be 10 percent of the time at the design load of 250 GPM, 30 percent of the time at 175 GPM, 30 percent at 125 GPM and 30 percent of the time at 50 GPM. Table 1 below will compare the consumption of each system at the various operating points.

TABLE 1

PUMP COMPARISON : 2 @ 3-HP vs. 1 @ 5-HP C.S. vs. 1 @ 5-HP V.S.

% Time	Demand GPM	KW Input			KWH/Year		
		2-3HP/5HP/5HP			2-3HP/5HP/5HP		
		C.S. V.S.			C.S. V.S.		
----	-----	-----			-----		
10	250	4.1	4.0	5.5	3606	3475	4861
30	175	2.2	3.2	2.4	5666	8334	6291
30	125	2.1	2.6	0.7	5408	6839	1799
30	50	1.4	1.8	0.9	3690	4841	2325

Total Consumption (KWH/Yr):

1. 2 @ 3-HP Pumps	18370
2. 5-HP Constant Speed	23493
3. 5-HP Variable Speed	15276

The above table is presented in a simplified manner to illustrate various points of operation for three different pumping systems. Even though not shown, typical pump, motor and variable speed drive efficiencies were taken into account.

In final analysis, at 250 GPM demand the 5-HP constant speed pump indicates as having the lowest consumption. At 175 GPM the two-pump system shows the lowest consumption, and the 5-HP variable speed pump indicates minimum consumption at 125 GPM and 50 GPM. When the annual consumption figures are analyzed the 5-HP variable speed pump has the lowest consumption figures for a typical range of operation.

Using the numbers presented in Table 1, one can easily calculate the annual operating expenses by multiplying the annual KWH consumption by the local energy costs. These numbers, however, should not be the lone determining factor in designing a pumping system. Initial costs as well as maintenance costs should be considered in making such a decision. The actual load profile for a particular project will strongly influence the decision. Each proposed system should be analyzed in detail. Small systems will probably be better served by a single pump installation, while large systems will require a variable speed arrangement.

TYPES OF VARIABLE FREQUENCY DRIVES

Variable Frequency Drives, known by their acronym as VFD's, are also referred to as "Variable Speed Drives" or "Inverters". They are designed to operate standard induction motors. This fact allows them to be easily added to an existing system. The basic drive consists of the inverter itself which converts the 60 Hz incoming AC power to a variable frequency and variable voltage. The variable

frequency is the actual requirement needed to control the speed of the motor.

There are three major types of inverter designs available in the market today. These are known as Current Source Inverters (CSI), Variable Voltage Inverters (VVI), and Pulse Width Modulated Inverters (PWM). These different types will be further explained below along with their positive and negative characteristics.

CSI Inverters. The Current Source Inverter controls the current output to the motor. The actual speed of the motor is sensed by the use of other circuits. This is then compared to the reference speed and an error is used to generate a demand for more or less current to the motor. The output switching devices, usually SCR's, are switched at the desired frequency to "steer" the current to the motor. Current source inverters are available in a wide range of horsepower capacities, but most often are found in the range of 50 HP and above.

Some of the features of CSI inverters include the use of standard induction motors, efficiencies of 90 percent at full speed, direct by-pass in case of inverter failure, overload prevention due to acceleration of high inertia loads, and fault current limiting. The disadvantages of these inverters include the possible need of tachometer feedback for speed regulation, the possibility of running at full speed if the tachometer feedback signal is lost, matched electrical characteristics for motor and inverter, maintenance difficulties since the inverter can not be run or tested without the motor, low power factor at low speeds, larger overall inverter sizes, and need for large power devices to handle power delivered to the system.

VVI Inverters. Variable Voltage Inverters control the voltage and frequency to the motor to produce variable speed operation. The distinguishing characteristic between this type of inverter and the PWM inverter, described below, is the scheme used to control the voltage. VVI inverters control the voltage in a separate section than the output section used for frequency generation. Usually the voltage control is done using a phase controlled input bridge rectifier circuit which switches the variable voltage to the motor at the desired frequency. These drives are available from fractional horsepower to about 500 HP.

Features of VVI inverters include the use of standard induction motors, efficiencies of 90 percent at full speed, by-pass in case of inverter failure, overload prevention due to acceleration of high inertia loads, ease of installation without the need for tachometer feedback, ease of maintenance and testing, and multi-motor operation from single inverter as long as inverter rated current is not exceeded. The few disadvantages of these inverters include high initial cost, high power components within the inverter for power conversion, and service complexity due to its large portion of sophisticated circuit design requiring skilled technicians for service.

PWM Inverters. Pulse Width Modulated Inverters accomplish both frequency and voltage control at the output section of the drive. The output voltage is always a constant amplitude and by chopping, or pulse width modulation, the average voltage is controlled. These drives are available from 1 to 1,000 HP.

Features of these drives include the use of standard induction motors, efficiencies of 90 percent at full speed, good power factor throughout the full operating speed range, by-pass in case of inverter failure, overload prevention due to acceleration of high inertia loads, ease of installation

without the need for tachometer feedback, ease of maintenance and testing, and multi-motor operation from single inverter as long as inverter rated current is not exceeded. The disadvantages of these inverters are few but they include high initial cost, high power components within the inverter for power conversion, and service complexity due to its large portion of sophisticated circuit design requiring skilled technicians for service.

CHAPTER 3 - APPLICATIONS

VARIABLE FREQUENCY DRIVE APPLICATIONS IN PHOENIX

During the last decade the City of Phoenix has used Variable Frequency Drives in numerous air handling, water handling, and specialty applications. These VFD's are part of HVAC operations in facilities of various sizes, as well as special water production operations. The following projects have been outlined to demonstrate the versatility of VFD's as energy conservation measures.

CENTRAL AIR HANDLING FANS

This project involved the Municipal Building (City Hall) of the City of Phoenix. This building was constructed with a dual duct, hot and cold system, using constant air volume with variable temperature for cooling and heating. Four supply air fans and two return air fans with a total of 340 HP installed capacity provided the air circulation through the building. Realizing the tremendous energy savings potential, a computerized analysis was performed to indicate the actual volume of supply air needed. The analysis indicated that two of the supply air fans and both the return air fans could be eliminated. In addition, a VFD would be utilized to control the operation of the remaining two air supply fans in operation. The air distribution system was converted from constant volume to variable air volume.

A constant volume of supplied air provided by conventional HVAC systems results in wasting energy, due to the constant amount of energy used by the fan motors irrespective of the cooling or heating load. A variable air volume system controls the temperature of a conditioned space by varying the volume of constant temperature air supplied to that space. A variable air volume system has dual benefits. First, since the temperature of the supply air is held constant, the operational efficiency of the equipment is maximized. Second, since the supply air fans circulate less air, their energy usage is considerably reduced.

Traditional methods of variable air volume, such as damper control and variable inlet vanes, result in minimum energy savings. Using a VFD is the most efficient means of fan capacity control. The speed of the motor is controlled by regulating the frequency of the power supply. By controlling the frequency, the speed of the fan is controlled and, since the speed is proportional to the volume of air supplied, the volume of supply air is also controlled. Reducing the volume of air supplied by the fan reduces the power consumed by the fan. The relationships of speed and power consumption were presented in Chapter 2.

The conversion of constant air volume to the VAV system at the Municipal Building was relatively simple. The constant volume mixing terminal boxes into which both hot and cold high pressure air was introduced were converted to VAV. The interior zones were converted to cooling only, by utilizing a pneumatic damper operator that opened as the demand for cooling was sensed by the zone thermostat. The perimeter zones were converted to heating and cooling by utilizing thermostats and damper motors to both hot and cold dampers. During system operation, as the zones become satisfied the dampers begin to close. This causes a rise in duct static pressure which is sensed by the static pressure sensor located in the fan outlet plenum. This static pressure is amplified by a reverse acting pneumatic transmitter receiver from 15 PSI

at full speed to 2 PSI at minimum speed. The 15 PSI to 2 PSI pressure is then converted to 20 mA to 4 mA DC signal at 24 volts. This current, in turn, controls the phase inverter which changes the 3-phase AC power to DC power. The DC voltage is then chopped to form a varying frequency (Hertz) 3-phase AC power to control the speed of the fan motor by increasing and decreasing the phase time.

In October, 1981, the installation of two VFD's controlling two 60 HP supply air fans was completed. The maximum savings in demand (KW) recorded at any one time were 78 percent. For a 24-hr period the average recorded savings was 70 percent. It was estimated that an overall average of 50 percent savings was possible on a yearly basis. This estimation has held true up to this date. The tables below illustrate the energy consumed by fans prior to and after the VAV system conversion.

TABLE 2

FAN EQUIPMENT DATA (Prior to VAV Conversion)

<u>Equipment</u>	<u>Qty.</u>	<u>HP ea.</u>	<u>Hrs/Day</u>	<u>Days/Year</u>	<u>Kwh/Yr</u>
Supply Air Fans	4	60	11	260	686,400
Supply Air Fans	2	60	13	260	405,600
Supply Air Fans	2	60	24	104	299,520
Supply Air Fans	2	50	24	365	876,000
TOTAL					2,267,520

Assume 1 HP needs 1 KW input.

The elimination of two supply air fans and two return air fans resulted in tremendous savings. This was determined through the use of a computerized analysis. Additional savings of 50 percent of the energy consumed by the remaining two fans was possible with the installation of the Variable Frequency Drive. The savings calculations due to VFD control, utilizing a yearly average of 50 percent savings, are listed below:

$$\begin{aligned}
 &2 \text{ (no. of fans)} \times 0.50 \times 60 \text{ KW (ea.)} \times \\
 &365 \text{ days/yr} \times 24 \text{ hrs/day} = 525,600 \text{ Kwh/year}
 \end{aligned}$$

Net savings of 1,741,920 Kwh were achieved during the first year. At the then rate of electricity of \$0.066 per Kwh, these energy savings resulted in a cost avoidance of \$ 114,967 for that year.

Total cost of project : \$90,000

$$\begin{aligned}
 \text{Simple payback} &= [\$90,000 / (\$114,967/\text{yr})] = 0.783 \text{ years} \\
 &= 9.4 \text{ months}
 \end{aligned}$$

TABLE 3

ECONOMIC ANALYSIS OF VAV RETROFIT

Annual Energy Consumption of fans (1,000 Kwh)		Savings (1,000) Kwh	Cost \$/Kwh	Pay- Back (mos)	Cost Avoidance \$
Before	After				
2,268	526	1,472	0.066	9.4	114,967

This project represents the application of Variable Frequency Drive in conjunction with Variable Air Volume conversion in central air distribution systems. A more in-depth analysis of the project can be found in the Urban Consortium Energy Task Force publication "Variable Air Volume System - A Management Report", of February 1982.

A recent energy study, at the Municipal Building, has revealed additional energy savings potential by slightly modifying the control scheme of the existing supply air fans. Of the four original supply air fans, two were turned off while the other two were put on VFD control as part of the Variable Air Volume system. The new control scheme will have all four supply air fans on VFD control. The energy savings are presented below:

- i) Two supply air fans on VFD control operating at 80% speed.

$$2 \times 60 \text{ HP} \times (0.8)^3 = 61.44 \text{ HP}$$

- ii) Four supply air fans on VFD control operating at 40% speed.

$$4 \times 60 \text{ HP} \times (0.4)^3 = 15.36 \text{ HP}$$

Assuming 1 HP needs 1 KW of power, constant operation throughout the year, and existing utility costs of \$0.075/KWH, the potential energy savings and cost avoidance are as follows:

$$61.44 \text{ HP} - 15.36 \text{ HP} = 46.08 \text{ HP saved}$$

$$46.08 \text{ HP} \times 1\text{KW}/1\text{HP} \times 8,760 \text{ Hrs/Yr} = 403,661 \text{ KWH/Yr}$$

$$403,661 \text{ KWH/Yr} \times \$0.075/\text{KWH} = \$ 30,275/\text{Yr}$$

The benefits of this control scheme will be immediately realized, as the City of Phoenix is preparing to implement this new VFD project.

COOLING TOWER FANS

A cooling tower is designed to remove heat from the incoming water at a specific rate (BTU/hr). It delivers a specified flow of water at a temperature that should not exceed the design temperature. Because the cooling of the water is due to evaporation, the wet bulb temperature of the ambient air is important. Cooling towers are designed to provide water no higher than the specified temperature at the highest wet bulb conditions the cooling tower could ever experience. When the actual wet bulb temperature is lower than the design wet bulb, an energy savings potential exists. Daily as well as seasonal changes in the ambient wet bulb temperature allow the fan speed to be modulated. This reduces energy consumption by the fan's motor. The magnitude of the savings potential depends upon the range of wet bulb temperatures actually encountered. A Variable Frequency Drive will operate the fan at the slowest speed which will maintain the design output temperature. This is a predetermined temperature setting which according to system requirements and configuration can be set between 70 F and 85 F. A temperature to electrical transducer, located at the cooling tower outlet, supplies the VFD with a 4 to 20 mA signal which varies with water temperature. This signal is sent to a set point controller. The set point controller is set for the desired output water temperature. The signal from the set point controller sets the speed of the VFD.

The set point controller can be either a proportional control or a proportional integral derivative (PID) control. A proportional controller requires that a dead-band, typically 10 F, be established to avoid excessive speed fluctuation. A PID controller provides more precise control of the cooling tower outlet water temperature and maximizes the energy savings.

The City of Phoenix has installed VFD's on numerous tower fan motors. The most recent installation took place at the Police Training Academy. This facility was also retrofitted with a smaller, more efficient, chiller and thermal energy storage. The original aging and inefficient 120 ton chiller was replaced with a high efficiency 60 ton chiller. The existing 150 ton cooling tower was retained. The 20 HP tower fan motor was controlled by a temperature sensor which allowed the fan motor to cycle ON and OFF in order to maintain a preset 80 F condenser water temperature. In the operating mode the fan would run at 100 percent speed until the condenser temperature would be satisfied. With the knowledge that the power requirement of a cooling tower fan varies according to the cube of its speed, a VFD was installed. This method allowed the cooling tower fan to operate at whatever speed was necessary to meet the cooling demand. Monitoring the tower fan speeds revealed that the motor operated at only 35 to 70 percent of full speed. The savings associated with such reduced speeds are substantial. They even exceed any savings that could be realized through the use of typical two speed motors.

A typical question usually arises that deals with the intermittent operation at full speed versus the continuous operation at reduced speed of the tower fan motor:

"Since the same amount of heat is rejected into the atmosphere in any one hour interval, whether operating one half hour at full speed or one full hour at half speed, how does energy consumption differ between the two cases".

Utilizing the affinity laws established in Chapter 2, a typical example is given in the page that follows.

Case I:

Intermittent operation, at 100 percent speed, of a typical 10 HP tower fan motor operating a total of 30 minutes per hour. Assume 1 HP requires 1 KW input.

$$10 \text{ HP} \times 1\text{KW/HP} \times (1.0)^3 \times 0.5 \text{ Hour} = 5 \text{ KWH}$$

Case II:

Continuous operation, at 50 percent speed, of a typical 10 HP tower fan motor operating a total of 60 minutes per hour. Assume 1 HP requires 1 KW input.

$$10 \text{ HP} \times 1\text{KW/HP} \times (0.5)^3 \times 1.0 \text{ Hour} = 1.25 \text{ KWH}$$

This example illustrates that even though the motor operates for the full hour to reject the same amount of heat, the total energy consumed at half speed is reduced by 75 percent. The reduction in energy consumption at the Police Training Academy along with the energy cost avoidance is calculated below:

$$20 \text{ HP} \times 1\text{KW/HP} \times 2,000 \text{ Hrs/Yr} \times [1^3 - (0.6)^3] = 31,360 \text{ KWH/Yr}$$

$$31,360 \text{ KWH/yr} \times \$0.0724/\text{KWH} = \$ 2,271/\text{Yr}$$

With an installation cost of \$ 5,145, the anticipated payback period is 2.27 years.

EVAPORATIVE COOLERS

Evaporative cooling, using high efficiency media, has proven to be energy-efficient, environmentally safe, and cost effective in a number of cooling applications. The drier southwestern climate is a natural candidate for evaporative cooling. Evaporative cooling reduces the dry-bulb temperature of the air stream to provide a better environment for human occupancy. The City of Phoenix maintains a number of facilities that utilize evaporative cooling. They include maintenance centers, warehouses, and central store facilities.

The most commonly used method is direct evaporative cooling. In a hot environment, where ambient heat control is difficult or uneconomical, cooling is performed by passing below-skin-temperature air over the human body. The performance of evaporative cooling is directly related to climatic conditions. The entering wet-bulb temperature dictates the final dry-bulb temperature of the air discharged from the direct evaporative cooler. The capacity of the direct evaporative cooler is determined by how much the dry-bulb temperature exceeds the wet-bulb temperature. The direct evaporative cooling process is an adiabatic exchange of heat. In order for water to evaporate, heat must be added. This heat is supplied by the air into which water is evaporated. The dry-bulb temperature is lowered, and sensible cooling results. The amount of heat removed from the air equals the amount of heat absorbed by the water evaporated as heat of vaporization.

Based on design parameters, evaporative cooling motors are sized to handle maximum air velocities for extreme conditions. Since weather conditions fluctuate seasonally as well as daily, air velocities can be regulated based on certain comfort zone, dry-bulb, criteria. Variable Frequency

Drives can be used to regulate the speed of the evaporative cooling motor and achieve considerable energy savings. Large warehouse facilities use multiple evaporative coolers for comfort conditioning. It is advantageous to use a single VFD to control either all or a section of the evaporative cooler motors. This requires that the connected load be on the same circuit, and that the VFD is properly sized so that it can handle the total connected load.

A Variable Frequency Drive project has recently been completed at the Central Stores facility. Twenty evaporative coolers which had been operating at full speed to achieve comfort conditioning, are now controlled by VFD's. Fan speeds are maintained only fast enough to achieve comfort conditions as before, at the occupied level. The only difference now is that the evaporative cooler motors will operate at reduced speeds during mornings, and spring and fall periods with considerable energy savings.

Each evaporative cooler motor has a rating of 2 HP. The total controlled capacity of the twenty evaporative coolers is 40 HP. A total of three VFD's were used to control the twenty evaporative coolers. Three separate sections were established with seven, seven and six evaporative coolers each. Each VFD controls one section of evaporative coolers. The sizes of VFD's used are 15 HP, 15 HP, and 10 HP. Speed control is regulated from the VFD based on dry-bulb temperature. A temperature sensor is strategically located to reflect the average temperature of the surrounding environment. A temperature input is received by the VFD in the form of a 4-20 mA signal. This signal is analyzed by the controller and based on the desired temperature which is preset, the speed of the motor is controlled by the VFD. Monitoring of the speeds with VFD control indicates that comfort conditions can be met with speeds ranging between 40 percent and 75 percent.

CHILLED WATER PUMPS

Chilled water systems are used through out the City of Phoenix to provide comfort cooling through the transfer of heat by water flow. Standard engineering practice has been to size pumps, water lines and associated hardware for maximum capacity loads. The average heating, ventilating, and air conditioning (HVAC) system is generally at full capacity less than three percent, and at a minimum capacity less than five percent of the time. The systems usually operate between 50 and 60 percent of their rated capacity approximately 50 percent of the time. During the time of less than maximum cooling load, a portion of the design water flow is by-passing the cooling coils through modulating three-way by-pass valves. The pumping capacity, however, remains constant at the maximum level, which results in higher energy consumption than is required. A potential solution exists with the installation of a VFD for the pump motor. Because of the "affinity laws" governing pump performance, the rate of pumping varies directly as the speed of the pump while the power used for pumping varies as the cube of the speed. Thus, as cooling energy requirements fall below maximum, pumping speed can be reduced with substantial electrical energy savings.

A Variable Frequency Drive was installed to control the chilled water pump at the Police Training Academy. Installation of the VFD was very simple. Only electrical alterations were needed to put the VFD in the electrical supply to the pump, and install signal control from the control element. Pump and piping remained unchanged. Four control strategies were examined so that the operation mode of least energy use would be found. Figure 13, on page 43, shows a typical chilled water system. The four strategies analyzed follow the chilled water system schematic.

The estimated energy savings based on annual operation of 1,500 hours is calculated below:

$40 \text{ HP} \times 1 \text{ KW/HP} \times 1,500 \text{ Hrs/Yr} \times [1^3 - (0.6)^3] = 47,040 \text{ KWH/Yr}$
(Assuming 1 HP requires 1 KW input.)

Cost avoidance based on existing energy costs of \$0.108/KWH.

$47,040 \text{ KWH/yr} \times \$0.108/\text{KWH} = \$ 5,080/\text{yr}.$

With a total installed cost of \$ 10,000, the anticipated payback period is just below two years.

As noted previously, when controlling evaporative cooler motors with the same VFD the motors must be on the same control circuit. This can present difficulties at times when major electrical redesign must take place to satisfy this condition. For this reason a pre-installation audit must be conducted to reveal the control points of evaporative coolers. When the expense of rewiring controls to allow evap coolers to be controlled by a single VFD is high, payback criteria should always be the determining factor. When the payback is considered lengthy, alternate locations should be examined.

Figure 13
Typical Chilled Water System

- i) Chilled water pump operating without the use of the VFD. To allow free circulation of the chilled water without obstruction, by-pass valves at the air handling units were left open. This, being the original control mode, was used as a standard for comparison.
- ii) VFD control of the chilled water pump, and 10 F differential temperature across the chiller. Control performed through pneumatic temperature transmitters located at the inlet and outlet of the chiller. Through the use of pressure transducers, electrical signal is

sent to the VFD for control of speed based on temperature difference across the chiller. As the temperature difference increases, the electrical signal increases, causing the pump to speed up. Smaller temperature differences will cause the pump to slow down. In this manner, the speed of the pump was automatically regulated to provide flows that would maintain the temperature difference. In this control mode, by-pass valves at air handling units were open.

- iii) VFD control of the chilled water pump, by-pass valves closed. Speed control was regulated by system pressure. With the by-pass valve closed, the automatic valves operate as two-way valves controlled by room thermostats. As the thermostats become satisfied, they will close the two-way valves causing the system pressure to increase. Pneumatic pressure transducers sense the rise and fall of the system pressure, send a signal to the VFD which in turn regulates the speed of the pump.
- iv) VFD control of the chilled water pump, by-pass valves closed, VFD control set for 10 F temperature difference across the chiller. As more cooling was needed for any particular zone, more chilled water was needed at the air handling unit and the automatic two-way control valve would open to allow more chilled water circulation. The pneumatic controls operated to vary pump speed and output similar to the 10 F temperature difference control mode (strategy ii).

The following table illustrates the results of this project. The consumption figures indicate average calculated power.

TABLE 4

CHILLED WATER PUMP POWER CONSUMPTION

<u>Control Strategy</u>	<u>Power Consumption, KWH/HR</u>
i) Without VFD	13.16
ii) Temperature Difference By-pass Valves Open	1.37
iii) Pressure Difference By-pass Valves Closed	1.40
iv) Temperature Difference By-pass Valves Closed	1.33

The table above indicates that operation with a VFD can substantially reduce the energy required by the chilled water pump.

Savings = $13.16 - 1.33 = 11.83$ KWH/Hr, or 90% of the use prior to retrofit.

With operating hours of 1,716 per year the energy savings, and cost avoidance were:

$$11.83 \text{ KWH/Hr} \times 1,716 \text{ Hr/Yr} = 20,300 \text{ KWH/Yr}$$

$$20,300 \text{ KWH/YR} \times \$ 0.075/\text{KWH} = \$ 1,523/\text{Yr}$$

The original chilled water pump was rated at 20 HP. Based on the results of the study, it was determined that the existing pump was grossly oversized. A smaller capacity pump could circulate enough water in the existing system to satisfy the needs under any condition. A more detailed analysis revealed that a 2 HP pump would be adequate.

This VFD project had such an impact that the 20 HP pump was replaced with a 2 HP pump. The original 20 HP pump and the VFD were installed at other locations. The 2 HP pump has been operating without any problems for the past two years. For a more in-depth study of this project refer to the Urban Consortium Energy Task Force publication "Capacity Optimization of Hydronic Flows", of January 1985.

FLOCCULATION DRIVES

The City of Phoenix as any other municipality has several Water Treatment Plants. At these plants water is chemically treated before it is allowed to reach the public. One of the essential processes that take place in these plants is called flocculation. The purpose of the flocculation process is to stir the water slowly to cause the solids formed from the addition of chemicals to grow in size so that they can be removed by gravity settling. Flocculation (particle contact) is usually accomplished by mechanically driven paddles. Increased particle contact promotes floc growth. However, if the agitation is too vigorous, the shear forces that are set up will break up the floc into smaller particles. Agitation needs to be carefully controlled so that the floc particles

will be of suitable size and will settle easily. The speed of the paddles has to be determined by the operator so that sufficient turbulence can be achieved without breaking up the floc. Viscosity of the treated water, and volume in the basin will determine the speed of the paddles. The speed, which is adjusted by the operator, can fluctuate depending on the above mentioned conditions.

The City of Phoenix, in March of 1990, added eight VFD's to sixteen individual 5 HP motors controlling the flocculation agitators at the Deer Valley Water Treatment Plant. The existing system utilized a gear box drive which was manually operated. The energy savings using the gear box drive were minimal, due to losses within the gear box assembly. Variable Frequency Drive control proved to be more energy efficient while eliminating maintenance problems of the gear box drives. The speed of the motors is manually controlled by the operator, by adjusting the manual speed control knob on the VFD. Speeds are normally set at 100%, 75%, or 50%. The associated energy savings and cost avoidance figures are listed below:

Power consumption with gear box drive:

$$(3.774 \text{ KW} \times 8,760 \text{ Hrs/Yr}) \times 16 = 528,964 \text{ KWH/Yr}$$

Power consumption with VFD control:

$$(2.223 \text{ KW} \times 8,760 \text{ Hrs/Yr}) \times 16 = 311,576 \text{ KWH/Yr}$$

Energy savings (with a 90% usage factor):

$$(528,964 - 311,576) \text{ KWH/Yr} \times 0.90 = 195,650 \text{ KWH/Yr}$$

With an energy cost of \$0.062/KWH the estimated cost avoidance is:

$$195,650 \text{ KWH/Yr} \times \$0.062/\text{KWH} = \$12,130/\text{Yr}$$

Project cost: \$56,480

Simple payback = [\$56,480 / (\$12,130/Yr)] = 4.66 years

Similar projects were undertaken by the City of Phoenix as early as 1984. The flocculation drives at Val Vista and Squaw Peak Water Treatment Plants were converted to VFD control in 1984 and 1985 respectively.

CHAPTER 4 - PURCHASING SPECIFICATIONS

CAPACITY CONSIDERATIONS

Variable Frequency Drive projects have proven to be excellent energy conservation measures. They address any system oversizing situation while constantly adjusting to system demands. Generally, VFD's are excellent in retrofit applications and new system designs as well. A limitation, however, exists as to the minimum size of motor HP that a VFD can be economically considered for. Motor sizes of 10 HP and above make the best candidates for VFD applications. While VFD's have been installed on motors of 7.5 HP and 5 HP with considerable savings, system parameters and operating hours usually govern the payback criteria. Having a fixed project cost, the longer the annual operating hours the shorter the payback.

TECHNICAL SPECIFICATIONS

The specifications that follow have been used in the past, by the City of Phoenix, in bidding format when purchasing Variable Frequency Drives. They are listed in this chapter in order to assist other jurisdictions in preparing similar specification criteria for purchasing VFD's. It is pointed out, however, that these specifications should not be used as the single determining factor in purchasing and awarding contracts. Contractors or suppliers should be able to

demonstrate that they have been conducting business for a minimum number of years determined by each jurisdiction, and that they furnish a number of VFD installations for review by the jurisdiction. This is recommended procedure in order to insure that reputable contractors are involved with the VFD projects, and that they will be available in the future for maintenance and service if required. The specifications that follow are the latest revision, and they have been used by the City of Phoenix when purchasing Variable Frequency Drives.

1. General

The manufacturer and/or supplier is cautioned to review the requirements of these specifications as presented in the following paragraphs. Some components may require modification from the manufacturer's standard or optional equipment to be supplied to meet the special requirements of the City of Phoenix. The supplier shall furnish the complete Variable Frequency Drive (VFD) in one enclosure with all internal electrical connections completed, ready for installation. The VFD shall be designed so that the only field installation work required will be connection from a source of power, connection of variable frequency output power to an existing motor, and connection of speed control. The VFD may be of any type as long as it conforms to all the specifications and requirements contained herein.

Equipment shall be designed and manufactured in accordance with applicable NEMA recommendations and be designed for installation in accordance with the National Electrical Code (NEC).

Bidders will be required to include with their bid a brochure of each model of VFD being offered showing the

model number, the standard features of the unit, the optional features being furnished (High-lighted in such a manner that reviewer may easily recognize the options), and a direct statement that other specification requirements not shown as a regular feature or option will be furnished. Bidders will also be required to furnish one copy of the manufacturer's standard maintenance manual for each model submitted. Failure to submit the above documentation will be cause for rejection of the bid.

2. Enclosure

The enclosure shall be NEMA 1 or any NEMA rated type. Enclosures other than NEMA 1 shall be modified, if required, to prevent a build-up of heat when operated in ambient temperature conditions up to 105 F. Enclosure shall be suitable for wall mounting for gross VFD weight of 150 pounds or less, and floor mounting for gross VFD weight of greater than 150 pounds. All enclosures shall have provisions for locking. All electrical and electronic components required by the VFD shall be mounted either entirely within the enclosure or mounted in its door.

The following devices shall be mounted on the face of the door of the VFD enclosure. Meters shall be grouped near eye level when the VFD is in mounted position. Size of meters shall be standard for the manufacturer, but in no case smaller than 2 1/2 inches.

- a. Start/Stop switch.
- b. Power "ON" light with green lens.
- c. "FAULT" indicator light with red lens.
- d. Status and fault indicator light-emitting diodes (LED) denoting at least:
 - (1) Charge of capacitors.

- (2) Over current.
- (3) Over voltage.
- (4) Under voltage.
- (5) Over heating.
- (6) Phase loss.
- e. A flush mounted analog ammeter, graduated in amperes, amperage range - 0 to 135% (min) of standard NEC current rating of specified motor.
- f. A flush mounted analog speed indicator, graduated in percent, percentage range - 0 to 100%. Meter shall have compensating adjustment for precise readings.
- g. Manual/Automatic selector switch.
- h. Manual speed potentiometer for operation in manual mode.

3. Open Disconnect Testing

The VFD shall be arranged so that it can be operated in an open circuit mode, disconnected from motor, for installation adjustments and trouble shooting.

4. Power Factor

The VFD shall provide a power factor of 0.95 or above as measured on the input power line, throughout the full range of frequency that the inverter is designed to operate.

5. Efficiency

The VFD shall provide a minimum system efficiency (input power line to output power terminals) of 95 percent throughout the range of frequency that the inverter is designed to operate.

6. Electrical Noise

The VFD shall not produce line noise on the electrical system to the extent that there is interference with

other electronic devices operating on the secondary of the same distribution transformer that serves the VFD. The VFD shall have the ability to operate with any input power noise that might be encountered.

7. Speed Adjustments

There shall be individual speed adjusting potentiometers for setting the maximum and minimum speeds possible under both the manual and automatic modes. Maximum setting shall be adjustable from 60 percent to 100 percent; minimum setting shall be adjustable from 0 percent to 60 percent speed. There shall be adjustment for linear acceleration and deceleration time. The linear acceleration and deceleration shall be adjustable from 5 seconds minimum to 60 seconds maximum.

8. Automatic Speed Control Signal

The input control signal to the VFD will be a variable 4 to 20 mA direct current (DC) at 24 volts. The VFD shall be designed to control the motor speed at the percentage set by the minimum speed potentiometer with a 4 mA signal and the percentage set by the maximum speed potentiometer with a 20 mA signal. The VFD shall control proportional intermediate speeds with proportional inputs between 4 mA and 20 mA.

9. Equipment Protection

The VFD shall be designed to protect itself and the driven motor against all surges, transients, overvoltage, undervoltage, any failure of the electrical supply (including single-phasing), any grounding of its output power, and any interruption or "run away" of the incoming speed reference signal.

The VFD shall be designed to protect itself and the driven motor against over current of 115 percent of rated

motor current. This overcurrent protection shall be field adjustable from 95 percent to 135 percent of standard NEC current rating of the specified motor. Protection shall consist of normal shutdown of equipment with no damage to inverter components or driven motor.

10. Automatic Restart

The VFD shall be designed to remain in service for short-term over/under voltage of up to 30 percent for periods of up to 3 seconds duration. This feature shall not negate provisions specified hereinbefore for equipment protection against over/under voltages of other magnitudes and/or durations.

After equipment protective devices have shut down the equipment for overvoltage or undervoltage (including complete loss of voltage), and upon restoration of acceptable voltage and a time delay, the VFD shall automatically restart the driven motor. The time delay shall be adjustable from 90 seconds to 180 seconds. Automatic restart of a 3-phase motor, which has shut down due to voltage failure by single phasing, shall not be attempted until acceptable 3-phase power is available, at which time automatic restart shall occur.

11. Factory Test

Before shipping the VFD, the manufacturer shall test and "run in" the inverter and all associated equipment to assure reliability of the equipment and conformance with specification requirements. All components shall be "run in" under temperature and load conditions. A copy of the complete records of test shall be furnished to the City of Phoenix at the time of delivery of equipment.

12. Operation and Maintenance Instructions

In depth training shall be provided by the VFD supplier

covering installation, operation, circuit analysis, advanced trouble-shooting and repair of all the different models and types of VFD furnished. Instructor shall be qualified factory technician/engineer and shall provide and use diagrams, schematics, operation and instruction manuals, text books, and such other instructional material as appropriate. Presentation by the instructor shall be by lecture, demonstration, hands-on experience, films and such other method as will present the material adequately. Students will be City of Phoenix employees (up to ten in number) trained and skilled in electrical and electronic fundamentals. Period of instruction shall be a minimum of 8 hours of actual instruction. Instruction shall take place at a City of Phoenix maintenance facility within 30 days after delivery of inverters at a mutually arranged date and time.

One (1) copy of operation and maintenance instruction manuals showing the installation, operation, maintenance and trouble-shooting procedures shall be supplied for each VFD furnished. One (1) copy of technical manual showing test points, part numbers, wave forms, and advanced electrical and electronic schematics shall be provided for each model furnished. These manuals shall be delivered to the City of Phoenix with the equipment.

13. Spare Parts

Two (2) sets of spares per unit shall be furnished for all fuses used in the VFD. These spare fuses shall be delivered to the City of Phoenix with the equipment.

The inverters furnished under this specification will be installed in location where serious damage would result in prolonged "down" time. Consequently, two spare electronic "packages" shall be furnished. The electronic "packages" shall consist of all electronic parts and

their immediate electrical and structural accessories, "packaged" or assembled to the point that a journeyman electrician, familiar with generic operation and maintenance of inverters, can replace defective inverter parts with spare "package" in two hours or less. Spare electronic "packages" shall be identical in layout to inverters furnished so that rapid replacement "in kind" is possible.

Inverters will be installed immediately upon receipt and the spare electronic "packages" will be installed in inverters to assure that the ones held as spares are viable units.

14. Warranty

The equipment shall carry a minimum twelve month warranty as to workmanship, materials and satisfactory functioning from the date of acceptance by the City of Phoenix. All materials and shipping expenses, labor, travel and per diem expenses for the personnel necessary to perform warranty work shall be borne by the supplier of the equipment.

CHAPTER 5 - INSTALLATION PROCEDURES

GENERAL INSTRUCTIONS

All Variable Frequency Drive installations should be performed by qualified personnel with adequate knowledge of electrical, electronic and control systems. The instructions that follow are generic in nature and should only be used as a guide for the safe installation of VFD's. All certified drawings and specific installation instructions that are supplied with each VFD package must take precedence over these instructions. Refer all questions and requests for additional information to the address given by the manufacturer, or contact the sales personnel or local supplier.

HARDWARE INSTALLATION

It is important that the VFD be installed and operated within the environmental conditions for which it was specified. Any deviation from standard service conditions must be clearly defined in the purchase order and contract specifications. Electrical and electronic control equipment should be located in an area providing an unobstructed flow of clean cooling air. Equipment must be accessible to maintenance personnel. The job site should be cleared of heavy construction, before beginning installation. Remove construction debris, unnecessary equipment and all accumulated dirt and scrap from work location before bringing in new equipment. Equipment must be adequately supported to prevent excessive vibration,

distortion and settling. Electrical accessories also require support to prevent abrasion to insulation and component failure. Normal electrical and mechanical tools available to most technicians are all that is required for the installation of a Variable Frequency Drive. Each VFD leaving the factory will have been inspected and tested prior to shipment; however, a thorough visual inspection of all electrical components, printed circuit boards, plugs and connections should be made. For specific mounting instructions refer to the instruction manual supplied by the manufacturer.

ELECTRICAL WIRING

All wiring must be in accordance with the National Electrical Code (NEC) and/or other local codes as required. The electrical connections completed by the installer must conform to the engineering wiring diagram supplied. All connections should be checked for tightness; they may have become loose during shipping.

Careful consideration must be given to the layout of the conduit and wiring to prevent problems with electrical interference. The drive or other nearby electronic equipment may be subject to malfunctions or nuisance shutdowns if the following precautions are not observed:

- i) Control wiring must be separated from power wiring.
- ii) Use shielded cable where indicated on the connection diagram.
- iii) Keep the motor wiring separated from wiring to any electrical equipment which may be sensitive to electrical noise.

Ground Connections. For personnel safety and reliable equipment operation, ground each cabinet according to

connection diagram. The ground conductor should be the same size as the incoming power wires or sized according to NEC. A copper or aluminum conductor must be used.

Input Power Connections. Electrical codes require an input power disconnect device such as a circuit breaker or fused disconnect switch. This device is usually not included with the equipment unless specifically ordered. Input power wire size should be selected in accordance with applicable codes based on the input power data listed on the VFD nameplate. For long wire runs, wire size should be adequate to prevent excessive voltage drop. Input voltage should be within +5% and -10% of the rated input voltage listed on the nameplate.

Output Power Connections. Output power wire size should be selected in accordance with applicable codes based on the output power data listed on the VFD nameplate. For long wire runs, wire size should be adequate to prevent excessive voltage drop. This is particularly important since the VFD output voltage is reduced as the speed is reduced while the output current may remain constant. Connect the motor according to the motor nameplate. Motor nameplate voltage and frequency should correspond to the output voltage and frequency on the VFD nameplate. If the horsepower and full load current listed on the motor nameplate do not exceed the figures listed on the VFD nameplate, the motor can be operated continuously at full load without exceeding the VFD rating.

Control Connections. Refer to the connection diagram to determine the necessary control connections to the Speed potentiometer, Run/Stop switch and other operator control devices which may be required. Also refer to instruction sheets which are furnished for operational features or modifications and auxiliary equipment which may be part of the drive system. For wire runs up to 500 feet, No. 22 AWG wire is adequate for control circuit wiring. Inductive loads, such

as relay coils, solenoids, brake coils and transformer type pilot lights, generate electrical noise when they are switched ON and OFF. This noise can interfere with the operation of the VFD or other electronic equipment. If such loads are operated by relay contacts in the VFD, powered from VFD control power or connected to wiring routed near the VFD control wiring, transient suppression should be connected across these devices. For most such loads, a 100 ohm resistor, in series with a 0.25 mfd capacitor, provides adequate protection.

LESSONS LEARNED

The problems encountered by the City of Phoenix are not unique and therefore a presentation of these problem areas may assist others who are planning Variable Frequency Drive installations. The City of Tempe, which neighbors the City of Phoenix, has already benefitted from this particular type of technology transfer.

Heat has always been a problem associated with motors. Furthermore any motor operated by a VFD will produce more heat than if run on line power. Standard induction motors are equipped with shaft-mounted fans for cooling. At lower operating speeds these fans are less efficient. Any motor to be operated by a VFD should have a 1.15 Service Factor rating, and Class F (155 deg. C) or higher insulation rating. The service factor will generally provide protection against the normal increase in heating.

The condition and age of a motor should always be considered. Based on knowledge gained from applying VFD's, it is recommended that if a VFD is to be installed to operate an old motor, the motor should be replaced with a new efficient one at the same time that the VFD is installed.

In Chapter 4, under technical specifications, the matter of equipment warranty was addressed. The City of Phoenix has always requested a minimum of twelve month warranty from its suppliers. However, some jurisdictions might find it necessary to request a full two year warranty, especially when complicated control schemes are involved. It has been known that when a problem occurs, a supplier may perform the minimum warranty service required to keep the VFD operational without completely addressing the problem. A two year warranty is helpful when trying to obtain warranty service past the first twelve months.

Most of the VFD installations, at the City of Phoenix, have been done in-house by the Energy Conservation Staff. This is beneficial in that the projects are thoroughly understood by the technical staff. The disadvantage is that some installations are more time consuming than originally estimated. Once the installation has been completed, regular maintenance should be performed in order to keep the equipment functioning properly. This usually requires training of technical personnel who are not familiar with this type of technology. The City of Phoenix also maintains a video tape library containing instructional videos on installation and maintenance procedures. These instructional tapes have been used to train new personnel on technologies unfamiliar to them.

Finally, VFD's are effective only when they are operating properly. However, VFD's are installed with "by-passing" capabilities for quick switching to full speed motor operation in case of malfunction or failure of the VFD. A "by-passed" VFD is a sign of energy waste if left unrepaired. Facilities maintenance personnel may "by-pass" a VFD when a problem occurs. A "by-passed" VFD gives the impression that the problem with the system is eliminated, while operating the motor at full speed and consuming energy unnecessarily. It is recommended that quick action be taken to repair the VFD and return it to correct operation.

APPENDIX A - BIBLIOGRAPHY

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TYPICAL VAV SYSTEM
POWER CALCULATIONS
Annual Power Consumption - KWH/HP/YR

% Rated RPM	% Rated HP	KW Out per rated HP	VFD System Efficiency	Input KW/HP	Running %	Time Hrs/YR	KWH/ HP/YR
100	100.0	.746	.85	.878	0	0	0
90	72.9	.544	.84	.648	3	262	170
80	51.2	.382	.83	.460	9	788	362
70	34.3	.256	.82	.312	21	1840	574
60	21.6	.161	.81	.199	23	2015	401
50	12.5	.093	.78	.119	23	2015	240
40	6.4	.048	.68	.071	16	1402	100
30	2.7	.020	.54	.037	5	438	16
					100%	8760	1863

ANNUAL POWER CONSUMPTION COMPARISON*

	1863	KWH/HP/YR
VFD	1863	
Eddy-Current Coupling	2817	" "
Inlet Vanes	5003	" "
Outlet Dampers	6496	" "
Constant Volume	7266	" "

* Annual power consumption based on typical VAV system duty cycle

REPORT AND INFORMATION SOURCES

Additional copies of this report, "Variable Frequency Drive Applications Guide" are available from:

Publication and Distribution
Public Technology, Inc.
1301 Pennsylvania Avenue, NW
Washington, DC 20004

For more information on the experience and techniques used to develop this guide, or for the additional activities of the Phoenix Energy Conservation Program, please contact:

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81-305	Technology Transfer: Unit Report from the Energy Task Force	15.00
81-304	Development of Local Energy Management Preparedness	10.00
81-303	Municipal Energy Management	10.00
80-314	Methodology for Energy Impact Analysis of Urban Development Projects	15.00
80-313	Evaluation of Landfill Gas as an Energy Source	15.00
80-309	Decision Process for the Retrofit of Municipal Buildings	20.00
80-308	Primary Urban Energy Management Planning Methodology	7.50
80-306	Local Government Use of Thermography for Energy	15.00
79-300	Planning for and Purchasing Computer Technology	6.50

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