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VARIABLE FREQUENCY PUMP CONTROLS
SECTION INDEX

VARIABLE RATE PUMPING

Optimum biological treatment of sewage calls for continuous flow-through the treatment plant. Shocks to the system of high flows, or periods of no flow, should be avoided as much has possible. The flow should match, as nearly as possible, the gravity flow-through the sewer system. This, of course, entails either a complete gravity system or some sort of variable rate pumping.

There are also other advantages associated with variable rate pumping. If maintenance to the variable speed equipment can be kept to a minimum, the overall maintenance cost may even be reduced. For instance, bearing life may be greatly extended.

Bearing life is inversely proportional to the speed and directly proportional to the cube of the load. Bearing load varies exponentially with the system curve. Thus, in general, we can only say that the load decreases with speed, life of the bearing, then increases as the cube of the load decreases. Therefore, we at least extend the life of the bearing by the factor of the decrease in speed and, in most cases, by a much greater factor.

Perhaps, even more importantly to the life of the bearings, we eliminate the shock loading at start-up due to the sudden up-thrust on the bearings, which then changes to down-thrust. This happens at a time when the bearings are cold and, thus, not lubricated. Since it is the usual practice to limit pump cycle time to 10 minutes, the above shock loads occur at least 144 times a day, compared to once for a variable rate motor.

That same frequency of operation occurs on the starter contacts. The chief wearing factor on starter contacts is breaking of full motor amps. Since this only happens once per day and then probably at greatly reduced currents, the contact life is also greatly extended. Since these are the wear points of a constant speed station, if we can greatly extend their life without adding too much complexity or more wear points, it is possible to actually reduce maintenance costs.

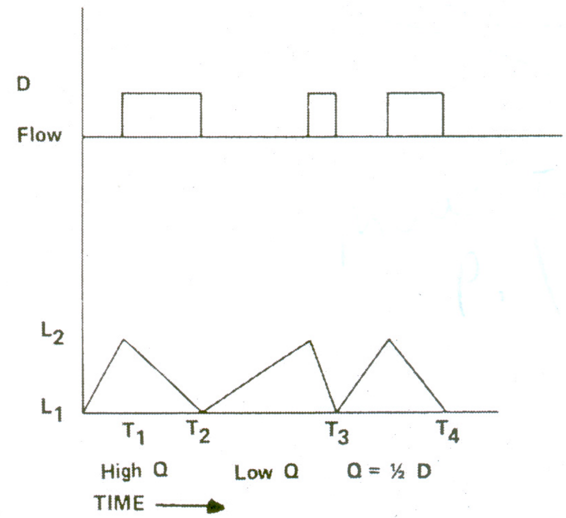

Figure 1

In the above discussion, we briefly mentioned desirable cycling rates. This leads into another area, which involves overall construction costs. That is wet well design and sizing. If we start with the assumption that it is undesirable for retention time in the wet well to exceed 10 minutes under any anticipated condition of influent rate, we can look at a wet well sized for one constant speed pump operation from Figure 1. Level one turns the pump off and level two turns it on. The time the pump is off is then a function of the storage capacity of the wet well between level one and level two and the influent rate. Simply stated: Time off = storage capacity divided by the influent rate, or:

$$T_{off} = \frac{V}{Q_i}$$

Where: V = Storage capacity in gallons.
Q_i = Influent rate in gallons per minute.

The on time of the pump will be the storage capacity divided by the difference in inflow rate and outflow rate, or:

$$T_{on} = \frac{V}{D - Q_i}$$

Cycle time is then time off plus time on:

$$T_{cycle} = T_{off} + T_{on} \quad \frac{V}{Q_i} + \frac{V}{D - Q_i}$$

or

$$T_{cycle} = V \left[\frac{1}{Q_i} + \frac{1}{D -} \right]$$

If we assume constant pump rate and constant influent rate, we find minimum value of T_{cycle} by setting the derivative of T_c with respect to influent rate equal to zero.

$$dt_c = V_s \left[-1\,Q^2 \right] - \frac{1dD + dQ}{(D - Q)^2}$$

$$\frac{dT_c}{dQ} = V_s \left[\frac{-1}{Q^2} + \frac{-1}{(D - Q)^2} \right] = 0$$

$$\frac{1}{Q^2} = \frac{1}{D^2 - 2QD + Q^2}$$

$$Q^2 = D^2 - 2QD + Q^2$$

$$D^2 = 2QD$$

$$D = 2Q$$

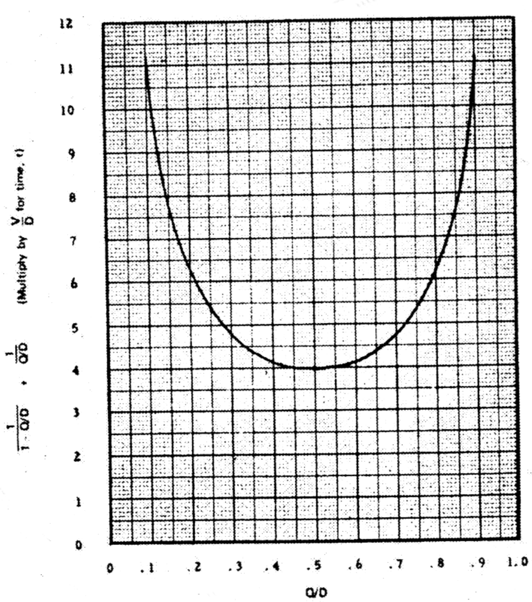

Figure 2

Thus, the minimum cycle time, regardless of wet well storage capacity, occurs when the influent rate is half the pumping rate. For a given pumping rate, we can calculate the minimum storage capacity by substituting Q = 1/2 D into the equation:

$$T_c = V_s \left[\frac{1}{Q} + \frac{1}{D - Q} \right]$$

$$T_c = \left[\frac{1}{2} D + \frac{1}{D - \frac{1}{2} D} \right]$$

$$V_s = \left[\frac{2}{D} + \frac{2}{D} \right]$$

$$V_s = \frac{4}{D}$$

$$V_s = \frac{T_c D}{4} \quad \text{(minimum for any desired pump cycle)}$$

The pump cycle time is limited by the electrical components, starter moving parts, motor windings, etc. As a general rule, it should be no less than 3 to 5 minutes. For very large motors or single-phase motors, it should be even longer. However the trade-off, as the cycle time, is lengthened in retention time of the sewage in the wet well.

For a 2-pump station, where one pump is a standby unit, the pump size or rate D must be able to handle the maximum inflow Q.

The designer then has a minimum pump size, can select a minimum cycle time and, from these, calculates a minimum wet well size.

However, at the beginning of this discussion, we said that we wanted a pump rate D, which matched the gravity flow of the system as nearly as possible. Instead of using the one big step pump rate function of the above 2-pump station, we could use several smaller pumps. This would give a multiple step pumping rate. The effectiveness of this method depends on the slope of the system curve. See Figure 3 for a graphical representation of wet well levels and discharge flows for a 4-pump station. For a perfectly flat system curve, $D_1 = D_2 = D_3$, the greater the slope, the greater will be the difference between D_1, D_2, and D_3.

In actual practice, the pumps would be sized so three of them in parallel would pump the maximum inflow. The fourth pump is a standby.

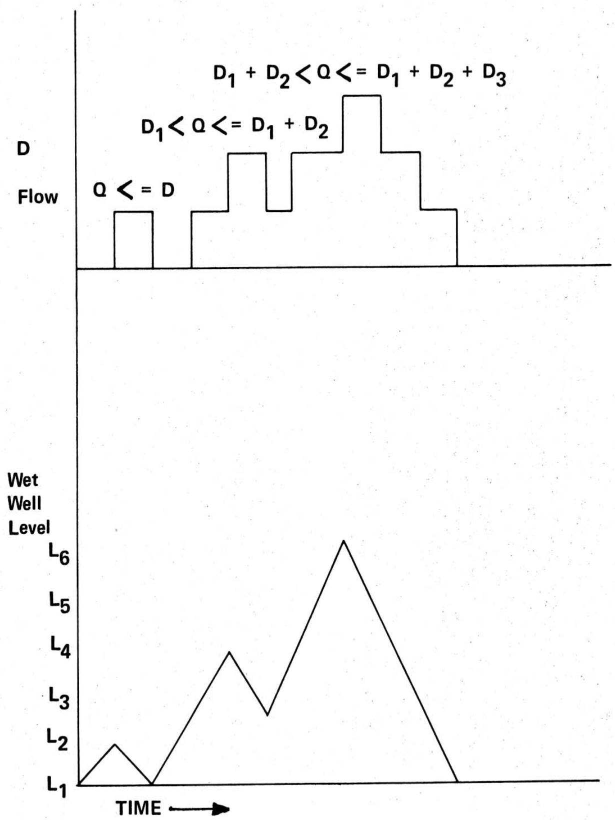

Figure 3

The minimum cycle will be the same or even shorter than one pump (when cycle time had to be extended because of very large motors). Storage is still given by the equation:

$$V = \frac{T_c D}{4}$$

And, since T_c remains constant and D decreases from the 2-pump example, the storage for any one pump is much smaller. However, storage for the wet well would be the sum of $V_1 + V_2 + V_3$. This would, if anything, increase the wet well size. The wet well size can be decreased by overlapping the ranges of each pump so that the number one "On" level is considerably above the number two "Off" level. This also results in a shorter retention time of the sewage in the wet well.

In general, multi-pump constant speed stations allow a somewhat more continuous flow and a somewhat smaller wet well. but the trade-off is more maintenance with more pumps, motors and controls, greater pump station size requirements, more initial expense with more motors, pumps and controls, and greater operating costs, in general, due to lower efficiency with smaller pumps and motors.

The only way to get the pump rate to truly follow the gravity flow of sewage in the wet well is to drive the pump with some sort of adjustable speed device or use an adjustable valve in the discharge to throttle the flow.

Let us first examine the throttling valve. In a 2-pump station, the valve is placed in the common discharge. The pumps are sized so one pump will discharge the maximum flow into the wet well. The control range of the valve is set so that at maximum pumping rates, the valve is wide open. As flow into the wet well decreases, the valve closes in proportion to the wet well level, creating a pressure loss across the valve. This serves to reduce the flow.

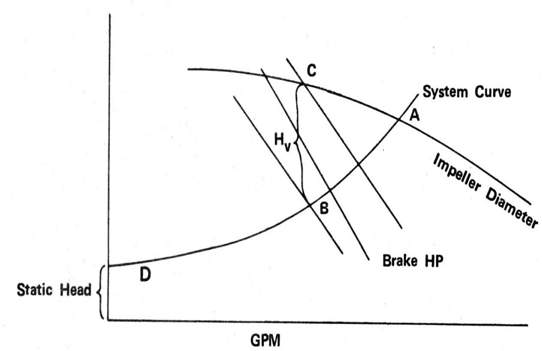

Figure 4

The performance of a throttling valve is given graphically by Figure 4. "A" is the maximum flow rate and the total dynamic head (static head plus friction losses) at maximum flow. "B" is a point at some reduced flow rate. The friction losses at that reduced flow rate will also be reduced. Since the same impeller is being used at the same speed, the reduced flow comes from the added head losses, H_v, across the valve. From the point of view of the pump, it is operating at point "C" not point "B", which is the operating point as seen by the system downstream from the valve. The control valve is set to vary the flow between point A at a maximum flow and point D slightly above zero flow.

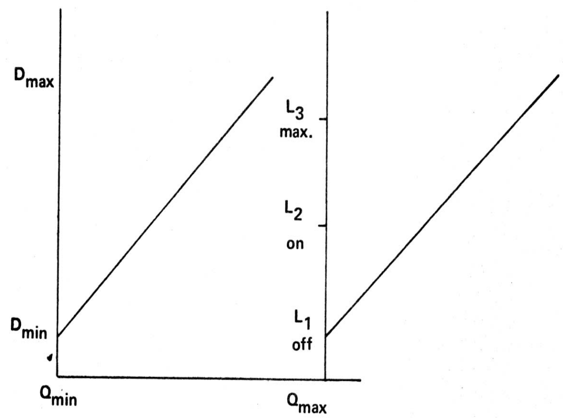

Figure 5

These would correspond to L_1 and L_3 in the wet well level charts of Figure 5; L_2 is on the "On" level. This would give the flow pattern of Figure 5.

This does an excellent job of matching the pumping rate to the flow into the wet well. The disadvantages of this method include very poor efficiency, limited size capability, and a reasonably large number of wear points in the control system. The inefficiency of the system is shown in comparing the brake HP at point C with that at point B. Mathematically, it can be shown to be:

$HP_{in} = \frac{Qh_1}{3960}$ *Power into the throttling valve where h_1 equals pump discharge head.*

$Hp_{out} = \frac{Qh_2}{3960}$ *Power of water on downstream side of valve. H_2 is pressure on downstream side of valve.*

$$eff = \frac{Hp_{out}}{Hp_{in}} = \frac{\frac{Qh_2}{3960}}{\frac{Qh_1}{3960}} = \frac{h_2}{h_1}$$

The losses across the valve are then:

$$HP\ loss = Hp_{in} - Hp_{out}$$

$$= \frac{Qh_1}{3960} - \frac{Qh_2}{3960} = \frac{Q}{3960}(h_1 - h_2)$$

A throttling valve is not as practical for over two pumps because the control range of the valve must be shifted depending on the number of pumps that are in use.

The above statement is not as much the case for most of the variable speed devices. However, for a basic 2-pump station, with one pump sized for maximum flow, the operation of the control is basically as shown in Figure 5. However, looking at a typical pump curve, as shown in Figure 6, and comparing it to Figure 4, we can see the difference in variable speed pumping versus a throttling valve. This time the curve is drawn for one specific impeller diameter, and has a family of speed curves. Instead of operating at various head vs. flow points, along the proper impeller diameter as we did in Figure 4, this time we operate at various speed points along the system curve (i.e., still along the line AD). Comparing the operating point B in the two figures, in the case of the variable speed device, the pump actually operating at point B whereas, in Figure 4, the pump actually operated at point C. It is obvious then that no matter what the slope of the system curve is, less horsepower will be consumed, using variable speed pumping than using a throttling valve. This does not take into account, of course, the horsepower wasted by the driver, motor or motor and variable speed device.

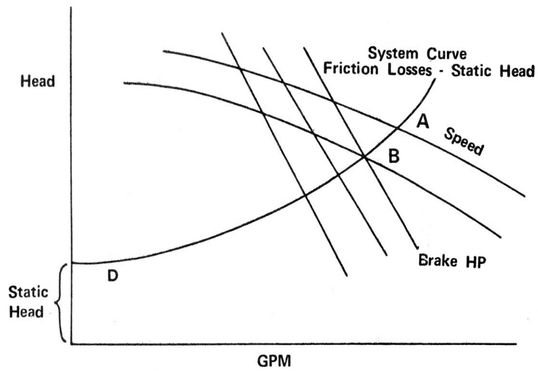

Figure 6

Let us now consider the case where more than one pump runs at a time (3-or-more pump station). To do this, we must go back and look at the use of wet well level as a device for measuring flow into the wet well and controlling pump output. The change in wet well is actually only a measurement of the difference between pump station discharge and inflow to the wet well. The actual wet well level is not proportional to anything, except how deep the water is in the wet well. When we wet a proportional pumping range between two levels L_1 and L_3, the response speed is going to be faster to correct for differences. Of course, if the range is too small, the speed-adjusting device may not keep up with change.

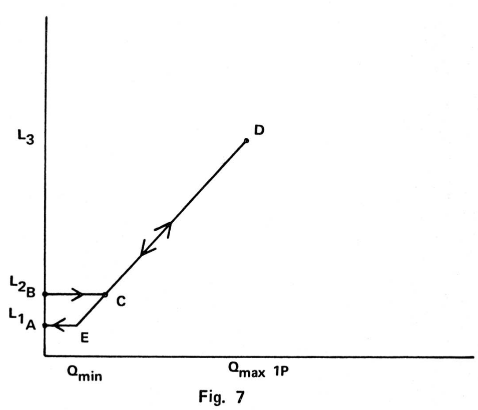

Figure 7

Let us observe the wet well level when more than one pump runs. Figure 7 shows one pump operation with flow varying along line DE with changes of wet well level. When level reaches L_1 (“off point”) up to L_2 (“on” point), the flow varies along line AB (remains zero). As the level reaches L_2 (pump “on”), the flow goes along BC and then is varied along DE as before.

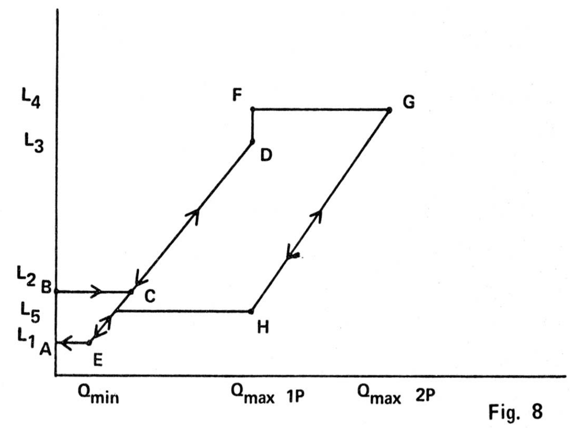

Figure 8

From Figure 8 flow varies along the same lines ABCDE as long as the flow into the wet well is less than Q_{max1p}. When it exceeds Q_{max1p}, wet well level rises to level L_4, with no change in Q, then jumps to G. This jump occurs with either two variable speed pumps or one variable speed and one constant speed if the control range of both variable speed devices is set to operate between L_1 and L_3 as is usually the case to facilitate alternation of pumps. The amount of the surge depends on the cross-sectional area of the wet well and the speed of response of the variable speed controller. As level in the wet well drops, flow varies between G and H. When the shutoff point of the second pump is reached, flow drops back to line ED and then varies along it. The slope of line GH depends on the system curve. With a flat system curve it would parallel ED; the sharper the system curve, the shorter line FG would be and the higher L% would be. L_5 or H is set slightly above zero pumping rate as is point E. This means that for influents between Q_{max1p} and Q_H, cycling of the second pump will occur. This is exaggerated if Q_{max1p} is greater than the full-speed pumping of the variable speed pump (if the variable speed pump cannot reach 100% of speed). It is minimized, and even eliminated entirely, if the variable speed pump is capable of pumping more than the constant speed pump (is a larger pump or has over 100% speed capabilities).

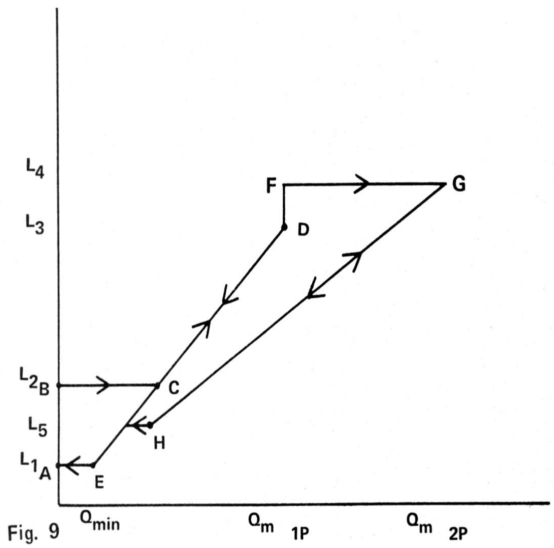

Figure 9

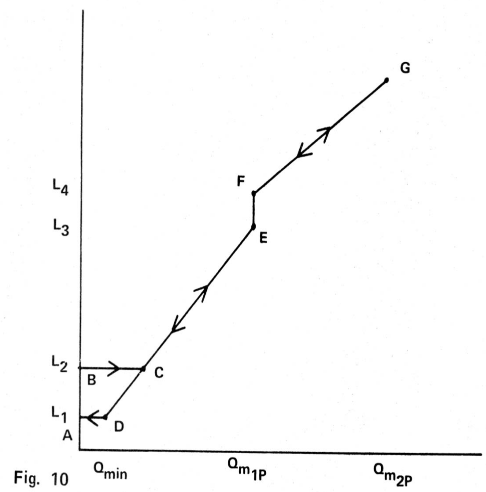

Figure 10

Figure 9 shows 2-pump operations, for the case of two variable-speed pumps with a common operating range. Operation varies along ABCDE, as before, if only one pump is called for. When flow to the wet well exceeds Q_{max1p} level rises to L_4 and flow surges to G, then drops back and varies along GH to match flow to the wet well with both pumps running at the same speed. As long as point H is selected below Q_{max1p}, there will be no cycling, but the surge of pumping at L_4 will occur.

Figure 10 shows use of two variable speed pumps with staggered control ranges, where flow varies as before with one pump running. Then, as before, when the inflow exceeds the capability of the one pump, level builds to L_4, and the second pump comes on. However, since it has a separate control range from the first, it varies along FG. The length and slope of FG, of course, would vary with the system curve. Properly planned, the pumps can be alternated between the controls so as to keep the second motor lubricated. If a perfectly straight line, C, D is desired, it can be obtained with a duplex or triplex variable frequency drive with dual control range. The 110% overspeed capability prevents pump cycling and the added advantage of one motor running at full speed usually gives extra efficiency. It also becomes more economical, because it can be used with only one controller. This is a disadvantage, of course, if it becomes disabled. In order to have the capability of a perfectly straight line with two equal sized pumps, the overspeed capability must be present.

SPECIFICATION
TWO-PUMP STATION WITH VARIABLE FREQUENCY CONTROLS

OPERATING CONDITIONS

The two variable speed pumps shall each be capable of delivering a maximum capacity of ___ GPM of raw, unscreened sewage against a maximum total dynamic head of ___' at ___ RPM of the pump motor and a minimum capacity of ___ GPM against a total dynamic head of ___' at not less than ___ RPM of the pump motor. The rated horsepower of each pump motor shall be ___.

The anticipated operating head range at maximum speed is from ___' minimum to ___' maximum.

All openings and passages shall be large enough to permit the passage of a sphere 3" in diameter.

PUMP OPERATION

Starting from a low wet well and neither pump operating, the pump operation sequence shall be as follows:

- When the wet well rises to a preset lead pump "ON" level, an electrical signal provides power to the controller causing the lead pump connected to the Variable Frequency Drive (VFD) be accelerated gradually from zero to maximum speed. If the inflow to the wet well does not exceed the maximum pumping rate of the lead pump, the lead motor speed shall be varied between maximum and minimum in response to a wet well level transducer and shall establish a discharge flow rate to match the inflow rate to the wet well.

- If the capacity of the lead pump is greater than the flow into the wet well, as the wet well level continues to drop, the speed of the lead motor shall decrease to a minimum. If the inflow to the wet well is less than the capacity of the lead pump at minimum speed, the wet well will reach the low level shut-off position and the lead pump shall shutdown.

- If the flow into the wet well increases beyond the capacity of the lead pump operating alone at maximum speed, a high-level electrical signal shall start the lag pump which shall pump up to full speed.

- Both pumps operating at varying speed, then pump the wet well down to the pumps "OFF" level, stopping both pumps and completing the pumping cycle. This process will repeat itself as the wet well liquid level rises.

- The variable speed operated pump-motors shall be alternated by the station controller between “Lead” and “Lag” to distribute the wear.

ADJUSTABLE FREQUENCY PUMP CONTROL SYSTEM

The control system shall consist of adjustable frequency drives and associated components necessary to automatically operate two identical pump motors to control the level in the wet well. The converters shall each be dedicated to a separate pump-motor.

The VFD shall be designed to accept a speed signal from a level transducer in an automatic speed control mode or from a programmable preset speed when the manual mode is selected. The selected speed signal shall control the motor speed between the adjustable minimum and maximum speed settings. The total speed signal shall follow a linear time ramp which is adjustable from 0 to 1800 seconds to provide acceleration and deceleration control. A circuit breaker shall be provided to disconnect the VFD from all power, and the VFD shall be segregated within the enclosure to reduce the danger of power-off servicing while the remainder of the control system is in operation. The VFD shall be capable of operating the motor continuously at 100% of rated speed.

The variable speed power unit shall be a completely solid-state converter. The unit shall transform (208) (230) (460) volt, 3-phase, 60 cycle input power into variable voltage, adjustable frequency, 3-phase output of suitable capacity and wave-form to control the speed of a NEMA B design AC motor. Control shall be throughout a step-less speed range, under variable torque load on a continuous basis. The converter shall be of the PWM (pulse width modulation) type and shall include the following features:

ADJUSTABLE SPEED DRIVES FOR 3-PHASE PUMP MOTORS

Construction

The drive shall be designed to provide for ease of maintenance.

The inverter section power semiconductors shall be of an approved-type, and shall not require commutation capacitors.

The drive shall consist of the following major components:

A. Input rectifier section to supply fixed DC bus voltage

B. Phase-to-phase and phase-to-ground MOV protection, a capacitor clamp and 5% impedance reactors

C. Smoother reactors for the DC bus (dual positive and negative)

D. DC bus capacitors

E. Sine weighted PWM generating inverter section

F. Separate terminal blocks for control and power wiring

The drive shall supply a constant volts output when operating above 60 Hz.

The volts-per-hertz output of the dive shall not be affected or require readjustment when other drive adjustments (such as maximum speed) are changed.

The drive output waveform shall be the PWM type waveform producing smooth torque at low frequencies and low harmonics.

The drive shall be capable of operating output opened circuited with no fault or damage.

CONTROL FEATURES

When specified, the speed potentiometer may be remotely located up to 100 feet (30 meters) from the drive.

The drive shall produce an output frequency proportional to the speed reference without external feedback.

For digital speed commands, the drive shall maintain set frequency to within 0.01 Hz during power line fluctuations or changes in ambient temperatures.

Two adjustable “skip bands” shall be available to prevent pump operation at resonant frequencies, if necessary, to avoid potentially damaging pump vibration.

Within the drive rating, the drive shall maintain set frequency, and not require readjustment due to changes in load.

Motor Overload Protection

The drive shall provide motor overload protection when a single motor is connected to the drive. Class 10, 20 or 30 (programmable) electronic motor overload protection shall be included.

The overload protection shall be adjustable from 50% to 115% of the drive full load current rating.

Motor overload protection shall provide the protection required by the NEC.

Under-Voltage Sensing

Should the input line fall below 10% of rated input voltage, the drive shall sense an under-voltage condition and annunciate it on the digital display panel.

Over-Voltage Sensing

Should either the input line rise above 10% of rated input voltage, or the internal DC bus rise above allowable levels due to load regeneration, the drive shall sense an over-voltage condition and annunciate it on the digital display panel.

Phase Protection

The drive shall have protection against (and indicate) a phase-to-phase short in the output load, or a short circuit in a phase of the output module.

Each output phase shall be monitored. If a short circuit condition occurs, a circuit shall guard against further damage by turning off the entire output section experiencing the shorted condition.

The drive shall shut down and annunciate the fault and display the appropriate fault on the digital display panel.

Drive Protection

The drive protection functions shall monitor and annunciate the following conditions as a minimum:

- Over-Current
- Short-Circuit/Ground Fault
- Under-Voltage
- Over-Voltage
- Over-Temperature
- Phase Loss