RESEARCH PAPER

Improving power efficiency of underloaded pipelines with variable frequency drives

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ABSTRACT

The paper considers the option to reduce power consumption in the operation of the underloaded trunk pipeline by engaging additional pump units with lower rotor r.p.m. control using variable frequency drive. Under these conditions, the operating point of the pumps (delivery rate, head) approaches to the rated output, thus increasing the efficiency of the pumps and decreasing the electricity power consumption for pumping operations. The paper presents comparative calculations of operating conditions for a section of the trunk pipeline with a specified pumping capacity of 35 million t/year (60 % of the design load) when one, two and three main line pumps with variable frequency drives are engaged. The power consumption for pumping is calculated using the dependence of the variable frequency drive and motor efficiencies on the electric motor load and rotational speed. Based on the results of calculations, the electric energy saving is determined when additional pumping units are engaged. The experience has shown that when the second main line pump was engaged, the electric energy saving for pumping was 3.7% compared to the condition with one pump running. However, if the third pump is engaged, the saving is only 1.9 % – the decrease is due to lower motor and variable frequency drive efficiencies in the underloaded condition.

Key words: power efficiency improving, trunk pipeline, variable frequency drive, energy saving, main line pump, booster station.

INTRODUCTION

PJSC Transneft system includes trunk oil and petroleum product pipelines that are currently loaded significantly less than their design capacity, as well as pipelines with derated operation for a significant part of time. As a rule, when planning operation conditions for such oil pipelines, the number of employed main line pumps at the oil pumping station (OPS) is selected as the minimum necessary to ensure the planned pumping volume, which is not always effective in terms of the electric power energy consumption [1].

Rigging the main line pumps (MLP) with variable frequency drive (VFD) facilitates the achievement of the required pumping performance with a various number of pumps (one, two or three) engaged at OPS by changing the MLP rotors revolutions per minute (RPM). When the rotor RPM decreases, the operating point of the pump (delivery rate, head), which is normalized to 100% rotor RPM, shifts towards the rated output, leading to an increase in the pump efficiency and consequently, to a reduction in energy consumption for pumping.

Methodology of the study

When RPM of MLP changes from \( n \) (r.p.m.) to \( n_1 \) (r.p.m.), its performance parameters – delivery rate \( Q \), head \( H \), efficiency \( \eta \) – change according to the known laws of similarity [2]:

\[
\begin{align*}
Q_1 &= Q \frac{n_1}{n} \\
H_1 &= H \left( \frac{n_1}{n} \right)^2 \\
\eta_1 &= \eta \frac{n}{n_1}
\end{align*}
\]

Where:

- pump parameters \( Q, H, \eta \) are given at rotor RPM equal to \( n \) r.p.m., and pump parameters \( Q_1, H_1, \eta_1 \) – at rotor RPM equal to \( n_1 \) r.p.m.
The formulas show that when RPM changes from \( n \) to \( n_1 \), the pump efficiency does not change in case when the pump delivery rate and head were changed strictly according to the similarity principle. The pump operating points, for which the similarity principles are valid, form the equal efficiency lines, when RPM of MLP changes from minimum to maximum (Fig. 1).

Let’s define the range of optimal efficiency as the range of operating points of the pump (delivery rate, head) with a possible decrease in the pump efficiency by no more than 3% relative to the maximum value (at rated delivery). The range of operating points with the optimal performance, with regard to the lower rotor RPM at 50% of the rated value (3000 r.p.m.) is shown in Fig. 1 (highlighted in yellow). One can see that the range of optimal performance is located within the area of acceptable operating points, for which the decrease in the efficiency relative to the maximum value can exceed 3%.

The efficiency value for any operating point in the selected range of optimal performance (with lower rotor RPM) is determined graphically in two steps (Fig. 1):

- **Step 1:** draw a line of equal efficiency from the specified RPM value for the selected operating point of the pump to 100% RPM and determine the pump delivery rate at this rotor RPM (according to the similarity formulas above).
- **Step 2:** determine the pump performance at the delivery rate set in step 1, which corresponds to 100% RPM of the pump.

**Example of calculation**

Let’s estimate the reduction in the electric power consumption for pumping. For example, let’s consider the DN 1000 362.7 km long pipeline, which includes three OPS: the source pumping station OPS-1 and booster pumping stations OPS-2 and OPS-3, equipped with MLP of NM-10000 type with 12,000 kW three-phase induction motors. The pumping units are equipped with VFD that enable to change the RPM of the pump rotors from 3000 r.p.m. (100 %) to 1500 r.p.m. (50 %) for all engaged MLP simultaneously; accordingly, the pumping performance under different conditions can vary widely. The rated delivery of MLP is 8,000 m³/h (at 100% r.p.m.), which corresponds to a pumping capacity of 58.5 mln.t/year. However, currently the annual volume of pumping is 35 mln.t/year (4,789 m³/h), which determines the operation of the pipeline in derated conditions. If VFD is available, replacement of the MLP rotors at this pumping volume is impractical. To ensure pumping through the pipeline with a specified capacity of 35 mln.t/year, it is possible to engage a various number of pumps at OPS-1 (from one to three), considering the reduction in the rotors RPM using VFD.

Let’s consider three possible operation conditions of OPS-1 – OPS-4 pipeline section with the same pumping capacity, provided that one, two or three MLPs are engaged at the source OPS-1 with the rotor RPM control only at OPS-1. At that, the system of automatic control of MLP rotors RPM at OPS-1 maintains the same output pressure to ensure the specified performance regardless of the number of operating...
Figure 2. Pressure plot in the pipeline section OPS-1 – OPS-4 for derated pipeline operation conditions (pumping volume 35 mln.t/year):

- \( \nu \) – oil kinematic viscosity, cSt;
- \( \rho \) – oil density, kg/m\(^3\);
- \( N_c \) – power consumed by the pump, kW;
- \( \eta \) – hydraulic slope at the pipeline section, m/km;
- \( x \) – position tag of OPS along the pipeline route, km;
- \( Z_{MLP} \) – elevation tag of MLP, m;
- \( Z_{tf} \) – elevation tag of tank farm, m;
- \( w \) – oil flow speed in the pipeline, m/s;
- \( P_{out} \) – output pressure, MPa;
- \( P_{in} \) – inlet pressure, MPa;
- TF – tank farm.

pumps – see the operation pressures plot for the pumping conditions (Fig. 2). The operation parameters of OPS-2 and OPS-3 (the number of operating MLPs and the rotor RPM) remain unchanged. Thus, in this example, we estimate the electric energy savings for pumping only at the source station OPS-1; similarly, we can perform calculations for booster stations OPS-2 and OPS-3.

Fig. 2 shows that under the specified conditions, three MLP are engaged at each OPS with reduction in rotor RPM using VFD. For pumping 35 mln.t/year, the required output pressure at the source OPS-1, estimated by hydraulic analysis [3], amounted to 4.28 MPa (corresponds to MLP head 357 m, with due regard for the rotor RPM reduction). The required OPS-1 output pressure can be provided when one, two or three MLP equipped with VFD are engaged.

If the pumping throughput is fixed for a given conditions, then changing the number of operating MLP leads to a change in the required pump head at a fixed delivery rate by changing RPM of MLP rotors; this results in a change of the pump efficiency [4]. Fig. 3 shows the QH-performance curve (on the left axis) and the efficiency (on the right axis) of the NM-10000 pump operating at OPS-1 under the considered conditions, with indication of the pump operating points at one, two or three MLP engaged. One can see that when the number of operating pumps increases, the operating point normalized to 100% rotor RPM shifts to the rated pump delivery with the maximum efficiency. Thus, an increase in the number of engaged pumps leads to an increase in the efficiency of the pump and to a reduction in OPS electric energy consumption for pumping.

The operating point for a single operating MLP is not included in the optimal efficiency range, since the decrease in efficiency relative to the maximum value for this particular operation conditions exceeds 3% (Fig.3). For operating conditions with two and three pumps engaged, the efficiency of the pumps is in the optimal efficiency range, since it differs from the maximum value by no more than 3%.

For various number of pumps engaged at OPS-1, the pump efficiency (ignoring VFD and electric motor efficiencies) is:

- 76.1% when one MLP operates with rotor RPM 93.8% of the rated value (outside the optimal efficiency range)
- 84.3% when two MLP operate with rotor RPM 69.6% of the rated value (in the optimal efficiency range)
• 85.6% when two MLP operate with rotor RPM
• 59.4% of the rated value (in the optimal efficiency range).

Thus, the increase in the pump efficiency with the second MLP engaged was 8.2%, and with the third MLP engaged – 9.5% compared to a single MLP engaged operation conditions.

However, estimating the energy efficiency of the pumping conditions, one shall consider changes in the induction motor and VFD efficiencies versus the load and RPM of the electric motor (Figs. 4 and 5).

Fig. 4 and Fig. 5 show the plots of three-phase induction motor and VFD efficiencies versus the load of the motor at 100%, 70%, and 60% motor RPM (r.p.m. parameters correspond to the values obtained in the hydraulic calculation for the example in question). One can see that RPM reduction leads to an increase in the efficiency of the motor and to a decrease in the efficiency of VFD at any (fixed) load of the electric motor.

Let’s compare the energy efficiency of the pipeline operation with one, two and three MLP engaged, taking into account the VFD and electric motors efficiency. The summary results for calculating energy savings in annual terms are shown in the table.

The results of calculations indicate that when additional pumps are engaged, the efficiency of the main line pump increases, but the MLP combined efficiency (pump, VFD and electric motor efficiency) increases unevenly due to the lower VFD and electric motor efficiency (Fig. 4) when reducing the rotors RPM, namely:
• by 4% at two MLP engaged compared to the combined efficiency for the condition with single MLP operating (from 69 to 73%)
• by 2% at three MLP engaged compared to the combined efficiency for the condition with single MLP operating (from 69 to 71%).

Therefore, of the conditions under consideration the best option is with two engaged MLP. Thus, in the derated operation conditions of the pipeline with pumping units equipped with VFD, it is possible to reduce the energy consumption for pumping by engaging additional operating MLP.

One can notice that the performance curve of the pump has a maximum (at the rated delivery), after which this indicator begins to decrease. Therefore, at a certain value of the performance parameter, it may not be advisable to engage an additional pump, since the result will be a decrease in the

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1 Reporting materials under the R&D contract ‘Analysis of the efficiency value changes in the operation of power equipment in various operating conditions. Drafting proposals for the efficiency improvement’.
efficiency of the pump and an increase in energy consumption for pumping.

It should be noted that it is possible to reduce the developed pump head at a given delivery rate not only when using MLP with VFD, but also when machining the rotors. For this example, the estimated dimension of the MLP rotor machining will be:

- 5.6% of the rotor diameter with one operating MLP
- more than 20% of the rotor diameter with two and three operating MLP.

According to the current norms\(^2\), for pumps with a rated delivery of more than 2500 m\(^3\)/h, the maximum machining of the rotor is 10%. Therefore, machining the rotors in the conditions of two or three MLP operating is unacceptable, since the scope of machining exceeds the standard parameters.

It should be noted that for the considered NM-10000 unit size, the efficiency of the pump decreases by about 2% when the rotor is machined down by 10% of its diameter. Thus, the rotor machining even by 5.6% (for a single working MLP) will reduce the pump efficiency by 1.1%, so this article does not cover operation conditions with the rotors being machined.

**Findings**

1. A method is considered to improve the power efficiency of a trunk pipeline equipped with VFD at underloaded conditions (or at derated operation) by increasing the efficiency of pumps when additional MLP are engaged with a decrease in the rotor RPM using VFD.

2. As an example, the operation conditions of an oil pipeline with a 60% load of the design capacity are considered. It was found that when the second MLP was engaged at OPS-1, the electric energy saving for pumping was 3.7% compared to the condition with one pump running. However, when the third pump was engaged, the energy saving is 1.9%; the decrease is due to electric motor and VFD lower efficiency at

| Number of engaged MLP | Capacity | MLP operation parameters | Power consumed by OPS for pumping, kW | \( \frac{E_e}{h} \), mln.kWh/year | Saving electric energy for pumping, mln.t/m\(^3\)/year |
|-----------------------|----------|--------------------------|-------------------------------------|-------------------------------|----------------------------------------|
| 1                     | 35.0     | 4789                     | 357                                 | 93.8%                         | 0.76                                   |
| 2                     | 179      | 69.6                     | 0.84                                | 30.2%                         | 0.96                                   |
| 3                     | 119      | 59.4                     | 0.86                                | 31.3%                         | 0.91                                   |

Note: when calculating energy savings for pumping, the power consumption for OPS-1 own needs is not considered.

**Table.** Results for calculating energy savings of the pipeline operation with one, two and three MLP engaged at OPS-1.

**Figure 4.** Efficiency of the induction motor (12,000 kW) versus the load and RPM of the electric motor.

**Figure 5.** Efficiency of VFD (12,000 kW) versus the load and RPM of the electric motor.
underloaded conditions. Thus, the conditions with two operating MLP at OPS-1 are optimal in terms of electric energy consumption.

Competing interests
The authors declare that there is no competing interest regarding the publication of this paper.

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