HVAC

Efficient driving at variable speeds

Circulation pumps are widely used in HVAC systems but are heavy consumers of electricity. Here, M. Karaca and M. Aydin consider strategies to optimize the energy use in a closed-loop system of parallel, variable-speed circulation pumps, and demonstrate the potential of the speed ratio to provide large energy savings.

Variable-speed drives (VSDs) provide the user with a variety of benefits, including potentially significant energy savings and improved reliability in pumping applications. Assessments of the technical and economic advantages gained by using VSDs on circulation pumps have been widely publicized in recent years. According to statistics, pumps consume around 20% of the world's total electrical energy[1]. The energy efficiency of a system depends not only on the design of the pump but also, and more so, on its working conditions and system design.

An optimal control method for variable-speed pumping stations with similar pumps in parallel has been proposed by Fulai and Hexu[2]. This control method gives the minimum total power consumption for similar variable-speed pumps running in parallel.

A number of researchers and experts in the heating, ventilation and air-conditioning (HVAC) field have also devoted considerable efforts to applying proper and optimal control strategies to enhance the efficiencies of circulation pumps. Optimal control strategies to enhance the energy efficiencies of variable-speed pumps with different configurations in complex building air-conditioning systems have been presented[3]. Ahonen *et al.*[4] have proposed two model-based methods for the estimation of pump operation. One of the methods is based on the flow rate and head of the pump and the other method is based on the system curve. Tianyi *et al.*[5] recently proposed an on-line control optimization method for variable flow pumps in air-conditioning systems. This method includes the optimized allocation of parallel, variable-frequency pump speed ratios and the optimized number of operating pumps.

The main purpose of the study described in this article is to determine the optimal control strategy for similar variable-speed circulation pumps under parallel running conditions. The control strategy is based on the optimal combination of speed ratios of multiple parallel variable speed pumps that utilize the same hydraulic operating conditions. In addition, the control strategy determines the optimal number of pumps in parallel operation taking into account their power consumptions.

Circulation pumps

Circulation pumps are among the largest consumers of electricity in private houses and commercial buildings, and are widely used in heating and cooling systems. They are generally in-line-type pumps and are typically used to recirculate heating or cooling media within a closed loop (Figure 1). They only need to overcome the friction losses of the piping system.

Speed variation is the most energy-efficient method to respond to variable system demands[4]. Frequency converters are widely used nowadays to control the head and flow rate of circulation pumps. Traditionally, a circulation pump was driven by a constant-speed induction motor with system demand controlled by

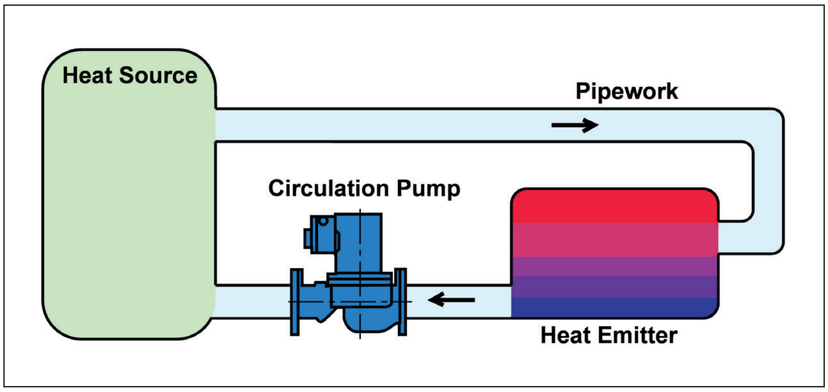

Figure 1. Simplified diagram of a typical heating system with a circulation pump.

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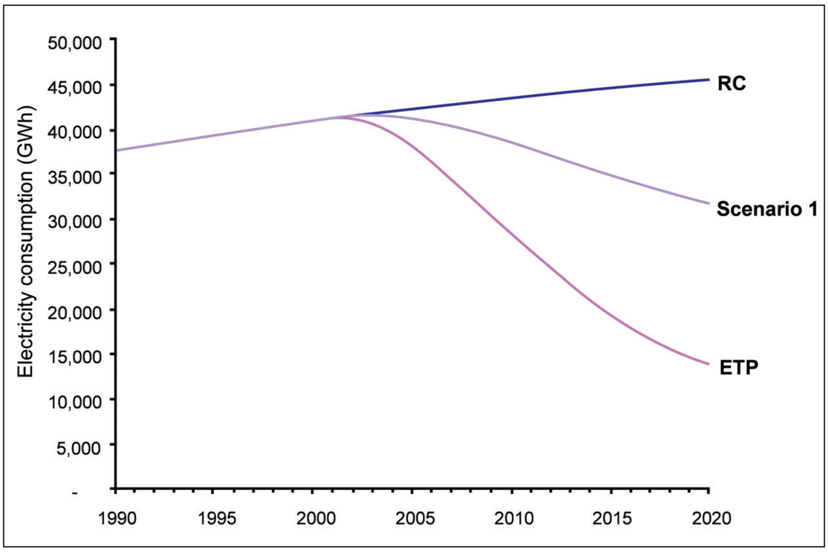

Figure 2. Electricity consumption by circulation pumps in the EU according to current (RC) and potential consumption scenarios[6] (reproduced courtesy of Grundfos A/S).

Table 1. Summary of EU electricity consumption scenarios and potential savings for circulation pumps

	Electricity (TWh)	Electricity costs (million Euros)	CO_2 emissions (Mt CO_2)
RC, 2000	37.6	3,756	15.1
RC, 2020	45.6	4,558	18.4
ETP, 2020	13.9	1,394	5.6
Scenario 1 (Sc1), 2020	31.7	3,173	12.8
(RC–Sc1), 2020	13.9	1,385	5.6

From Ref. 6 (reproduced courtesy of Grundfos A/S)

a throttling valve. However, system demand can now be regulated through frequency converters without the additional losses caused by throttling.

By introducing more-efficient pumps and control strategies, it is possible to reduce electricity consumption considerably, as shown in Figure 2. In this figure, realistic policy measures (Scenario 1; Sc1) applied to circulation pumps are projected to reduce electricity consumption in the European Union (EU) dramatically[6] compared to maintenance of the status quo as indicated by the reference curve (RC). Here, ETP refers to economically justifiable and technically feasible potential energy savings by circulation pumps.

The potential reductions in electricity usage would positively affect consumers' electricity bills as well as carbon dioxide emissions. Depending on the emission factor used, carbon dioxide emissions could be reduced by in excess of 5 million tonnes per year by 2020, as indicated in Table 1 from the difference between projected RC and Sc1 outputs.

Mathematical model

A mathematical model to characterize pump performance is given as follows:

$$H = a_1Q^2 + a_2Q + a_3 \quad (1)$$

$$\eta = b_1Q^2 + b_2Q + b_3 \quad (2)$$

where H (m) is the head of the pump at the rated speed; Q (m^3/s) is the flow of the pump at rated speed; and a_1, a_2 and a_3 are constants obtained from the sample pump performance curve. In Equation 2, η (%) is the pump efficiency at the rated speed; and b_1, b_2 and b_3 are further constants obtained from the pump performance curve.

The power, head, flow and efficiency produced by the pump are defined as follows:

$$P = \frac{P_F}{w^3} \quad Q = \frac{Q_F}{w} \quad H = \frac{H_F}{w^2} \quad \eta = \eta_F \quad (3)$$

where P (kW) is the power of the pump at the rated speed; w is the speed ratio, that is, the ratio of the variable speed to the rated speed; and the subscript F denotes operation at variable speed. The power at the rated speed (P) and at variable speed (P_F) can be expressed as follows:

$$P = \frac{10QH}{\eta_M \eta_{VFD} \eta} \quad (4)$$

$$P_F = \frac{10Q_F H_F}{\eta_F \eta_M \eta_{VFD}} \quad (5)$$

where η_M (%) is the efficiency of the motor and η_{VFD} (%) the efficiency of the frequency converter.

According to the mathematical model, for any two or more identical pumps running in parallel that correspond to the same hydraulic conditions (i.e. operating at the same temperature and pressure), the best overall efficiency can be achieved with the same speed ratio. The mathematical model was explained in detail by Tianyi *et al*[5]. Normally, changing the speed does not affect the pump efficiency. However, when a pump with a frequency converter is driven at a lower speed than the rated speed, the motor efficiency and the frequency converter efficiency will change due to the loading. Because of that, the system efficiency ($\eta_F + \eta_M + \eta_{VFD}$) can be changed at lower speeds than the rated speed (Figure 3).

Experimental setup

Tests were conducted to analyse the optimal control strategy when a pump operating in parallel is driven in different operating point configurations. Different speed ratios were applied to utilize the same hydraulic conditions.

The equipment used in the tests is listed below:

Circulation pump: in-line type 40-160 pump

Induction motor: Wat 1.1 kW, 1,500 rpm

Frequency converter: ABB ACS310 2.2 kW

Pressure transmitter: Keller PA-21 Y/4 bar (0–4 bar, 4–20 mA)

Electromagnetic flow meter: Khrone IFC100 DN50

Multimeter: Entes EPM-07

The experimental test system is shown in Figure 4; all equipment was calibrated before carrying out the measurements. As shown, three in-line circulation pumps of the same type were connected to a common collector.

The head was measured with pressure sensors placed on the suction and discharge flanges of the circulation pumps; the flow rate is measured by the electromagnetic flow meter. Frequency converters are able to control the pump according to the pressure difference between pump outlet and inlet. It is worth noting that a constant differential pressure algorithm was generated for the measurements of the operating points. Different operating points were generated using the frequency converter.

The sample flow demand curve (Figure 5) was generated for circulation pumps running continuously for 24 hours to analyse the control strategy. The nominal flow demand, indicated on the graph by the blue dashed line, was 19.7 m^3/h. The relative flow rates at the four selected operating (duty) points were 14.7 m^3/h, 19.7 m^3/h, 24.6 m^3/h and 25.3 m^3/h. The system's static pressure was constant at 2 bar during the experiments.

Results and discussion

In pumping applications, the exact amount of saved energy depends on the system characteristic. This article focuses on the application of parallel variable-speed circulation pumps in a closed-loop system. Four different duty points were evaluated in the tests to demonstrate the energy saving potentials associated with the use of the optimal control method for variable-speed circulation pumps. For each duty point, the supplied power (P_{sup}) – which is the basic factor for the energy consumption of the entire pump unit – was obtained by means of a multimeter changing the speed of the pump, which otherwise operates under the same hydraulic conditions during the test. Table 2 presents the supplied powers for the different operating conditions and for various configurations of the test pumps.

Based on the test results as shown in Table 2, the pump speed ratio significantly affects the energy saving. In addition to that, the overall best efficiency is obtained when pumps have the same speed ratios. In the variable-speed condition, with the same speed ratio and the minimum number of pumps, power savings of 16.9% for duty point 1, 4.3% for duty point 2 and 17.3% for duty point 3 were achieved, according to the test results. Therefore, the main criteria for optimal system control are to use the minimum number of pumps to meet the system demand and the same speed ratio; P_{sup} was a minimum for these conditions.

The experimental results show that some 70% of the pump energy could be saved by using this optimal control strategy when compared to traditional control methods. For instance, consider duty

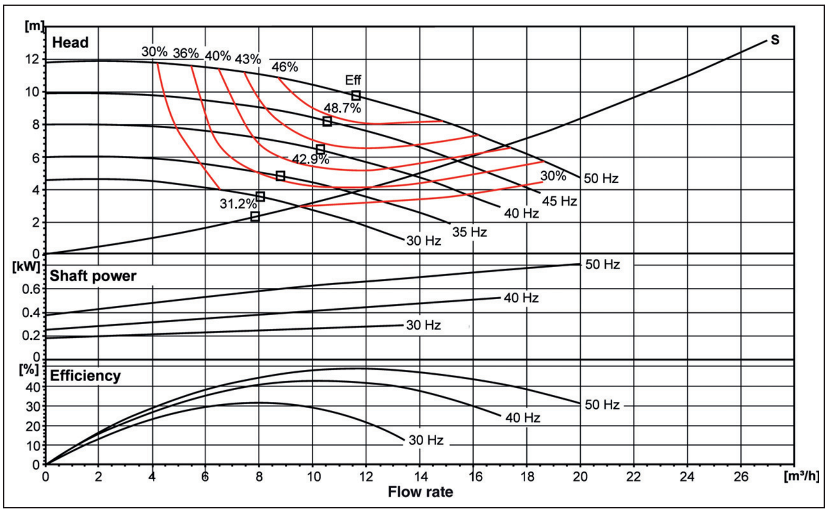

Figure 3. The reference single pump performance curve for the variable-speed circulation pump used in the study.

Figure 4. The closed-loop test system.

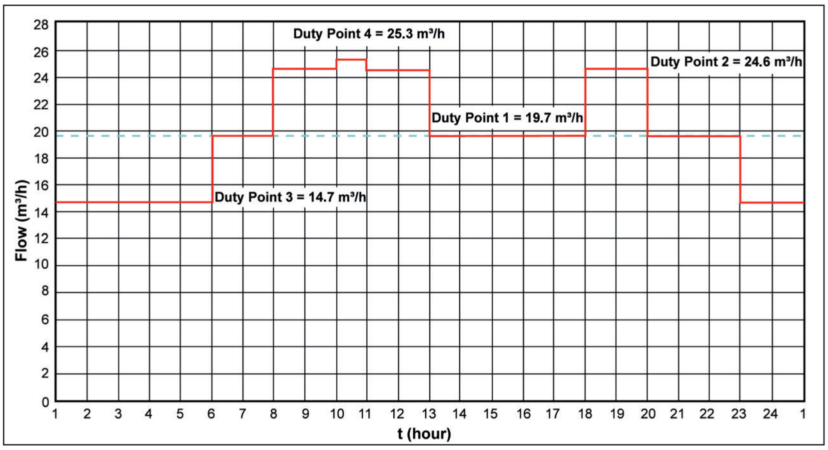

Figure 5. The sample flow demand curve.

Table 2. Experimental results

Duty point 1: H = 7 m	**P_{sup} (kW)**
2 pumps working at 37.1 Hz and 1 pump at 50 Hz	1.54
2 pumps at 42.7 Hz	1.15
3 pumps at 39.4 Hz	1.3
1 pump at 38.1 Hz and 1 pump at 50 Hz	1.28
Duty point 2: H = 10.3 m	**P_{sup} (kW)**
1 pump at 46.4 Hz and 2 pumps at 50 Hz	2.08
2 pumps at 47.5 Hz and 1 pump at 50 Hz	2.02
3 pumps at 48 Hz	1.99
Duty point 3: H = 3.7 m	**P_{sup} (kW)**
1 pump at 42.7 Hz	0.67
2 pumps at 33 Hz	0.68
3 pumps at 30.4 Hz	0.81
Duty point 4: H = 10.7 m	**P_{sup} (kW)**
3 pumps at 50 Hz	2.21

point 3, where the flow rate (Figure 5) is 14.7 m^3/h. Referring back to Figure 3, the power for one pump running at 50 Hz power at this flow rate is 0.66 kW. For the traditional control method, involving the three test pumps running at 50 Hz, the total supplied power would thus be:

$0.66 \times 3 = 1.98$ kW

If this figure for the traditional control method is compared with the optimum result determined for duty point 3 in Table 2 – namely, one pump running at 42.7 Hz with a power usage of 0.67 kW – this gives:

Power savings = (1.98–0.67)/1.98 = 0.66

The potential power savings for this duty point is therefore 66%.

Conclusions

This study is based on the energy-efficient system operation of parallel-running, variable-speed circulation pumps in a closed-loop system. The results of this investigation indicate that the best energy saving can be obtained when the same type of pumps, running in parallel, have the same speed ratio. In addition, the number of pumps running in parallel also affects the energy-saving potential. The test results show that the main criteria for optimal system control are the minimum number of pumps to meet the system demand and the same speed ratio. Life cycle assessment would also be needed to reach a conclusion about the future usefulness of this control system.

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