Application of Variable Frequency Drives for Energy Savings

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Abstract- While almost any facility could potentially benefit from Variable Frequency Drives (VFDs), there are a variety of pitfalls that can lead to misapplication. Avoiding those pitfalls requires an understanding of the physical laws governing the system under consideration, and of the operational characteristics and efficiencies of the individual components.

I. Introduction

VFDs are typically utilized either to provide improved control or energy savings. This paper will describe the characteristics of systems with the potential for energy savings, and the parameters to consider when making energy savings calculations. The utilization of VFDs strictly for speed control is typically a function of the system requirements, and will not be the subject of this discussion.

VFDs can provide energy savings primarily with variable torque centrifugal loads such as fans and pumps. Other types of loads typically do not provide energy savings, and will not be analyzed.

II. Power Requirements for Pumps and Fans

Pump and fan power requirements are very similar, with liquids and gases following the same laws of fluid dynamics. We will examine pumps in detail, with the understanding that the same principles apply to fans.

The fluid power, $P_f$, measured in horsepower for a given pumping application is governed by the following equation:

$$ P_f = Q(KQ^2 + H_s)sg / 3960 $$

where $K$ is a system constant, $Q$ is the flow rate (gpm), $sg$ is the specific gravity of the fluid, and $H_s$ is the static head (ft). The $KQ^2$ component represents the frictional head in the system.

Static head is defined as the difference in elevation between the pump and the discharge location, typically measured in feet.

Frictional head results from the friction between the fluid and the walls of the pipe, and is defined by the Darcy-Weisbach relation:

$$ H_f = f \left( \frac{L}{D} \right) \left( \frac{V^2}{2g} \right) $$

where $f$ is a friction factor based on the characteristics of the pipe, $L$ is the length of the pipe, $D$ is the diameter of the pipe, and $V$ is the average velocity of the fluid. Notice that for a given pipe, the frictional head is proportional to the square of the fluid velocity, which is reflected by the $KQ^2$ component in the fluid power equation (1).

Equation (1) is critical for understanding the role of VFDs in energy savings. Equation (1) shows that for a system dominated by static head, fluid power is directly proportional to flow.

$$ P_f = QH_ssg / 3960 $$

In a system dominated by frictional head, fluid power varies with the cube of the flow rate.

$$ P_f = KQ^3sg / 3960 $$

Equation (3) shows a linear relationship between fluid power and flow rate in a static head dominated system, whereas equation (4) shows that fluid power is proportional to the cube of the flow rate in a frictional head dominated system. The pump in a static head system works to lift a liquid to a higher elevation by overcoming the force of gravity. In a frictional system, the pump works to overcome the force of friction. The greatest opportunity for energy savings is in frictional head dominated systems, because of the non-linear relationship between work and flow rate. In a static head dominated system, the work required is linearly dependent on the flow rate. VFDs in static head dominated
systems can save energy only by eliminating less efficient flow control devices, such as throttling valves, though the reduction in power consumption is significantly less than in frictional systems.

Many pump installations in industrial facilities are frictional head dominated systems. All closed loop systems, such as glycol loops and chilled water loops, are frictional head dominated. Refer to Figure 1 for a simple example. Note that while the fluid in this example changes elevation, the net change is zero, resulting in zero static head.

![Figure 1: Frictional Head Dominated System](image1)

A system with static head would be one in which a fluid is being pumped from one elevation to a higher elevation. An example would be a product pump used to fill a tank, or an evaporative condenser water makeup pump. Refer to Figure 2 for an example.

![Figure 2: Static Head Dominated System](image2)

In frictional head dominated systems where a variable rate flow is required, VFDs have the potential to save energy by reducing the frictional losses in the system via a reduced flow rate. Other means of flow control, such as throttling valves or bypass valves, do not take full advantage of the reduced frictional losses, and therefore consume more energy at reduced flow rates than a VFD equipped system.

This analysis focuses on systems that are either static or frictional head dominated. Many systems, particularly in HVAC applications, have both static and frictional components, and require a detailed analysis to assess the impact of VFDs on the system.

### III. Affinity Laws

A set of equations known as the “affinity laws” are typically used for energy savings calculations. The equations can be derived from equation (4), and are defined as follows:

\[
\frac{Q_1}{Q_2} = \frac{N_1}{N_2} \tag{5}
\]

\[
\frac{P_1}{P_2} = \left(\frac{N_1}{N_2}\right)^2 \tag{6}
\]

\[
\frac{HP_1}{HP_2} = \left(\frac{N_1}{N_2}\right)^3 \tag{7}
\]

Where:

- \(N\) = Speed
- \(Q\) = Flow
- \(P\) = Pressure
- \(HP\) = Horsepower

Equation (7) is frequently used to justify installation of VFDs. Comparing equation (7) to equations (3) and (4), it is apparent that the affinity law relating horsepower to speed assumes a frictional head dominated system, and does not take into account any static head. This assumption can lead to significant errors if applied to systems that do include a static head component.

Carlson’s paper\(^3\) explains this error in detail. In Carlson’s sample calculation, a pump with initial conditions of 4000 gal/min flow, 3282 ft head, and 4025 bhp (brake horsepower) is slowed to provide 1000 gal/min in a system with both static and frictional head. Using the affinity laws, the required brake horsepower at the
reduced flow rate would be 63 bhp. When the analysis accounts for the static head in the system, the actual brake horsepower at the reduced flow rate is 427 bhp. The actual power requirements are more than six times greater than the affinity laws suggest.

Understanding the difference between static and frictional head is essential to avoid errors in energy savings calculations. The affinity laws may be used in closed loop systems, but should not be used in systems with a static head component.

**IV. System Efficiency**

The previous discussion focused on fluid power requirements, which define the power output requirements of a pump. When considering application of a VFD to such a system, the efficiency of the VFD, motor and pump should be considered to determine the total power input required to operate the system.

Efficiencies for VFDs, motors and pumps all vary with speed. VFDs and motors decrease in efficiency as speed decreases, while pumps may increase or decrease in efficiency depending on the pump and application. According to Bernier and Bourret, this causes the total input power to be “significantly higher” than the pump affinity laws would predict.

The efficiency of a VFD is affected by its rated horsepower, carrier frequency, and torque rating. Efficiency is lower in smaller drives, for higher carrier frequencies, and for variable torque drives. Table 1 lists efficiencies for variable torque drives with a carrier frequency of 15kHz.

<table>
<thead>
<tr>
<th>VFD HP Rating</th>
<th>Percentage of Full Operating Speed</th>
<th>25%</th>
<th>50%</th>
<th>75%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.4% 64.2% 70.5% 82.5%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>29.6% 74.7% 88.3% 92.4%</td>
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<td></td>
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<tr>
<td>10</td>
<td>35.3% 79.0% 90.3% 93.5%</td>
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<tr>
<td>25</td>
<td>35.6% 79.4% 90.6% 93.8%</td>
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<td></td>
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<tr>
<td>50</td>
<td>43.3% 83.5% 92.1% 94.4%</td>
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<tr>
<td>250</td>
<td>61.2% 91.3% 96.1% 97.3%</td>
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</tr>
</tbody>
</table>

*Table 1: VFD Efficiency*

Isolation transformers or line reactors are frequently included in VFD installations, and the losses from these components further reduce the overall efficiency of the system.

Component efficiency is important to consider not only in evaluating energy savings, but also to avoid applications where a VFD actually increases the cost of operating a motor. For example, a conveyor motor that has a VFD for providing soft starts and stops will cost more to operate than the same motor controlled by a soft start controller with a bypass contactor. The input power to the VFD in this example would be:

\[
P_{\text{input}} = \frac{P_{\text{shaft}}}{(\text{Motor Efficiency})(\text{VFD Efficiency})}
\]  

where \( P_{\text{input}} \) is the power input to the VFD and \( P_{\text{shaft}} \) is power output of the motor. The input power to the soft start controller would be:

\[
P_{\text{input}} = \frac{P_{\text{shaft}}}{(\text{Motor Efficiency})}
\]  

Assume we have a conveyor motor with an output of 700W and an efficiency of 90%. The VFD efficiency from Table 1 for a 1HP rated VFD operating at full speed is 82.5%. The VFD power input in this example would be 943W, versus 778W for the soft start, a difference of 21.2%.

**V. Quick Screening for Payback**

Given the complexities in accurately calculating energy savings with a VFD, a simple screening tool can help by eliminating scenarios that are unlikely to show a payback. The Electric Power Research Institute (EPRI) publishes ASDMaster software, which assists the user in determining whether or not a VFD will pay for itself in a specific application. One feature of the software is a screening routine, which provides a quick analysis of whether or not a VFD is financially justified, based on energy savings alone, for typical applications. The screening characteristics are derived from the analysis of hundreds of VFD applications, and are intended only as a guide. EPRI recommends a complete energy analysis prior to proceeding with a VFD installation. The application characteristics employed by the screening routine are listed in Table 2, and Figure 3 is the corresponding decision tree.
VI. Other Considerations

While energy savings or the need for speed control typically determine whether or not a VFD will be used, other factors should be considered prior to installation.

VFDs require a cleaner environment than single speed starters. The electronic components in a VFD require cooling, which is accomplished by a ventilated enclosure, and sometimes fans. It is important that the air passing through is relatively clean, to prevent the buildup of dust on the electronic components, which can cause overheating.

VFDs emit a significant amount of heat. An electric room with a large number of VFDs may require mechanical cooling to prevent the drives from overheating and shutting down.

The fast switching characteristics of VFDs can cause a voltage spike at the motor, leading to motor failure. Voltage spikes can be mitigated by application of filters, proper branch circuit design, and use of inverter duty motors.

The electronic switching in VFDs produces harmonics. The impact of harmonics should be considered on a case-by-case basis. Sometimes the harmonics do not pose a problem, other times mitigating solutions should be provided.

Misapplication of utility rate structures frequently leads to errors in energy savings calculations. Even “measured” results can be misleading; for example, measuring reduced power consumption and calculating savings with an average rate can overstate the savings significantly. Refer to the Hixson white paper “Electrical Energy Savings Calculations” for a detailed discussion of the topic.

VII. Conclusions

The application of VFDs for energy savings can be very complex. Understanding the physical laws governing the system under consideration and the efficiencies of the equipment involved is essential for proper application.
References


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