Control of Liquid Density to Prevent Abnormal Pumping Performance

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Abstract: - This paper describes a new method of on-line liquid density control for prevention of abnormal pumping performance. The proposed approach is intended for pumping systems, consisting of centrifugal pumps based on induction motors running by variable speed drives. The density calculation is implemented by software running in the programmable logical controller, which acquires the data from the drive via the Profibus link. The control algorithm was tested using the multi-pump test bench.

Key-Words: - Pumping, Liquid density, Variable speed drive, model-based control.

1 Introduction

It has become an inevitable trend to use advanced automation technology to design the steady water supply system with high energy conservation and high reliability. As the water supply management is an important question, quite a lot of studies deal with the development of this area, and there are strict regulations for the parameters of the water, which is flowing into the pipelines. In a great deal it concerns the centrifugal pumps capable of transporting high-viscosity fluids and solid–liquid mixtures used in various industrial settings, including cement plants, sewage treatment plants, food plants, and multiple medical fields [Saito].

Parameters of the water flowing into these systems are generally below the permitted threshold value. During pumping, external conditions are usually alternated, so the liquid velocity and the pressure in the pipelines are changed.

Although centrifugal pumps can operate over a wide range of capacities, they commonly encounter difficulty at increased fluid density [O’Keefe]. In general, high-density problems are worse for large high-energy pumps, for pumps handling hot or abrasives-laden liquids, and for pumps designed for high efficiency at best efficiency point. The source of the pump distress at increased liquid density are fourfold – thermal, hydraulic, mechanical, and abrasive ware. The thermal source results in inescapable energy conversion loss in the pump that warms the liquid. Because of the hydraulic source, when flow decreases far enough, the impeller encounters suction or discharge recirculation, or perhaps both. Flashing, cavitations, and shock occur, often with vibration and serious damage.

Because of the mechanical source, both constant and fluctuating loads in the radial and axial directions increase as pump capacity falls. Bearing damage, shaft and impeller breakage, and rubbing ware on casing, impeller, and wear rings can occur. As an abrasive ware is a concerned, liquid containing a large amount of abrasive particles, such as sand or ash, must flow continuously through the pump. In the case of their increased density, the particles can circulate inside the pump passage and quickly erode the impeller, casing, and even ware rings and shaft.

Resulting from the system analysis of working conditions in pumping systems, many other problems are encountered, such as hydraulic hammers, dynamic stresses in the mechanical parts, high starting currents in the driving motors, energy saving problems and other issues [Steward], [Ionel].

To improve situation, an on-line measuring equipment is often applied which purpose is a dynamic water assessing and management to estimate the temporary state of the pipeline and to makes decision of its use [Éva Hajnal]. In these situations, the safe pump control must exclude pump damage [Chenghu].

This paper describes a new method of on-line liquid density control for prevention of abnormal pumping performance. The proposed approach is intended for pumping systems, consisting of centrifugal pumps based on induction motors running by variable speed drives (VSD).

In such a system the energy of processed fluid is changed along with the flow velocity. The fluid flow is generated by a rotating impeller located inside the pump casing. The most common pump type is a radial flow centrifugal pump, usually – single-volute end-suction radial flow pump. The
energy is imparted to fluid by the impeller, which has radial vanes that lead the incoming flow from the inlet (suction) into the outer edge and further into the volute casing. The impeller is attached to the pump shaft. The shaft is equipped with a sealing system which prevents the leakage. By far, the most common motor used to drive the centrifugal pumps is the squirrel-cage induction motor thanks to its simple construction, good efficiency and high reliability [Divona]. A VSD adjusts the speed of the pump impeller rotation and provides the soft starting and reduction of the superior harmonics in the network.

The density calculation is implemented by software running in the programmable logical controller (PLC), which acquires the data from the VSD via the Profibus link. Density is estimated based on the Bernoulli’s principle. The input data for the calculation are speed and input power of the pump, and also the reading of the pressure sensor at the outlet of the pump.

2 Mathematical Model of Pumping

The required energy of the pumping system is determined by the referred flow rate, physical characteristics of the pumped fluid, and the efficiency of the installation.

The power, needed for the pump driving can be defined by the following equation:

\[ P_i = \frac{\rho g H Q}{\eta} \quad , \]

where

- \( P_i \) – required input power, W,
- \( \rho \) – fluid density, kg/m\(^3\),
- \( g \) – acceleration of gravity, 9.80665 m/s\(^2\),
- \( H \) – energy head added to the flow, m,
- \( Q \) – flow rate, m\(^3\)/s,
- \( \eta \) – efficiency of the pumping system.

Fluid pressure \( p \) results from the force applied to a pipeline surface counted as an amount of force acting per unit area. The total head of the flowing liquid \( H \) is defined by the Bernoulli’s equation, which, in turn, can be used for the pressure estimation at any point of the flow [Ionel].

\[ H_T = \frac{v^2}{2} + gz + \frac{p}{\rho} \quad , \]

where:

- \( v \) – velocity of fluid in the pipeline, m/s,
- \( z \) – elevation of the point above the reference plane, m.

Here some assumption can be made about the fluid:

- a. it is incompressible and ideal,
- b. its friction is characterized by zero viscosity.

The fluid velocity \( v \) can be defined as

\[ v = \frac{Q}{A} \quad , \]

where:

- \( Q \) - flow rate, m\(^3\)/s,
- \( A \) - cross-sectional area of the pipeline, m\(^2\).

3 Algorithmization of Density Calculation

Most of modern VSDs are equipped with the proper control units that employ the motor control and acquisition of modulation parameters. Knowing of such parameters as inverter output power and actual speed of the motor shaft rotation along with the pump specific characteristics enables a derivation of severe peculiar values of the liquid flow [Stewart] using the pump specific characteristics implied by the pump performance curves. Such curves usually plotted by a manufacturer in their datasheets represent the graphs describing the pump performance as a relation between the flow, the pump input power, and the total head. These diagrams, specific for each pump model, represent the essential parts of the pump documentation.

Every pump is equipped with two types of diagrams.

a. PQ curves represent the relation between the pump on-shaft power and its output flow. These traces show the power consumption of the pump at actual flow rate. The growth of on-shaft power along with of the flow increase is a typical phenomenon for the centrifugal pumps.

b. QH curves represent the relation between the total head and the output flow. The hydraulic head, which a pump is able to perform at actual flow rate is shown by these curves.

As an example, the performance curves of Ebara CDX 120 pump are shown in Fig. 1.
Using the relation between the on-shaft power and the actual flow defined by the performance curves, the system is capable to calculate the total head at the outlet of the pump. To this aim, the on-shaft power can be acquired as an output power measured among other actual modulation parameters in most of the modern VSDs.

The current flow rate can be obtained from the PQ curves. In the described system, the points obtained from the PQ and QH curves are stored in the look-up table inside the calculating software. The flow rate is acquired by interpolation method utilizing the triangles similarity rules. This approach is illustrated in Fig. 2.

Typically, manufacturers provide the pump performance curves for the nominal conditions when the pumps rotate at the rated speed, and for several other speeds. These performance diagrams are valid for nominal conditions of the pump operation. At the same time, the pump characteristics are subjected to change dependently of the degree of wear (especially it concerns the impeller, which is exposed to most of threats e.g. mechanical damage or cavitation). The use of pump performance curves requires keeping in mind these threats and correcting adjustment of the calculated parameters.

An example of PQ curves for several speeds of the same pump is shown Fig. 3.

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In [Girdhar], an approach is proposed for calculation of the actual working point of the pump when the current speed is different from the nominal one. The affinity transformation rules are to be used in such calculation. This method allows to transform the existing curves in order to consider the changes in the pumping power, flow rate, and head, which are specified by the speed change [Ionel]. The head and the pressure vary with the squared pump speed as follows:

\[
H_2 = H_1 \times \left( \frac{n_2}{n_1} \right)^2, \quad (4)
\]

\[
p_2 = p_1 \times \left( \frac{n_2}{n_1} \right)^2, \quad (5)
\]

The power varies with the cube of the pump speed:

\[
P_2 = P_1 \times \left( \frac{n_2}{n_1} \right)^3, \quad (6)
\]

Here, the subscript 1 refers to the nominal (or initial) condition and 2 refers to the new condition.

As soon as the flow rate is known, the fluid density can be derived from the Bernoulli’s equation assuming the pressure (and hence, the total head) is
constant. In this way, the density deviations can be monitored.

The algorithm developed for the sensorless density calculation is presented in Fig. 4. To derive density, the actual speed and on-shaft power of the pump are required as the input data. This data are acquired from the VSD as mentioned above. Such constants like the cross-sectional area of the pipeline and the efficiency coefficient of the pump-motor combination are introduced to the software before calculation.

In this work, the PQ curve is defined by five key points whereas those coordinates are hardcoded in the program. The QH curve is defined in the similar way. Using this approach, the look-up tables containing five points of the PQ curve and five points of the QH curve are created in the program. The algorithm consists of the following steps:

1. Acquire the actual speed and on-shaft power from the VSD.
2. Calculate the actual input power of the pump using the affinity transformation and the efficiency coefficient of the pump-motor combination.
3. Estimate the value of the flow rate corresponding to actual power from the PQ graph using an interpolation principle.
4. Basing on the QH graph, find the total head being inline with the actual flow, calculated in the previous step. It is the value of the total head referred to the nominal speed, which should be brought to the conformity with the actual speed using the affinity laws.
5. Calculate the density using the Bernoulli’s principle.

The following notations are used in the description of the algorithm:

- $P_{\text{act}}$: actual power
- $P_{\text{pump}}$: output power of pump/motor combination
- $P_{\text{shaft}}$: on-shaft power
- $\eta$: pump efficiency
- $N_n$: nominal speed of pump
- $N_{\text{act}}$: actual speed of pump
- $Q_{\text{act}}$: actual flow
- $H_{\text{act}}$: actual head
- $p$: pressure
- $v$: speed of fluid in the pipe
- $g$: acceleration due to gravity
- $z$: elevation point above the reference plane
- $\rho$: density of the fluid

![Fig. 4. Algorithm of density calculation.](image-url)
4 System Implementation and Testing

Similarly to [Shuleng Dong], for the density estimation a PLC is used along with the Profibus link acquired the actual speed and actual power from the VSD (Fig. 5).

The components used have the following technical parameters:

- VSD ABB, ACQ810-04-02A7-4, 1.1 kW. The drive is equipped with the pump control firmware and uses an external speed reference. The speed controller has the following parameters: proportional gain 10, integration time 0.5 s, and derivation time 0 s.
- PLC ABB AC500, PM 571. The cycle time per instruction when processing the calculations with the floating point numbers is 1.6 μs. The PLC is connected to the VSD via the Profibus link.
- Pressure sensor Danfoss, 4-22mA, 0-10 Bar.
- Pump Ebara CDX 120/12, nominal power 0.9 kW, nominal current 3 A, nominal voltage 400 V, nominal speed 2760 rpm, impeller diameter 157 mm.

The calculation dataflow is shown in Fig 6.

![Fig. 5. Schematic view of the test stand.](image)

![Fig. 6. Data flow between the VSD and the PLC.](image)

![Fig. 7. System for the VSD response analysis.](image)

To test the developed methodology, the test bench shown on Fig. 7 was arranged.

In the proposed testing system, the calculation was implemented using PLC. The values of calculated density were then transmitted to the VSD. The transmitted values were logged by the means of the VSD monitoring functionality.

During experimentation, the power alteration of the tested centrifugal pump was simulated via...
starting and stopping of two auxiliary pumps. This affected on the loading of the tested pump resulting in changing of its input power.

The tested pump rotated at constant speed. The auxiliary pumps were located in parallel with the tested pump. Both of them rotated with constant speed. The switching on of the auxiliary pump decreased the load at the tested pump. In this way, a fluid density drop was imitated. The switching off of the auxiliary pump increased the load at the tested pump. In this way, a fluid density rise was imitated.

The auxiliary pumps were started gradually, in cascade. In the same way, their stopping was provided. In such a way, the complex loading at different levels of pumped liquid density was imitated.

The results of testing are shown in Fig. 8. Two stepping load alternations were simulated. First, the high load level was assigned (all auxiliary pumps were stopped) thus simulating the high density of the liquid. Herein, the input power of the tested motor was about 0.4 kW. Then, the auxiliary pumps were started one by one which resulted in two-step fall of density (and also the input power of the tested pump). Next, both auxiliary pumps were started simulating the load grow at the tested pump, at which the power increased. According the analysis, the designed software was properly reacting on the load change of the tested pump.

![Fig. 8. Measuring the density. Simulating the density change by increase/decrease of the tested pump loading.](image)

### 5 Conclusion

The new method for on-line liquid density control for prevention of abnormal pumping performance is developed. The proposed approach is intended for pumping systems, consisting of centrifugal pumps based on induction motors running by variable speed drives. The density calculation is implemented by software running in the programmable logical controller, which acquires the data from the drive via the Profibus link. The control algorithm was tested using the multi-pump test bench.

### References:


