Energy Efficiency (2013) 6:495–509
DOI 10.1007/s12053-012-9188-0

ORIGINAL ARTICLE

Energy-efficient control strategy for variable speed-driven parallel pumping systems

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Received: 11 April 2012 / Accepted: 10 December 2012 / Published online: 29 December 2012

Abstract The article aims to find a solution for the energy efficiency improvements in variable speed-controlled parallel pumping systems with lesser initial data and without additional flow metering and start-up measurements. This paper introduces a new control strategy for variable speed-controlled parallel pumps based on flow rate estimation and pump operation analysis utilizing variable speed drives. The energy-saving potential of the new control strategy is studied with simulations and laboratory measurements. The energy consumption of the parallel pumps using the new control strategy is compared with the traditional rotational speed control strategy of parallel pumps. The benefit of the new control strategy is the opportunity to operate variable speed-controlled parallel pumps in a region which suggests improved energy efficiency and lower risk of mechanical failure of the controlled pumps compared with traditional control. The article concludes by discussing the implications of the findings for different applications and varying system conditions.

Keywords Variable speed drives · Pumps · Energy efficiency · Process control · Fluid flow control

Introduction

Pumps are widely used in industrial and service sector applications. They consume approximately 10–40 % of the electricity in these sectors (de Almeida et al. 2003). Pumping systems are found to have a significant potential for energy efficiency improvements (Binder 2008; Kaya et al. 2008; Ferreira et al. 2011; Pemberton and Bachmann 2010; Zhang et al. 2012). The pressure for energy efficiency improvements has led to an increasing number of variable speed drives (VSDs) in pumping applications, since in many instances, variable speed pumping has been shown to be an effective way to reduce the total pumping costs, especially in systems that require a wide range of flow (Bernier and Bourret 1999; Pemberton 2003; Europump and Hydraulic Institute 2004).

Pumping systems with a widely varying flow rate demand are often implemented using parallel-connected pumps (Hooper 1999; Volk 2005). There are several control methods available for operating the parallel-connected pumps. In the simplest case,

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parallel-connected pumps are operated with an on–off control method, where additional parallel pumps are started and stopped according to the desired flow rate. In the systems where more accurate flow regulation is needed, the adjustment can be carried out by applying throttling or rotational speed control for a single pump, while other pumps are controlled with the on–off method. The benefits using rotational speed control instead of the throttling control method are widely studied (Rossmann and Ellis 1998; Carlson 2000; Europump and Hydraulic Institute 2004; Hovstadius et al. 2005) and are therefore excluded from this study.

Energy optimization of parallel-connected, rotational speed-controlled pumps has been studied to some extent (Izquierdo et al. 2008; Bortoni et al. 2008; Yang and Borsting 2010), and the results have shown that there is a major energy-saving potential in the sector of parallel pumping. In Bortoni et al. (2008), the optimal rotational speed for parallel pumps is predicted, in order to gain energy savings, using a mathematical optimization-based tool suitable for programmable logic controllers. However, the suggested optimized control method requires adequate information from the system curve, including start-up field measurements using pressure sensors and flow meters. In many parallel pumping cases, sufficient data for energy optimization from continuously changing systems are available only to limited extent (Kini et al. 2008; Aranto et al. 2009). An alternative approach to obtain the required system information can be the model-based flow monitoring method in which the flow rate of each parallel pump is estimated without separate flow meters based on pressure metering or torque and rotational speed estimates of the VSD (Hammo and Viholainen 2006; Ahonen et al. 2012).

The aim of this study is to introduce a new control strategy for variable speed-controlled parallel-connected centrifugal pumps (later referred to as parallel pumps) in a system where pumps in individual piping parts feed a common outlet pipeline. The suggested control strategy can offer a justified base for the energy efficiency improvement in variable speed-controlled parallel pumping systems, even in such cases where the information on the pumping system is limited or changing. The suggested control strategy is based on the simple use of existing pumping monitoring solutions of a modern VSD and a known relation between the preferable operation area of a centrifugal pump and the energy efficiency of the pumping. By implementing the suggested control strategy in the control procedure, the flow rate of the parallel pumping system can be adjusted with improved energy efficiency compared with traditional rotational speed control. The control strategy can be applied for instance to parallel pumps located in water stations, wastewater pumping stations, and industrial plants.

The relation between the pump operation point location and pump reliability and energy efficiency has been discussed in many occasions (ANSI/HI 1997; Ahonen et al. 2011). In the suggested new control strategy, the preferable operating area (POA) of each pump represents only the selected operating area between the set markups in the pump performance curve. The markup points are selected based on pump efficiency data and parallel pumping system details.

The structure of the article is as follows. First, the basics of rotational speed-controlled parallel pumping systems are discussed and the idea of the new parallel pump rotational speed control strategy is introduced. Next, the operation of the proposed strategy is verified by simulations using two parallel pumps in a system. After this, the performance of the proposed control strategy is demonstrated with laboratory measurements.

Control of parallel-connected pumps

The use of centrifugal pumps in parallel allows the production of a wider range of flow rates than it would be possible with a single pump. In other words, the parallel connection of centrifugal pumps increases the flow rate capacity of a pumping system (Hooper 1999; White 2003; Volk 2005). A simplified example of a pumping system consisting of two parallel pumps and two water reservoirs combined by individual suction piping and common outlet piping section is illustrated in Fig. 1. An example illustrating the operation of the parallel-connected pumps in a system is given in Fig. 2.

A parallel-connected pumping system can provide the sum flow rate Q_1+Q_2 of individual pumps 1 and 2 with a common amount of head H as shown in Fig. 2. In practice, the individual head value of each parallel pump connected to common outlet pipe can also vary according to system characteristics, especially if there are valves on individual piping parts or the pumps are

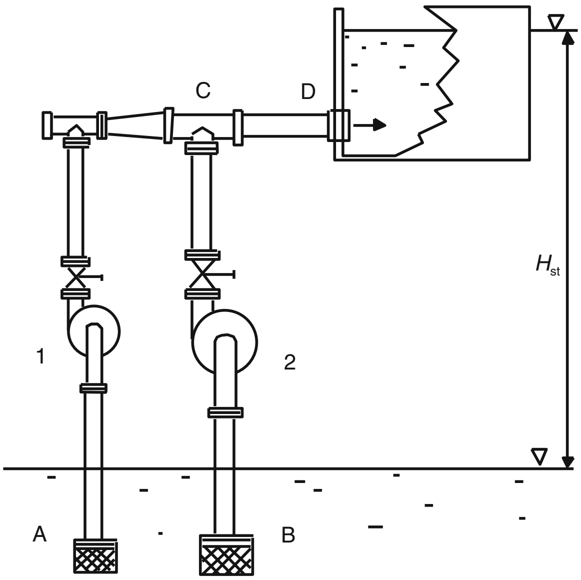

Fig. 1 Two parallel pumps feeding a common outlet pipeline. The parallel pumps (marked *1* and *2*) have their individual piping parts between points *A–C* and *B–C* feeding the common pipeline between points *C* and *D*

operated with different rotational speeds. In this simplified case, the operating point location of this parallel-connected pumping system (marked with C in Fig. 2) is in the intersection of the system and parallel operation curve which is the sum of individual pump characteristic curves. The individual operating point locations (A and B) of pumps 1 and 2 can also be determined with the flow rates Q_1 and Q_2, respectively (Volk 2005). In many instances, the pumps are

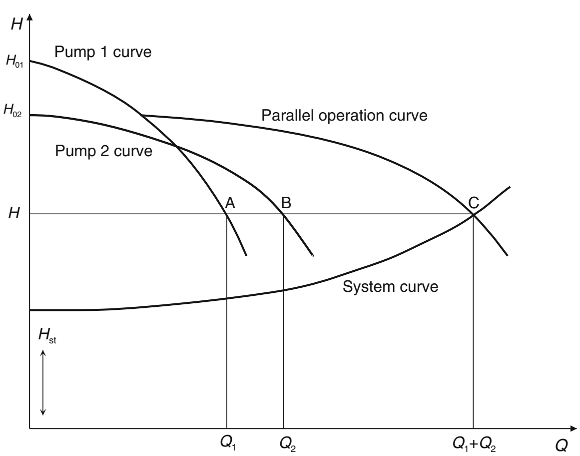

Fig. 2 Parallel operation of pumps 1 and 2 (points *A* and *B*) and the resulting operating point location *C* with the total flow rate Q_1+Q_2 (Bortoni et al. 2008)

selected according to system so that the operation point would be near pump's best efficiency point (BEP) during normal use. This is justified, since when operating considerably afar from BEP, the pumping efficiency can decrease rapidly and the pump service life may be affected by the flow recirculation, high flow cavitation, and shaft deflection (ANSI/HI 1997; Karassik and McGuire 1998; Ahonen 2011).

The output of the parallel-connected centrifugal pumps in a system can be adjusted, for example, with an on–off, throttle, or rotational speed control methods. The use of the on–off method is justified for applications having a tank or a reservoir and no need for accurate control of the flow rate. Correspondingly, the throttle control method can be used to regulate the flow rate produced by the pump, but because it can have a negative effect on the pumping efficiency, it is not always justified. In many pumping systems, the rotational speed control of pumps can allow the flow rate adjustment with a lower energy use compared with the throttling method. In some cases, the rotational speed control can be used in an on–off control scheme to fix the rotational speed lower than nominal, thus gaining more energy-efficient operation. The basic version of the rotational speed control for parallel-connected pumps, the *traditional rotational speed control* strategy, is based on the adjustment of the rotational speed of only a single pump at a time. This is illustrated in Fig. 3 in the case of two parallel pumps. Before the additional pump is started, the rotational speed n of the primary pump is increased to the nominal rotational speed n_{nom} (Shiels 1997; Karassik et al. 2001; Volk 2005; de Almeida et al. 2005; Jones 2006).

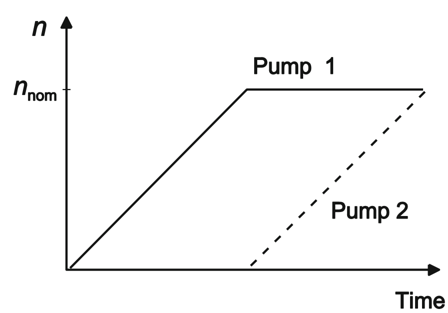

Fig. 3 Traditional rotational speed control of two parallel-connected pumps as a function of time. The flow need is increasing when moving to the right on the time axis. When the primary pump (pump 1) reaches its nominal speed, more flow is striven by starting the secondary parallel pump (pump 2)

A higher energy efficiency compared with the traditional rotational speed control can be achieved if both parallel pumps are rotational speed-controlled (Viholainen et al. 2009a). In addition to the saved energy, using rotational speed control in multiple parallel pumps provides an opportunity to avoid situations where parallel pumps are operating in shut-off or in a region where the risk of reduced pump service life is higher (ANSI/HI 1997; Karassik and McGuire 1998; Ahonen 2011). An example of a preferable option compared with the traditional rotational speed control can be demonstrated if the operation of two identical raw water pumps (Ahlström P-X80X-1) is observed in a system of a 15-m static head. In this example, the system curve is chosen so that both pumps will have a high pumping efficiency when they are operated at the nominal rotational speed (Jones 2006). An example case of adjusting the output of the pumps to a lower flow rate using the traditional rotational speed control or delivering the same flow rate by reducing the rotational speeds of both pumps is illustrated in Fig. 4.

Figure 4a plots the *QH* curves of the parallel-connected pumps, the system curve, and the combined parallel pump curve. In Fig. 4a, the first pump is operating at the nominal 740-rpm rotational speed and the second pump at a 540-rpm rotational speed. Figure 4b shows the corresponding *QH* curves when both pumps are operating at a reduced rotational speed (605 rpm) delivering the same total flow Q_1+Q_2. In the traditional rotational speed control, it is quite common that parallel-connected pumps are not operating near their BEP curve (see points B and C) which in this figure represents the rough estimate of justified operating region at different pump rotational speeds, rather than just the location of the best pump efficiency (ANSI/HI 1997; Barringer 2003; Martins and Lima 2010). If the same flow rate is delivered using a decreased rotational speed for both pumps, the operation points of the pumps (point D) are closer to the BEP curve which in this case suggests a higher energy efficiency and mechanical reliability (Fig. 4b). This kind of solution is not possible in parallel pumping systems, unless all pumps are rotational speed controlled.

The effectiveness of a single pump is often observed with the pump efficiency

$$\eta_{\mathrm{p}} = \frac{Q \cdot \rho \cdot g \cdot H}{P_{\mathrm{p}}} \quad (1)$$

where Q refers to the flow rate of the pump (in cubic meter per second), ρ is the fluid density (in kilogram per cubic meter), g the gravitational constant (in meter per square second), H the head of the pump (in meter), and P_{p} the power input of the pump (in watt). If the total input power including the motor's and drive's losses is observed in Eq. (1), the system efficiency (Yang and Borsting 2010) is

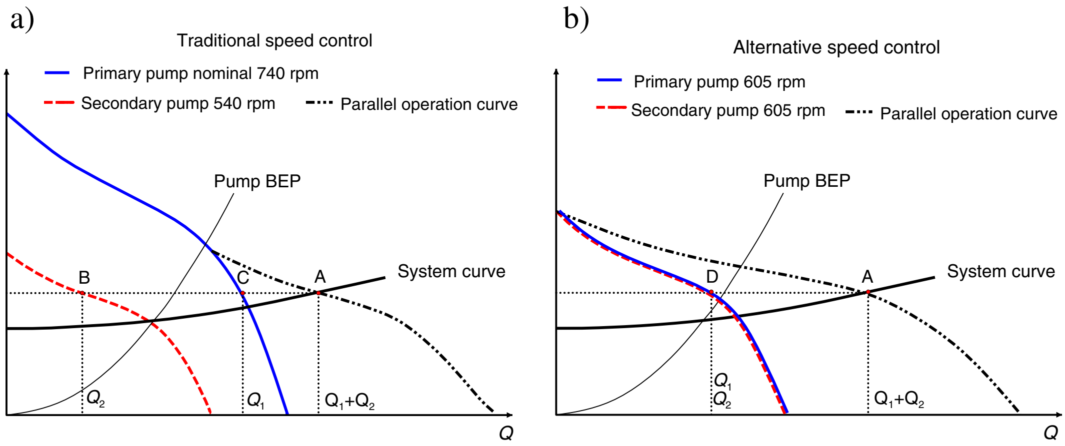

Fig. 4 Speed-controlled parallel pumping using the traditional rotational speed control (**a**) and when both pumps are running at a reduced speed (**b**). Adjusting the flow rate by running the primary pump at the nominal speed (740 rpm) and decreasing the secondary pump's speed to 540 rpm delivers the desired flow rate (Q_1+Q_2), but the operation points are located far from the best efficiency point (*BEP*). Adjusting the flow rate by reducing the speed of both pumps to 605 rpm by using VSDs results in the same flow rate, and the operation points can be located in a region of better energy efficiency and mechanical reliability

$$\eta_s = \frac{Q \cdot \rho \cdot g \cdot H}{P_{in}} \quad (2)$$

where P_{in} represents the total input power to the pump drive (in watt). The energy efficiency of parallel pumping can be evaluated using specific energy which describes the energy used per pumped volume (Europump and Hydraulic Institute 2004). The specific energy is given by:

$$E_s = \frac{P_{in} \cdot t}{V} = \frac{P_{in}}{Q} \quad (3)$$

where E_s is the specific energy (in kilowatt-hour per cubic meter), P_{in} the pump drive power (in kilowatt), t time (in hour), V the pumped volume (in cubic meter), and Q the flow rate (in cubic meter per hour). Since the delivered flow rate is often the control variable in parallel pumping, the specific energy can be seen as a justified metrics to evaluate the energy efficiency of parallel pumping system instead of the pumping efficiency or the system efficiency.

Control strategy based on preferable operation area and pump operation point estimation

In this study, the improved energy efficiency of the variable speed-controlled parallel pumps compared with the traditional control is striven by introducing a new control strategy for the parallel pump control. The introduced control strategy of parallel-connected pumps was designed based on the following requirements:

- The suggested control strategy should be able to work with as little amount of initial information as possible, even without additional sensors in the pumping system.
- Compared with the existing and known flow adjustment methods, the suggested control strategy should be able to reduce the energy consumption of the pumping system.
- The suggested control strategy should also prevent the inefficient or harmful operation with a higher risk of reduced pump service life of an individual pump when a certain flow rate is produced with parallel-connected pumps.

The possible harmful and inefficient operation in parallel pumping can be avoided if the POA of each parallel pump is taken into account in the control strategy. Thus, these risks can be controlled by preventing the pumps from operating outside the selected region during the rotational speed control if possible.

In the case of two similar parallel pumps, the rotational speed of the primary pump is not necessarily increased to its nominal value, but instead, at the determined point, the rotational speed of the primary pump is kept constant while the rotational speed of the second pump is increased in order to produce flow. When the secondary pump has started to produce flow, the rotational speed of the pumps can be balanced to the same pump head value, and in the case of more flow demand, both pumps can be controlled closer to their nominal rotational speeds. Balancing the rotational speed of the parallel pumps has been suggested already by Hammond (1984), although not from the perspective of energy savings but to even out the pump working hours and wearing. Especially, if parallel pumps are dimensioned according to the flow rate at the nominal rotational speed, the balancing procedure should enable a lower specific energy consumption compared to the traditional rotational speed control of parallel pumps, and both pumps can be kept closer to each pump's best efficiency area during the control.

Figure 5 plots the POA between the efficiency markups at different pump rotational speeds according to the affinity laws. The area outside the flow limits in the QH axis can be described as high H and high Q range areas. The flow rate limits to start the balancing of the rotational speeds of parallel pumps can be set using only the pump characteristics. To select the flow rate limits, the pump efficiency can be seen as a justified variable for limiting values, since centrifugal pump performance curves usually contain efficiency data (Sulzer 1989; Karassik et al. 2001). As illustrated in Fig. 5, balancing the rotational speeds shifts the operation point of pump 1 to a higher efficiency region at the same time when pump 2 is being run towards the same head level. Consequently, both pumps are running in a region that can be considered beneficial from the perspectives of energy efficiency and reliability. Similar control steps can also be applied to systems with higher number of parallel pumps. In this case, the ongoing pumps are seen as a unit representing the primary pump (pump 1), while the next pump in turn represents the secondary pump (pump 2).

Observing the output of parallel pumps during operation is usually limited by the lack of metering in the

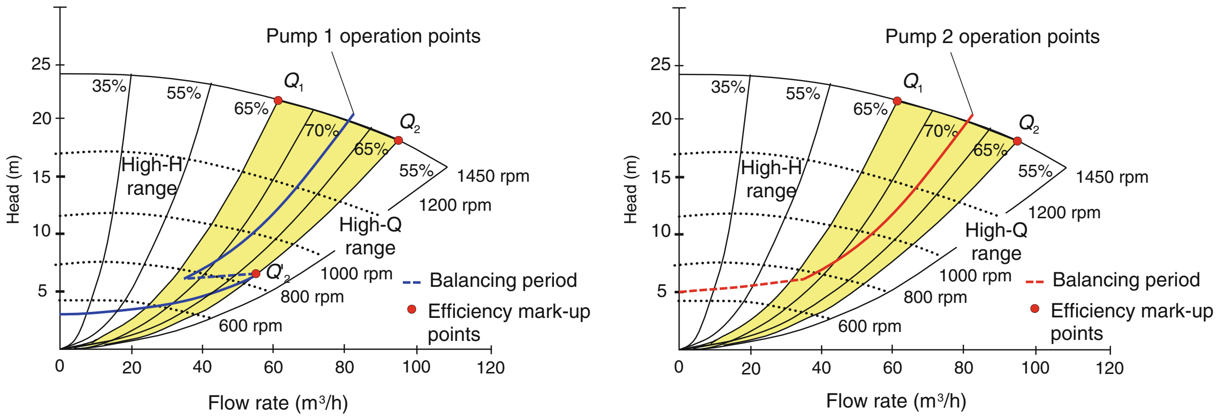

Fig. 5 Operation points of pump 1 (on the *left*) and pump 2 (on the *right*) in the suggested control strategy when the flow rate of the system is increased to nominal. The speed balancing of the parallel pumps starts when the operation point reaches the set flow limit (Q_2) at Q'_2. The area between the limit values Q_1 and Q_2 in the QH axis according to the affinity rules is the set preferable operating area (POA). The area outside the flow limits can be described as high H range and high Q range areas

pumping systems. However, information from parallel pump operation can be gathered by utilizing the pump operation point estimation available in a modern VSD. The operating point of individual variable speed-driven pumps can be monitored using the pump characteristic curves and the measured head or estimated power of the pump (Hammo and Viholainen 2006; Ahonen et al. 2010). In these estimation methods, the pump characteristic curves are shifted to the used rotational speed with the affinity equations

$$Q = \left(\frac{n}{n_0}\right) Q_0 \tag{4}$$

$$H = \left(\frac{n}{n_0}\right)^2 H_0 \tag{5}$$

$$P = \left(\frac{n}{n_0}\right)^3 P_0 \tag{6}$$

where H is the pump head (in meter), P is the pump power (in watt), n is the pump rotational speed (in revolutions per minute), and the subscript 0 denotes the initial values given by the characteristic curves. In the flow rate estimation, the flow rate corresponding to the measured head is found on the shifted pump QH curve in the case of the QH curve-based method. Correspondingly, QP curve-based method determines the pump flow rate by using the estimated pump shaft power and the shifted QP curve.

Adequate flow metering of individual pumps in the suggested control strategy allows the adjusting of the pumped volume according to the process changes, and each pump can be monitored to operate in the selected POA. Therefore, a separate flow meter installation or start-up field measurements are unnecessary. The estimation of the operating point of the pump with VSDs in suggested control strategy can be done either using only the pressure sensors for inlet and outlet pressure measurements or utilizing the sensorless option based on the motor power estimate. VSDs not containing such flow estimation features are excluded from this study, since the requirement of not to use additional flow meters would not be met.

Implementing the control strategy

The objective of the introduced control strategy is to prevent the variable speed-controlled parallel pumps from operating in regions with poor energy efficiency and increased risk of mechanical failure. Since the suggested control strategy is based on pump operation point estimation and POA, which in this case can be limited by the pump user based on pump efficiency data and process conditions, implementing the control strategy does not require any mathematical optimization tools. Instead, the control can be set with a simple feedback control based on pump output (Fig. 6). As illustrated in Fig 6, the information on each pump's operation point and individual rotational speed data are gathered from the VSD supporting it. The VSD's flow monitoring can supply the head, flow rate, and power values of each pump based on the input power

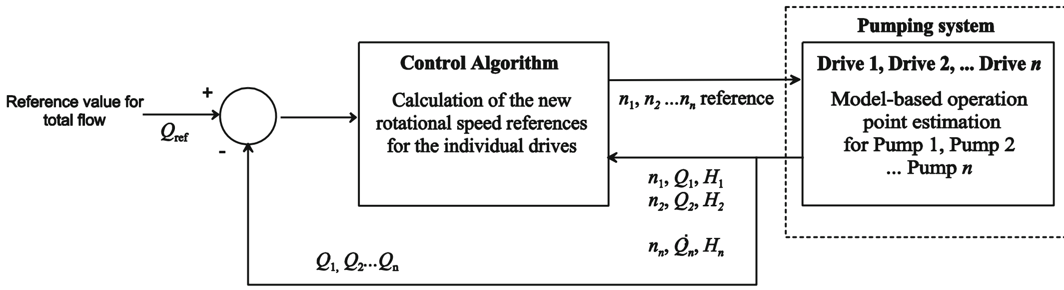

Fig. 6 Implementing the control strategy to a parallel pumping system. The pump operation point estimation gives the pump output values to the control algorithm. The control algorithm calculates the reference speed to each pump drive based on the monitoring data and the set preferable operating area of each pump

reference or measured head. Using the reference value for the total flow rate and selected preferable operating area for each parallel-connected pump in the current system, the control algorithm returns the reference speed for each pump drive.

An example of the control algorithm to provide the suggested control strategy in parallel pumping systems was created. The block diagram of the prototype algorithm is illustrated in Fig. 7. The block diagram illustrates the control procedure in the case of increasing or decreasing the total flow of the parallel pumps according to required output marked as Q_{ref} in Fig. 7. In the block diagram, the system is started with just one pump regardless of the required flow rate. After starting, the output of the parallel pumps is adjusted to meet the process requirements based on Q_{ref}. In this case, the operation point of each pump (Q, H) is determined by utilizing the VSDs' QH curve-based flow estimation, although the head of the pump could also be determined with the QP curve-based method.

As mentioned, mathematical tool-based optimization of rotational speeds of the parallel pumps may require start-up measurements and detailed system data (Bortoni et al. 2008), which may have to be repeated or reevaluated if there are changes in the system conditions, e.g., in the amount of the static heads or the shape of system curve. The implementation of the suggested control strategy to a parallel pumping system does not require start-up measurements, additional flow meters, or data related to the piping system characteristics, although the system conditions should be considered when selecting the preferable area in the pump QH axis. Thus, changes in the pumping system do not result in the reediting of the control setup. Instead of the optimization of the speed of each parallel-connected pump, the energy efficiency and reliability are obtained by ensuring that the pumps are operated on the selected operating area, if possible. Including POA as a control factor in the parallel pump control strategy can also ensure that the pump user does not have to decide, whether the efficiency or reliability should have more value in varying conditions. Because of these qualities, the suggested control strategy can be justified in parallel pumping systems in which the requirements for a complete energy optimization are not met.

Simulations and measurements

Since the aim of the suggested control strategy is not to optimize the energy efficiency of the variable speed-controlled parallel pumps, but to ensure that they are operated in an area of justified efficiency and pump reliability, the comparison of such control with an optimization-based control schemes can be seen controversial. Instead, the benefits of the suggested control strategy are compared with the explained traditional rotational speed control strategy.

The comparison is made using a simulation tool for the pumping system observation. The simulated operation is verified by laboratory measurements in a parallel pump setup. Differences between the control methods are evaluated in terms of power consumption and specific energy use.

Laboratory setup

The laboratory contains two pump systems; both of them include a single-stage centrifugal pump and a VSD connected to a three-phase motor. The primary pump (pump 1) system consists of a Serlachius DC 80/255 centrifugal pump, a four-pole 15-kW Strömberg induction motor, and an ABB ACS 800 frequency

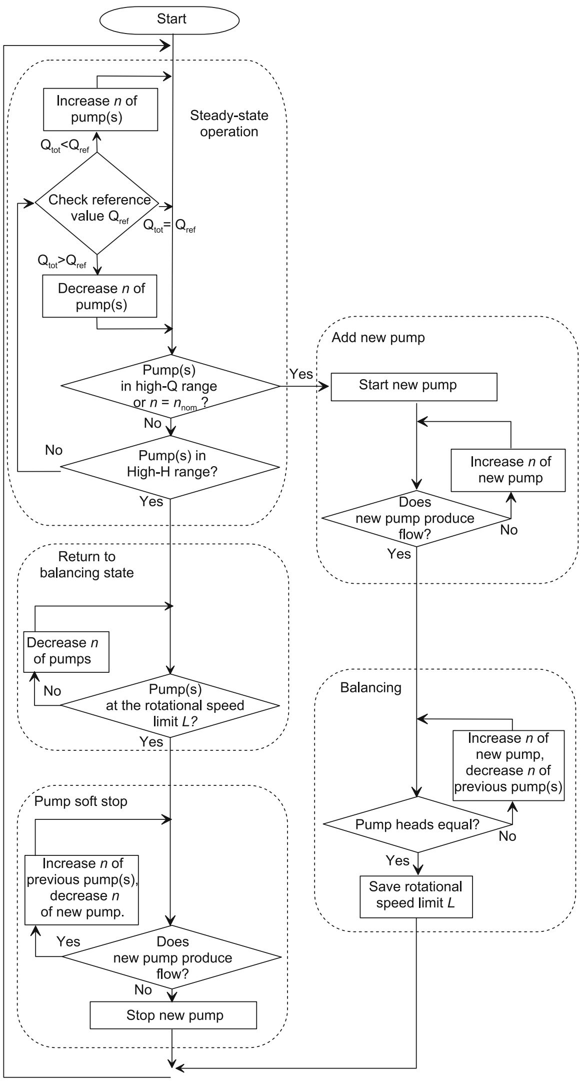

Fig. 7 Block diagram for the control algorithm which can provide the suggested control strategy for parallel pumps. The control step to increase or decrease pump speed should be decided based on the pump nominal speed. The point marked as *Start* is a point when the first parallel pump is started

converter. The secondary pump (pump 2) system consists of a Sulzer APP 22-80 centrifugal pump, an ABB 11-kW induction motor, and an ABB ACS 800 frequency converter. Both VSDs estimate the individual flow rates using pump head measurements. The total flow rate is also measured using a Venturi tube. The pumps were connected in parallel, and the basic layout of the measurement setup is presented in Fig. 8.

The control algorithm is implemented in a dSPACE DS1103 PPC controller board which was used as a separate platform for the control strategy in this prototype testing. The dSPACE board has analog voltage inputs and outputs; the inputs for the controller board are the rotational speeds, heads, and flow rates of the individual pumps, and the total flow rate from the VSDs. The outputs of the controller board are the rotational speed references for the individual pumps. The sample time for the control algorithm was 1 s. In the laboratory measurements, the flow rate is controlled based on the requirement for more flow, less flow, or no change in the flow rate.

The static head of the piping system was 2.5 m, and the system curve was set using valves located in individual piping branches so that both pumps would gain a reasonable efficiency when operating parallel at the nominal rotational speed. This illustrates a case where a parallel pumping system is dimensioned according to the highest flow rate. The operating values of the parallel pumps in the test setup system are shown in Table 1. Since the pump systems have separate piping parts causing individual friction head to each pump, the head levels are not equal in parallel use (Table 1).

Simulation sequences

The operation of the presented control methods is simulated for the laboratory pumping system with a Matlab Simulink model. The model is constructed to enable energy efficiency calculations of pumping systems and has been reported by Viholainen et al. (2009b). A similar simulation model has been utilized to characterize hydraulic systems also by Pannatier et al. (2010). In the simulation of this study, the performance, the combined power consumption, and the specific energy consumption of two parallel-connected pumps, having the same characteristics as the introduced pumps in the laboratory setup, are evaluated in a case where the total flow of the pumping system is increased using either the traditional rotational speed control strategy or the presented new control strategy. In the "Results" section, the operation based on the new control strategy is represented as the *alternative control*.

Results

Simulation results

The simulation was conducted from the flow rates 0 to 189 m^3/h. The rotational speeds of the individual

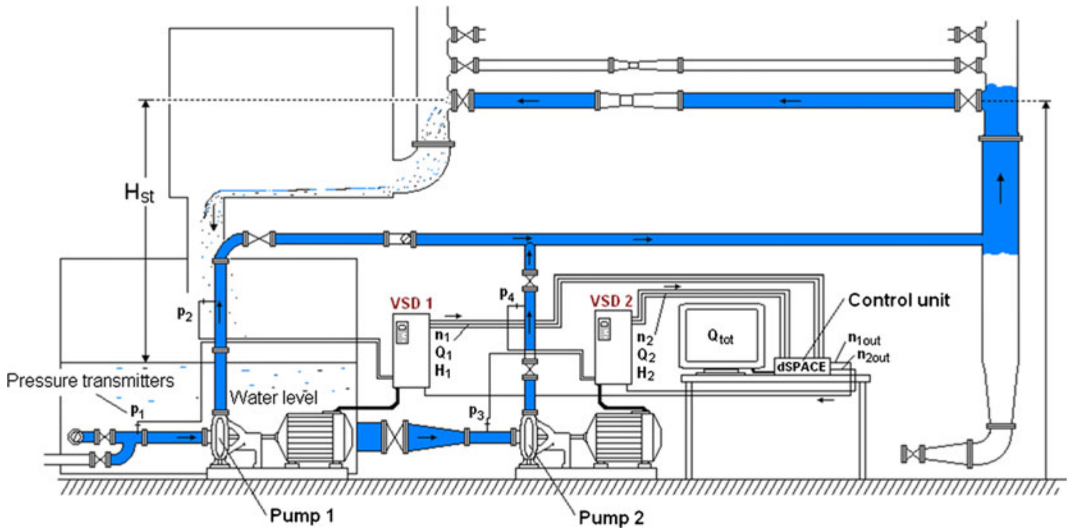

Fig. 8 Test setup used in the laboratory measurements. The pressure transmitters are installed to the inlet and outlet section of each pump, and the pressure signals are wired to the frequency converters to enable the flow calculation. The control board, a dSPACE system, is attached to both VSDs. The values from VSDs' pump monitoring application; speed (n), flow rate (Q), and head (H) signals are led from the VSDs to the dSPACE system. The determined speed commands (n_{out}) are transmitted to the VSDs from the dSPACE unit

pumps using both control methods during a simulation sequence (0–1,200 s) are given in Fig. 9.

It can be seen that in the traditional control, the rotational speed of the primary pump (pump 1) is increased to 1,450 rpm, after which the secondary pump (pump 2) is started and run towards the nominal rotational speed (Fig. 9). When using the alternative control, the secondary pump is started before the primary pump reaches the nominal rotational speed because the primary pump hits the set flow limit (point A in Fig. 10 a), as described in the previous section. This means a smaller flow rate difference at the secondary pump's starting point compared to the traditional control scheme. The simulated operation points of both parallel-connected pumps using either the traditional or alternative control are illustrated in Fig. 10. The figure also shows the chosen flow rate limits for the alternative control algorithm based on the pump data given by the pump manufacturers.

Figure 10 shows that even though traditionally controlled parallel pumps are operating in the same operation point as in the alternative control when both pumps have reached their nominal rotational speed, the alternative control enables the continuous operation between the set flow rate limits. Therefore, the operating points, especially in the case of pump 1 (~65–90 m^3/h) shown in Fig. 10a, are located in a better efficiency area compared with the traditional rotational speed control. Because of the balancing, the duty point of the secondary pump is located only temporarily in an unwanted region, and the actual

Table 1 Parallel pumping system in laboratory setup

Type	Pump 1 Serlachius DC 80/255	Pump 2 Sulzer APP 22–80
BEP[a]		
Speed (rpm)	1,425	1,450
Flow rate (m^3/h)	76	90
Head (m)	17.4	15
Efficiency (%)	69	73
Parallel operating point[b]		
Speed (rpm)	1,448	1,449
Flow rate (m^3/h)	91	83
Head (m)	16.3	17.6
Efficiency (%)[c]	68	70
Selected POA (% BEP flow)	70–130	70–130

[a] Operating values in a rated efficiency point according to the characteristics curves given by pump manufacturer

[b] Operating values (measured) of the parallel-connected pumps in a test setup system

[c] Based on pump characteristic curves

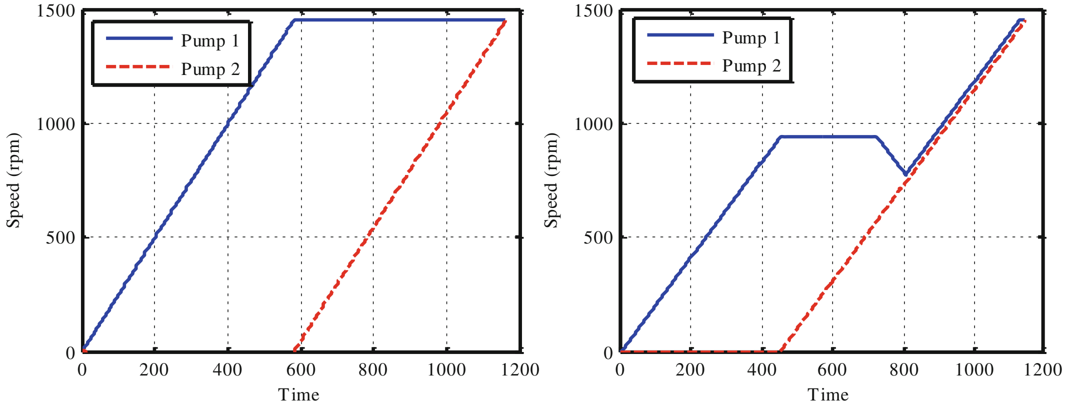

Fig. 9 Operation speeds of two parallel-connected pumps in a system in the case of the traditional speed control (on the *left*) and the alternative control (on the *right*). In both cases, the pumps were operated to deliver the total flow rate from 0 to 100 %. The *time axis* shows the direction of increasing flow demand

operation (~40–90 m^3/h) takes place between the set limits (Fig. 10b). During the balancing period, the primary pump is always delivering flow and head, and hence, the secondary pump (pump 2) can generate a flow rate only when it has exceeded the required head (~4 m). However, the required head for the secondary pump can be smaller than the primary pump's total head, since the friction head values for both pumps are not necessarily equal during the control.

The benefit of the alternative control can be seen best when observing the total pump power consumption and the specific energy consumption of both parallel pumps in the same simulation (Fig. 11). The results suggest that in this particular case, the alternative control enables much lower power consumption and specific energy consumption in the flow range of 70–175 m^3/h compared with the traditional control. Outside this range, the energy consumption was equal. However, the difference in the energy use seems to be more than 50 % at the highest point (110–120 m^3/h) between the alternative control and the traditional rotational speed control.

a)
b)

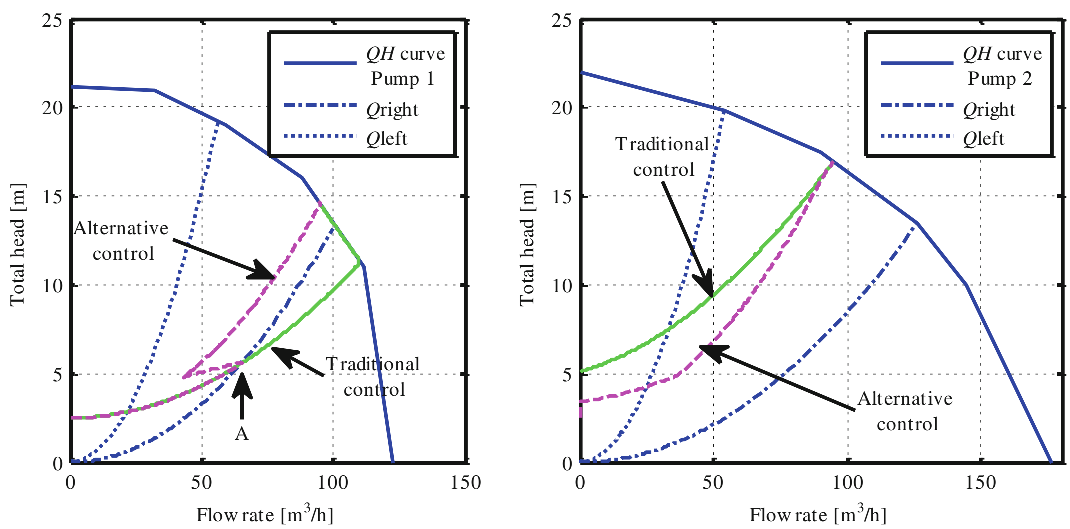

Fig. 10 Simulated operating points of pump 1 (**a**) and pump 2 (**b**) using either the traditional or the alternative control. With the alternative control, pump 2 is started when the pump 1 operating point reaches the set flow rate limit (Q_{right}) in point A. When pump 2 starts to deliver flow, the speeds of both pumps are balanced to have the same head

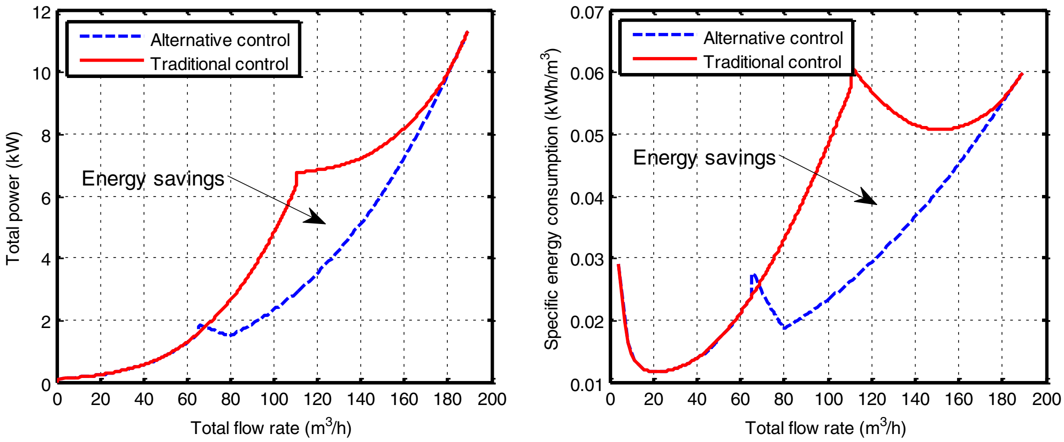

Fig. 11 Simulated total pump power (on the *left*) and specific energy consumption (on the *right*) of both pumps according to the total flow. The figure plots the simulated values in the cases of alternative control and traditional control. Energy savings using alternative control can be found when operating on a flow range, where the electric power use and specific energy consumption are lower compared with traditional control

Experimental results

The new parallel pump control strategy was tested in an actual pumping setup using measuring sequences where the flow rate was increased using the rotational speed control of parallel pumps. The total flow of both pumps varied from 0 to 175 m^3/h during the sequences. These values represent the minimum and maximum total flow rate values of the parallel pumps in the used system conditions. The measured operation points of each pump represent the average values gathered manually from the data control unit and the measuring equipment.

Figure 12 plots the test results of the sequences where the flow rate is increased from zero to maximum using either traditional control or alternative control. Figure 12a shows the measured operation points of the primary parallel pump when the total flow of the system is increased from 0 to 175 m^3/h. The balancing of pump 1 starts when the flow rate reaches the set markup line (Q_{right}) in alternative control. When traditional control is used, the speed of

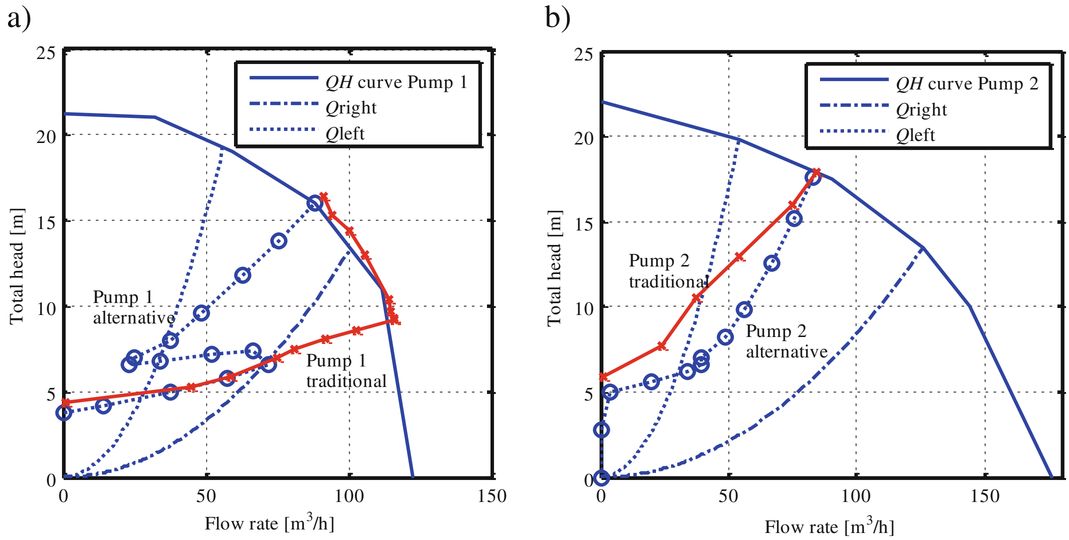

Fig. 12 Operation points of pump 1 and pump 2 during the alternative control and traditional control. The graph on the *left* shows the measured operation values for pump 1, and the graph on the *right* shows the pump 2 operation points

pump 1 is adjusted to nominal rotational speed before pump 2 is started. Figure 12b shows the pump 2 operation points. It can be seen from Fig. 12 that pump 1 and pump 2 are not operated on the same head in a point when pump 2 starts to deliver flow. This is because of the losses in elbows and valves in system, causing that dynamic head losses in individual piping parts are significantly different for pump 1 and pump 2 in this particular parallel operation point. However, a brief look at Fig. 12 shows that the alternative control is operating the parallel pumps as simulated. Since the laboratory equipment used in this study does not include the measurement of the pump shaft power, only the consumed total input power to each drive during parallel pumping was estimated using the input power reference of the VSDs. The results of the estimated total input power of both drives during the traditional and alternative control measurement sequences are illustrated in Fig. 13. The first look at Fig. 13 shows that in contrast to simulations, the measured total flow rate is not increasing during the balancing period (~75 m^3/h). Despite this, the advantage of the alternative control compared with the traditional control can be seen in the total power consumption and in the specific energy use.

Even though the estimated total input power rates during different control schemes are directly not comparable with the simulated pump shaft power values, the measured results seem to agree with the simulations. The results suggest that in this case, the alternative control seems to reduce the combined input power consumption and the specific energy use up to 20–25 % on the flow rates from 80 to 160 m^3/h. The benefits of using alternative control can also be seen in the higher system efficiency of parallel pump drives (Fig. 14).

Discussion

The simulation results showed (Fig. 11) that using the suggested new control strategy (*alternative control*) resulted in the improved energy efficiency in pumping compared with the traditional rotational speed control strategy, since the same flow rate could be delivered with a lower energy use (in the flow range of 70–175 m^3/h). In the illustrated examples, the alternative control enabled parallel pumps to operate in the set POA on the *QH* axis (Fig. 10) which in this case was defined simply as an area between the set efficiency limits based on the pump characteristics. The improved energy efficiency was verified by observing the simulated power consumption and the specific energy use of parallel pumps during the control procedure.

The benefits of the suggested control strategy were verified also by laboratory measurements with an actual parallel pump setup (Figs. 12, 13, and 14). In laboratory measurements, the amount of saved energy was 20–25 % at highest (in the flow range of 80–160 m^3/h). The measurement results showed (Figs. 12 and 14) that in that flow range (80–160 m^3/h) when using alternative control, the parallel pumps are located in an area which results in improved system efficiency compared to the situation, where the same total flow is delivered with traditional control.

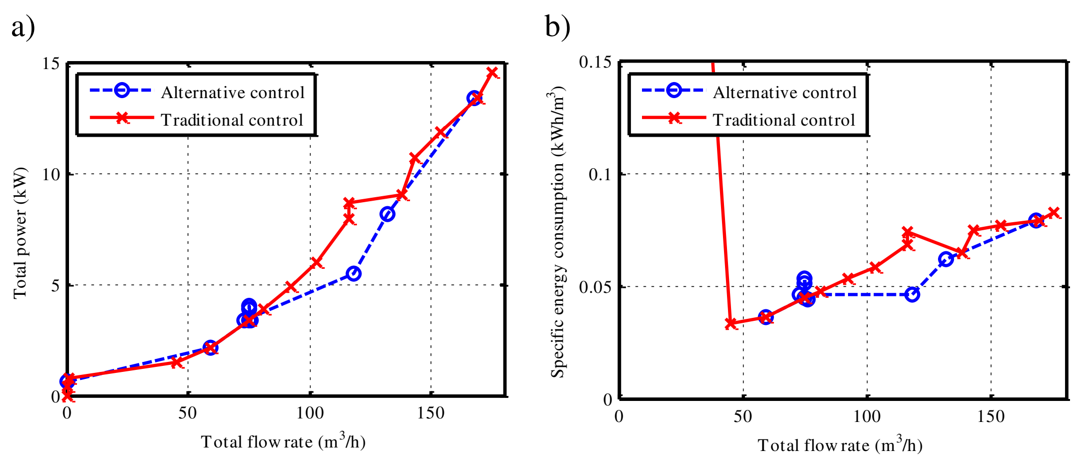

Fig. 13 Estimated total input power (on the *left*) and specific energy consumption (on the *right*) of parallel-connected pump drives in the alternative control and the traditional speed control

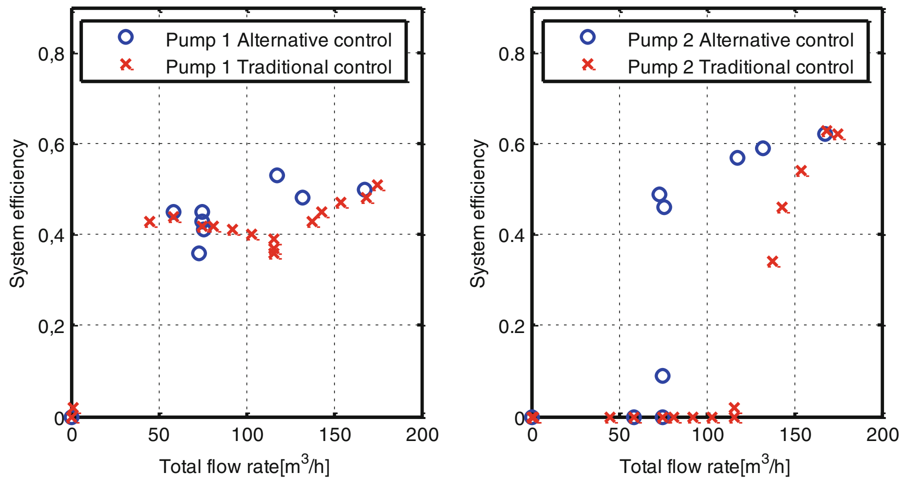

Fig. 14 Estimated system efficiency of parallel-connected pump drives in alternative control and traditional control. The system efficiency of pump 1 (on the *left*) and pump 2 (on the *right*) drives are shown according to total flow rate of both pumps, showing the variation of system efficiency during measuring sequences

Although the measurements indicated quite a similar operation as simulated, differences were found in the shut-off heads of the pumps and in the point where pump 1 reaches the set efficiency limit. The reasons for these differences can be the inaccuracies in the pressure metering, resulting in a further error in the flow metering of the VSDs. Based on the measurements, the oscillation of reference values (pressure, flow rate, pump rotational speed) can also disturb the control algorithm. Despite this, the collected data support the assumption that the presented control strategy could be implemented in VSD-controlled parallel pumping systems without separate flow metering devices or field measurements except the pressure sensors for the flow metering of the VSDs. The results also showed that the parallel pumps do not have to be identical, although significantly dissimilar pumps may need further considerations.

The prototype testing was performed using VSDs which are known to have applications to estimate the flow rate of the controlled pump. Without providing a similar monitoring of pump output with VSDs, the use of the introduced method would need additional metering of pump flow rate.

In the laboratory measurements, the control procedure including the prototype control algorithm based on suggested control strategy was tested using a separate controller board (Fig. 8), but the introduced method could also be implemented in VSD software.

It is clear that because the presented parallel pump control strategy is based on the VSD's pump system monitoring applications, its adequate operation depends on the monitoring accuracy. It is also known that the model-based pump monitoring cannot provide accurate flow metering in certain pump types and this may exclude the implementation of the introduced control strategy in some pumping systems.

A challenge for a justified control is to set the POA based on pump data only, since the efficiency data are not the only relevant factor when determining the preferable operation region of the pump. The pumping process can set limitations for instance to the minimum flow and pressure rate. Also, higher pump rotational speeds that can increase radial and axial forces in the pump and thereby affect the pump mechanical reliability should be taken into account for a more systematic approach. If the POA is chosen according to the pump efficiency data, but the parallel pump system is dimensioned so that the reasonable efficiency cannot be achieved when operating at the nominal rotational speed, it is likely that the operation points of parallel pumps can be located outside the defined flow limits. In addition, depending on the amount of static head and the shape of the system curve, the primary pump may operate mainly between the flow limits regardless of its rotational speed. In these situations, the alternative control operation greatly resembles the discussed traditional rotational speed control. Based on the results, the introduced new rotational speed control strategy for parallel pumps can enable higher energy efficiencies compared with the traditional rotational speed control, especially in parallel pumping systems with a varying flow need, relatively flat system curve, and when the pumping systems are dimensioned according to the highest flow rate.

Conclusions

In addition to the energy-efficient flow control in pumping, the rotational speed control using VSDs for each parallel-connected pump can open new opportunities for the advanced control of pumping processes. Utilizing VSDs to both system monitoring and system control provides opportunities not only to meet the varying requirements of the parallel pumping process, but also help in operating pumps with a lower energy consumption and reduced risk of mechanical failure.

The paper introduced a new control strategy for parallel pumps, which can improve the energy efficiency in variable speed-driven parallel pumping systems. The introduced control strategy is based on real-time pump operation point estimation and the selection of the preferable operating area of parallel pumps in a system, making it suitable for different applications and varying system conditions. The suggested control strategy can be implemented using the sensorless flow rate estimation of parallel pumps excluding separate flow meters and additional field measurements. The presented control was compared with a traditional rotational speed control strategy, and both the simulations and laboratory measurements showed that a lower energy consumption could be achieved using the introduced new control strategy. Further on, the discussed method showed to be able to run parallel pumps in the determined operating range, which suggests lower risks of reduced pump service life.

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