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CONSIDERATIONS FOR APPLYING VARIABLE FREQUENCY DRIVES TO VARIABLE SPEED PUMPS

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INTRODUCTION

Energy conservation in a centrifugal pump installation begins with an accurate determination of system requirements and pump operational characteristics. It is a common engineering practice to apply "safety factors" in determining flow and system head requirements. Consequently, to assure adequate flow and overcome possible oversimplification in engineering calculations and selection procedures, systems are designed for excess capacity. This, of course, leads to higher than necessary energy costs.

Today's high energy costs are projected to go even higher. There-fore it becomes prudent to apply all available tools and operational and engineering skills toward improving the overall pump and system total operating effectiveness. **Pumping costs** and system **operational costs** can be controlled and minimized substantially by applying these factors:

1. Accurate determination of system flow (gpm) requirements.
2. Accurate determination of system head requirements by using appropriate system pressure drop data.

3. Avoidance of excessive use of "safety factors".
4. Use of energy effective control valves.
5. Pumping arrangement most suitable for effective energy managements, such as zone pumping, primary-secondary pumping, series or parallel pumping, or variable speed pumping.
6. Equipment that will complement the application requirements for initial cost, reliability, maintenance skills and costs, and operator confidence.

In systems which experience substantial periodic demand changes variable speed drives will reduce pumping energy costs. To maximize economy and reliability, matching a drive to a pumping system requires the application of good judgments in addition to engineering skills. Reduction of energy and operational costs can be illusive and often unobtainable if pump and system performance estimates are not accurate or if the proposed equipment will destroy the process, reduce reliability, or is unfamiliar to the operating personnel. If becomes important, therefore, that not only efficiency, but the entire spectrum of application, knowledge and experience be used to determine the total cost of operation.

GENERAL

The application of variable speed drives to centrifugal pumps is one of the fastest growing practices in the industry. The technology applied to the electrical drives is complex and changes quite rapidly, bringing to the marketplace many innovative features which, at first glance, appear desirable. However, caution is highly suggested in the utilization of equipment in pumping applications where there may be peripheral attributes which, in total evaluation, contribute to unsatisfactory performance. For example, a rapid speed of response in the electronic circuitry can cause hunting because pumps cannot respond as rapidly to the change of flow as the electronics call for a change in system requirements.

The best application is one where the user is comfortable with the equipment and knows the product is reliable and adequately serviced by a company that will not suddenly withdraw from the marketplace but will be around for many years.

VARIABLE FREQUENCY DRIVE – DISCUSSION

There are today many variable speed drive suppliers, particularly those who make variable frequency equipment. Many of them make only the controller (inverter). Thus, most of the information regarding the controller's performance is related only to the controller. Therefore, to evaluate the attributes of a variable frequency unit it is important to understand both the controller and the effects that the controller imposes upon the A.C. induction motor.

A.C. MOTORS PERFORMANCE WITH VARIABLE FREQUENCY DRIVES (VFD)

Through the years there have been a number of methods employed to make induction motors into suitable variable speed drives for centrifugal pump applications. In every instance each method resulted in the motor operating at a high noise level and at temperatures that were ultimately unacceptable for the application. To some degree these same negative attributes are also true of A.C. induction motors whose speed is varied by frequency changes because of resultant harmonics in the electrical power supplied by the inverter. To compensate for the increased motor losses and resultant motor heating, A.C. motors used with the variable frequency inverters on

pumps, fans, or variable torque duty controls are recommended to be de-rated about 10%. High efficiency motors with their improved thermal characteristics and a service factor of 1.15 are used; hence, a 20hp motor with a 1.15 S.F. is applied at 20hp max., a 20hp motor with a 1.0S.F. is applied at 18 hp max. Harmonics will affect motor losses and will vary with specific motor design. It becomes prudent to ask from each motor manufacturer if the A.C. motor used with the selected inverter is suitable for the intended application.

VFD TYPES

Variable frequency A.C. motor controls (inverters) can be obtained in three basic designs – **Six Step Inverter** (variable voltage source), **Current Source Inverter**, and **Pulse Width Modulated Inverter** (PWM; constant voltage source). Each type possesses unique electrical characteristics which must be considered in the application for load requirements, motor selection, system operating efficiency, and power factor.

The **Six Step Inverter** is frequently used for pumping applications. Performance is influenced by the method used to convert A.C. input to D.C. output and invert to a variable frequency output. The use of SCRs (thyristors) in the converter section will result in a lower power factor (i.e. changes linearly with frequency, about 10% at 10Hz and 0.95% at 60Hz) than the use of diodes with a D.C. chopper which would maintain a P.F. in the mid 90%-100%; but the D.C. chopper will generate additional inverter noise. The use of SCRs in the inverter section will be less efficient than using power transistors or gate turn-offs (GTOs) because SCRs require commuting circuits while power transistors and GTOs do not.

Commutating circuits contribute to inverter losses. In applying the Six-Step inverter, the following items should be considered:

- Motor: Heating
- Inverter: Short Circuit Protection
Noise
Efficiency
Power Factor

In the horsepower range for most pumping applications, it appears to be the least costly of the three basic types.

The **Pulse Width Modulated Inverter**, though more complex and expensive than the Six Step Inverter, is also frequently used for pumping applications. Of major concern for pumping applications is that PWM controlled motors produce more noise than those used with Six Step or Current Source Inverters - - they tend to “sing”. This could be particularly annoying when the units are used in offices, hotels, hospitals and other occupied buildings. Additional motor heating could also become a problem in certain environments. The performance characteristics of a PWM inverter are also greatly influenced by the method used to convert A.C. in-put to D.C. output as in the Six-Step. However, the inverter section, i.e., the power circuit to the motor of the PWM inverter uses power transistors or gate turn-offs (GTOs), thus eliminating inefficient commutating circuits. The PWM inverter maintains high efficiency, mid 90s range, and power factor approaching unity (1.0) from 6 to 60Hz. The PWM inverter will usually require short circuit protection. In applying the PWM inverter, the following items should be considered:

- Motor: Noise
Heating
Voltage Stress
- Inverter: Short Circuit Protection
Noise
Efficiency

The **Current Source Inverter** is usually applied to larger horse-power sizes and is available for application to variable speed pumps in horse powers ranging from 5 hp to 1500hp. The major attributes associated with this inverter are lower motor noise, inherent short circuit protection and somewhat lesser electronic complexity. The current source inverter will use SCRs (thyristors) in the inverter section i.e., the power circuit to the motor, and SCRs or diodes with D.C. chopper in the front end. The power factor of the **Current Source Inverter**, as with the six-step, is determined by the front end circuit. In circuits that use SCRs, the power factor will be poor at reduced speeds; in circuits using diodes with D.C. chopper the power factor will be high throughout

the speed range, similar to the PWM inverter. The efficiency of the current source inverter will also vary according to the horse-power rating and circuitry. The inverter efficiency will be relatively high, upper 80s to mid 90s, from about 70-100% of rated motor speed.

In applying the current source inverter, the following items should be considered:

- Motor: Voltage Stress (due to high voltage spikes)
Heating
Cogging below 6Hz
- Inverter: Noise
Efficiency
Power Factor

The **inverter** and the **A.C. induction motor** are sources of additional noise and heat.

VFD OPERATING CHARACTERISTICS:

The overall efficiency of a variable frequency inverter-motor combination is the product of the inverter and motor efficiencies. There are a number of variables involved in determining the efficiencies of the inverters: the type of inverter used, horsepower size and speed range. Because of these variables the inverter efficiency must be determined for each specific design and application parameter. A.C. induction motors have always been considered to be constant speed drivers. When applied to non-sinusoidal electrical power obtained from the inverter there exists little, if any, published information on A.C. motor efficiencies at reduced speeds. On pumping applications where the load profile may be heavily weighted toward lower speeds it is imperative that the motor manufacturer provide accurate motor efficiencies and power factor value at reduced speeds to allow for complete and accurate evaluation. Efficiency comparisons, therefore, must consider the particular application requirements of the specific control and driver employed.

Adjustable Frequency Controllers have the inherent ability to start motors at reduced inrush currents and are commonly furnished without motor starters. Solid state devices such as inverters usually fail short-circuited.

The motor cannot be operated without having a means to transfer the electric power from the controller to the motor for operation as a constant speed A.C. drive. Therefore, on pumping applications where it is desirable to operate the units at all times it is mandatory that the controller be equipped with a transfer switch and fully rated motor starters. This is a cost factor often overlooked in payback calculations.

Variable frequency electronic control applications must also consider other environmental effects which can contribute toward equipment malfunction. In part, they are as follows:

1. Humidity greater than 90% R.H.
2. Excessive dirt, dust or gaseous chemicals.
3. Radio frequency or stray high frequency signals.
4. Ambient air temperature must be between 32°F. and 104°F.
5. Line voltage variation \pm 10%.
6. Line frequency variation \pm 2Hz.
7. Altitude – sea level to 3300 feet (1000 meters).

Additionally, because most variable frequency controllers inject harmonic currents into the incoming A.C. line, a “buffer” transformer may be recommended by the inverter manufacturer to isolate A.C. line disturbance created by the controller from other sensitive electrical in-line equipment such as computers, to meet local code requirements and to increase reliability and inverter protection.

CONSIDERATION FOR VARIABLE SPEED PUMP APPLICATIONS

Variable speed applications of centrifugal pumps require that a control interface be employed to allow the speed of the motor to respond to the needs of the system, i.e. speed changes to complement the pumping system requirements. This is usually accomplished by

having the pump manufacturer accept the entire responsibility for the proper integration of the pump, A.C. motor, inverter and system controls – e.g., transducers. The pump manufacturer who assumes this responsibility must understand the system requirements and have the experience to apply properly designed control hardware from the sensing location (transducers) to the firing circuit of the inverter. Invariably, this function is performed by a third party. Hence, for a variable frequency pumping unit the variable speed drive unit can consist of motor by Manufacturer A, inverter by Manufacturer B, and system control hardware and interfacing to inverter by Manufacturer C. Because the inverter manufacturer will not take the responsibility for the proper application of the motor to the inverter, and vice-versa, it remains for the pump manufacturer to assume the responsibility. This is not always in the best interests of the customer, especially when problems in the motor controller interrupt water supply.

One final consideration must be given to the used of variable frequency controls – reliability, maintenance cost, and skills of maintenance personnel. Presently, in the opinion of some power plant engineers, the inverter is of unproven reliability. Maintenance costs can be excessive, and maintenance personnel must be trained in the special skills required for electronic equipment. Therefore, proper evaluation for a drive system must consider more than singular attributes such as full load efficiency or initial cost. A complete analysis must consider operating cost for the anticipated load profile. Investment cost for spare parts, maintenance, and the cost of either training personnel or contracting for repairs and routine maintenance. The evaluation should consider present and future needs to which the equipment is applied.

Variable frequency speed control for A.C. induction motors is, and will continue to be, a viable high technology product. However, for centrifugal pumping applications the highly-touted claims of efficiency advantage over other drives such as fluid couplings cannot be the sole point of evaluation. After all, at the lower speed the KW requirements of the centrifugal pump reduce at the cubic rate. (See Table 2 – Addenda)

The efficiency of the variable frequency unit, i.e. inverter and motor, may not be of great advantage over a fluid coupling, for example, when considering the other attributes associates with variable frequency, such as:

- Greater initial cost
- Power factor reduction at the lower speeds with six step and current source inverters
- Heat and noise increase
- Higher maintenance costs
- Greater complexity of operation

TABLE 1
COST COMPARISON – 3500 RPM – 460 V (ESTIMATE)

VFD Units Include:	Energy Efficient Motor
	Pressure Transducer
	Set Point Control
	Inverter
Peerless Hydroconstants Include:	Standard Motors
	Hydraulic Speed Control
	Controller with Disconnect, Starters and Control Circuit

H.P.	MFG A	MFG B	MFG C	Peerless Hydroconstant Drive
10	\$5,938	\$10,125	\$7,100	\$2,058 (M8)
20	7,536	10,450	10,060	4,632 (M9A)
40	10,027		—	5,831 (M9A)

Cost addition for isolation transformers and starter with transfer switch. Estimate is for all inverter manufacturers; not required on Hydroconstant drive.

HP	\$ Approximate
10	\$2,140
20	2,545
40	3,010

HYDRAULIC PERFORMANCE ESTIMATES

The following tables can be used to assist in making some expedient calculations of flow and horsepower requirements for a centrifugal load (Table 2). This ready reference will assist in determining projected power costs using the estimated load profile (Table 3).

AFFINITY LAWS – TABLE 2

Speed	Flow/GPM	HP Required
100%	100%	100%
90	90	73
80	80	51
70	70	34
60	60	22
50	50	13
40	40	6
20	20	0.8

CONCLUSION

Today's technology has made available to the user numerous choices of variable speed drives – mechanical, electrical and fluid types. The correct choice can best be made only after proper consideration and evaluation of the particulars associated with the equipment. To achieve a cost effective installation it is important *that equipment such as pumps, variable speed drives, motors and*

controllers be selected with a complete understanding of their operational attributes and interaction effects. Armed with this knowledge, the equipment selected will have much greater probability of achieving the expectations for the successful operation of a pumping system and investment goals.

LOAD PROFILE – TABLE 3

See Note 1.

% Time	Flow/GPM
5%	100%
5	90
10	80
15	70
15	60
15	50
10	40
10	30
10	20
5	0-10

NOTE 1: The load profile is an example of organizing operational times at specific flow rates. Pumping equipment should be selected to provide maximum operating efficiencies in all flow ranges. Hence, for a system, multiple pumps could be applied to span the total flow requirements. For example, one single pump rated for 10-20% of total flow requirements and two identically sized pumps to share equally the total system capacity.

Variable frequency as a means of varying the speed of an A.C. induction motor has been known for many years. It is because of the recent technological improvements in the logic power switching elements, and lower manufacturing costs, that a greater interest in variable frequency speed controls for A.C. induction motors has occurred.

The state of the art in the electronics field changes quite rapidly. Therefore in these products new ideas and modifications are constantly introduced. One company may offer a controller with features that differ from those of another company, or from the controller they manufactured in the past. Generalities of control parameters cannot be used as being comprehensive for all manufacturers. It is imperative that comparisons be made using the **specific controller and A.C. induction motor.**

ADDENDA

Equipment Cost

Quite often it is desirable to make a cost comparison between the VFD and a Hydroconstant unit. The ultimate cost of the inverter depends upon the respective

manufacturers and the types of inverter used plus pricing levels in effect at time of quotation. The following tabulation therefore is intended only as a guide.

MOTOR PERFORMANCE

Table 4 represents the efficiency of an energy efficient 20HP, 3 phase, 60Hz, O.D.P., 15% S.F., 3500 RPM motor. These values will vary with each motor manufacturer; therefore they should only be used for estimating purposes.

VFD CONTROLLER (INVERTER) EFFICIENCY AND POWER FACTOR

The efficiencies and power factors of the three types of inverters described therein are influenced by the type of converter and inverter components used in the controller, the horsepower size and range of speed. Because of these variables, it is impractical to tabulate the values of efficiency and power factor for each type of voltage source and current source inverter. These values should be obtained from the inverter manufacturer.

MOTOR EFFICIENCY – TABLE 4

% RPM	% Load H.P.	% Eff. Motor W/VFD Control	% Eff. Motor At Constant RPM
100	100	92	92
90	73	91	94
80	51	89.5	94
70	34	87	92.5
60	22	83.5	92
50	13	78	83
40	6	68	73
20	0.8	(Approx.) 27	(Approx.) 60