Simple Visual Tool to Analyse Pump Battery Efficiencies for Various Pump Combinations

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Abstract

A simple graphical tool was developed, that finds optimal combination of pumps and their rotational speeds for all possible working points for the given set of pumps. The tool allows analyzing and optimizing non-identical parallel pump with different minimum and maximum frequencies. Characteristic and efficiency curves can be given in tabular format in addition to analytical functions of flow. Degradation of pumps’ efficiency at lower rotational speed is taken into account, as is motor and variable speed drive efficiencies at partial loads. The optimal solution provided by the tool was compared to actual measurements in a case study.

Keywords: parallel pumping; variable speed drive; optimization; case study

1. Introduction

The need for the tool presented here rises from practical engineering problems in choosing optimal pumps and their control strategy. Many pumping stations are planned so that they can handle the maximum situation, but only a little attention is paid on the overall energy efficiency or life-cycle costs of pumping. This has lead to over-sized and under-performing pumping stations.

Current methods in hydraulic network modeling and SCADA data analysis provide much insight to the actual and estimated future working regime and the relative probabilities of different working points, but the tools for optimizing the pumping station design and operation have been lacking.

While there has been some work done in this field recently, the research have mostly neglected the effects of lower rotational speed on pump efficiency, and variable-speed drive and motor load on the total efficiency. The recent academic research, for example Koor et al.[1] and Ulanicki et al.[2], have focused on identical pumps or characteristic curves which can presented in analytical formulation, and they have paid little attention to motor and variable-speed drive (VSD) efficiencies. However, in order to get an accurate view on the pump performance and capacity, the changes in pump’s, motor’s and VSD’s efficiency has to be taken into account, and sometimes analytical formulation of pump and efficiency curves can be too inaccurate. Many a time it can be beneficial to install differently sized pumps,
if the required working regime is large. Often the older pumping stations can have pumps both with and without VDS, so the tool have to cope with this too.

2. Materials and methods

2.1. Basis

The pump battery is described as a set of pumps. Each pump is given a characteristic curve, an efficiency curve, minimum and maximum allowed frequency, nominal motor power $P_{NOM}$, and either IE efficiency class and number of poles, for standard motor efficiency values based on IEC 60034-30 [3], or motor efficiency values at both 100 % and 75 % load, $\eta_{M,100}$ and $\eta_{M,75}$ respectively. Minimum and maximum frequencies can be equal, when no VDS is present or in use. A flag can be set, indicating that the pump is always on.

The pump characteristic curve can be expressed either in tabular format or in analytical format as in EPANET [4]

$$H(Q) = \omega^2 \cdot H_{max} - \omega^2 - \sigma \cdot \tau Q^\sigma ,$$

(1)

where $\omega = \frac{n_2}{n_1} = \frac{f_2}{f_1}$ is the relative rotational speed, and $\sigma$ and $\tau$ are flow exponent and flow coefficient, obtained by curve fitting. If the analytical pump characteristic curve is described by only one point, then the curve is fitted through the given point $(Q, H)$, and points $(0, 1.33 \cdot H)$ and $(2, 2 \cdot Q, 0)$. In EPANET the functional curve continues until $H = 0$, which results in maximum flows pumps typically cannot deliver [5]. The tool described here, uses a separate $Q_{max}$ value that determines the maximum flow at the nominal speed.

Flow and head at different rotational speeds are calculated using affinity laws [5]

$$\frac{Q_1}{Q_2} = \frac{n_1}{n_2} = \omega \quad \text{and}$$

$$\frac{H_1}{H_2} = \left(\frac{n_1}{n_2}\right)^2 = \omega^2 .$$

(2a)

(2b)

Pump efficiency curve can also be given either in tabular format, when linear interpolation is used, or in functional, second order polynomial best efficiency point curve with either one or two points. For one point, the best efficiency point, BEP, $(Q_{BEP}, \eta_{BEP})$ the efficiency curve is

$$\eta(Q) = a \cdot Q^2 + b \cdot Q ,$$

(3)

where

$$\begin{cases}
a \cdot Q_{BEP}^2 + b \cdot Q_{BEP} - \eta_{BEP} = 0 \\
2a \cdot Q_{BEP} + b = 0
\end{cases}$$

(4)

and for two points $(Q_{BEP}, \eta_{BEP})$ and $(Q_2, \eta_2)$, $Q_2 > Q_{BEP}$ the curve is

$$\eta(Q) = \begin{cases}
a \cdot Q^2 + b \cdot Q , & Q < Q_{BEP} \\
2a \cdot Q_{BEP} + b_2 + c_2 \cdot Q + q_2 , & Q \geq Q_{BEP}
\end{cases} ,$$

(5)

where $a$ and $b$ are solved as above and

$$\begin{cases}
a_2 \cdot Q_{BEP}^2 + b_2 \cdot Q_{BEP} + c_2 - \eta_{BEP} = 0 \\
2a_2 \cdot Q_{BEP} + b_2 = 0 \\
a_2 \cdot Q_2^2 + b_2 \cdot Q_2 + c_2 - \eta_2 = 0
\end{cases}$$

(6)

Pump hydraulic efficiency at different rotational speeds is calculated using [6]

$$\eta_P = \eta_2 = 1 - (1 - \eta_1) \cdot \left(\frac{n_1}{n_2}\right)^{0.1} = 1 - (1 - \eta_1) \cdot \left(1 - \omega\right)^{0.1} .$$

(7)
Hydraulic power

\[ P_H = \rho g Q H \]  \hspace{1cm} (8)

and pump shaft power

\[ P_S = \frac{P_H}{\eta_p} \]  \hspace{1cm} (9)

Motor load [7]

\[ L = \frac{P_S}{P_{50/60}} \]  \hspace{1cm} (10)

where \( \eta_{M,100} \) is the motor efficiency at rated load.

IEC 60034-31 [8] standard provides an equation to calculate an approximation of motor efficiency at any partial load based on motor’s rated and 3/4 load efficiencies (\( \eta_{M,75} \)):

\[ \eta_M = \frac{1}{1 + \frac{\eta_{M,100} - 1}{\eta_{M,75}} \cdot \frac{1}{2}} \]  \hspace{1cm} (11c)

Both Wallbom-Carlson [9] and IEC 60034-31 [8] show similar reduction in 10 kW VSD efficiency from about 97% at 50 Hz to about 92% at 25 Hz. The efficiency drop is less pronounced in VSDs with high nominal power output.

Wallbom-Carlson [9] proposes usage of an idealized VSD efficiency factor, that would include losses from the VSD itself and losses generated in the motor by the VSD. However, experiments presented in Burt et al. [10] support the notion that the motor’s efficiency doesn’t change much if a VSD is used. Thus this work assumes that modern VSDs can mostly compensate the VSD generated losses in motors, and only VSD efficiency itself is considered as per IEC 60034-31 [8] (see Fig. 1). VSD load is calculated similarly to motor load in Equation (10).

Motor power thus becomes

\[ P_M = \frac{P_S}{\eta_M} \]  \hspace{1cm} (12)

the pump train electrical power

\[ P_E = \frac{P_M}{\eta_{VSD}} \]  \hspace{1cm} (13)

and the total pump train efficiency

\[ \eta_{TOT} = \frac{P_H}{P_E} = \eta_p \cdot \eta_M \cdot \eta_{VSD} \]  \hspace{1cm} (14)

Table 1 shows an approximation how load and different efficiency components change. When pump’s rotational speed is reduced in a zero static head system. The motor presented in the table is a 75 kW IE2 class motor, with 4/4 load efficiency of 95.4% and 3/4 efficiency of 94.6%. The VSD is also 75 kW in power. Pump’s BEP is 75% at nominal rotational speed at 50 Hz. It is assumed, that pump’s shaft power is 75 kW at BEP at nominal rotational speed. While pump’s BEP decreases from 75.0% to 73.2% when the rotational speed is reduced from 50 Hz to 25 Hz, motor’s efficiency reduces from 95.4% to 77.6% and VSD’s efficiency from 98.0% to 95.3%. This results in total efficiency of 70.1% at 50 Hz and only 54.5% at 25 Hz.
2.2. Algorithm

A parallel, exhaustive search is performed on the full pump battery working regime. All possible combinations of different pumps and their frequencies are considered, and for each working point, the optimal combination of pumps and their frequencies is chosen and stored in the results array. Optimal combination is defined as the one with highest total efficiency $\eta_{TOT}$.

The algorithm and user interface were developed using Java programming language 1.7 and Swing toolkit, JFreeChart 1.0.17 charting library and Apache POI 3.10 library for Excel file access. The programming language was chosen for rapid development cycle, good industry acceptance and penetration, and easy multi-thread programming features.

All immediate and final results are stored in two-dimensional arrays, where each cell presents a fixed-sized Q-H area. Good step sizes are typically $Q_{step} = 1.0\text{l/s}$ and $H_{step} = 0.5\text{ m}$, but smaller step sizes can be used for smaller pumps, and larger for bigger pumps.

First each pump’s working regime is determined. Minimum and maximum allowed head, and maximum allowed flow are calculated based on the pump characteristic curve and the allowed frequency range. The code loops over the pumps in the set. For each pump the code loops over allowed frequencies using step size of 0.01 Hz. Each resulting pump frequency combination is pushed to a First In, First Out (FIFO) queue, from which one of the processor threads
picks it up and calculates all possible flow and head combinations for the given frequency. The calculation loops over the pump’s allowed flow range for the frequency, and calculates matching the head and the total pump train efficiency \( \eta_{TOT} \). If multiple frequencies result in overlapping working points in the \( Q_{step} \times H_{step} \) resolution, the frequency that produces the highest total efficiency is chosen for that particular working point.

The results of the working regime calculation are stored in two pump specific lookup arrays (15). The first, \( F \), contains the optimal frequency for all possible working points and the other, \( H \), contains the total pump train efficiencies. Arrays elements that present invalid working points are set to 0.

\[
F = \begin{bmatrix}
Q_1, H_1 & Q_2, H_1 & \cdots & Q_n, H_1 \\
Q_1, H_2 & Q_2, H_2 & \cdots & Q_n, H_2 \\
\vdots & \vdots & \ddots & \vdots \\
Q_1, H_n & Q_2, H_n & \cdots & Q_n, H_n
\end{bmatrix},
H = \begin{bmatrix}
\eta_1, H_1 & \eta_2, H_1 & \cdots & \eta_n, H_1 \\
\eta_1, H_2 & \eta_2, H_2 & \cdots & \eta_n, H_2 \\
\vdots & \vdots & \ddots & \vdots \\
\eta_1, H_n & \eta_2, H_n & \cdots & \eta_n, H_n
\end{bmatrix}
\] (15)

Next all the possible non-identical pump combinations are considered. The available pumps are presented as a binary string, where 1 signifies the pump is on, and 0 signifies the pump is off. Minimum and maximum head is calculated for each combination so that every pump running in the combination can work within the limits:

\[
H_{min} = \max\{H_{min,1}, H_{min,2}, \ldots, H_{min,n}\}
\]
\[
H_{max} = \min\{H_{max,1}, H_{max,2}, \ldots, H_{max,n}\}
\] (16)

where \( n \) is the number of pumps running in the combination.

For each combination the algorithm iterates over the allowed heads in the range \([H_{min}, H_{max}]\) using the predefined head step size. Each head step \( H_i \) is added to a FIFO queue, where one of the processor threads picks it up for calculation.

A processor thread calculates all possible combinations of flows for the running pumps in the given pump combination for the head \( H_i \). The flow step used in this step is \( Q_{step} \). Each pump’s total efficiency for are looked up from that pump’s working regime array \( H \). Every time there are multiple possible combinations that produce the same total flow, the one with best over all efficiency is chosen and stored in the results arrays. Each row in the result arrays, ie. all flows with certain head, is protected by an own lock so that the computer’s multi-processing capabilities can be used effectively with too much lock contention.

The end result is two arrays, that cover the full possible working regime of the whole pump battery. Each element represents an area defined by \( Q_{step} \) and \( H_{step} \). Results array \( C \) contains the numerical presentation of the optimal combination binary string and \( R \) contains the optimal total pump train efficiencies:

\[
C = \begin{bmatrix}
C_1, H_1 & C_2, H_1 & \cdots & C_n, H_1 \\
C_1, H_2 & C_2, H_2 & \cdots & C_n, H_2 \\
\vdots & \vdots & \ddots & \vdots \\
C_1, H_n & C_2, H_n & \cdots & C_n, H_n
\end{bmatrix},
R = \begin{bmatrix}
\eta_1, H_1 & \eta_2, H_1 & \cdots & \eta_n, H_1 \\
\eta_1, H_2 & \eta_2, H_2 & \cdots & \eta_n, H_2 \\
\vdots & \vdots & \ddots & \vdots \\
\eta_1, H_n & \eta_2, H_n & \cdots & \eta_n, H_n
\end{bmatrix}
\] (17)

The program contains a graphical user interface, shown in Fig. 2, where the results are presented graphically as two-dimensional graph. Each cell’s color depends on one of the parameters, selected by the user: specific power, total efficiency, number of pumps running, or pump combination number (i.e. decimal representation of the combination binary string). All the other parameters are shown in a tool-tip, and in a separate panel, if user clicks on the chart.

The user can optionally import a set of working points and their relative probabilities to the program. Working points can be imported from an Excel file, or comma or tab separated files. If the file contains no probability information, or points are considered to be equally probable. The program then shows the working points on the chart, and calculates total annual energy consumption for the set of points.

The result array and the working points including their total efficiencies, if available, can be saved to an Excel file for further processing and analysis. The saved file can be reopened in the program saving the need to recompute the results.
3. Case study

The tool was used for evaluating the current performance in Jäniksenlinna water treatment plant of Tuusula region water utility. The company serves water for cities of Järvenpää and Kerava and municipalities of Tuusula and Sipoo, all in Southern Finland – for 122 353 people in 31st December 2013. The company owns and operates 11 water sources, 26 pressure boosting and measurement stations and 8 water towers. Jäniksenlinna water treatment plant is biggest water source in the area. It uses artificial ground water as raw water. The average pumping from the plant was 10 522 m³/d in 2013. Annual energy consumption was 1 328 642 kWh/a (excluding the artificial ground water recharge) or 0.35 kWh/m³. [12] The geodetic head is about 32 m and the dynamic head is about 0–11 m when flow is 0–650 m³/h.

The station has four network pumps, that pump from a fresh water storage tank. The pump battery has two pairs of pumps: the older pumps, numbers 3 and 4, are Grundfos NK100-200/219 (see Fig. 3a) with 110 kW, 3 000 rpm ABB HXR 280MC 2 B3W IE2 class motors with full load efficiency of 95.1 % and 3/4 load efficiency of 95.0 %, and the new pumps, numbers 1 and 2, are Flygt L150-400U3SN-7504 pumps (see Fig. 3b) with 75 kW, 1 500 rpm FFD SEE 280 S4 IE2 class motors with full load efficiency of 95.2 % and 3/4 load efficiency of 94.9 %.

The Grundfos pumps have BEP 84.3 % at 338 m³/h and the Flygt pumps 86.4 % at 450 m³/h. Every pump has own VSD.

The SCADA system collects VSD power, and pump flow and pressure, and fresh water tank level information from Jäniksenlinna plant on one minute interval to comma separated files files. This data was processed and five minute averages were computed for the above parameters for the year 2013. Only total flow and pressure are measured, and no frequency data is stored. Power and efficiency measurements are collected on single pump basis, but in this analysis only the total power value was used.

The collected data shows, that median flow was 420 m³/h and median head was 35.5 m in 2013. Power measurements result in annual energy consumption of 548 486 kWh for the network pumping (41.2 % of the total energy used at the plant).

The pump battery was modeled in the pump battery analysis tool, and the optimal combinations for all possible working points were calculated. The averaged flow and head combinations calculated from SCADA were imported into the tool as working points, and later exported back to Excel with the optimal efficiency and power values. The computed optimal efficiency and powers values were compared with the values collected from the VSDs by the SCADA.

The optimal annual energy consumption with the current pump configuration is 515 561 kWh/a which is 6.1 % lower compared to the measured energy consumption 548 486 kWh. Fig. 4 shows how the optimized total efficiencies
compare to the measured efficiencies. From the figure it’s apparent, that the current control algorithm results in one pump pumping too high flows and two pumps pumping too low flows. The optimal flow to switch from one to two pumps and vice versa, is about 130 l/s, depending on the exact head required. Choosing optimal pump combination results equal or better than measured efficiency for almost all flows.

4. Discussion

The developed tool provides interesting insight into pump battery’s workings, like the available working regime, specific energy usage and efficiency. The calculated optimal pump combinations and their frequencies for different flow and head regimes provide a good basis for developing more optimal pump control strategies and comparing different sets of pumps for the case at hand.

Figure 4: Comparison between the measured (blue dots) and optimized (red dots) efficiencies as function of flow
The authors could not find an earlier work, where the combined effects of rotational speed to pump efficiency, motor efficiency at partial loads, and VSD efficiency had all been considered, when determining the optimal combination of pumps to be used. Both can have significant effect on the total efficiency and thus on what pump combination should be used, and should not be neglected.

The developed tool can handle non-identical pumps that can also be described by non-analytical methods. Both features are quite common in practical engineering work, but so far little research is done on the optimization of pump battery with non-identical pumps.

The problem with the tool is, that doing an exhaustive search on a large number of pumps results in exponential growth in computational time. The algorithm implementation optimizes calculation for identical pumps and combinations, and up to three or four concurrently running non-identical pumps can easily be calculated in reasonable time on modern workstation computers, but larger number of concurrent pumps can quickly result in multiple day long calculation.

More research is needed in areas of effects of rotational speed on pump efficiency and effects of VSD on motor efficiency. Both depend heavily on the specifics of the components, and research like Muszyński[13] shows that Equation (7) can not always accurately describe effects of rotational speed.

The case study shows, that the tool gives efficiency that is comparable to the values measured from VSDs, but optimizing the pump battery control can still lead to savings in the range of 5 %, when the pump battery contains differently sized pumps. Unfortunately the frequency data was not available, so the efficiency loss caused by wear in the pumps and impellers could not be accounted for, however the optimized efficiencies are very close to the observed values on small flows, which hints that the pumps’ efficiencies have not reduced much.

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