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VARIABLE SPEED DRIVES FOR GEOTHERMAL APPLICATIONS

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ABSTRACT

Controlling pump speed in any deep well pumping application can be a cost effective means of controlling flow. Several of the currently available speed control technologies (multi speed motor, wound rotor motor, AC variable frequency control, fluid coupling and eddy current coupling) are reviewed with respect to first cost and performance. Using this data, an analysis of an actual application is presented. Using the data and procedure presented in the paper can assist designers in the selection of an economical means of flow control for any application.

INTRODUCTION

Energy costs associated with the operation of production well pumps result in a large expense for many geothermal systems. In direct use systems, particularly those serving predominantly space heating loads, there is a wide variation in flow requirements. Since most systems employ centrifugal line shaft driven well pumps, there are two methods available for controlling flow: 1) throttling pump output; 2) varying the speed of the pump shaft. Throttling the output of any fluid handling device is simply dissipating energy through the addition of friction, which is an inherently inefficient approach to flow control. A review of the basic fan laws, which apply equally to centrifugal pumps, suggests that pump speed control is a much more energy efficient approach. 1) Flow varies directly with speed (Q N). 2) Pressure varies as the square of speed (H N^2). 3) Power varies as the cube of the speed (P N^3). It is important to realize that the above laws are based on a situation in which the pump head is composed of only friction head. In a geothermal system, pump head is composed primarily of static head. Static head is, of course, independent of flow. As a result, for a pump which is operating against a 100% static head, the fan laws become: 1) flow varies directly as speed (Q N); 2) pressure is independent of speed; 3) power varies directly as speed (P N). Savings to be achieved through speed control of a centrifugal fluid handling device under a 100% static head situation are then significantly less than the savings achieved in a 100% friction head situation. In addition, there is a limit imposed upon minimum pump speed in applications with a large static head.

The minimum speed is a function of the ability of the pump to develop sufficient head to move the water out of the hole. In general, large surface pressure requirements (which vary with flow) relative to static head requirements tend to make speed controls more attractive.

Most geothermal applications involve the use of a squirrel cage induction motor. As a result, there are two basic approaches to pump speed control.

1. Motor oriented control
   a. multi speed motor
   b. wound rotor motor
   c. AC variable frequency drive

2. Shaft oriented control
   a. adjustable pulley system
   b. mechanical adjustable speed drive
   c. eddy current coupling
   d. fluid coupling

The choice between the above approaches should involve a number of considerations such as: capital cost, horsepower, efficiency, speed/pump head relationship and maintenance.

MOTOR ORIENTED CONTROL

Multi Speed Motors

Multi speed motors in the integral (greater than 1 horsepower) horsepower size are available in 1 horsepower, constant torque and variable torque configurations. There are three basic varieties of multi speed motors: one winding two speed, two winding two speed, two winding four speed. The one winding two speed motor offers a 2:1 speed reduction ratio, such as 1750 rpm/875 rpm, 1750 rpm/1150 rpm, 1750 rpm/1450 rpm, etc. The constant torque arrangement would be most applicable to geothermal applications. Under this configuration, horsepower varies directly as the speed in accordance with most well pumping situations. The one winding two speed motor offers somewhat greater choice of speeds in that it is not limited to the 2:1 ratio. The two winding four speed motor offers somewhat greater speed control. This is typified by a common configuration such as 1750 rpm/2300 rpm/3000 rpm/4000 rpm/5000 rpm. The constant torque arrangement would be most applicable to geothermal applications. Under this configuration, horsepower varies directly as the speed in accordance with most well pumping situations. Obviously, the multi speed motor offers a stepped adjustment of output. For systems with infinitely varying requirements (such as space heating) throttling would be required to adjust flow in between the available speeds. This, of course, would decrease the potential savings available from this type of speed control. In addition, the sudden
Changes in speed which would result from multi-speed operation could impose additional mechanical constraints on pump shaft and bearing design. The multi-speed motor approach has in its favor relatively low cost, simplicity and efficiency in comparison to other drives. However, if throttling is required to regulate flow between speeds, efficiency falls off substantially. The only costs incurred are those of incremental motor cost (multi-speed over single speed) and speed switching equipment. Motor efficiency is comparable to, though slightly less than, an equivalently sized single speed motor. Costs for multi-speed motors are a function of speed combination, number of windings and speed torque type (constant horsepower or constant torque). As a result, it is not possible to characterize costs in general terms.

Wound Rotor Induction Motor

The wound rotor induction motor has historically been limited to industrial application in hoists and cranes and very limited use in pumping. The reason for this limited application was due to the inefficient nature of speed and torque control. This has resulted in a variable speed control system (wound rotor motor/slip loss recovery inverter) which rivals the efficiency of the AC variable frequency system (2). For speed reduction beyond 50%, external motor ventilation is usually required. Efficiency of the unit is about 98% and is constant over the entire speed range. This efficiency applies to the recovery of slip loss energy only. Overall efficiency at any point is a function of motor loss and inverter loss. Typical performance curves for a wound rotor motor and slip loss recovery unit are shown in Figure 1.

![Figure 1. Performance of Wound Rotor Motor with Slip Recovery](image)

The figure applies only to the drive. Total energy input calculations would have to include pump efficiency also. For example, at 75% torque and 50% of full speed, drive efficiency would be 85%. Assuming a hydraulic horsepower requirement of 50 and a pump efficiency of 60%, energy input requirement would be 50/(.85 x .60) = 98 horsepower or 73 kW. Annual energy use would be derived by calculating the energy requirement at each operating point or flow and multiplying by the time at that point. Summing the results of the individual operating point calculations would result in total annual usage which could then be compared to other control techniques. Maintenance requirements are similar to those for a hydraulic coupling type control as regular attention is required for the rotor slip rings. Speed control below 50% would require external cooling fans and duct work, thus increasing first cost and maintenance costs. The slip loss recovery unit itself is relatively maintenance free. Costs for the device are shown in Table 1. Additional costs for a wound rotor motor over a standard squirrel cage induction motor are included in the figures.

It is worth mentioning that some manufacturers offer optional power factor correction capacitors with their units.

AC Variable Frequency Control

In order to understand an AC variable frequency control it is necessary to first review some basics of induction motor operation. The speed of an induction motor is a function of the number of poles and the frequency of the applied voltage according to the following relationship: 

\[ N_s = \frac{120f}{p} \]

where \( N_s \) = synchronous speed, \( f \) = applied frequency, \( p \) = # of poles. In reality, there is a slight "slip" in the motor speed compared to synchronous speed. This slip amounts to about 2-6% at full load, depending upon motor design. As suggested by the above speed equation, motor speed can be adjusted by controlling the frequency of the applied voltage. This frequency adjustment must be carried out at a constant relationship to voltage or a constant volts per Hz. Magnetic flux is directly proportional to the voltage applied and inversely proportional to the frequency. Therefore, as motor speed is reduced by frequency adjustment, voltage must also be reduced to avoid unreasonable motor losses and magnetic saturation. This task of frequency and voltage adjustment is accomplished by drives referred to as inverters. Two basic designs are employed for the inverter: six step method; pulse width modulation method (PWM). In both cases, there is a potential for motor overheating. The heating effect of the frequency controller is compounded by operation at constant torque. Under a constant torque load, as speed is reduced, motor current remains fairly constant due to the load. As a result, motor losses and heating are also constant. However, the self cooling produced by the motor fan is reduced by the lower speed. This raises motor winding temperature. Although some manufacturers state that these controllers can be used with standard induction motors, it would obviously be wise to employ motors with high temperature insulation and high service factor characteristics.
Efficiency of variable frequency drives is generally quoted by the manufacturers at 95%. This figure applies only to the base frequency, which is usually 60 Hz. Figure 2 outlines efficiency at other operating points.

**Figure 2. Performance of AC Variable Frequency Controller**

The plot is based only on the efficiency of the frequency controller, and motor performance at the same torque must be considered for overall drive efficiency. For example, at 50% speed and 75% torque, a value of approximately 88% is read from the diagram. In order to obtain drive efficiency, this figure would be multiplied by the motor efficiency at that point (75% torque). Assuming a 100 horsepower motor, this figure might be 90%. As a result, drive efficiency would be 0.90 x 0.88 = 0.792. Using the same pump figures from the example in the wound rotor section (50 horsepower hydraulic requirement, 60% pump efficiency), a total electrical input of 50/(0.792 x 60) = 105 horsepower or 78.5 kW is found. Maintenance requirements for the variable frequency drive are very low. The controller itself is constructed of primarily solid state components which require virtually no attention. However, the controller units generally have a minimum ambient requirement of 10°C. As a result, they would have to be housed in some type of heated well head structure for protection. This type of speed control is the only one which would still permit system operation in the event of controller failure since electrical supply to the motor could be routed around the inverter. List prices are shown in Table 1 according to horsepower requirements. These figures are for the inverter only and additional costs would be incurred for control interface, starter, manual or automatic bypass equipment.

**TABLE 1**

<table>
<thead>
<tr>
<th>Horsepower</th>
<th>Fluid Coupling</th>
<th>AC Variable Frequency</th>
<th>Wound Rotor with Slip Recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>10,700</td>
<td>13,500</td>
<td>22,100</td>
</tr>
<tr>
<td>75</td>
<td>12,300</td>
<td>15,500</td>
<td>22,300</td>
</tr>
<tr>
<td>100</td>
<td>12,300</td>
<td>20,500</td>
<td>25,500</td>
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<tr>
<td>150</td>
<td>16,500</td>
<td>23,300</td>
<td>29,300</td>
</tr>
<tr>
<td>200</td>
<td>16,500</td>
<td>30,000</td>
<td>30,400</td>
</tr>
</tbody>
</table>

**SHAFT ORIENTED CONTROL**

The first two methods of shaft oriented control, adjustable speed pulley system and mechanical adjustable speed drives, have seen little if any application in geothermal or well pumping projects and will not be addressed here.

**Eddy Current Coupling**

As a shaft oriented device, the eddy current or magnetic coupling is placed between the driving motor and the driven shaft. The coupling consists of rotating input and output portions which are not mechanically coupled. DC current from an external field coil excites the winding on the output member. This induces eddy currents in the input member, resulting in a torque at the output shaft. Flow control is accomplished by adjusting the field current. An eddy current coupling is considered a "slip loss" type device. The slip loss is a function of the transmitted torque and the "slip" or the difference in the speeds of the input and output shafts as follows:

\[ \frac{2\pi \times (\text{rpm out} - \text{rpm in}) \times T}{33,000} = \text{Slip Loss} \]

It is apparent that for constant torque loads or for large slips (speed reduction) this loss is a significant value. In fact, the overall efficiency of the eddy coupling can never exceed the ratio of output to input speed. Because of the slip loss, this type of device is best applied to loads which do not experience a large speed reduction. In addition to slip loss, the eddy current coupling also experiences friction and windage losses of approximately 1.5% of input rating. This loss is constant over the entire speed range. Losses which result from excitation are very small and decrease with output speed. Figure 3 shows a plot of eddy current coupling efficiency versus % speed.

**Figure 3. Performance of Eddy Current and Fluid Couplings**

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In order to obtain overall system efficiency, pump and motor efficiency would have to be considered. For example, a motor driving a pump with a 50 hydraulic horsepower requirement at 75% speed and 50% torque, drive efficiency from Figure 3 would be 73.6%. Assuming a 60% pump efficiency and 90% motor efficiency, this would result in an input requirement of 50/(.738 x .90 x .60) = 125 horsepower or 93.6 kW. It is apparent from the slip loss nature of the eddy current coupling that it is best applied in situations where output speed is in the 75% or above range. Costs for eddy current couplings are shown in Table 1. Maintenance requirements for eddy current couplings are relatively low since there are no external moving parts or equipment requirements.

Fluid Coupling Systems

The fluid coupling falls into a class of fluid drives known as hydrokinetic drives. Like the eddy current coupling, the fluid coupling consists of input and output members which are mechanically independent. The impeller or input member accelerates the oil which then enters the runner or output member where it is decelerated and the kinetic energy in the fluid is converted into shaft power. The level of oil in the impeller/runner area varied by a scoop tube to adjust speed output. Lost energy or inefficiency is dissipated as heat. This heat is rejected to an external heat exchanger, supplied by a small oil circulating pump. Speed reduction capabilities are 4:1 with a constant torque load and 5:1 with variable torque loads. Sizes range from five to several thousand horsepower. As with the eddy current coupling, the fluid coupling is a slip loss type device. Efficiency is primarily a function of the slip or the difference in the input and output shaft speeds. In addition, losses amounting to approximately 1.5% of unit rating are experienced due to parasitic loads for oil cooling and circulating. Figure 3 illustrates typical unit efficiency. The values are very comparable though slightly less than those of the eddy current coupling. Steady state and annual energy calculations are similar to those of previous sections. Costs for fluid couplings are shown in Table 1. Maintenance requirements of the fluid coupling itself are relatively low. However, the external heat exchanger and circulating pump increase requirements above those for the eddy current coupling.

SYSTEM EXAMPLE

In order to evaluate the relative merits of some of the above speed control technologies, the following example has been prepared. Information was taken from a well currently operated by Oregon Institute of Technology having the following characteristics:

- Static water level: 360'
- Drawdown: Minimal-not considered
- Peak production rates: 450 gpm
- Well head pressure: 20 psi constant
- Motor horsepower: 75
- Duty cycle: as in Table 2
- Pump efficiency: varies
- Motor efficiency: Assumed constant @ .90

This well supplies 191°F geothermal water for use in winter space heating and summer cooling (via an absorption chiller), and a very small amount of domestic hot water heating. Based on the information above and that contained in the pump curve, four methods of flow control were compared. These included throttled output, wound rotor motor with slip recovery, AC variable frequency control and fluid coupling. Calculations for electrical consumption were made at each production level and summed to arrive at annual use as suggested in the previous sections. The results of these calculations were: throttling = 473,614 kWh/year; fluid coupling control = 298,306 kWh/year; AC variable frequency = 243,816 kWh/yr and wound rotor with slip loss recovery = 226,042 kWh/year. It is important to point out that this example is based on a 100% static head. As a result, savings are not as great as would be expected if there was a large friction head on the system. The wound rotor motor with slip loss recovery shows the best performance followed closely by the AC variable frequency control. The fluid coupling does surprisingly well in this case. This is due to the combined effect of the pump performance and large static head. The minimum speed of the pump in this example is approximately 70% of full speed. Since fluid coupling efficiency is primarily a function of input and output speeds, efficiency stays high. In a situation in which there is a lower minimum shaft speed, a greater difference would be seen between the variable frequency drive and the fluid coupling. Figure 4 shows the energy requirement in kW versus percent peak flow for each of the four control methods.

![Figure 4. Electrical Requirements for Various Flow Control Techniques on OIT Well #5](image-url)
For comparison purposes, theoretical energy requirement is also shown. This is based upon hydraulic horsepower converted directly to kW (i.e. assuming 100% pump and drive efficiencies). As with any energy saving strategy, the magnitude of the energy savings is only one part of the story. Costs for maintenance, energy and capital are equally important. In order to evaluate the options discussed above, in this light, life cycle costs have been calculated for three of the systems (current costs for wound rotor slip loss recovery were not available at the time of this writing). Table 3 summarizes the input.

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Capital Cost</th>
<th>Maintenance</th>
<th>Electrical Use Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Throttling Valve</td>
<td>0</td>
<td>24 $/yr</td>
<td>21,313 $/yr</td>
</tr>
<tr>
<td>Fluid Coupling</td>
<td>$11,000</td>
<td>330 $/yr</td>
<td>13,424 $/yr</td>
</tr>
<tr>
<td>AC Frequency Drive</td>
<td>16,000</td>
<td>240 $/yr</td>
<td>10,972 $/yr</td>
</tr>
</tbody>
</table>

Inflation at 5% per year
Electrical inflation at 2% per year (real)
Maintenance at 0% per year (real)

The incremental investment in the fluid coupling over the throttling valve shows a cumulative 20 year savings of $335,428 ($115,636 discounted at 10%) and a simple payback of 1.15 years. There is no question that the fluid coupling would be the wiser approach of the two. The incremental investment in the AC variable frequency drive over the fluid coupling shows a cumulative 20 year savings of $110,682 ($38,295 discounted at 10%) and a simple payback of 1.79 years. Due to the simplicity of the analysis, these two figures, 1.79 vs 1.15 years, can be considered equal. As a result, the choice between the fluid coupling and variable frequency drive would be based on other considerations such as maintenance, ease of installation, torque speed requirements, etc.

CONCLUSION

In conclusion, the choice among the various drive technologies available is a function of a host of project specific parameters. The information presented in this article along with pump and well information from your project should permit an accurate analysis to be carried out. The results of this analysis can then be employed in an informed decision making process.

REFERENCES


