DEVELOPMENT OF A SMART PUMPING SYSTEM

by

Anthony E. Stavale

Senior Project Manager

Jerome A. Lorenc

Senior Research Engineer

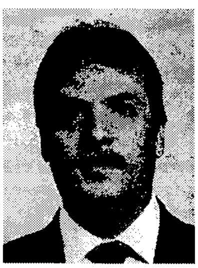
and

Eugene P. Sabini

Director of Technology

ITT Industries, Fluid Technology Corporation

Seneca Falls, New York

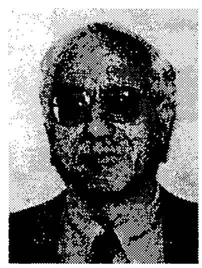


Anthony E. Stavale is a Principal Engineer for ITT Industries Industrial Pump Group, in Seneca Falls, New York. He is primarily responsible for the product development and commercialization of high technology projects. Mr. Stavale joined ITT Marlow in 1991 as Manager of Special Projects. In 1993, he was promoted to Manager of Research and Development for ITT A-C Pump, in Cincinnati, Ohio. Previously he was employed by Worthington Pump Corporation. He has 26 years' experience covering the design and application of ANSI B73, API 610, and sealless magnetic drive pumps. He has published several papers, received a U.S. patent, and previously served as a member to the ASME B73 Committee for Chemical Standards Pumps.

Mr. Stavale holds a B.S. degree (Mechanical Engineering Technology, 1975) from the New Jersey Institute of Technology, and is a registered Professional Engineer in the States of New Jersey and Ohio.

Jerome A. (Jerry) Lorenc is Senior Research Engineer in the Industrial Pump Group of ITT Industries, in Seneca Falls, New York. He has been with ITT since 1976, serving as Instrumentation Engineer, Supervisor of the R&D Lab, and his present position. His responsibilities include design of pump test facilities, managing new technology projects, and engineering assistance to sales and field service. Mr. Lorenc has been involved in vibration, pressure pulsation, and condition analysis of pumps for the past 25 years. He has published four papers and has a centrifugal pump related U.S. patent.

Mr. Lorenc received a B.S. degree (Aircraft Maintenance Engineering, 1970) from Parks College of Saint Louis University, completed a full year of graduate work in Mechanical Engineering at Rochester Institute of Technology (1976), and is certified Vibration Specialist III (1996). He is a member of ISA and the Vibration Institute.



Eugene P. (Gene) Sabini is the Director of Technology for the Industrial Pump Group of ITT Industries, in Seneca Falls, New York. He is responsible for applied research and hydraulic design of all new products and field rerates. Other responsibilities include testing, FEA, CFD, rotordynamics, rapid prototyping, and condition monitoring. Mr. Sabini was previously Manager of Energy Engineering Design with Goulds. He was responsible for both the product engineering and the mechanical/hydraulic design and testing of the energy related double suction and multistage API pumps.

Mr. Sabini has 32 years of experience in the pumping industry including design and development of many centrifugal pumps for the chemical, API, power utilities, and municipal industries. He spent 25 years with Worthington Pump designing, engineering, and testing custom centrifugal pumps from both a mechanical and hydraulic standpoint.

Mr. Sabini received a BSME (1968) and M.S. (1975) degree from Stevens Institute of Technology.

ABSTRACT

In today's global economy, process plants are under constant pressure to reduce costs. Users can no longer afford their attempts to make pumps bulletproof by upgrading component specifications. The development of a smart pumping system was fostered by a challenge from a major chemical user to reduce the total cost of pump ownership. A smart pumping system was successfully developed that can react and adjust itself to system changes without manual intervention.

The system is fault tolerant by virtue of the control software, which will not permit the pump to operate outside user specified ranges, or under conditions that typically cause pumps to fail. A variable speed controller can match pump output to exact system head requirements, without the need for energy consuming control valves. The smart pumping system can significantly reduce all major components of life-cycle cost.

Field-testing proceeded without incident after initial installation problems were resolved.

INTRODUCTION

To survive in the global marketplace, process plants are under constant pressure to move liquids both reliably and inexpensively. Today many plants have cut back on operating and maintenance personnel and are often left with inexperienced people. This presents a dilemma; users can no longer afford their attempts at making pumps bulletproof (Swalley, 1999) and the exodus of experienced personnel only serves to exacerbate their predicament.

As a result, a major chemical user issued a challenge to drastically reduce the total cost of pump ownership in their plants. They presented a specification for the desired performance of this "futuristic" pump, covering the following key items:

- *50,000 hour mean time between failure*
- *Ability to survive 10,000 start-stops*
- *Able to run dry*
- Operating temperature range −100°F to 700°F
- Capacities to 7500 gpm, heads to 1075 ft
- Pump to be unaffected by two years' nonoperation
- Easy to decontaminate
- Operation on 50 or 60 Hz
- Standardized connections and locations
- Technical and service support as needed
- *First cost 25 percent less than equipment replaced (pump, seal, motor, baseplate, coupling, and guard)*
- *Rebuild cost less than 50 percent of new assembly*

The above items can be segregated into those that can be handled by proper pump selection, materials, and construction and those that are more challenging to today's state-of-the-art pump design. This paper will focus on the design challenges (shown in italics) and presents a novel approach to reducing the total cost of pump ownership.

ALTERNATIVES CONSIDERED

Heavy-Duty Pump

Nearly all the design challenges identified above either directly or indirectly have an influence on increasing the mean time between failure (MTBF) of a pump. One approach to increasing MTBF might be to design a heavier duty pump, one with a larger shaft and bearings, more liberal internal clearances, and thicker casing. However, clearly this approach is at odds with the requirement that the first cost be 25 percent less than the equipment being replaced. A heavy-duty close coupled vertical inline (VIL) pump could be designed that will eliminate the cost of the pump coupling, coupling guard, and baseplate. It would also eliminate any maintenance costs relating to coupling misalignment and excessive nozzle loads due to poor baseplate/foundation stiffness. Installation costs could also be reduced due to the elimination of baseplate setting and grouting work. Although this approach appears to make for a more robust pump design and contributes to some reduction in initial cost, maintenance cost, and installation cost, it does not address pump failures caused by operator error or system upsets. A pump with an extra heavy shaft and bearings will fail just as quickly as a standard pump when operating in a dry run condition or against a closed suction or discharge valve.

The two primary causes of failures in centrifugal pumps relate to bearings and seals. There are many reasons for failures of these components. Some are application related such as operation outside specified flow regimes and inadequate NPSHA. This can result in increased vibration, bearing loads, shaft deflection, recirculation damage, and a poor seal chamber environment that is counterproductive to long seal life. Other reasons relate to improper installation techniques that can cause alignment problems due to pipe strain and poor baseplate and foundation stiffness. Clearly, many technical articles, books, and manufacturers guidelines exist today, which promote proper pump application and installation. Yet the norm in MTBF for chemical process pumps is only about 24 months. This is well below the MTBF for the refining industry, which approaches five years (Erickson, et al., 2000). Logic would indicate that MTBF could be improved further by designing the pump to be more fault tolerant. Fault tolerance protects the pump from damage if it is forced outside the desired operating envelope. This protection can be achieved through a combination of mechanical design, materials of construction, and protective devices.

Another opportunity to reduce the total cost of ownership is to minimize energy consumption. Advances in hydraulic design and computerized tools such as computational fluid dynamics (CFD) have significantly reduced the opportunities for further improvement in pump efficiency. However, many articles have been written concerning the significant opportunity to reduce energy consumption with variable speed operation. It is not unusual to achieve a 50 percent reduction in energy consumption and an increase in pump reliability when using a variable frequency drive (Hovstadius, et al., 2000). Maintenance and operating costs are two of the largest opportunities for reducing the total cost of pump ownership and cannot be ignored. For this reason the heavy-duty pump design concept was removed from further consideration.

Computer Controlled/Artificial Intelligence Pump

A novel concept considered was to design a system rather than a pump. This system would consist of a standard centrifugal pump, a variable speed drive, instrumentation, a microprocessor, and special software. There are several objectives that this system would be expected to accomplish. If a variable speed drive is employed operating costs could be reduced significantly by eliminating the pressure drop across a control valve. Fault tolerance could also be built into the pumping system by developing special software that would interact with instrumentation signals that sense process conditions. The software would require the ability to recognize and prevent the pump from operating under damaging conditions. Finally, if a method could be developed to use the pump casing as a flow-measuring device; in many applications the need for a separate flowmeter would be eliminated.

The total cost of pump ownership could clearly be reduced by decreased energy and maintenance costs. Additionally, the opportunity to eliminate equipment such as a control valve, external flowmeter, separate starter, and recirculation line piping could also decrease initial and installation costs. There would be additional costs associated with the purchase and installation of a variable frequency drive and instrumentation; however it was expected that the aforementioned savings could offset these costs in many cases. It was concluded that this concept approach had merit since it worked at significantly reducing all the major components of the total cost of pump ownership.

VISION OF A SMART PUMPING SYSTEM

What It Should Do

A smart pumping system must be capable of knowing when to adjust itself to system changes without manual intervention and must match pump output exactly to system head requirements. If upstream conditions change due to a system transient the pump should either increase or decrease its speed in order to maintain a constant output. A side benefit of this concept virtually eliminates the need to add safety margins that can result in oversized pumps.

The system must be capable of recognizing and safeguarding itself from operating under conditions that may adversely affect its life. Conditions such as dry running, operation against a closed suction or discharge valve, and inadequate NPSH must all be recognized and reacted to before damage occurs. The smart pumping system must also be capable of understanding when the system transient or unusual operating condition has cleared, thereby allowing normal pumping operation to resume.

Control modes should be flexible enough to offer system control over a wide range of applications. Control modes should be capable of maintaining constant values of speed, capacity, pressure, level, temperature, or pH.

How It Should Protect

Some of the more common causes of pump failures are attributed to the following upset conditions:

- Dry running caused primarily by closed suction valves. Dry running is also common in batch and transfer applications.
- Prolonged operation below minimum flow.
- Cavitation due to insufficient NPSH available.
- Heat buildup and subsequent liquid vaporization due to a closed discharge valve.

Smart pumping systems should be capable of detecting and reacting to all these conditions. The following safeguards should be available to protect the pump against operating under adverse conditions.

NPSH Monitor

An NPSH margin tailored to the particular application should be specified as one of the protective parameters in the software. If the measured suction head drops below this margin the smart pumping system can either alarm, alarm and control, or alarm and fault depending on user requirements. The alarm and control mode would reduce the pump speed just enough to maintain the specified NPSH margin requirements. However, once the transient has cleared, the pump must recognize it and resume normal pumping operation.

Flow Monitor

A low flow monitor will detect a dry running condition, operation below minimum flow, or against a closed suction or discharge valve. If flow cannot be maintained user settings can be selected to alarm, alarm and control, or alarm and fault as described earlier. Magnetic drive pumps can especially benefit from this dry run protection (Stavale, 1994). The success of power monitors and current monitors has been mediocre at best when used for dry run protection in sealless pumps since these devices depend heavily on proper settings by the user.

Other Safeguards

Other safeguards must be available to warn and protect against overpressure, overtemperature, overcurrent, and overspeed. Setpoints can be selected to restrict operation to user-specified ranges.

Smart pumping systems should also incorporate self-diagnostic features to compare current pump performance to the as-new factory performance. An alarm setting will advise the user when the actual performance degrades past a certain preset value. This will give ample warning to the user to schedule planned maintenance on the unit during the next outage. If a fault history and time stamp are provided it will enable the user to accurately determine system behavior at the time of the fault. This will facilitate troubleshooting and remedying of system upsets.

VALUE PROPOSITION

As stated earlier the value of smart pumping systems to the user is in the reduction of the total cost of pump ownership or total life-cycle cost. Total life-cycle cost encompasses the following major components:

- Operating cost
- Maintenance cost
- Plant downtime and loss of production
- Initial cost
- Installation cost

Operating Cost

System Curves

A system curve comprises a static component and a dynamic component. The static component of the system curve does not change with flow rate. The dynamic component is essentially proportional to the square of the rate of flow. It is also a function of other variables such as pipe configuration/size, surface roughness, quantity and type of fittings/valves, and fluid viscosity. These can be represented by a single system constant and the dynamic or frictional head can be expressed as:

$$H_f = K Q^2 \tag{1}$$

The dynamic head constant K is a constant for a given system. However, if a control valve position changes in the system the constant K will also change.

Conventional Systems

Figure 1 shows a typical control scheme for a conventional pumping system. Note the system curve includes a static component of 6 m (20 ft). This is the change in elevation between the suction and discharge source. In this type of system the pump operates at a fixed speed and the pump performance curve is based on an impeller diameter preselected to match the system requirements as closely as possible. It should be noted that it is common practice to add a safety margin to the design point where it is difficult to accurately define system losses. This can result in an oversized pump that runs out too far on the curve and absorbs too much power.

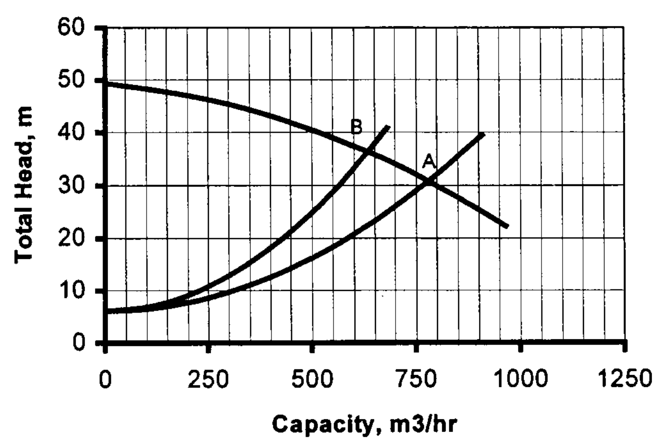


Figure 1. Conventional Pumping System Control.

The total system head curve intersects the pump head-capacity curve at point "A" with the control valve wide open. The design flow for this system is about 640 m^3/hr (2800 gpm) so the friction head (point "B") must be increased to about 37 m (120 ft) in order to operate at this point. The most common method of varying the capacity in a conventional system is to introduce a variable resistance device that will alter the system friction curve; this is the main function of a control valve. Control valves are throttling devices, which use some of the available pumping energy to control the process. The amount of consumed energy will vary depending on the method of control, valve sizing, and the operating point. In the U.S., a common control valve standard (PIP PCECV001) specifies that the control valve shall be 50 to 80 percent open at design flow, at least 10 percent open at minimum flow, and no more than 90 percent open at maximum flow. Other methods base the amount of pressure drop on past plant practice or rules-of-thumb.

Variable Speed Systems

In a variable speed system the controller will match the pump output to system head requirements without the need for a control valve. Safety factors and pressure margins typically built into dynamic head systems can be eliminated and in some cases result in a lower cost pump selection. Since the smart pumping system can adjust the pump speed to suit the required system conditions only one impeller diameter need be stocked. This offers the benefit of lower inventory cost. In variable speed systems the design point no longer needs to be based on a fixed speed. This yields a larger number of selections over a given pump range with a better chance of operating at or near the best efficiency flow. Variable speed control is most effective and efficient in all friction head systems. The effectiveness diminishes somewhat for applications having high static head and low dynamic head, since the intersection of the pump and system curve moves further to the left of the best efficiency flow (Casada, 1999). Careful selection is required for these applications to avoid operation below minimum allowable flow and possible deadheading.

Figure 2 shows a variable speed system with system curve "A" identical to that shown in Figure 1. Head-capacity curves are shown at various speeds. If the desired operating flow is 640 m^3/hr (2800 gpm) it is shown that the pump can operate at a substantially lower speed and head. In this example, the savings of the variable speed system over a conventional system is represented by the difference in head between points "B" (Figure 1) and "C" (Figure 2). This difference in system head requirements can often translate to thousands of dollars in annual energy savings over the life of a pump.

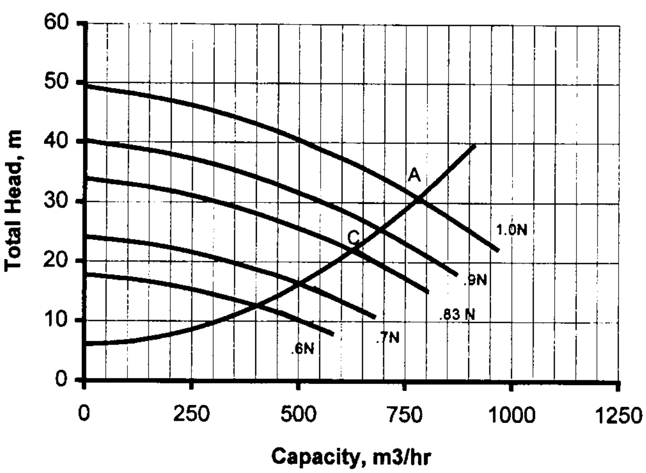


Figure 2. Variable Speed Pumping Control.

Maintenance Cost

As mentioned earlier, the primary components in pump failures are bearings and mechanical seals. Excessive vibration, excessive loads, and/or poor lubrication are the primary causes of failure for these parts. Designing a pump with a larger shaft and bearings may appear to be more robust but does not guarantee longer life. Many failures can be attributed to operator error and application factors. Operating range, impeller diameter, operating speed, and protection against system upsets all have an effect on the overall reliability of a pump.

Operating Range

A centrifugal pump is designed to operate most reliably at one capacity for a given speed and impeller diameter. This capacity is usually at or near the best efficiency flow. As pump operation moves away from this optimum capacity, turbulence in the casing and impeller increases. As a result hydraulic loads, which are transmitted to the shaft and bearings, increase and become unsteady. These loads are related to the impeller diameter in a cubic manner. The severity of these loads can have a negative effect on reliability.

Impeller Diameter

Impeller diameter affects reliability by the loads that are imposed to the shaft and bearings as the impeller vanes interact with the volute cutwater. These loads are also related to the impeller diameter in a cubic manner. Maximum or near maximum impeller diameters result in a less than optimum gap between the cutwater and impeller. As each vane passes the cutwater a large pulse is produced that results in an accompanying unsteady deflection of the pump shaft. These unsteady deflections can be very damaging to mechanical seals. There is an optimum cutwater gap that will limit these unsteady deflections. With larger than optimum gaps the damaging cutwater effect is minimized but the effects of suction and discharge recirculation become of more concern, especially if vane overlap is lost due to large impeller trims.

Operating Speed

Operating speed affects pump reliability through rubbing contact and wear in seal faces, reduced bearing life due to increased loads, lubricant breakdown due to excessive heat, and wetted component wear due to abrasives in the pumpage.

In addition, an increased operating speed can easily push a low suction energy pump into a high suction energy region (Budris, 1993) with accompanying noise, vibration, and possible cavitation damage. The onset of high suction energy levels in pumps is directly related to operating speed, suction specific speed, specific gravity, and the thermodynamic properties of the liquid being pumped, as well as impeller geometry and operating point.

Quantification of Reliability Improvements

The protection that smart pumping systems offer will no doubt translate to extended mean time between failure and improved life-cycle maintenance cost. One method of quantitatively predicting these life-cycle cost savings is outlined by Bloch and Geitner (1994). In this method, reliability factors for operating speed, operating point, and impeller diameter are assigned values between zero and one, where higher values indicate more reliable selections. A reliability index, which is the product of the three reliability factors, can then be compared to pumps of similar design to give an indication of overall reliability. Note this method is only valid for comparing pumps of similar design since it does not take design characteristics into consideration. An independent test program generally confirmed the validity of these published reliability factors and offers recommendations for improvement (Erickson, et al., 2000).

Plant Downtime and Loss of Production

Even a properly selected pump with materials of construction suitable for the application is no guarantee of long life. As described earlier, smart pumping systems must also be fault tolerant. This protects the pump against operator abuse, improper startup, operation in damaging flow regimes, dry running, inadequate NPSH, overpressurization, overtemperature, overtorque, overspeed, and underspeed. These upsets often result in unplanned premature equipment failure with consequential plant downtime and loss of production.

It should be noted that the added protection that fault tolerance provides is not quantified in the Bloch and Geitner (1994) method.

Initial Cost

Initial cost is the smallest of the life-cycle cost components but usually receives the greatest focus during the procurement cycle. Many users become predispositioned at the sound of the words "smart pumping system" and "variable speed controller" when they think of cost. However, if the total initial cost of a smart pumping system is compared to that of a conventional system it can be shown that smart systems can be very competitive in price. When compared to total life-cycle cost, these systems can have an overwhelming advantage.

As mentioned earlier in this paper, smart pumping systems continuously monitor both pump and system conditions and match pump output to system requirements, exactly. Since the smart controller is a variable speed device there is often no need for an automatic control valve in the system. One manufacturer has a patented method of measuring process flow internal to the pump discharge nozzle. In many applications this could eliminate the need for a separate external flowmeter in the system. Additionally, smart controllers have integral starters thereby eliminating the need for a separate starter.

One of the many safeguards built-in to smart controllers is to protect against operation below minimum flow. Operation can be restricted to user-specified ranges. Depending on system design, recirculation lines and valves can also be eliminated. Since added safety margins are not required when controlling with a variable speed system, in some cases a smaller pump can be used. The added fault protection and safeguards may also eliminate redundant systems in some applications.

Installation Cost

By reducing the amount of equipment in a system both installation and maintenance costs are decreased. The installation costs associated with piping, air lines, wiring, and communication lines can all be decreased by eliminating a control valve, flowmeter, separate starter and recirculation line valve, and piping.

PROTOTYPE EVALUATIONS

Early concept approaches were required to help define what the product should be. Three separate concepts were evaluated:

- The proof of concept (POC) unit utilized a laptop PC communicating with a 10-channel data acquisition system and a 1 hp 230 VAC commercially available variable frequency drive (VFD).
- A black box (BB) unit that incorporated a custom eight input channel/two output channel PC board having basic computing capability similar to a programmable logic controller (PLC). A 10 hp 460 VAC commercially available VFD was also used.
- A five input channel/two output channel custom programmed smart VFD (3 hp 460 VAC).

Proof of Concept

The POC was connected to a one-half scale model end suction pump. The centrifugal pump was mounted on a rigid baseplate and coupled to a .86 kW 3420 rpm, 230 VAC electric motor. The VFD controlled the speed of the motor. The baseplate was mounted on a portable bench. The pump was piped to a 15-gallon clear cast acrylic tank with clear acrylic tubing, as shown in Figure 3. A hand-operated ball valve was installed at the pump discharge to artificially change system friction. An additional hand-operated valve was piped to the pump suction to vary the NPSHA.

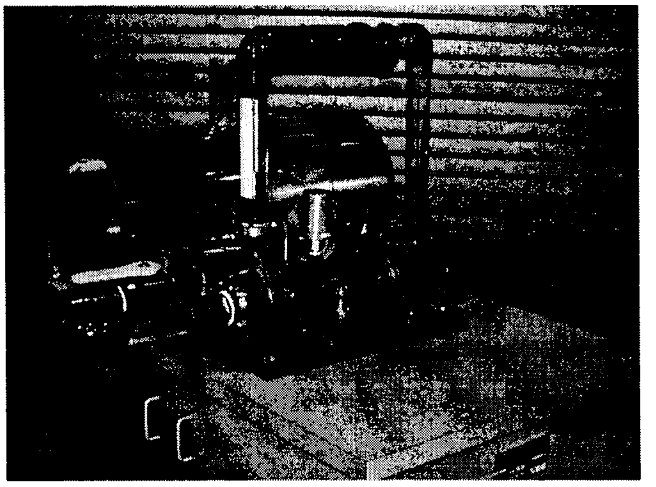


Figure 3. Proof of Concept Model.

The proof of concept unit focused on pump sensing, pump control/management, fault tolerance, and condition monitoring. The unit logged the following data:

- Differential pressure measured across the casing throat and the discharge flange (psid)
- Discharge pressure (psia)
- Suction pressure (psia)
- Fluid temperature (°F)
- Pump speed (rpm)
- Mechanical seal face temperature (°F)
- Seal chamber temperature (°F)
- Outboard bearing vertical vibration (in/sec)
- Bearing housing oil temperature (°F)
- Water concentration in bearing housing (ppm)

The model pump was tested for head, brake horsepower (bhp), NPSHR, and differential pressure (dP) versus capacity at four different speeds (3600, 2800, 2000, and 1200 rpm). The dP was measured across the casing throat and discharge flange and was used along with speed and fluid temperature (specific gravity) to characterize flow over the entire operating range of the pump. Subsequent testing showed that the flow accuracy for this unit was within ± 1 percent for operation between 40 and 115 percent of best efficiency point (BEP) and better than 5 percent over the entire operating range (0 to 140 percent of BEP).

The pump curves, flow characterization, and fluid properties were loaded to a QuickBasic (QB4.5) program. These curves established a baseline to which the pump performance could be compared. A custom control algorithm was developed to control flow and pressure. This eliminated the need for proportional-integral-derivative (PID) loops in the program. This algorithm was originally developed to control a pump with a flat or drooping head-capacity curve operating against a flat system curve. The POC controlled constant flow or pressure under any induced system friction changes. The QB4.5 program acquired data and updated the VFD at rates ranging from 1 to 2 Hz.

Once control was established, the program compared the head that the pump was producing at a given flow and speed to its baseline value. An alarm "Renew Clearances" was programmed to warn of a 10 percent loss in head.

Transients caused by quickly opening and closing valves resulted in pump system instabilities because of the slow 1 to 2 Hz update rate. The update rate was limited by the speed of the PC and the 10-channel data acquisition system.

Any VFD can control a pump to maintain constant flow, pressure, etc. What would differentiate this pumping system from any other is its fault tolerance. The unit was programmed to react to the most common causes of system-induced pump failure. The unit constantly monitors and calculates flow and NPSHA and compares these values to the baseline NPSHR. The program incorporated a 3-ft NPSHA margin above the pump NPSHR to trigger an alarm. The pump was programmed to slow down just enough to maintain the required 3-ft margin. Once the condition corrected itself, the pump automatically resumed operation at the proper setpoint. The unit was also programmed to alarm and/or react to a low flow, a closed suction valve, or closed discharge valve condition. The pump will react to these faults by slowing down to a predetermined speed where damage will not occur. Again once the condition corrected itself, the pump automatically resumed operation at the proper setpoint. The unit was also programmed to shut down automatically on overpressure or overtemperature condition (safety related).

The POC unit also logged, alarmed, and reacted to a variety of condition monitoring sensors. The unit trended bearing lubricant temperature and overall vibration. An abrupt change in vibration or temperature for a given setpoint would trigger an alarm.

Seal chamber pressure and seal face temperature was also monitored. An increase in seal face temperature would result in a corresponding increase in the vapor pressure of the fluid. If the vapor pressure exceeds the seal chamber pressure fluid flashing at the seal faces would occur with potential seal damage. A protective alarm/fault was programmed in the software for this condition. This fault could occur when the pump is cavitating, running dry, or operating below its recommended minimum thermal flow. It should be noted that the program and controller reacted within one to two seconds to all induced faults; as a result we were unable to induce bearing or seal problems.

Water concentration in the oil was also constantly monitored. The unit was set to trigger an alarm with water concentrations greater than 180 ppm (ISO 68 oil).

Black Box

The QB4.5 program used on the POC was rewritten in C++ and downloaded to the BB unit. The condition-monitoring portion of the program was not incorporated due to input/output (I/O) limitations.

The original BB program did not contain the custom flow/pressure control algorithm. Instead control was carried out using standard PID loops. These loops at best were not as stable as the custom algorithm and in need of constant tuning as the system parameters changed. The program was then updated to the control algorithm.

This unit had an update rate of 3 to 4 Hz and performed very similarly to the POC. Consequently it experienced the same instability problems as the POC due to quick opening and closing of valves.

Smart VFD

The program was rewritten in assembly language and loaded onto the smart VFD. It was decided that condition monitoring would be made available later as an optional add-on to the system. The concept of the smart pumping system was to protectively react to a fault and greatly reduce the risk of pump failure. Condition monitoring should be available for users who choose not to react to a fault protectively. It would also be useful in detecting nonsystem-induced faults; e.g., poor alignment or excessive piping loads.

Transients did not affect operation. The drive reacted to all system-induced faults in a very stable manner. Extensive fault testing was carried out with no mechanical seal or bearing problems encountered.

The unit met its desired goals of sensing, managing, and controlling the pump. This unit helped define the final product specification.

TEST VALIDATION—CHALLENGES AND PROBLEMS

Response Time

A poorly designed automatic control system will exhibit overshoot, undershoot, or porpoising (oscillation) about the setpoint. In a proportional controller the output signal is proportional to the difference between the setpoint and actual conditions. The gain adjustment is an inverse function of the controller proportional band. Figure 4 shows a typical system response curve to a sudden change in load with low gain adjustment (wide proportional band), i.e., the system response to the error signal is small. Figure 5 shows a typical system response curve to a sudden change in load where porpoising occurs. This system has a high gain adjustment (narrow proportional band), i.e., the system response to the error signal is high. Note, in systems with proportional action only, there is always some residual offset (Wachstetter, 1994). Testing of the initial POC and BB concept designs previously described had many of these problems even when PID loop controllers were used.

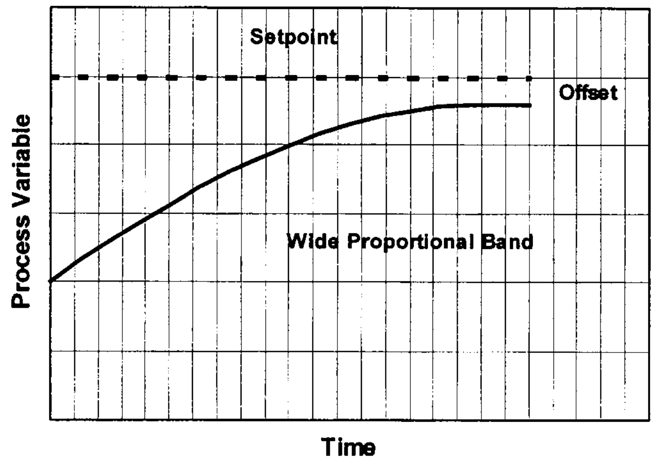


Figure 4. Proportional Control with Offset.

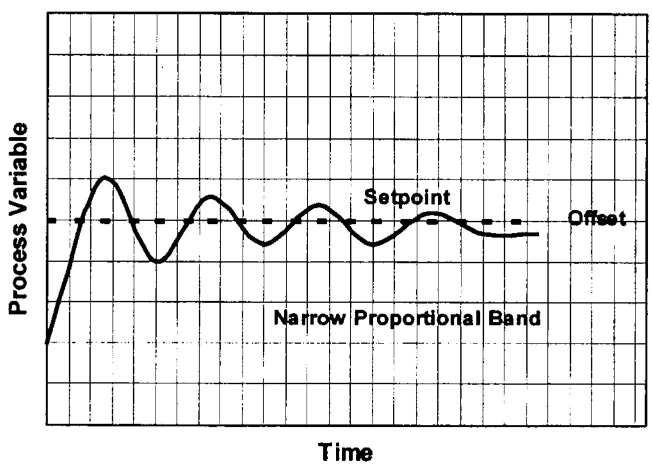


Figure 5. Proportional Control with Porpoising.

It was not until the VFD-based smart pump concept was developed that a successful optimization of the pump hydraulic response characteristics, the motor dynamic response characteristics, and the VFD response were achieved. This optimization was partially attributed to an increased update rate of process signals that the VFD offered when compared to the initial prototypes. The stability was made independent of the system that the pump was operating in by developing proprietary control algorithms. Figure

6 shows the typical system response possible when using the proprietary control algorithm coupled with an increased update rate of the process signals. It should be noted that major changes or upsets in a pumping system that could cause a PID loop controller to become unstable and necessitate retuning would not affect the algorithm-based control.

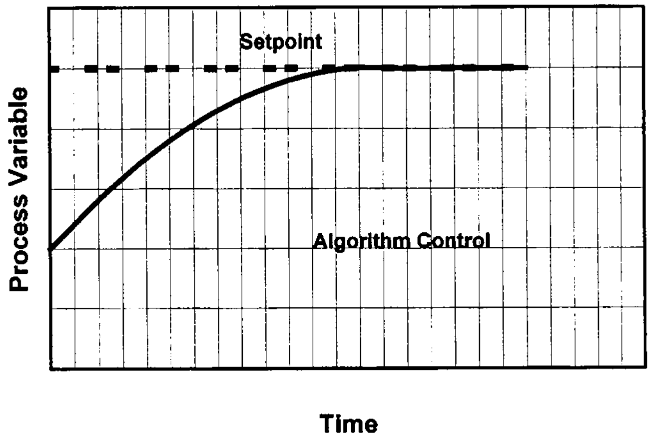


Figure 6. System Response with Algorithm Control.

Ground Fault Loops

Ground loops presented another challenge. Whenever there is three-phase power present (motor voltage and current) along with 4 to 20 milliamp (mA) instrument signals there exists the potential for ground loops. This is especially true for voltages generated using pulse width modulation (PWM) variable speed drives. The first ground loop problem occurred with metal diaphragm pressure transmitters that exhibited erratic signals but only when the VFD was delivering electrical power to the motor. Even though the cabling from the VFD to the motor was grounded per manufacturer's recommendations, the high switching frequency of the VFD would create a voltage potential in the motor/baseplate/pump. This high frequency voltage potential would return to the variable frequency drive not only through the motor power lead ground but also through the metal diaphragm pressure transmitters. It was found that the electromagnetic induction (EMI) capacitor in the transmitter was acting as a short circuit at the high switching frequency thereby allowing the voltage to modulate the 4 to 20 mA signal. This was resolved by switching to a different transmitter design.

A second ground loop problem occurred when the smart system was applied to an end user that had a nuclear level indicator. Despite the fact that the cables from the VFD to the motor were routed through solid wall conduit connected at both the motor and VFD, a high frequency voltage potential was detected in the conduit that was sufficient to disrupt the 0 to 1 mA DC signal from the level indicator. Grounding straps or bars welded across each conduit coupling and at the motor and VFD were recommended. This eliminated the insulation effects of the pipe sealant and created a better path to ground for the high frequency voltage potential generated in the conduit.

Flow Accuracy

As part of the objective of reducing total life-cycle cost, a method was developed to measure flow directly in the pump discharge nozzle. The pump casing is calibrated by relating flow to differential pressure and rotational speed. As the nozzle area changes from the casing throat to the discharge outlet a differential pressure is produced similar to a venturi effect. Figure 7 shows a typical dP versus flow curve at several speeds for an ASME B73 3×4-13 pump.

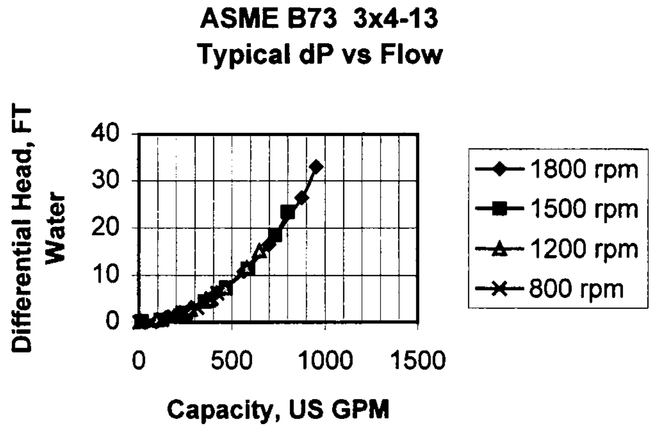


Figure 7. Typical Curve—Differential Pressure Versus Flow.

As expected it was found that the amount of differential pressure available varied by nozzle design and was also influenced by casting variations. Casting variations between different metallurgies necessitated that each pump casing be calibrated in order to assure flow accuracy. This concept in flow measurement is similar in limitation to other differential pressure (dP) measuring devices. These devices have a flow accuracy of 2 to 5 percent depending on size, a rangeability of 3:1, and are limited to clean liquids. As with other dP measuring devices field accuracy was dependent on good piping practice immediately downstream of the casing discharge nozzle.

Stable Algorithms for High Static Head Systems

A real concern with applications involving variable speed pumping in high static head systems is that a reduction in pump speed may cause the pump to operate in a deadhead condition. In high static head systems as the pump speed decreases, the intersection point between the pump and system curve moves further to the left of the best efficiency point. If the pump speed is reduced far enough where the pump total head falls below the system static head, a zero flow condition will result. This can result in overheating, liquid vaporization, and a possible explosive condition.

The smart system was designed so that there are two user-defined parameters that preclude deadhead operation. The first parameter is the minimum speed of the pump. This parameter is selected such that the pump generated total dynamic head (TDH) is always greater than the static lift in the system. This ensures that even if the pump is operated at the minimum speed there is sufficient pump TDH generated to produce flow through the system. The second parameter defines the minimum flow of the pump at the maximum operating speed. This parameter is used to calculate the minimum continuous flow for the pump at all other speeds. If the flow at any pump speed falls below the minimum flow calculated for that speed an alarm and/or fault condition will occur to alert the end user that the pump is operating in a potentially damaging situation.

FINAL DESIGN CONCEPT

Major Components

The final design concept for the smart pumping system consisted of a standard centrifugal pump, standard variable speed controller, instrumentation, microprocessor, and special control software. The instrumentation includes an absolute suction pressure transmitter, suction temperature transmitter and sensor, absolute discharge pressure transmitter, and a differential pressure transmitter (required only if flow is measured in the pump casing). If an external flowmeter is used an analog signal must be provided to the microprocessor in order to measure flow. The instrumentation senses process conditions and transmits 4 to 20 mA signals to the microprocessor. There are five analog inputs and two analog output signals available which are setup for 4 to 20 mA (24 VDC power required). There are also six digital inputs and three digital outputs available. Control is available by using either analog or digital inputs. The control algorithm developed inhouse was used for capacity and pressure control due to its superior performance.

The microprocessor resides in the variable speed controller. It stores the pump control software that enables the controller to sense pump and process conditions and react accordingly. The system is designed to maintain constant values of speed, capacity, pressure, or level and can be controlled by a local keypad, hardwired control, or through a distributive control system (DCS). The following fieldbus adapters support communication with the DCS: CS-31, DeviceNet™, INTERBUS-S, Modbus, Modbus Plus, and PROFIBUS®.

Application Specific Data

Each pump is hydraulically characterized at the factory to identify the entire pump performance envelope including NPSHR. Fluid characteristics such as specific gravity and vapor pressure are also identified over the entire temperature range of the liquid being pumped. Next, the pump manufacturer and user jointly identify the control parameters and alarm/fault settings desired for the application. Table 1 shows a partial listing of the control parameters and alarm/fault settings required.

Table 1. Typical Control Parameters and Alarm/Fault Settings.

Control Parameter	**Alarm/Fault Settings**
Local or Remote Control	TDH Alarm Level
Maximum/Minimum Speed	NPSH Monitor
Maximum/Minimum Flow	Flow Monitor
Maximum/Minimum Pressure	Pressure Monitor
Specific Gravity Constants	Pressure Alarm Value
Vapor Pressure Constants	Pressure Fault Value
Max. Signal Feedback	NPSH Control Time
Control Method	Flow Control Time
Suction/Discharge Diameter	Pump Shutoff Temperature

All the pump hydraulic data and fluid characteristics are then processed through a test utility that calculates the polynomial curve fit coefficients. The utility also gathers and formats user-defined parameters, control settings, and alarm/fault values that are used in the control software. To complete the process the control software and all application related data are downloaded to the microprocessor via fiber optic cables.

FIELD TESTING

Installation

The first unit was installed on a cooling tower service for a hydrogen purification plant (Kratowicz, 2000). The plant runs automatically and is unattended. The pump that was provided is an ASME B73 8×10-13 pump driven by a 100 hp 1780 rpm motor. The installation consisted of two pumps, one main and an installed spare. Each of two units is sized to supply approximately 2800 gpm at 120 ft total discharge head to the cooling water header serving the plant. Although it was intended that both pumps be installed as smart pumping units, initial problems with the installation and setup resulted in only one of the units being configured in this manner. The backup unit was configured as a conventional fixed-speed pump.

Startup

The pump was started in speed mode and operated near full speed (1780 rpm) with the pump discharge throttle valve set at about 55 percent open. Once the system was stabilized, the unit was placed in pressure control mode with the setpoint equal to the pressure developed at full speed with the valve at 55 percent open. The setpoint was reduced in steps by increasing the amount of valve open until the desired downstream pressure was achieved with the discharge valve wide open. This resulted in a speed reduction of over 300 rpm and a corresponding power reduction of about 40 hp when compared to the installed spare that was operated in a conventional system.

Operating Experience

The unit has been in unattended operation for nearly 9000 hours. During this period there have been no reported alarms, faults, or other problems to date. The calculated energy savings based on 9000 hours' operation for the smart pumping system in this application is $15,500. The primary goal of the user in this application was to prove out the reliability of the system before moving into a more aggressive application. To this end the user is reported to be very satisfied with the performance of the system.

LIFE-CYCLE COST EVALUATION

Operating Cost Savings

The following life-cycle cost evaluation (Stavale, 2000) is based on the cooling tower installation described in the field test section. Figures 1 and 2 illustrate the savings of a variable speed system over a conventional system for this installation. This is shown as the difference in head between points "B" (Figure 1) and "C" (Figure 2) and is exemplified in Table 2.

Table 2. Life-Cycle Operating Cost Savings.

	Conventional System	Smart Pumping System
Pump Size	8x10-13 (ANSI B73)	8x10-13 (ANSI B73)
Rating at design, m^3/hr (gpm)	639 (2800)	639 (2800)
Rating at design, Total Head, m (ft)	37 (120)	23 (75)
Speed, r/min	1780	1476
Yearly Operation, hrs	8760	8760
Rating at Design, kW (Bhp)	77.3 (104)	47.7 (64)
Equipment Life, Years	15	15
Yearly Energy Use, kW-hr	707,700*	456,400**
Total Energy Use, kW -hr	10,615,000*	6,845,000**
Electricity Cost, $(US)	0.06	0.06
Total Life Cycle Operating Cost, $(US)	636,900*	410,700**

Life Cycle Operating Cost Savings: $(US) 226,200

* Includes motor losses
** Includes motor and VFD losses

Note that the total pump head has been reduced from 37 m (120 ft) to 23 m (75 ft). As a result the pump power has dropped nearly 30 kW (40 hp) and operating speed has been lowered by over 300 rpm.

Maintenance Cost Savings

Table 3 shows the effect on life-cycle maintenance savings for the cooling tower application using the Bloch and Geitner (1994) method described previously. It assumes an average MTBF for a conventional sealed pump of 18 months at an average cost per repair of $2500. Note the savings shown should be considered to be conservative since the Bloch and Geitner (1994) method does not take into account potential savings due to fault tolerance.

Table 3. Life-Cycle Pump Maintenance Cost Savings.

	Conventional System	Smart Pumping System
Reliability Index	0.2	0.3
Average MTBF, Months	18	27.1
Equipment Life, Years	15	15
Total No. of Repairs	10	6.6
Total Pump Maintenance Cost (US)	25,000	16,600

Life Cycle Pump Maintenance Cost Savings: $(US) 8,400

The difference in pump life-cycle maintenance savings for this application represents a 33.5 percent decrease when compared to a conventional system, and MTBF is extended from 18 to 27 months.

Initial Cost Savings

Figure 8 shows a conventional system with pump/motor, control valve, flowmeter, isolation valves, recirculation line, DCS, and starter. Smart pumping systems integrate the functionality of several of these pieces of equipment as shown in Figure 9.

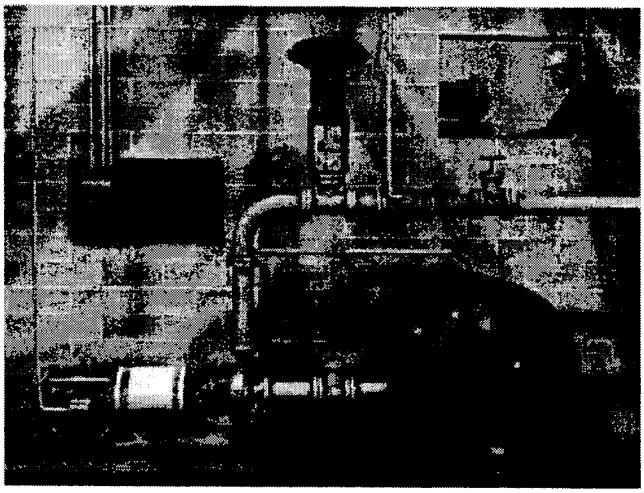


Figure 8. Conventional Pumping System.

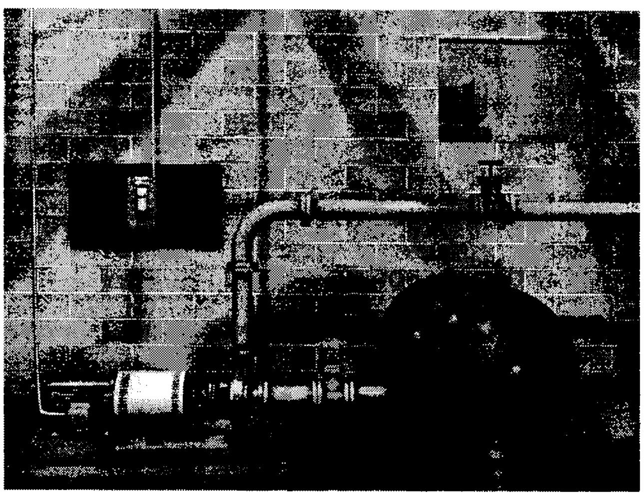


Figure 9. Smart Pumping System.

Table 4 shows that the life-cycle initial cost savings for this cooling tower application compares favorably with a conventional system.

Table 4. Life-Cycle Initial Cost Savings.

	Conventional System, (US)	Smart Pumping System, $(US)
Pump, baseplate, coupling and motor	10,600	10,000
Smart Controller and Instrumentation	0	9,800
Control Valve	4,700	0
Flowmeter	4,300	0
Recirculation Line	0	0
Motor Starter	1,000	0
Total Life Cycle Initial Cost, $(US)	20,600	19,800

Life Cycle Initial Cost Savings: $(US) 800

Installation Cost Savings

Table 5 shows the effect on life-cycle installation savings for the cooling tower installation. In this example pump installation costs are based on 5× initial cost. Installation costs for the control valve, flowmeter, and starter are based on 3× initial cost of these components.

Table 5. Life-Cycle Installation Cost Savings.

	Conventional System $(US)	Smart Pumping System $(US)
Pump, baseplate, coupling and motor	53,000	50,000
Smart Controller and Instrumentation	0	3,750
Control Valve	14,100	0
Flowmeter	12,900	0
Recirculation Line	0	0
Motor Starter	3,000	0
Total Life Cycle Installation Cost, $(US)	83,000	53,750

Life Cycle Installation Cost Savings: $(US) 29,250

The difference in pump installation savings for this application represents a 35 percent decrease as compared to a conventional system.

Since the control valve and external flowmeter have been removed from the smart pumping system, maintenance for these items can also be eliminated as shown in Table 6.

Table 6. Life-Cycle Other Maintenance Cost Savings.

	Conventional System $(US)	Smart Pumping System $(US)
Smart Controller and Instrumentation	0	2,000
Control Valve	3,200	0
Flowmeter	2,800	0
Total Life Cycle Installation Cost, $(US)	6,000	2,000

Life Cycle Other Maintenance Cost Savings: $(US) 4,000

Total Life-Cycle Cost Savings

A summary for each of the major life-cycle cost components is shown in Table 7 for a conventional and smart pumping system for the cooling tower installation.

Table 7. Life-Cycle Cost Summary.

	Conventional System $(US)	Smart Pumping System $(US)
Life Cycle Operating Cost	636,900	410,700
Life Cycle Pump Maintenance Cost	25,000	16,600
Life Cycle Other Maintenance Cost	6,000	2,000
Life Cycle Initial Cost	20,600	19,800
Life Cycle Installation Cost	83,000	53,750
Total Life Cycle Cost	771,500	502,850

Total Life Cycle Cost Savings: $(US) 268,650

The total life-cycle savings for this installation is $268,650. This represents a 35 percent savings over a 15-year equipment life. The present value of these savings, assuming a 10 percent interest rate, is $148,300, and the difference in initial capital investment is negligible.

CONCLUSIONS

A smart pumping system has been successfully designed that can react and adjust to system changes without manual intervention. The system is capable of recognizing and safeguarding itself from operating under conditions that may adversely affect its life. This fault tolerant design has the ability to protect itself from operating under conditions such as dry running, operation against a closed suction or discharge valve, operation below minimum allowable flow, and cavitation due to insufficient NPSH available. The system has the ability to recognize when the adverse operating condition has passed and will resume normal pumping operation when it is safe to do so. Field-testing proceeded without incident after initial installation problems were resolved.

The system can significantly reduce all major components of life-cycle cost. A variable speed controller is able to match pump output to system head requirements exactly without the need for an energy consuming control valve. This can reduce operating costs significantly over the life of the pump. The control software will not permit the pump to operate outside user specified ranges or under conditions that typically cause pumps to fail. As a result maintenance costs will decrease and MTBF will increase for these systems. When comparing the cost of smart pumping systems to conventionally operated systems all aspects of total life-cycle cost should be evaluated.

FUTURE SYSTEMS

The advent of smart pumping technologies for the first time gives the plant the ability to use the pump as:

- An asset sensing device
- An asset maintenance device
- A process controlling device

Plants finally have the ability to mine the data obtained from these devices and use this information to optimize entire operations.

The technology is available to automatically write work orders, obtain parts from stock, or place parts orders (as required) once a fault is encountered. Plant personnel will be notified of the problem and given copies of the work order, pertinent drawings, and installation manual.

Future systems will incorporate:

- Condition monitoring capabilities.
- Microelectromechanical systems (MEMS) miniature sensors will be built into pumps and motors. Artificial intelligence and neural networks will be used to validate sensor readings. If a sensor fault is detected a virtual sensor will be substituted until the faulty sensor can be replaced.
- Wireless communications of data will become commonplace.
- Cascaded loop control programs will be part of every drive.

The current trend is to have the control function move from the large centralized distributed control system (DCS) to the appliance level at the plant floor.

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