Measurements of operational and energy optimization of pumping

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Abstract

In this paper we will review the measurement of parameters to assure an optimal functioning of an automatic pumping process. The optimization is made by a (quasi)continuous control of these parameters and assisted by an computing program.

1 Introduction

The optimum automated exploitation of a pumping plant requires the use of real characteristic/functional curves for all equipment. This equipment comprises: the pumps, the a.c. motors and the converters (where the pumps have speed control). Because of the wear and tear, at least some of these curves change.

Therefore, to ensure that the automated exploitation remains at the optimum level, a continuous update of characteristic curves of the equipment is required. This is why is necessary a simultaneously parameter measurement.
This paper intends to systematize the required parameters to be measured in order to update the characteristic curves, thus allowing an optimum exploitation of an automated pumping plant, equipped with electropumps.

2 The optimum exploitation of a pumping plant

The optimum exploitation of a pumping plant supposes a functional and energy optimization.

The simultaneous functional and energetic optimization of a pumping plant may be assured only by its automated control, using a proper algorithm.

Such an algorithm must consider each characteristic curve as an analytical curve, generated by series of n points \((x(i), y(i)) (i=1,n)\), obtained by direct measurements.

3 Characteristic curves of pumps without speed control

For a given pump which has a certain outlet diameter of impeller the following characteristic curves (***) [4]) are given:

- the head -- capacity characteristic \(H = H(Q)\) (the characteristic curve of the pumping head);
- the efficiency -- capacity characteristic \(\eta = \eta_p = f_1(Q)\) (the characteristic curve of the efficiency);
- the power -- capacity characteristic \(P_{\text{shaft}} = f_2(Q)\) (the characteristic curve of the power);
- the characteristic curve of cavitation: \(NPSH = f_3(Q)\).

In case of appropriate design of the pumping plant, a minimum risk of cavitation can be ensured by choosing an adequate inlet diameter of the impeller and speed and according the cavitational curve of the suction pipe-line to the cavitational performances of the pump.

So for well designed pumping plant, the curves \(H = H(Q)\) and \(P_{\text{shaft}} = f_2(Q)\) or \(\eta_p = f_1(Q)\) are sufficient to ensure the optimum working of pumps without speed control.

4 Characteristic curves of motors without speed control

For an electric motor with a given nominal power, voltage and speed, the manufacturers offer the curves of efficiency as a function of clamp power (power of terminal, \(P_{\text{term}}\)): \(\eta_m = f_4 (P_{\text{term}})\).

But in the optimization process, we usually use another characteristic which is derived from the one above: \(\eta_m = f_5 (P_{\text{shaft}} m)\), the power at the shaft
level $P_{\text{shaft}}$ being obtained from the definition of the motor efficiency:

$$\eta_m = \frac{P_{\text{shaft}}}{P_{\text{term}}}.$$  

The majority of the pumps being run by asynchronous motors, we have a sliding curve as a function of clamp power: $s = f_6(P_{\text{term}})$; from this curve one can easily obtain the slide curve as a function of shaft power: $s = f_7(P_{\text{shaft}})$.

Supposing that the pump and the electric motor are directly coupled, we have the relation: $P_{\text{shaft}} = P_{\text{shaft}} = P_{\text{shaft}}$.

## 5 The variation of flow, pumping head, power and efficiency function of speed.

The adjustment of the speed of a pump from the synchronous one $n_0$ to a certain effective value $n$ ($n < n_0$), leads to an adequate modification of flow, pumping head, power and efficiency according to well known relations:

$$Q = Q_0 \cdot \frac{n}{n_0} \quad (1)$$

$$H = H_0 \left( \frac{n}{n_0} \right)^2 \quad (2)$$

$$\eta_P = 1 - \left( 1 - \eta_{P_0} \right) \left( \frac{n_0}{n} \right)^{0.1} \quad (3)$$

$$P_{\text{shaft}} = P_{\text{shaft0}} \left( \frac{n}{n_0} \right)^3 \quad (4)$$

where

$$P_{\text{shaft0}} = \rho \cdot g \cdot Q_0 \cdot H_0 \eta_{P_0} \quad (5)$$

respectively:

$$P_{\text{shaft0}} = \rho \cdot g \cdot Q_0 \cdot H_0 \eta_{P_0} \quad (6)$$

(with "$g$" = acceleration due to gravity; "$\rho$" = water density at the working temperature; all sizes are measured in S.I.units).

Also, for small variations of speed, we can consider $\eta_P \approx \eta_{P_0}$.

For the asynchronous motors, the variation of slide as a function of speed is given by:

$$s = \frac{n_0 - n}{n_0} \cdot 100 \quad (7)$$

The flow, the pumping head and the shaft power, vary with the speed and the slide. It is to be noted that for a 3% modification of slide or speed, the shaft power varies by 8%.
6 The influence of asynchronous a motor slide on the pump characteristic curves

Choosing a maxim value for the admissible error $\varepsilon$ to effective shaft power from nominal power $P_{nom}$, for example, having $\varepsilon = 0.1\%$, the maximum error of the power will be $0.001 P_{nom}$.

In each moment, the pumping plant must assure a certain flow $Q_{st}$ and head $H_{st}$. To ensure at each moment a greater value for $\eta_{st}$, one must optimize the flow distribution to all the pumps from the pumping plant in order to assure the needed $Q_{st}$.

- Curve $H(Q)$ for speed $n_0$,
- Curve $\eta_p = f_1(Q)$,
- Curve $\eta_m = f_2(P_{shaft\_m})$,
- The value $P_{nom}$,
- The value $H_{p}$.

From curve $H(Q)$, having $H_{p}$ can obtain $Q_0$.

From curve $\eta_p(Q)$, having $Q_0$ can obtain $\eta_0$.

Calculate a new curve $H(Q)$, see (1) and (2).

Figure 1: Logical scheme for iteration for a pump driven by an asynchronous motor without adjustment of speed.
This necessity is shown by a specialized program which calculates all the possible alternatives of the active pump groups to assure the needed parameters $H_{st}$, $Q_{st}$, and to chose the alternative which assure the maxim value for the plant's efficiency.

For this purpose, the program must "know":
- for each pump, the curves $H = H(Q)$, $\eta_p = f_1(Q)$, ($P_{shaft} = f_2(Q)$);
- for each motor, the curves $\eta_m = f_5(P_{shaft})$, $s = f_7(P_{shaft})$.
The calculus then develops according to Figure 1. An initial value for the power $P_{shaft init}$ is taken into account (for example $P_{shaft init} = 0$). Having the curve $H(Q)$ for a value $n_0$, the value $Q_0$ results from a value $H_0$. Given the result $Q_0$ and the curve efficiency $\eta_p = f_5(Q)$, we can get the pump efficiency $\eta_{P0}$.

With $H_0$, $Q_0$ and $\eta_{P0}$, using (6), $P_{shaft 0}$ results. Then, the calculus error for the power will be:

$$\Delta P = \text{abs} \left( P_{shaft 0} - P_{shaft init} \right)$$

If this error has a value $\Delta P > \varepsilon \sqrt{P_{nom}}$, then the program enters in an iteration cycle. So it adopts $P_{shaft init} = P_{shaft 0}$, then from curve $s = f_7(P_{abs})$ results the correspondent value $s$, i.e. the value $n_i$ for the effective speed, using (7). From the curve $H(Q)$ for $n_0$, using (1) and (2) the respective curve for the value $n_i$ results. The iteration continues to obtain a negligible value $\Delta P$. At that moment, the value $P_{shaft 0}$ is known and, from the curve $\eta_m = f_5(P_{shaft})$ results the effective value $\eta_m$ for the motor and finally the clamp power:

$$P_{term} = \frac{P_{shaft 0}}{\eta_m}$$

In Figure 2, the curves $H(Q)$ are presented generated by these procedures, for a pump with an asynchronous motor having 315kW, 380V, $n_0 = 1500$ rot/min.

Figure 2: Curves $H(Q)$ for a pump driven by an asynchronous motor at speeds $n_i$ ($i=0...4$)
7 Electrical equipment for variable speed pumps

For an electrical motor, the control of speed may be obtained by varying the frequency of alternative voltage, using a static frequency converter. Generally speaking, the converters works at low voltage (380V) and the motors by powers higher than 200 kW, at average voltage (6kV). Therefore the pumping plants having pumps that require higher power, have transformers. So, each high power pump having variable speed can be equipped according to the following solutions:

a) a normal motor of medium voltage, with a medium voltage converter (this solution is technically the most effective but is more expensive);

b) a special motor with low voltage, coupled with an ordinary low voltage converter; a step-down transformer is placed between the electrical network and the converter there (in this case, the converter is relatively cheap, but the motor has a high price to which the price of the transformer is added);

c) an ordinary medium voltage motor, coupled which a low voltage ordinary converter; the converter is coupled to the electric network by a step-down transformer and there is a step-up transformer between the converter and the motor (for this solution, the motor and the converter are relatively cheap, but the electrical equipment prices is increased by the transformers which, occupy space and reduce the global efficiency by their losses).

8 Electrical equipment efficiency, in the case of variable speed pumps

In order to optimize pumping performance, the efficiency curves of all electric equipment must be utilised. In all these cases, the efficiencies vary as a function of two parameters: the shaft power $P_{\text{shaft}}$ and the converter's outlet frequency $f_2$.

Frequency adjustments by static converters have a negative effect. This equipment induces in the electrical network certain harmonical waves that cause distortion of electromagnetic fields. These distortions must be filtered, but the necessary equipment is expensive. Finally there must be a trade off between the filtration degree and its price. In addition, these distortions cause supplementary losses on the electrical chain.

So, due to supplementary losses, the curves of efficiency function of shaft power $P_{\text{shaft}}$ and frequency $f_2$ are, practically impossible to be established by theoretical means. That is why, to assure the optimum performance of pumping, the efficiency of global electrical equipment can be used, which is easy to measure.

For every kind of electrical chain (see paragraph 7), the variation of efficiency as a function of shaft power and outlet frequency $f_2$ is given in several ways; one of these is presented in Figure 3 and Figure 4.
Figure 3: Maximum power as a function of frequency for an electrical motor

Figure 4: Efficiency curves for an asynchronous motor as a function of relative power $P_r$, at frequencies of 50, 40, 30, 20, 10 Hz
Figure 3 presents the motor maxim power $P_{\text{max},f}$ as a function of frequency $f_2$. Obviously, at the nominal frequency (50Hz), the maximum value of power is equal to the motor's nominal power (315kW, in the case presented in Figure 3).

Figure 4 presents the motor efficiency as a function of relative power $P_r$, having as parameter the outlet frequency $f_2$. The relative power is a function of effective power $P$ and maxim power $P_{\text{max},f}$ at the same frequency:

$$P_r = \frac{P}{P_{\text{max},f}} \cdot 100$$

(10)

Obviously, Figure 4 can be build for the entire electrical chain.

9 Parameters to be measured.

To assure a continuous control of pumping and create the necessary conditions to optimize the pumping process, the following parameters' measurements for each pump of a pumping plant must be known:

- the flow $Q$,
- the pumping head $H$,
- the shaft torque $M$,
- the speed $n$,
- the input power of electrical equipment ($P_{\text{term}}$).

9.1 Measurement of the flow

At present, it is very difficult to measure the flow for each pump of a pumping plant to be done; by design, only the global flow at the outlet of pumping plant is stipulated.

In these conditions, according to standards in force, the most convenient flow transducers are those which are not require influence by the low level perturbations of the hydrodynamic field. In this respect, we must mention ultrasonic flow – meters and those of the ACUTUBE type.

9.2 The determination of the pumping head

According to one of its definitions, the pumping head is the difference between specific energies in the outlet and the inlet limits of the pump, i.e.:

$$H = \left( \frac{p}{\gamma} + \frac{v^2}{2g} + z \right)_d - \left( \frac{p}{\gamma} + \frac{v^2}{2g} + z \right)_s$$

(11)

with:
- index "d"= discharge/outlet limit of the pump;
- index "s"= suction/inlet limit of the pump;

The heights $z_d$ and $z_s$ correspond to the weight center of discharge and suction limit.
The speeds' $v_d$ and $v_s$ are given by the mass-transfer law in stream tube, as an average value on section:

$$v = \frac{Q}{\pi r^2}$$  \hspace{1cm} (12)

($r =$ radius of the pipe-line)

In order to determine the pumping head, the pressure at discharge/outlet and suction/inlet limits of the pump must be measured. The measurement of these pressures can be done in two ways:

- to measure both values $p_d$ and $p_s$, using adequate transducers;
- to measure the difference $p_d - p_s$, using a differential transducer.

9.3 The measurement of shaft torque

The measurement of shaft torque is necessary especially in the case of pumps with variable speed.

To the pumps without speed variation, the shaft torque can be obtained from the motor characteristic curve $\eta_m = f_4 (P_{term})$.

There are at least 3 patents (Vitone [1], Coulter [2], Vertan [3]) for the measurement of shaft torque and they do not require the modification of the pump and motor axial displacement.

9.4 The measurement of speed $n$

9.4.1 Pumps with synchronous motors

9.4.1.1 Pumps without variable speed. In this case, the speed may be considered invariably, equal to the synchronous speed and known from the motor adoption.

9.4.1.2 Pumps with variable speed. In this case, the speed should be directly measured, or determined indirectly, by measuring the frequency $f_2$.

9.4.2 Pumps with asynchronous motors. In this case, the effective speed $n$ must be measured in all situations.

9.4.2.1 Pumps without variable speed. In this case the speed varies with the motor slide $s$. So, the speed $n$ can be:

- directly measured, with a proper transducer;
- determined from the curve $s = f_6 (P_{term})$, by measuring the clamp power $P_{term}$.

9.4.2.2 Pumps with variable speed. In this case the speed must be measured by a proper transducer.

9.5 The measurement of clamp power ($P_{term}$).

In all the situations, as a control measure, this power should be directly and permanently measure. In the case of the use of converters, because of the induced distortions, proper instruments (transducers) must be used.
9.6 The measurement of other parameters.

To assure an adequate exploitation of pumps and motors the following parameters, must be measured, also: the bearing temperature, vibrations, the motor temperature, etc.

10 Conclusions

a) For an optimal automated guidance of a pumping plant, the proper characteristic curves of both pumps and electrical equipment must be used. For the pumps these curves are the pumping head-capacity $H(Q)$ and the shaft power-capacity $P_{shaft}(Q)$ (or the efficiency-capacity $\eta(Q)$). For the electrical machine's chain (transformer + converter + motor--under the type of necessary equipping)--the curves are $\eta_{lm}=f_5(P_{shaft})$ and $s=f_7(P_{shaft})$.

b) Given a pumping plant, at all times one must know, both parameters for every individual pump ($Q, H, P_{shaft}, \eta, n, P_{term}$) and the global plant parameters ($Q_{st}, H_{st}$).

c) Having constantly measured the parameters of the pumps, it is possible to determine when the pumps must be repaired, i.e. when the parameters are out the guaranteed domain.

d) The continuous measurement of the pump and electrical machine chains is also important for control computer program.

References


2. Coulter, C.A., German Patent DE 3736983.0 Int. Cl. G01L3/02 registered date 31.10. 1987 publishing date 05. 05. 1988.


4. German Standard DIN 1944, class II.