General processing

Increasing control over energy and running costs

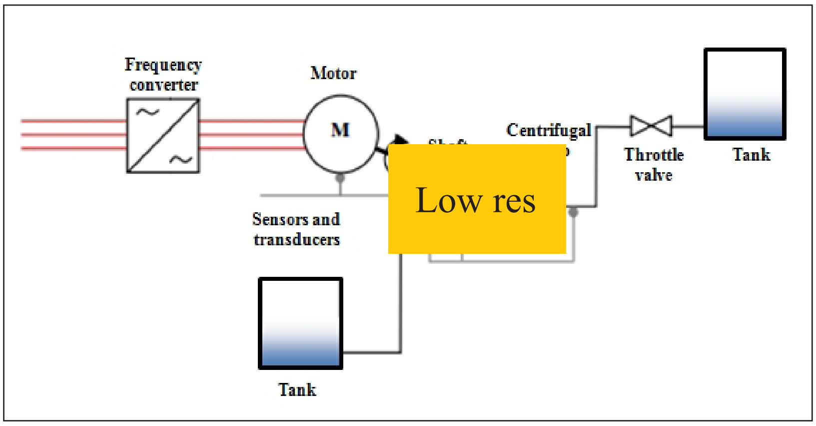
Centrifugal pumps are widely used in industrial applications and absorb nearly a quarter of Europe's electrical energy. The purpose of this paper is to explain how a centrifugal pump model-based control system can offer the energy benefits related to variable speed drive technique and offer complete protection monitoring and machine diagnostics using a minimum number of installed sensors.

Increasing demand, growing awareness of environmental pollution and the need to reduce reliance on fossil fuels, highlight the need for careful management of energy with an increased focus on renewables.

Centrifugal pumps are widely used in industrial applications using vast amounts of energy as well as incurring management, maintenance and downtime costs which have a major impact on the overall running costs of an industrial plant. Despite this, the idea of control, protection and diagnostic systems being applied to medium-low power pumps, has not been widely applied. This kind of solution requiring external sensors could have a considerable impact on costs.

Proteo, a centrifugal pump model-based control system, offers the energy benefits of variable speed drive technique and provides complete machine protection, monitoring and diagnostics using a minimum number of installed sensors.

Modern control systems are able to change the pump rotational speed with frequency converter variable speed drive (VSD) techniques. Also it is now possible to improve outputs of processes and reduce overall machinery-related production costs through provision of accurate, precise and reliable real-time information about how the machinery is actually working and what action may need to be taken.



Typical pumping system structure.

Continuous monitoring

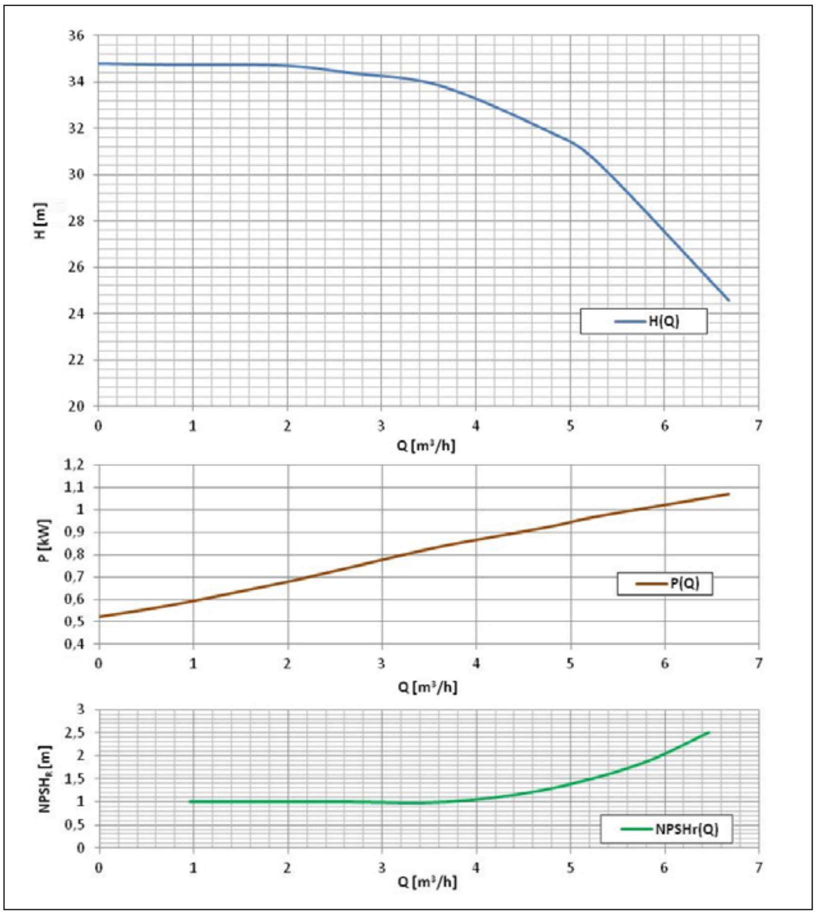
Recent literature has described how fully sensor-less control techniques have a considerable advantage in terms of energy and implementation costs. But without sensors, no continuous monitoring and diagnostic of the machine can be obtained.

The Proteo system controls the operational state of the pumping system using a minimum number of sensors with a consequent reduction of installation costs. It also provides continuous automatic complete protection from all possible causes of failure through the implementation of a pump performance model.

While the utilization of a minimum number of sensors and additional components reduces the possibility of malfunctions, the system provides a continuous machine monitoring and diagnostic thanks to an advanced algorithm that integrates field measurements and predicts performance.

The algorithm is based on field data acquisition and "expected" parameters from the implemented pump model. The system monitoring and diagnostic capabilities are aimed at increasing machine availability and reliability with consequent benefits arising from the reduction of downtimes and maintenance costs. The system also cuts the cost of surveillance by operators.

A typical pumping system consists of many elements: a driver, a centrifugal pump, valves and tanks. Advanced systems may include a VSD block and sensors producing the process variable feedback (Fig. 1).

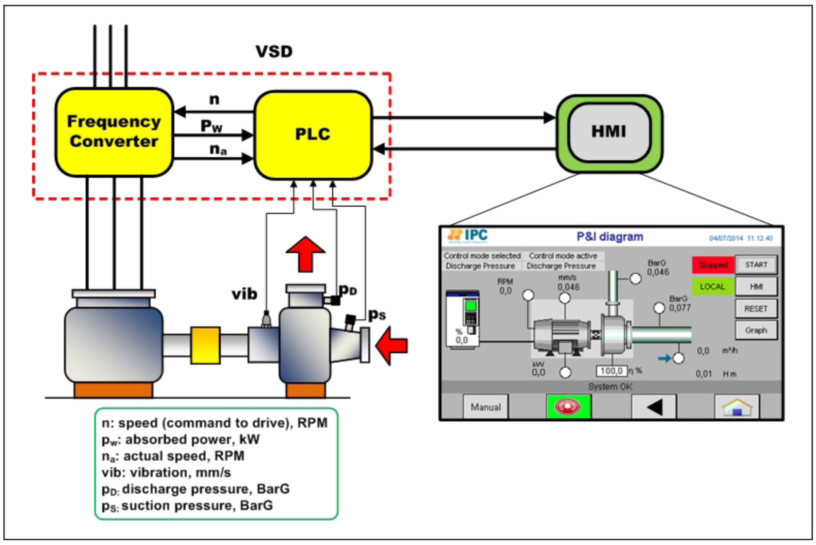


Pumps performance curves.

Process parameters

In each instance, the overall process status can be described by the group of all relevant process parameters (flow rate, liquid level, process pressures and fluid properties, etc). In this group we can also find the pump operative parameters (pump operative status).

The actual value of the process parameters depends on the coupling of the actual characteristics of the pump to the actual characteristics of the hydraulic load. When the load changes, the operative state of the pump changes too. The significant pump parameters susceptible to variations are the flow rate, suction and discharge pressure, power and the efficiency. The pump operation must then be controlled in order to fit the requested process parameters specifications and simultaneously to protect the pump itself.



Proteo Architecture.

Selection of the most suitable control system depends on several factors such as the existing plant configuration, the required operational process state and the economics. State of the art industrial control systems have four main control techniques: throttle control; by-pass control; on/off control and variable speed drive control.

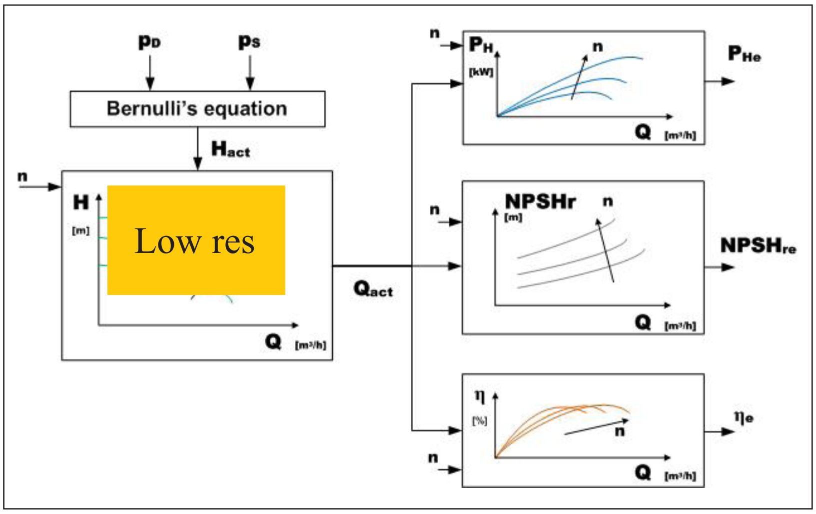
The first three of these are simple and low-cost but they run the pump at a fixed speed and are consequently inefficient and inaccurate, producing higher operating costs such as energy consumption and machine wear. Only the last method is efficient.

The VSD technique has clearly higher implementation costs. This kind of control system adjusts the pump motor speed permitting the pump to match the user's demand.

In a pumping system, the total head of flowing liquid is defined by Bernoulli's equation

$$H = \frac{p_D - p_S}{\rho g} + \frac{v_D^2 - v_S^2}{2g} + z_D - z_A$$

where H is the total head; p_D and p_S are discharge and suction pressure respectively; g is the standard acceleration of gravity; ρ is the fluid density; v_D and v_S are fluid velocities at discharge and



Algorithm employed by the PLC.

suction respectively, being v the ratio between the flow rate and cross-sectional area of pipeline and z_D and z_S represent the elevations of the discharge and suction point above the reference plane.

Pump efficiency

The power required by the pump depends on the characteristics of the fluid ρ, the head (H), the flow rate (Q) and the overall pump efficiency (η).

$$P = \frac{\rho g H Q}{\eta}$$

VSD systems are equipped with powerful control units which enable the monitoring of several modulation parameters: inverter power output and actual motor speed. The relationship between these variables and the pump process parameters are defined by pump performance curves: flow-head (QH) and flow-power (PQ) (Fig.2).

Another relevant parameter is the net positive suction energy (NPSE) or the net positive suction head (NPSH). The QH and QP curves show the trend of the head and the power consumption of the pump against the flow rate respectively.

These correlations are used in the Proteo system to determine the flow rate without the use of sensors. For variable speed pumps, manufacturers give the pump performance map as an array of curves plotted for different speeds. Even when only the nominal speed curve is available it is always possible to determine the operational points at an arbitrary speed by the affinity laws. The affinity transformations define the changes in the pumping flow rate, head and pump absorbed power following the change of speed.

This level of pump modelling is well suited to be implemented by the VSD technique. In order to perform pump diagnostics, further characterization of the pump is necessary. In particular, the curves NPSHrQ, ηQ and PHQ (PH, hydraulic power) varying with the speed of rotation of the pump, shall be determined.

Diagnostic capabilities

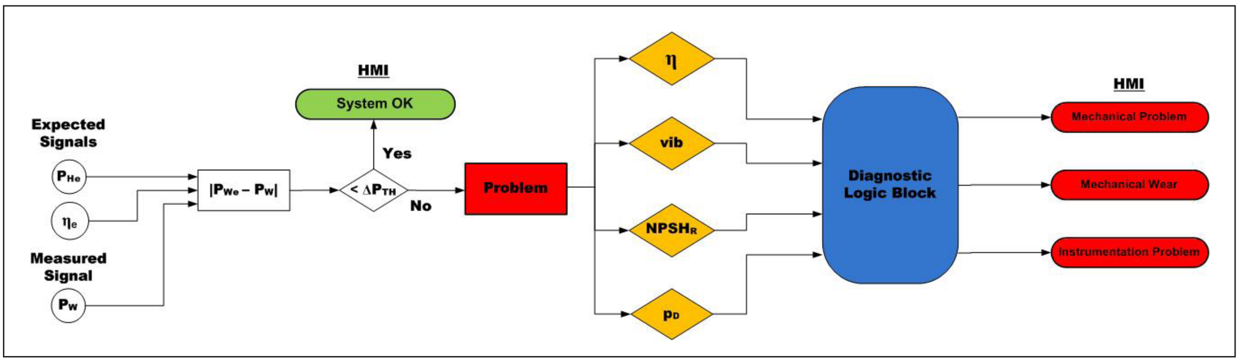
In order to develop additional diagnostic capabilities, the Proteo system implements few elementary sensors. Compared to the fully sensor less technique this choice has very low additional installation costs but offers the benefits of enabled diagnostic capabilities.

The choice of the sensors for the implementation of the proposed method starts from considerations related to cost. The flow transducer is typically more expensive, while pressure transducers and transmitters are cheaper and so preferred. The proposed system uses two pressure transducers installed near the pump flanges and a vibration sensor to perform control tasks and to implement the pump diagnostic feature respectively.

The complete architecture of the system also includes a frequency converter and a PLC as shown in Fig. 3. The PLC is used to provide multi-variable control features, to execute sequences tasks and provide computation required by the pump dynamic model, in particular the calculation of the actual flow rate. Also, the model-based algorithm allows for the calculation of the "expected" values for power, efficiency and NPSHr.

Figure 4 shows the algorithm employed by the PLC where p_D is discharge pressure; p_S, suction pressure; H_{act}, actual total head; Q_{act}, actual flow rate; n, actual speed; PHe, hydraulic power expected; NPSHre, net positive sSuction head required expected and ηe, efficiency expected.

The proposed diagnostic algorithm (Fig.5) is based on the real-time monitoring of the main machine and process parameters. In fact, the system calculates in real-time the deviation between the "expected" and "actual" performance parameters. An "expected" performance is a parameter obtained from reference/design characteristic, adjusted to actual operative condition, while an "actual" performance is a value



Proteo Diagnostic algorithm.

directly determined from field measurements and acquisitions in a specific operative condition (off design).

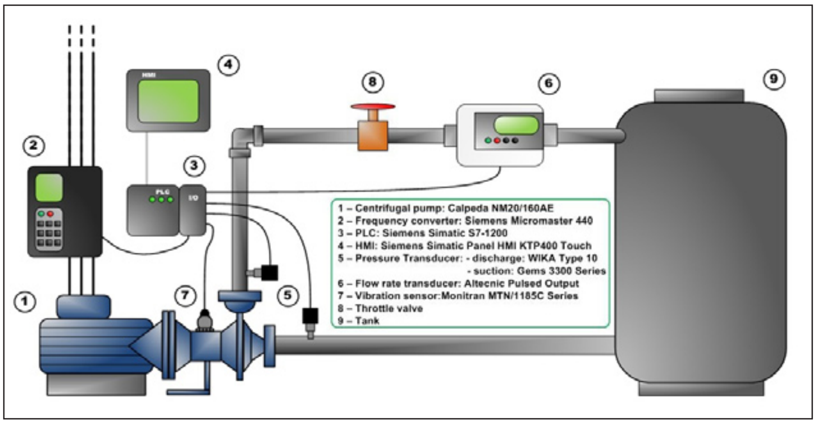
Diagnostic tool

The time trend of this deviation is a powerful diagnostic tool able to give an early indication of incoming problems. The diagnostic system is based on the knowledge of the hydraulic power (Phe) and the expected pump efficiency (ηe). This information is used to determine the "expected" power (Pwe= Phe/ ηe) and then compare this value with the "actual" power (Pw), measured by frequency converter on-board sensor.

The difference ΔPw between the "expected" and "actual" power is then compared to the power threshold, pre-set during the system configuration phase. The threshold value (ΔPTH) is also related to metrological features of transducers used. When the difference between the two powers parameters is less than the threshold (ΔPw < ΔPTH), the algorithm returns a "System OK" state. Otherwise, (when ΔPw > ΔPTH), the system enters the "Problem" diagnostic state.

In the specific case of the Proteo, the diagnostic signal generates a message on the HMI panel with the following indications- Mechanical Problem: detection of high vibration; Mechanical Wear: low efficiency state and Instrumentation Problem.

All thresholds used by the control blocks are determined by pump models implemented within the PLC. So all thresholds change dynamically as function of the actual machine operating conditions.



Laboratory test bench plant.

Flow rate

In Fig.6, flow rate measurements are carried out in order to evaluate the precision and accuracy of the flow rate calculated by the system. During the testing procedure, the flow rate values were obtained from the calculation algorithm and compared to the values measured by a flow rate volumetric transducer.

In each test, the flow rate was changed by throttling a valve installed on the discharge pipeline. The valve has been used to simulate load variations. In this way, the full range of the pump flow rate was covered. The relative errors and their respective standard deviation values calculated at different speeds are less than 2% and 1.25 respectively. The measurement points have been chosen within the pump operating range.

The verification of the diagnostic features with respect to the algorithm logics, was performed by replacing the field measured signals with artificial step signals. The artificial signals have been applied to the measurement of power at first and subsequently to the measurement of the pump body vibrations.

The control systems described in this paper show Proteo obtaining a reduction of operative energy costs by integration with the VSD technique. The proposed model-based method also allows real-time pump diagnostics to be carried out without the need for flow measurements and relative sensors. This consequently increases the machine reliability and availability (lowering maintenance and downtime costs). The moderate additional costs and the high reliability of the proposed solution along with advanced diagnostic capabilities make the system suitable to meet the oil and gas industry centrifugal pumps control and protection requirements. ●

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