APPLICATION, CONTROL, AND SET-UP OF VARIABLE FREQUENCY DRIVES FOR ELECTRIC SUBMERSIBLE PUMPING APPLICATIONS IN THE SALT CREEK FIELD UNIT

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Abstract:

This paper will describe the sizing techniques for field applications using variable frequency (speed) drives (VFDs or VSDs) with electric submersible pumps (ESPs). The field installations will be described along with reservoir and production information. Then the controls available with the VSD's and their uses will be discussed. Finally the various control and transformer settings for different applications will be presented.

Introduction:

Salt Creek Field Unit (SCFU) is located in Kent County, Texas and is approximately 45 miles north of Snyder, Texas. Salt Creek Field Unit produces from the canyon limestone at an average depth of 6300 feet. The field was originally discovered in 1950 and was subsequently developed to a 20 acre inverted five spot waterflood. Carbon dioxide injection began in November 1993 and is expected to continue beyond the year 2000. Currently, there are 144 ESPs operating in this field.

The water alternated with gas (WAG) cycles in the CO_2 flood have caused some very dramatic changes in wells. Some individual producing wells have very wide swings in production as offsets are "wagged" (switched from water to gas or gas to water). Changes seen as a result of CO_2 breakthrough are as follows.

1. Higher gas to liquid ratios (GLRs) result in higher friction loss up the tubing. In order to provide the additional lift for these losses the pump must operate further to the left on the head capacity curve at a lower producing rate.

2. Higher GLRs also create a much higher wellhead pressure due to the increase flowline friction (Especially in wells which produce over 4000 STBPD and over 1 MMSCFPD). This problem also results in the pump producing to the left of the recommended range.

3. Wells with high CO_2 breakthrough rates, which are pumped off, (pump intake pressures less than 300 psig) cause severe wear on the pump and produce excess volumes of gas. In several instances, the pumps are compressing the gas in the lower stages, operating to the far right side of the head capacity curve in upthrust, and moving liquid CO_2 in the top stages and operating on the left side of the head capacity curve in down thrust.

4. An increase in scale ($CaCO_3$) , solids (Fe and polymer) and asphaltene production has been noted in several parts of the field. A good indication of this is an increase in amperage as seen on the recording amp-chart. This usually results in the chemical treatment of the well.

5. Pumps producing with pump intake pressures over 1300 psig are pumping liquid CO_2. Gas separators become ineffective under these

conditions. As the CO_2 moves up the tubing it loses pressure and changes into the gas phase, which further complicates the tubing friction calculation.

The use of variable frequency controllers (VFDs) in this field has dramatically helped the ESPs adjust to the these changing producing environments. The VFDs also help engineers in sizing equipment because they provide a much wider range of operation for individual ESPs. This is especially beneficial during "add pay" workovers or new well completions in the CO_2 flood area.

VSD Sizing Techniques:

Sizing can be divided into new installations and placing VFDs on existing ESP wells. Sizing the new installtion will be discussed in this paper. Sizing a new variable speed electric submersible pump can be accomplished by using the following set of rules.

1. Based on the casing drift, determine the diameter (or series) of the ESP equipment.

2. Decide upon a desired producing range at desired pump intake conditions.

3. Use the pump curve software or manufacture's catalogs to find a pump that covers the desired producing range at a lift per stage closest to the best efficiency point for that pump. It is important that the pump is in range at the <u>minimum</u> desired producing rate. References 2, 3 and 4 all address the consideration of down thrust and how it can decrease the life of the pump at higher speeds (RPM). The technical aspects of these papers can be generalized with the following "rule of thumb". For best operational life, the lift per stage should be at or about the lift per stage at the best efficiency rate on the 3500 RPM (60 HZ) catalog curve.

4. Determine the approximate worst case total dynamic head that the pump must develop. Select the number of stages for the pump so that the lift per stage is at or about the lift per stage at the best efficiency point rate on the 3500 RPM curve (60 HZ).

5. Select a motor that will accommodate the highest desired producing rate. The highest design rate (BPD) will of course occur at the maximum design frequency.

The following is an example to illustrate this procedure. The Pump Curve Software will be used. (An address is located at the end of the paper for obtaining this free Windows based program.)

Given:
- 6300 ft. to the perforations
- 7 inch, 26lb casing
- 2-7/8 inch tubing
- 75 PSI surface tubing pressure
- 1.04 average specific gravity through the pump
- A producing rate of 500 to 1200 BPD with 300 psig pump suction pressure.
- Pump is set just above the perforations.

Solution:

1. Since the casing is 7 inch with a drift diameter of 6.151 inches, 400 series (4.00 inch) or 500 series (5.40 inch) pumps can be

examined for the application. Four inch diameter pump types start with the prefixes TD, D, DN, R, and FC on the pump list in the Pump Curve software. The 5.4 inch diameter pumps start with the prefixes TG, G, GN, K, and GC. The number in the pump name represents the barrels per day (or the BPD/100) where the pump is most efficient at 3500 RPM. This is the center of the pump's recommended producing range.

2. The desired producing range of 500 to 1200 BPD is given. A desired pump intake or suction pressure of 300 psig will be assumed.

3. For the pump selection start with the lowest rate 500 series pumps which are the TG2000, GN1600, K16, and the GC1200. The general rule is that for a given pumping rate the larger the diameter of the equipment the lower the cost. However, all of these pumps produce at rates higher than the 500 BPD minimum that is desired. Therefore, only the 400 series pumps will be examined.

The 500 BPD rate will be the controlling number for the initial search. Pumps should be selected that will produce down to 500 BPD and stay in range with a reduction in RPM or hertz. This leads to the following short list of pump types.

TD450, TD750, DN450, DN610, DN800D, RC5, R7, FC470, FC650

Figure 1 is the single stage performance for the first pump, a TD450. Using the "rule of thumb" given in step 3 above, enter the curve at the best efficiency rate of 450 BPD and move up to the 60 HZ curve. The lift per stage at the best efficiency rate is 18 feet per stage. Next, move horizontally to the left until the minimum rate line is intersected. This occurs at just under 320 BPD. This is the minimum rate for this lift. Since 500 BPD is as low a rate as needed, the next pump curve should be examined.

Figure 2 is the single stage performance for a TD750 pump. Entering the curve at the best efficiency rate of 750 BPD and moving up to the 60HZ curve, a lift per stage of 23 feet is found. Moving horizontally to the left, the minimum range line is intersected at about 520 BPD. Moving down the recommended range line to 500 BPD a lift per stage of about 21 feet is found. Using 21 feet as the worst case lift per stage would keep the pump in range at the minimum rate of 500 BPD.

Now the maximum rate can be determined. Following the 21 foot per stage line back to the right in Figure 2, it intersects the maximum recommended rate line at about 1080 BPD and around 68 HZ.

In reference 1 Wilson and Liu point out that a pumps useful performance may be greater than the published curve indicates. This is due to the fact that most submersible oilwell pumps are designed to have zero thrust at a rate well to the right of the best efficiency point. This means that VSD designs (and 60 hertz designs) may operate to the right of the recommended range without going into upthrust. This could allow the use of the TD750 at 21 feet per stage out to 72 HZ and 1200 BPD. However, field experience at the SCFU has shown that equipment operated out of range on the high rate side has a reduced run life. This design would be limited to a maximum rate of 1080 BPD.

The manufacturer can supply information regarding the rate that a pump moves between up thrust and down thrust for applications where operating to the right of the recommended range may be necessary.

To summarize, the TD750, when staged for 21 feet of lift per stage, can produce down to 500 BPD at 53 HZ and up to 1080 BPD at 68 HZ.

4. Now the total dynamic head is calculated to determine the number of TD750 stages required. The total dynamic head (TDH) is defined as follows:

$$TDH = Psd + Tf + \frac{Tp}{(.433)(SpGr)} - \frac{Psp}{(.433)(SpGr)}$$

Where:

Psd = pump setting depth in feet
Tf = Tubing friction in feet
Tp = Tubing pressure in psig
Psp = Pump suction or intake pressure in psig
SpGr= the average specific gravity of the produced fluid

and for this problem:

Psd = 6250 feet
Tf = 130 feet
Tp = 75 psig
Psp = 300 psig
SpGr= 1.04

$$TDH = 6250 + 130 + \frac{75}{(.433)(1.04)} - \frac{300}{(.433)(1.04)}$$

Solving for a TDH of 5880 feet.

The stages are found by dividing the TDH of 5880 feet by the lift per stage of 21 feet or 280 stages of TD750.

5. Finally the motor horsepower for the pump can be determined. Figure 3 is the performance curve for a 280 stage TD750. The Pump Curve program also calculates the horsepower requirements for the different operating frequencies. For 1080 BPD the pump would be operating at 68 HZ. The horsepower table in the upper right corner shows that the pump will require 103 brake horsepower (BHP) at 68 HZ.

The table also shows that a 91 name plate horsepower (NPHP) motor at 60 HZ could be used. This is because the submersible motor's name plate horsepower varies in proportion to the frequency applied when the name plate voltage is varied in proportion to the applied frequency.

The horsepower could also be calculated from the single stage curve. Figure 4 is the single stage 3500 RPM curve for the TD750. The maximum horsepower is .25 BHP per stage.

The required BHP is calculated as follows:
Note that there will be a small difference because reading the curve instead of calculating a point on the curve.

$$BHP=(Stages)(SpGr)\left(\frac{BHP}{stage}\right)\left(\frac{Hertz}{60}\right)^{3}$$

or

$$BHP=(280)(1.04)(.25)\left(\frac{68}{60}\right)^{3}=106$$

and the 60 hertz motor to select is calculated next:

$$NPHP=(BHP)\left(\frac{60}{HZ}\right)=(106)\left(\frac{60}{68}\right)=94$$

In summary, a 280 stage, TD750 pump and 100 horsepower motor has been selected to produce as low as 500 BPD at 53 hertz and as high as 1080 BPD at 68 hertz while still providing the 5880 feet of TDH. Below is a list of the other pump types for this application.

235 stage DN800D, 100 horsepower motor, 56 - 70 hertz
218 stage R7, 80 horsepower motor, 56 - 70 hertz
226 stage FC650, 80 horsepower motor, 57 -76 hertz

It should be noted that operation at the lower hertz and rates can cause the motor to operate near no-load or idle amps. This can make underload detection difficult. Under these conditions the voltage to the motor should be adjusted down so that the motor rating is closer to the load. This will allow for underload detection. If this voltage adjustment still does not allow for adequate underload protection then the unit would not be allowed to run at the reduced hertz.

Variable Frequency Basics

The configuration of variable frequency drives for ESP applications differs in several ways from the typical surface motor application. A typical setup consists of a step-down transformer, VFD, multi-tap step-up transformer, and junction box as shown in Figure 5.

The step-down transformer changes the high-voltage incoming power to 480 volt power for the VFD. This transformer must be rated for the full KVA load and capable of providing 480 volts power to the VFD.

A variable frequency drive performs the simple function of converting a constant voltage, constant frequency input to a variable voltage and variable frequency output. The output of the VFD may vary with frequency during operation, but will not be less than 480 volts at full speed.

Voltage vs Frequency

The relationship of voltage to frequency is the primary consideration for power applied to any induction motor. Fortunately this relationship is linear under normal operating conditions.

For an induction motor to maintain the rated torque vs. speed characteristic, the proper voltage must be applied at each frequency. Therefore the motor should be operated at a certain ratio of voltage to frequency, expressed as the Volts/Hz ratio. All variable frequency drives have adjustable voltage/frequency controls, although exact terminology may vary. Some VFD manufacturers allow adjustment of voltage for a given output frequency while others may provide for varying the frequency for a certain output voltage (Hz/volt). Whatever method is used, the proper ratio must be set in the field.

Adjustment of the voltage/frequency ratio is done at two points in the electrical equipment chain. The coarse adjustment is done by selecting taps on the multi-tap step-up transformers. Final adjustment is accomplished by adjusting the VSD controls. More about this procedure will be explained later.

Voltage Boost

The critical voltage at a given operating frequency is not the VFD output voltage or transformer output voltage, but the voltage in the motor which produces magnetic flux across the gap between rotor and stator. Resistance internal to the motor, cable resistance, and transformer impedance all result in voltage drops which reduce the effective voltage applied to the motor. This voltage drop is proportional to load current, not frequency. Therefore the output voltage of the VFD must be adjusted upwards to compensate for the various load dependent voltage drops. This alteration of the linear voltage/frequency relationship is called *voltage boost or V-boost.*

Variable frequency drives have adjustable controls to determine the amount of voltage boost which is applied. Voltage boost is most important in order to obtain enough torque to start the downhole equipment, a sometimes difficult proposition on deep, sandy, or high temperature wells. Voltage boost is usually used only during motor starting, but may be applied continuously in proportion to motor current, known as IR compensation in some industrial applications. See Figure 6.

Transformer Considerations

The transformers selected for variable speed application must be rated at sufficient KVA capacity over the desired operating range. The step-up transformers must be designed at a volts per hertz ratio to allow for the voltage boost described above. A normal 480 volt 60 hertz step-up transformer would have a volts per hertz design number of 480/60 = 8. VFD step-up transformers are usually designed with a volts per hertz number of 12 or higher to allow for voltage boost. This is the same as designing the transformer for 40 hertz operation therefore increasing the iron content and cost. Without this increased iron the transformer would saturate if boost voltage was applied and the ESP would not get the additional voltage for starting.

The KVA of the VFD and step-up transformer should be matched.This means that the full load amps of the VSD is the same as the full load amps of the step-up transformer.

Use of a step-down transformer which is too small may result in voltage sags to the VFD input during the starting of the downhole equipment.

Transformer Tap Setting

The procedure to determine how to set transformer taps is sometimes confusing to the casual observer. One may hear a VFD technician refer to tapping a transformer to 70 Hz, but the taps on transformers are marked in voltage units, not frequency. The explanation is that the transformer is tapped to provide the correct voltage to the motor up to a particular speed.

In other words, a transformer tapped to 70 Hz will produce the correct voltage for the motor at 70 Hz when the VFD is at the maximum output voltage, normally 480 Volts. If the voltage/frequency ratio remains constant, the VFD will produce 60/70 of full maximum output voltage or 411 volts at 60 Hz.

When selecting transformer taps, an iterative process is used to evaluate the various tap settings until a satisfactory setting is obtained. The maximum desired frequency is used to calculate the desired voltage at the motor terminals at that frequency. Then the voltage drop at full load due to cable resistance is added, resulting in desired output voltage from the transformer at maximum frequency (and VFD maximum output voltage). This is the voltage from the transformer with maximum VFD output voltage, so the nearest tap may be selected.

Example:

Consider the case where 210 HP is desired from a 150 HP motor at 84 Hz.

Motor Specifications : 150 HP, 60 Hz, 1240 Volts, 76 Amps.

The voltage drop for 6300 ft of #2 Cable, 76 Amps, 150°F is 156 volts.

The surface voltage should be:

$$1240\left(\frac{84}{60}\right)+156=1892$$

The power required is then.

$$1.892KV(76Amps)(1.732)=249KVA$$

This value must not exceed the KVA ratings of the VSD or transformer. An additional 2% can be added to cover the loses in the step-up transformer making the maximum KVA out of the drive 254 KVA. An additional 5% drive losses is added before sizing the step-down transformers the step down transformers would need to be at least 267 KVA.

A 250 KVA VFD and step-up transformer are rated at 480 volts and 300 amps. With a typical step-up transformer, Delta input, taps 9 & 8 provide 1860 volts out for 480 volts input. In the field, the VSD volts/Hz (or Hz/volt) must be set to provide 480 volts output at 84 Hz. The technician may run the VSD to 60 Hz and set the output voltage to the correct 60 hertz value.

(480 Volts)(60 Hz / 84 Hz) = 343 Volts at 60 Hz.

This transformer ratio is then 480 volts / 1860 volts = 1 / 3.875 = 0.2581
The VSD current out at full load motor current will then be (76 amps)(3.875) = 295 amps. *This current must not exceed the ratings of the VSD.*

Suppose the gravity of the pumped fluid increases, causing higher pump and motor loading so that 76 amps full load motor current occurs at 76 Hz. Note that the maximum VSD current rating will also be reached. The power available from the VSD has decreased to:

(295 amps)(480 volts)(76 Hz / 84 Hz)(1.732) = 221 KVA

Notice that the VSD is running at maximum current output, but only delivering 88% of rated KVA. The solution is to change the transformer tap settings to better match the source to the load.

According to the pump affinity laws, the power required varies with the cube of the speed. Therefore the transformer taps can be changed accordingly.

New maximum speed = (76 Hz) (250 KVA / 221 KVA)^(1/3)
= 76 Hz (1.042) = 79 Hz.

Again, calculate the required surface voltage .
(1240 volts) (79 Hz / 60 Hz) + 162 volts = 1795 Volts.

The transformer taps at 8 & 8 provide 1800 volts out with 480 volts input. The transformer has been re-tapped to 79 Hz".
The new transformer ratio is now 1800 volts / 480 volts = 3.75.

The VSD volts/Hz (or Hz/volt) must now be changed to provide 480 volts output at 79 Hz.
(480 Volts) (60 Hz / 79 Hz) = 364 Volts at 60 Hz.

Maximum motor current when VSD reaches full current rating is :
300 amps / 3.75 = 80 amps
With the new transformer tap setting, the VSD reaches full current rating when the motor is 5% overloaded. This is acceptable in many cases.
After start up, the VSD technician may adjust the volts/Hz ratio to minimize the motor current. For any given frequency and load , there is an optimum motor voltage at which the current will be minimized. If

this volts / Hz ratio is too low, the unit may be difficult to start unless voltage boost is utilized.

Current Limit

There are at least two "current limits" on most VFDs used for submersible applications. Current limit is sometimes referred to as I-limit. The VFD itself will have a current limit intended to protect the VFD components from over current. This is a safety feature provided to limit damage to equipment in the event of a failure on the load side of the drive. Most drives are capable of running safely for a limited time while connected to a short circuit. The protective current limit reduces the output voltage so that a limited amount of current flows in the output for some period of time after which the drive shuts down. This is sometimes referred to as "hardware current limit", even though modern drives may perform the function in software.

While not used at the SCFU, a second type of current limit is an operating feature for handling gassy conditions downhole. The current limit is set along with the maximum and minimum operating hertz. the VFD will then change frequency to try to maintain the current limit setting. If gas enters the pump, the resulting drop in motor current will cause the VFD to speed up to maintain the set level of motor current and, hopefully, move the gas through the pump, avoiding a gas-lock condition. Normally the speed is fixed and current allowed to vary, but in this mode of operation, the VFD varies the speed to maintain constant current.

Underload

Using some fraction of nameplate motor current may not be a good method of detecting a pumped off condition when using a variable speed drive. It could be that a unit would draw more than (60 Hz) idle amps even while pumped off if running at higher speeds. One common rule of thumb is to set the underload at 85% of "running" current. This should be done after any volts/Hz adjustments are made to match the motor to the load as mentioned in the sizing example above.

Controllers

Variable frequency drive vendors may include a controller designed specifically for submersible pumping applications. The controller is usually a microprocessor based circuit board or boards which determine the operating frequency based on motor current, bottomhole pressure, external inputs, etc. The most basic function of this component is to provide the operator with a method of setting drive speed and operating limits, and to display output current, motor current and measured frequency. Functions of the controller may also include the following :

Start/stop logic including timers, bypasses, etc.
Bottomhole pressure control
Flow line pressure or flow control
Critical Frequency Avoidance
Communications via radio or modem

Remote Speed control

It sometimes happens that the desired function is not provided by the VFD controller on hand. In this case, a programmable logic controller or PLC may be added to accomplish the additional control function.

Summary:

The variable frequency drives in use at the Salt Creek Field Unit have allowed for increased flexibility in the production operations. The VFDs must be set-up properly to provide the longest life for the downhole equipment. They must also be sized properly with the other surface components.

References:

1. Wilson, B. L., Ching-Chio Liu, Joseph, "Electric Submersible Pump Performance Using Variable Speed Drives", Presented at the 1985 ESP Workshop, April 9 and 10, Houston, Texas, Sponsored by the SPE Gulf Coast Section - Northside
2. Kobylinski, Lee, "The effect of Speed Variation on the Operating Range of Submersible Pumps", Presented at the 1988 ESP Workshop, April 28 and 29, Houston, Texas, Sponsored by the SPE Gulf Coast Section - Northside
3. Powers, M. L., "Effects of Speed Variation on the Performance and Longevity of Electric Submersible Pumps", SPE Production Engineering, February 1987, pages 15 - 24
4. Lea, James F., "Two Methods Extend the Operating Range of ESP's", Oil and Gas Journal, November 27, 1989, Pages 67-71

Software:

For a free copy of the Pump Curve software used in this paper call or write:

Pump Curve Software
David Divine
P. O. Box 80130
Midland, Texas 79709

Off. 915 699-7401
Fax. 915 699-4159

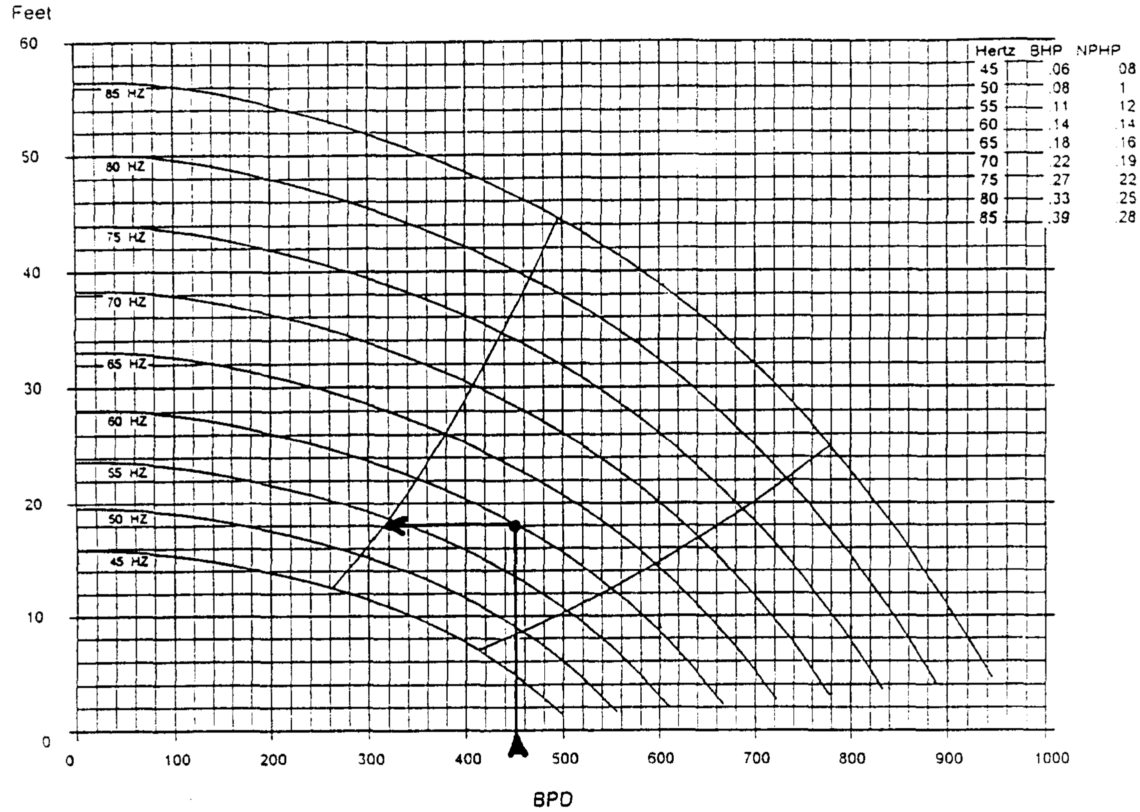

Figure 1 - Pump Performance Curve for a 1 Stage
TD450 at Multi-Hertz; SpGr=1.04

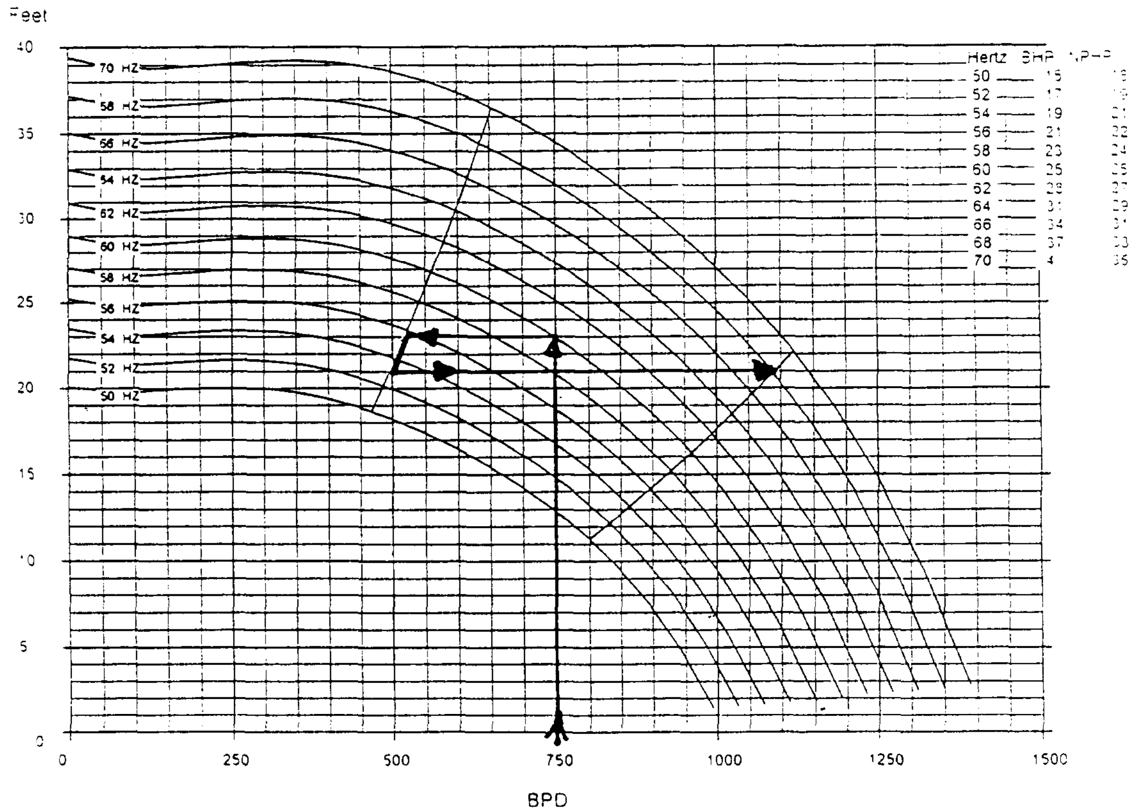

Figure 2 - Pump Performance Curve for a 1 Stage
TD750 at Multi-Hertz; SpGr=1.04

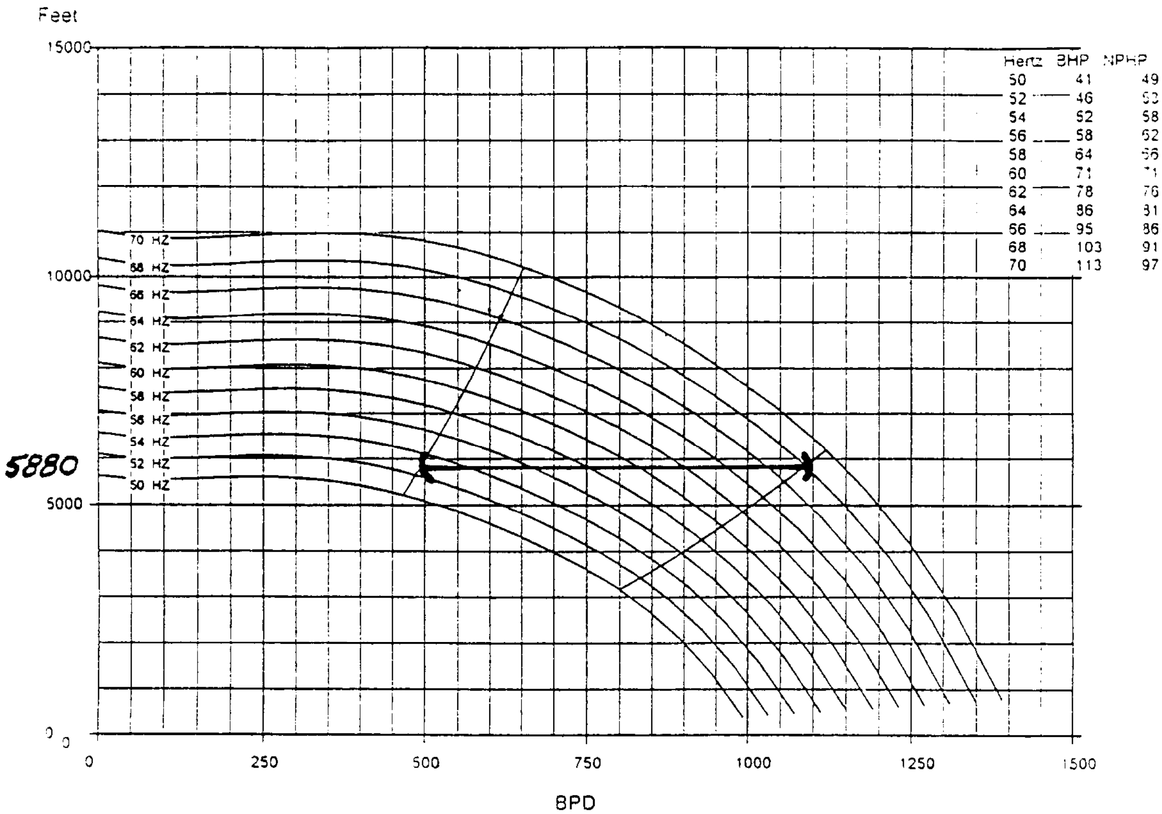

Figure 3 - Pump Performance Curve for a 280 Stage TD750 at Multi-Hertz; SpGr=1.04

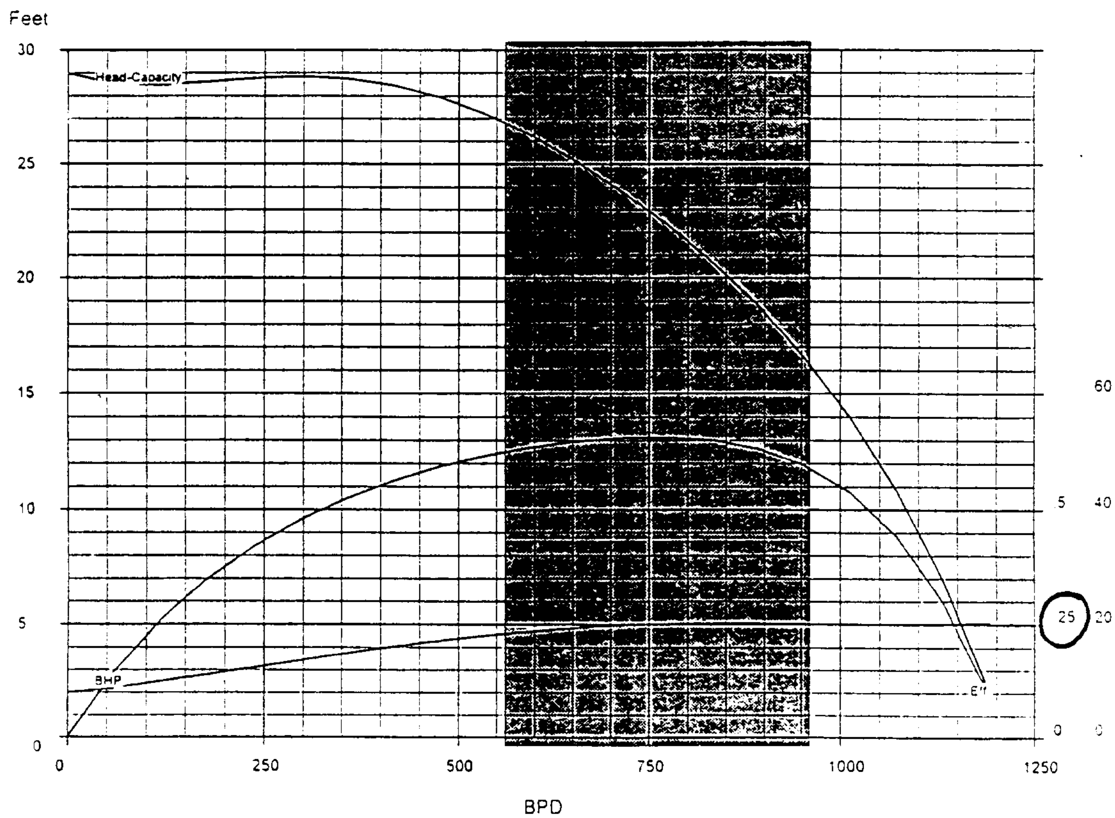

Figure 4 - Pump Performance Curve for a 1 Stage TD750 at 3500 RPM; SpGr=1.04

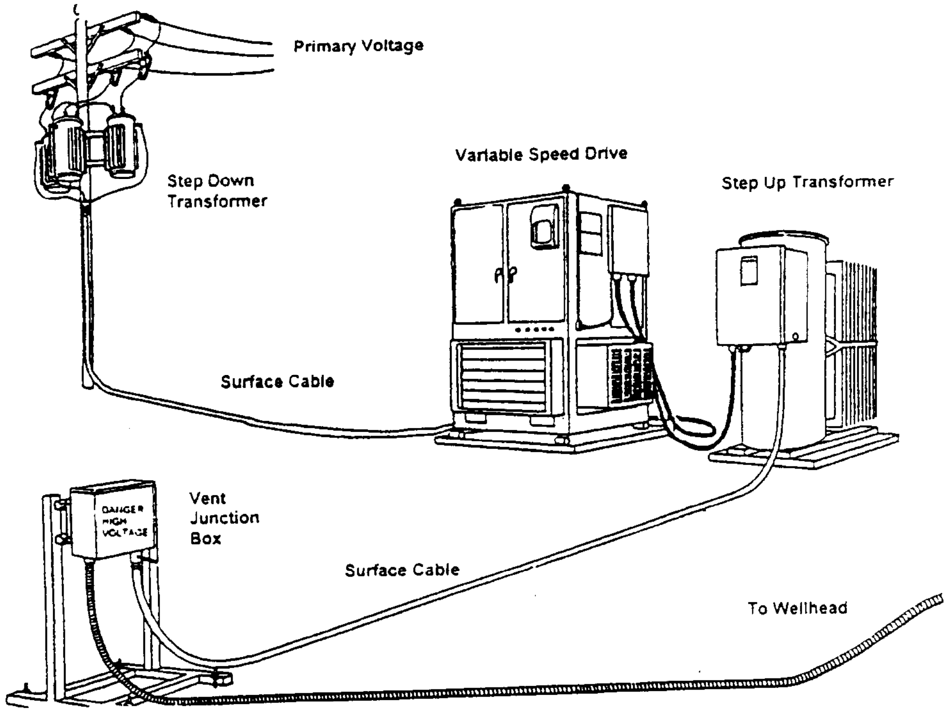

Figure 5 - VSD System Components

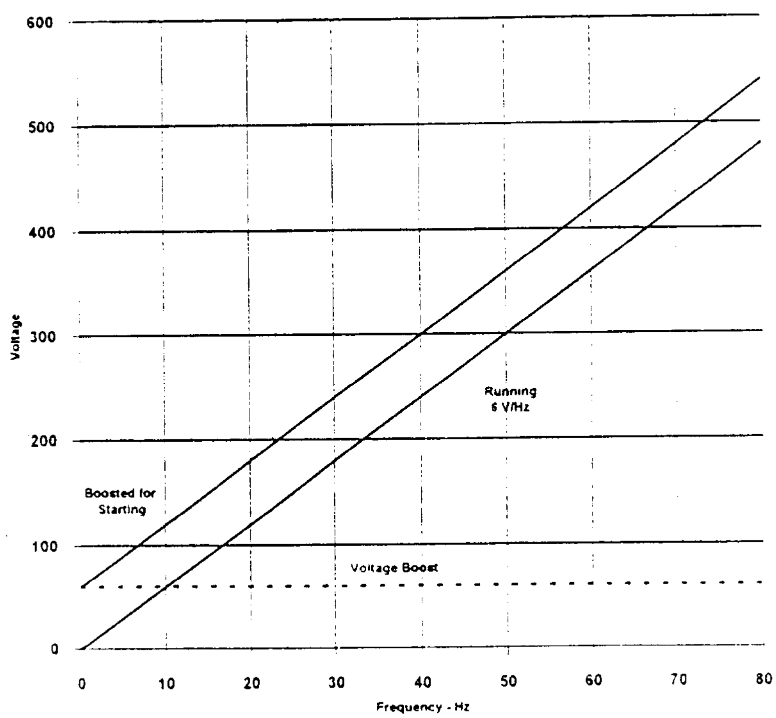

Figure 6 - Voltage vs. Frequency