IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received February 22, 2020, accepted March 8, 2020, date of publication March 12, 2020, date of current version April 7, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2980396

Improving Reliability of Pumps in Parallel Pump Systems Using Particle Swam Optimization Approach

ZHOUNIAN LAI[1,2,3], (Member, IEEE), QIAN LI[1], AN ZHAO[4], (Member, IEEE), WENJIE ZHOU[5], (Member, IEEE), HAILIANG XU[3], (Member, IEEE), AND DAZHUAN WU[1], (Member, IEEE)

[1]College of Energy Engineering, Zhejiang University, Hangzhou 310027, China
[2]College of Computer Science and Technology, Zhejiang University of Technology, Hangzhou 310023, China
[3]Junhe Pumps Holding Company, Ltd., Ningbo 315000, China
[4]Department of Mechanical Engineering, The University of Tokyo, Tokyo 113-8654, Japan
[5]School of Energy and Power Engineering, Jiangsu University, Zhenjiang 212013, China

Corresponding author: Dazhuan Wu (wudazhuan@zju.edu.cn)

This work was supported by the National Natural Science Foundation of China under Project 51906217.

ABSTRACT Parallel pump systems are widely used in industries. However, pumps are often operating under off-design conditions due to many reasons, which reduces the efficiency and reliability of the pumps. This paper aims at reducing the power consumption of parallel pump systems and improving the reliability of pumps by improving the operation points of pumps. To achieve this goal, a combination of selecting the proper number of pumps to put into operation and their speed is needed. Also, a control valve is adopted to further improve the operation points. The optimization model is built for a parallel pump system. Particle swarm optimization algorithm is used to solve the problem. Experimental verification shows that the proposed method improves the reliability and can also reduce power consumption for some cases compared to conventional PID speed regulation method. But for cases with large flow, extra power might be needed because the control valve introduces extra flow resistance in order to improve the operation point. The proposed method can be easily extended to applications based on their requirements on reliability.

INDEX TERMS Pump reliability, parallel pump systems, particle swarm optimization, operation points.

I. INTRODUCTION

Water supply systems are designed to pressurize and transport water to consumers, which are extensively used in wide range of industries, such as urban water supply networks, agricultural irrigation and power plants. Pumps are the key components in water supply systems to provide sufficient pressures. However, the reliability of pumps are difficult to define and predict. Although there are several researches about predicting pump failures [1], [2], the pump reliability curve proposed by Barringer [3]–[5], which uses the Mean Time Between Failure (MTBF) as the measurement of pump reliability, are widely used due to its simplicity. Usually a pump is designed for a certain flow rate, which is called Best Efficiency Point (BEP) flow rate. Barringer [3]–[5] and Bloch [6] found that the reliability of a pump reaches maximum at its BEP and decreases rapidly as the flow rate deviates from BEP. Typically the reliability of a pump reaches a satisfactory value within the flow range of -30% to $+15\%$ of BEP, as shown in Fig. 1, where the x-coordinate is the flow rate, the y-coordinate is the pump head. As shown in Fig. 1, the pump head decreases as flow rate increases, while the pump efficiency and reliability are highest when the flow rate is near the BEP and decreases as flow rate increases or decreases. The reason are analyzed as follows. The flow is uniformly distributed and the unbalanced axial and radial force is minimum when a pump operates at BEP flow rate, and consequently, its efficiency and the reliability are relatively high near its BEP flow rate. However, when a pump operates at off-design conditions, the unbalanced axial and radial force, which are transmitted the the shaft and bearings, increase and become unsteady. Also, the overheat,

The associate editor coordinating the review of this manuscript and approving it for publication was Jing Bi.

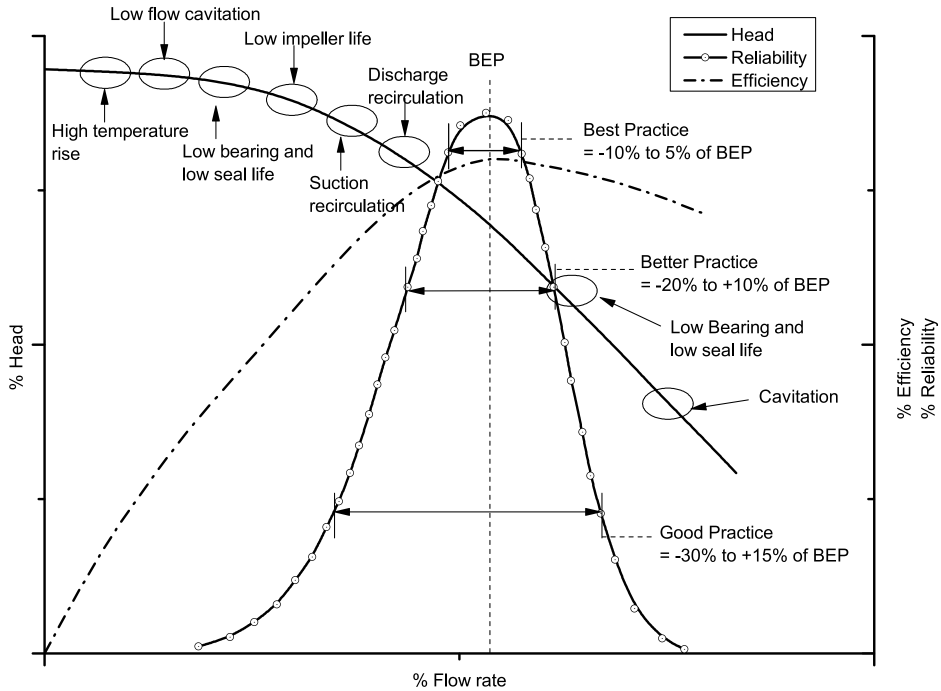

FIGURE 1. Relationship between pump reliability and pump curve [3]–[5].

recirculation and cavitation may occur [3]–[5], [7], [8]. Therefore, long-term operation at off-design conditions leads to low efficiency and high failure rate [3]–[5], [9]. However, pumps are often selected too large than the actual system demands due to safety margins. A pump would be operating at large flow rate points if it is too large for the system. Therefore, a large percentage of pumps are operating in off-design conditions. Moreover, the regulation methods nowadays, such as speed regulation and throttling regulation, do not take optimizing the operation point of pumps into consideration.

Parallel pumps are widely used in many applications, such as the cases with a high demand of flow rate or pressure and the cases with a wide range of demand variations. Shiels [10] compared the pros and cons of a single pump operation versus a two pump operation in terms of life cycle cost, reliability and safety and concluded that a two pump is often safer and more economic. The major problem in the operation of parallel pumps is to determine the number of pump that should be put into operation and their speed. Bortoni [11] used dynamic programming to optimize the pump number and their speed for parallel pump systems with different types of pumps, but the problem is that the method will become complicated when dealing with system with many pumps. In many applications, intelligent optimization algorithms are more suitable for many engineering problems because of their nonlinearity, non-convexity and many constrains,such as pump scheduling problems [12], single-machine scheduling problems in steel product systems [13], economic power dispatch problems [14] and many others [15]–[19].

The common intelligent optimization algorithms include genetic algorithm (GA), simulated annealing algorithm (SA), particle swarm optimization algorithm (PSO) and ant colony optimization algorithm (ACO). Savic [20] applied genetic algorithm to optimize the scheduling a pump station to minimize the energy consumption and maintenance cost, which achieved good optimization results and robustness. Wang [21] used an enhanced genetic algorithm to minimize the energy cost and the total work time for each pump and the validity was verified by experimental verification. Genetic algorithm is more complicated and more difficult to implement because it needs operations like chromosome encoding, selection, crossover and mutation. Kenny [22] developed PSO and since then PSO has been widely used in many applications. Montalvo [23] compared PSO with other GA and ACO in optimizing the water distribution system in Hanoi and found that PSO obtains good solutions with fewer iterations. Jung [24] adopted GA and PSO to optimize the types and locations of transient protection devices in pipeline systems and concluded that both algorithms works well. Hassan [25] compared the solution quality and computational effort of GA and PSO and concluded that both GA and PSO were able to arrive at solutions with the same quality but PSO consumes less computational resources for unconstrained nonlinear problems and constrained nonlinear problems.

This paper proposes a new solution to reduce the power consumption of parallel pump systems and improve the reliability of pumps simply by improving the operation points of pumps. PSO is chosen as the optimization algorithm in this

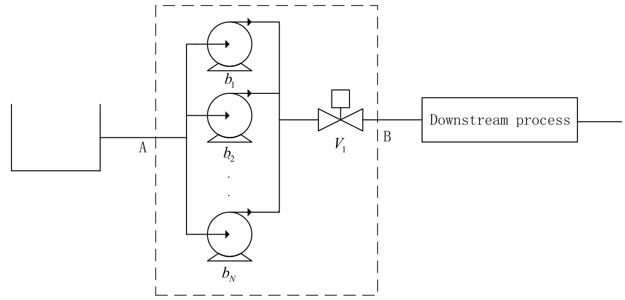

FIGURE 2. Schematic of N pumps in parallel.

work due to its the simplicity and fast convergence. The main contribution of this paper are summarized as follows.

1) It proposes a new solution to improve the reliability of pumps in parallel pump systems simply by improving their operation points, which is of great significance to engineering industries.
2) It presents an new application of PSO algorithm to an engineering problem in pump systems, which improve the value of PSO algorithm as well as other similar algorithms in real engineering problems.

The remained of the paper is organized as follows. Section II describes the problem and the optimization model of a parallel pump system. Section III briefly describes the PSO algorithm. The application of PSO algorithm to the problem and the experimental verification are discussed in Section IV. Section V gives the summary of this paper.

II. PROBLEM DESCRIPTION AND MODEL DEVELOPMENT

A. PARALLEL PUMP SYSTEMS

Fig.2 shows a schematic of N pumps assembled in parallel, where $b_1, b_2, \ldots, b_N$ are identical pumps; V_1 is a control valve installed in the main pipe. Usually, check valves are installed in each branch of parallel systems to prevent reverse flow, but previous study shows the resistance of check valves are relatively small [26], therefore the check valves are omitted.

B. OBJECTIVE FUNCTION

Previous studies have shown that the best efficient way is to keep each turned-on pump running at the same speed for parallel pump systems consisted of identical pumps [27]. Therefore, in this study, each pump in operation is running in the same speed.

The objective of this study is to reduce the energy consumption of a parallel pump system, therefore the objective function can be selected as Eqn. (1), where P is the total power of pumps, M is the number of the pumps that is running in the parallel pump system, P_i is the power of i-th pump that is in operation, $P_i = 0$ if it is not in operation.

$$\min \quad F = P = MP_i \tag{1}$$

The power of each running pump can be stated as Eqn. (2) [28], where P_i^* is the power of each pump at rated speed, where Q_i is the flow rate of each pump that is in operation, b_1, b_2, b_3 and b_4 are polynomial coefficients.

$$P_i^* = b_1Q_i^3 + b_2Q_i^2 + b_3Q_i + b_4 \tag{2}$$

By applying pump's affinity laws to Eqn. (2), we get Eqn. (3), where $k = n/n_r$ is the speed ratio of the pump, the ratio of actual rotational speed n to its rated rotational speed n_r.

$$P_i = b_1Q_i^3 + b_2Q_i^2k + b_3Q_ik^2 + b_4k^3 \tag{3}$$

By adapting Eqn. (3) into Eqn. (1), the objective function is presented in Eqn. (4).

$$\begin{aligned} \min F &= P = \sum_{i=1}^{N} P_i \\ &= MP_i = M(b_1Q_i^3 + b_2Q_i^2k + b_3Q_ik^2 + b_4k^3) \end{aligned} \tag{4}$$

C. CONSTRAINS

1) PUMP NUMBER IN OPERATION

The number of pump in operation should not exceed the total number of pumps in the parallel pump system, therefore the constrain for pump number in operation is

$$0 \leq M \leq N \tag{5}$$

2) SPEED RATIO

Usually the speed of a pump cannot exceed the rated speed. The efficiency of variable frequency drives (VFD) decreases rapidly when the speed ratio of the drives is less than 0.5 [29], so the speed of the pump should be kept larger than 0.5. Therefore, the constrain for pump speed ratio is

$$0.5 \leq k \leq 1 \tag{6}$$

3) TOTAL FLOW RATE

The total flow rate is the sum of the flow rate of each pump, which equals to the system requirement. Therefore, the constrain for pump speed ratio is set as Eqn. (7), where Q is the flow rate required by the system.

$$Q = MQ_i \tag{7}$$

4) HEAD

Define ΔH as the extra head loss at the control valve relative to its fully open state, then the head of the pump equals to the summation of system requirement (the head requirement between point A) and B in Fig.2) and ΔH. ΔH equals to 0 when it is fully open and it cannot be less than 0, so the head constrain is set as Eqn. (8), where H is the head requirement, $H_i = a_1Q_i^2 + a_2Q_i + a_3$ is the head of each running pump, a_1, a_2 and a_3 are polynomial coefficients.

$$\Delta H = H_i - H = a_1Q_i^2 + a_2Q_i + a_3 - H \leq 0 \tag{8}$$

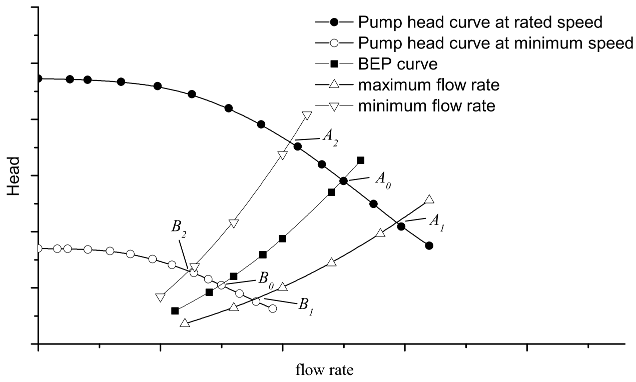

FIGURE 3. Optimum operating region for each pump.

5) PUMP OPERATING REGION

According to pump's affinity laws, the BEP flow rate at a given speed ratio $k$can be described in Eqn. (9), where kQ_r^{BEP} is the BEP flow rate of the pump at rated speed (often approximately equals to its rated flow rate which is provided by its manufacturers).

$$Q_k^{BEP} = kQ_r^{BEP} \tag{9}$$

To improve the reliability of the pumps, the operation point should be restricted nearby the BEP. Fig. (3) gives the optimum operating region for a pump, where point A_0 is the BEP at rated speed, point A_1 and A_2 are the maximum and minimum flow rate point at rated speed respectively, point B_0 is the BEP at minimum speed constrained by Eqn. (6), point B_1 and B_2 are the maximum and minimum flow rate point at minimum speed respectively. The optimum operating region for a pump is the region closed by $A_1A_2B_1B_2$. Define δ as the deviation of the actual flow rate with respect to the BEP flow rate at current speed, as shown in Eqn. (10).

$$\delta = \frac{Q_i - Q_k^{BEP}}{Q_k^{BEP}} \tag{10}$$

It is suggested by Barringer [4] that a pump should be operating within a range of -30% to 15% of the BEP flow rate to gain a good reliability. While Bloch [6] suggest a range of -10% to 10%. For simplicity, the range of δ is chosen as $-20\% - 20\%$.

Therefore, the constrain for the pump's operating region can be described as Eqn. (11)

$$|\delta| = |\frac{Q_i - Q_k^{BEP}}{Q_k^{BEP}}| \leq \delta_{\max} \tag{11}$$

D. OPTIMIZATION MODEL

Combining the objective function and the constrains above, the overall optimization model can be summarized as a constrained minimization problem in Eqn. (12).

$$\begin{aligned}
\min \quad & F = P = M(b_1Q_i^3 + b_2Q_i^2k + b_3Q_ik^2 + b_4k^3) \\
s.t. \quad & Q = MQ_i \\
& \Delta H = H_i - H = a_1Q_i^2 + a_2Q_i + a_3 - H \geq 0 \\
& 0.5 \leq k \leq 1 \\
& 0 \leq M \leq N \\
& |\frac{Q_i - Q_k^{BEP}}{Q_k^{BEP}}| \leq \delta_{\max}
\end{aligned} \tag{12}$$

E. DEALING WITH CONSTRAINS

The most common method to deal with constrains for constrained problems is penalty method. The penalty method transforms the constrained problems to unconstrained problems by adding a term to the objective function that consist of the consists of a penalty parameter multiplied by a measure of violation of the constraints.

For a parallel pump system as in Fig. (2), there are three factors affecting the operating status: the number of running pump M, the speed ratio of each running pump k and the extra head loss ΔH at the control valve. According to Eqn. (8), the head loss can be derived by subtracting the head requirement from the pump head. Therefore, the two variable remaining is the number of running pump M and the speed ratio of each running pump k. The number of running pump M and the speed ratio of each running pump k can be constrained by restricting the range of variable M and k. The head and pump operating region constrains are achieved using penalty functions as in Eqn. (13) and (14).

$$W_H = \begin{cases} 0, & H_i - H \geq 0 \\ (H_i - H)^2, & H_i - H < 0 \end{cases} \tag{13}$$

$$W_\delta = \begin{cases} 0, & |\delta| \leq \delta_{\max} \\ \delta_{\max} - |\delta|, & |\delta| > \delta_{\max} \end{cases} \tag{14}$$

From the analysis above, it can be seen that the parallel pump system optimization described in Eqn. (1) - (14) is a constrained nonlinear problem. Intelligent optimization algorithms are suitable for this kind of problems. Of the common used intelligent optimization algorithms, particle swarm optimization algorithm is more stable, more computational efficient and easier to program. Therefore, PSO is chosen for the parallel pump system in this study.

III. PARTICLE SWARM OPTIMIZATION

A. GENERAL FLOW CHART OF PSO

Particle swarm optimization is a kind of swarm intelligence optimization algorithm. The algorithm of PSO is simple and the convergence of PSO is fast. The basic methodology of PSO is that each particle moves toward the best position at a certain velocity using the information of particle best position and the global best position. Fig. (4) gives the genreal flow chart of PSO.

B. FITNESS FUNCTION

By combining the objective function in Eqn. (4) and the penalty function in Eqn. (13) and (14), the fitness function can be defined as Eqn. (15), where σ_1 and σ_2 are penalty coefficients for head penalty and operating region penalty. By choosing appropriate penalty coefficients σ_1 and σ_2,

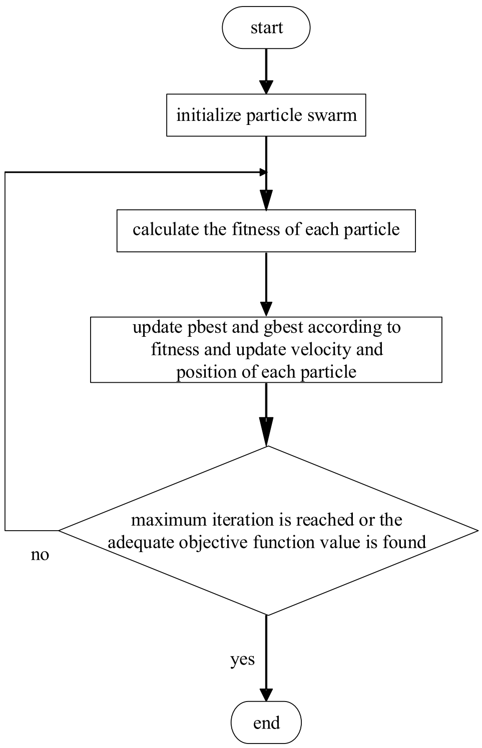

FIGURE 4. General flow chart of PSO.

the PSO can solve minimum valve of the fitness function and find the optimum of the problem.

$$\min F_t = P + \sigma_1 W_H + \sigma_2 W_\delta \quad (15)$$

C. PARTICLE VELOCITY UPDATE EQUATION

The particle velocity update equation is chosen as Eqn. (16),

$$v_{ij}^{K+1} = \omega v_{ij}^K + c_1 r_1(\text{pbest}_{ij}^K - x_{ij}^K) + c_2 r_2(\text{gbest}_j^K - x_{ij}^K) \quad (16)$$

where subscript i denotes the i-th particle, subscript j denotes the j-th dimension of particle velocity or position, superscript K denotes the K-th iteration, c_1 and c_2 are acceleration coefficients used to determine the influence of the local best position and the global best position respectively, r_1 and r_2 are random numbers between 0 and 1, ω is the inertia weight used to determine the influence of the older velocity in previous iteration. A higher value of ω enables the individuals to search in new areas to avoid premature convergence to a local optimum but also lower the convergence speed of the algorithm. Therefore, the value of ω is set to be linearly decreasing with iteration numbers as in Eqn. (17) to improve the global search ability at the beginning of the run and improve the local search ability near the end of the run [30], [31], where $K_{\max}$ is the maximum iteration number, $\omega_{\max} = 0.9$ and $\omega_{\min} = 0.4$.

$$\omega = \omega_{\max} - (\omega_{\max} - \omega_{\min})\frac{K}{K_{\max}} \quad (17)$$

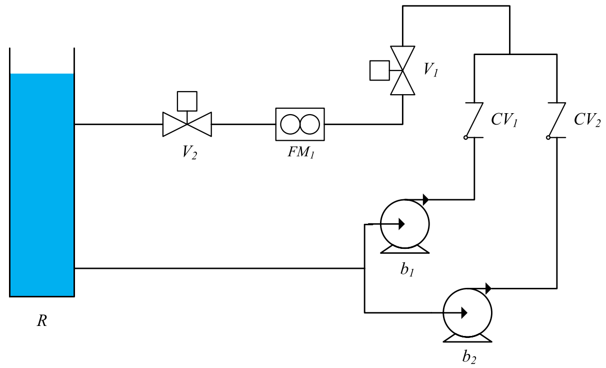

FIGURE 5. Schematic of the test bench. (*R*: reservoir, b_1/b_2: centrifugal pump, CV_1/CV_2: check valve, V_1/V_2: control valve, FM_1: flow meter.

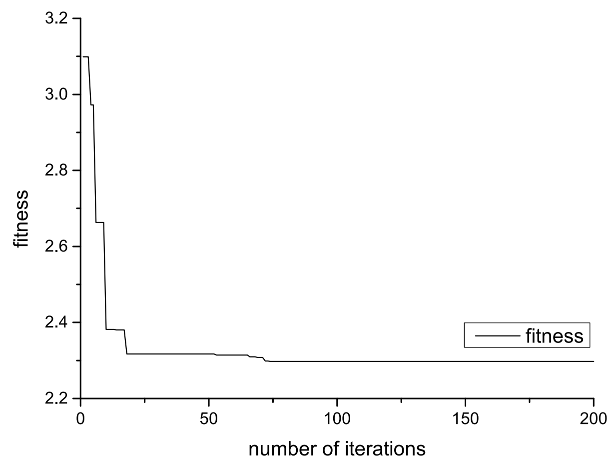

FIGURE 6. Fitness over number of iterations.

D. PARTICLE POSITION UPDATE EQUATION

The particle position update equation is chosen as Eqn. (18).

$$x_{ij}^{K+1} = x_{ij}^K + v_{ij}^{K+1} \quad (18)$$

IV. APPLICATION OF PSO IN A PARALLEL PUMP SYSTEM

The PSO algorithm above is tested on a test bench as shown in Fig. (5). It consists two VFD driven centrifugal pump, two check valves, two control valves and a reservoir, where the control valve V_1 is used as regulation valve and control valve V_2 is used to simulate the resistance in real water supply systems. The head curve and power curve of the pump can be fitted as Eqn. (19) and (20) respectively, which have been verified by experiments.

$$H_i = -0.01712Q_i^2 + 0.07864Q_i k + 40.4421k^2 \quad (19)$$

$$P_i = -1.4286 \times 10^{-4} Q_i^3 + 0.00618Q_i^2 k + 0.04416Q_i k^2 + 0.4402k^3 \quad (20)$$

Parameters of PSO algorithm are carefully selected. The acceleration coefficients are selected as $c_1 = c_2 = 1.3$, the size of particles is chosen as 20, the maximum number of iteration $K_{\max} = 200$. The penalty coefficients are chosen

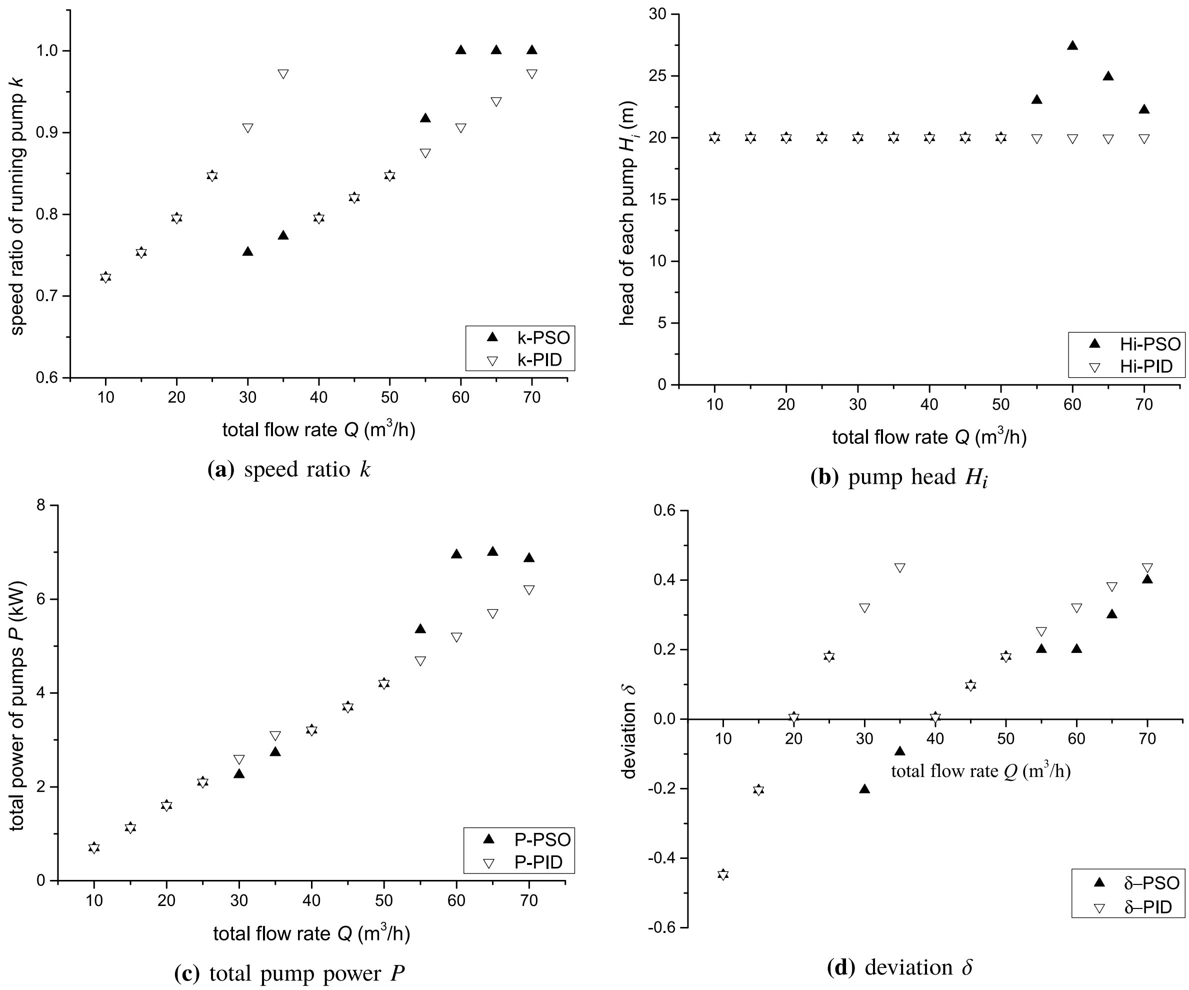

FIGURE 7. **Comparison between PSO and conventional PID.**

as $\sigma_1 = 100$ and $\sigma_2 = 10$ after several trial and error. The PSO algorithm is implemented in MATLAB. Special attention should be paid that the number of running pump M should be kept as an integer in the MATLAB code.

A. RESULTS ANALYSIS

Taking an example with a system demand of $Q = 30$ m^3/h, $H = 20$ m, the fitness over iterations is given in Fig.(6). The fitness decreases as the number of iterations increasing in the beginning, but the fitness keeps unchanged after 75 iterations, which indicates the algorithm is converged. The CPU time cost is about 3 seconds on a 2.3 GHz Intel CPU for each optimization case.

To verify the effectiveness of the proposed optimization on the test bench in Fig. (5), a comparison between the proposed optimization algorithm and conventional PID constant pressure water supply system was performed. The head demand of the water supply system is selected as 20 m, the flow rate varies from 10 m^3/h to 70 m^3/h. In conventional PID water supply systems, there is no optimization. When the speed of all running pumps reaches the minimum speed and the flow rate is still too large, one running pump will be turned off; when the speed of all running pumps reaches the maximum speed and the flow rate is still too small, another pump will be turned on. The comparison results are listed in Table 1.

Table 1 shows that there is a difference at the switch point of pump number between PSO and the PID method. In conventional PID method, the second pump is put into operation only when the first pump cannot provide enough pressure even if it reaches the maximum speed ($Q = 40$ m^3/h in Table 1). However, in PSO method, the second pump is put into operation since $Q = 30$ m^3/h. Fig.(7) gives a more clear comparison of k, H, P and δ between the proposed PSO and conventional PID method. Fig.(7b) shows that the pump head H_i equals to the system demand H for most flow rates for the PSO method, which indicates that the control valve is kept fully open for most cases and the pumps are kept operating in the high reliability region by the choosing proper speed ratio k and number of running pumps M by the PSO algorithm. Therefore, no extra energy is wasted for the PSO method. Fig.(7c) and Fig.(7d) show that the PSO method gets both

TABLE 1. Comparison between proposed PSO and conventional PID.

system demand		PSO results					conventional PID results				
Q (m^3/h)	H(m)	M	k	ΔH	δ	P	M	k	ΔH	δ	P
10	20	1	0.72311	0.00	-0.447	0.70	1	0.72311	0.00	-0.447	0.70
15	20	1	0.75348	0.00	-0.204	1.13	1	0.75348	0.00	-0.204	1.13
20	20	1	0.79550	0.00	0.006	1.60	1	0.79550	0.00	0.006	1.60
25	20	1	0.84731	0.00	0.180	2.10	1	0.84731	0.00	0.180	2.10
30	20	2	0.75349	0.00	-0.204	2.26	1	0.90703	0.00	0.323	2.61
35	20	2	0.77320	0.00	-0.095	2.73	1	0.97320	0.01	0.439	3.11
40	20	2	0.79554	0.00	0.006	3.21	2	0.79563	0.00	0.006	3.21
45	20	2	0.82031	0.00	0.097	3.70	2	0.82063	0.02	0.097	3.70
50	20	2	0.84724	0.00	0.180	4.20	2	0.84743	0.02	0.180	4.20
55	20	2	0.91671	3.02	0.200	5.35	2	0.87628	0.00	0.255	4.71
60	20	2	1	7.39	0.200	6.94	2	0.90703	0.00	0.323	5.21
65	20	2	1	4.91	0.300	7.00	2	0.93924	0.00	0.384	5.71
70	20	2	1	2.22	0.400	6.86	2	0.97309	0.00	0.439	6.22

lower power consumption and smaller deviation for flow rate between $30 - 35$ m^3/h.

When system demand is large ($Q = 55 - 70$ m^3/h), the pump will be running at large flow rate conditions for conventional PID method, thus the deviation δ will be large, which will affect the efficiency and the reliability of pumps. For the PSO method, the opening of the control valve will be reduced due to the effect of deviation penalty term. As a result, the deviation δ will be decreased and the pump will be running at better operating points. However, since the decreasing in the opening of the control valve induces extra resistance in the pipeline system, an increase in the pump speed is needed to provide enough pressure. Consequently, the total power consumption will increase as shown in Fig. (7c). This strategy is useful in industries that value reliability most, such as nuclear facilities. Traditional ways to ensure the reliability pumps is to allocate redundant pumps in nuclear power plants. By applying this strategy, the reliability of pumps are improved and the number of redundant pump switches can be reduced. If there is a third pump, the PSO algorithm will turn on the third pump instead of reducing the opening of the control valve, then no extra power is needed. The proposed PSO method can achieve a wider high reliability region for systems with more pumps.

V. CONCLUSION

This paper establishes an optimization model for parallel pump systems in the aim of reducing the power consumption pump systems and improving the reliability by fixing pumps' off-design operation problem. Particle swarm optimization method is adopted to solve the optimization problem, aiming at minimizing the total power consumption of the pump system. The deviation between the current operating point and the BEP are used as a constrain to fix the operating point of the pumps to a region near the BEP to gain high efficiency and good reliability. In most cases, the PSO method can achieve lower power consumption and higher reliability simply by adjusting the number of running pumps and their speed. But when the flow is large that all the pumps are running, the opening of the control valve will reduce to improve the operating point of pump and the total power consumption will increase.

In real industrial applications, it is supposed to choose different penalty coefficient σ_2 for different applications. For applications that are less strict with pump operating points and reliability, the value of σ_2 can be reduced. When $\sigma_2 = 0$, the term of deviation constrain will be no longer exist in the fitness function in Eqn.(15). Therefore, the PSO achieves the minimum power consumption only by adjusting the number of running pumps and their speed. The control valve is kept fully open constantly, so no extra power will be wasted by the control valve. In this way, the system runs at the most energy-saving mode. For applications that are more strict with reliability, such as water supply systems in power plants especially nuclear power plants, the value of $\sigma_2 = 0$ can be increased. In this case, the role of control valve is enhanced and more power will be consumed at the control valve to improve the operating points of pumps for higher reliability.

ACKNOWLEDGMENT

The authors would like to thank KSB AG for donation of the the test bench. The support of Junhe Pumps Holding Co., Hangzhou, China is also acknowledged.

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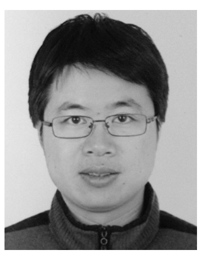
ZHOUNIAN LAI (Member, IEEE) received the B.E. and Ph.D. degrees in mechanical engineering from Zhejiang University, Hangzhou, China. He is currently an Assistant Professor with the College of Computer Science, Zhejiang University of Technology. He is also a Postdoctoral Fellow with Zhejiang University and Junhe Pumps Holding Company, Ltd., Ningbo, China. He has published more than ten articles in journals and conferences. His research interests include control and optimization of water supply systems, fault diagnostics in water supply systems, and control of unmanned underwater vehicles.

QIAN LI received the B.E. degree in mechanical engineering from Sichuan University, Chengdu, China. She is currently pursuing the M.Sc. degree in mechanical engineering with Zhejiang University, Hangzhou, China. Her research interests include fault diagnostic in fluid machinery and signal processing.

AN ZHAO (Member, IEEE) received the B.E. and M.Sc. degrees in chemical engineering from Zhejiang University, Hangzhou, China. He is currently pursuing the Ph.D. degree in mechanical engineering with The University of Tokyo. His research interest mainly concerns about the application of image processing, deep learning and evolutionary computing in fluid mechanics, and heat transfer fields.

WENJIE ZHOU (Member, IEEE) received the B.Sc. degree from the China University of Petroleum at East China, Qingdao, China, in 2011, and the Ph.D. degree from Zhejiang University, Hangzhou, China, in 2016. His research interests include rotordynamics of fluid machinery, specifically in pumps, fluid-induced force in annular seal, and nonlinear vibration.

HAILIANG XU (Member, IEEE) received the B.Sc. degree from the Zhejiang University of Technology, Hangzhou, China, in 2003. Since 2003, he has been with joint Junhe Pumps Holding Company, Ltd., Ningbo, China, as an Engineer, where he is currently the Vice General Manager of Research and Development. His research interests include design and development of new household water pump products.



DAZHUAN WU (Member, IEEE) received the B.Sc. and Ph.D. degrees from Zhejiang University, Hangzhou, China, in 1999 and 2004, respectively. He is currently a Professor with the College of Energy Engineering, Zhejiang University. He is also a member with the State Key Laboratory of Fluid Power and Mechatronic Systems, China. His major research interests include optimal design, control method, vibration, and noise in fluid machinery.