DECENTRALIZED OPTIMAL CONTROL OF VARIABLE SPEED PARALLEL-CONNECTED PUMPS

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ABSTRACT

This paper introduces a novel idea of decentralized method for the optimal control of variable speed parallel-connected pumps (VSPs) in Heating, Ventilation and Air Conditioning (HVAC) systems. In this decentralized control system, each VSP, which is equipped with a decentralized controller embedded with identical control algorithm, becomes a smart pump and could communicate with each other to work collaboratively to meet the control requirements and to be energy efficient. A decentralized optimal control algorithm is developed and validated through simulation by different cases, and further demonstrated through hardware application. Compared with the traditional centralized control method, this decentralized control method is much more flexible and more efficient.

INTRODUCTION

Circulation pumps are widely used in HVAC systems. A pumping system, which generally consists of several circulation pumps, is one of the main energy consuming parts in a chilled water based HVAC system. Energy efficiency of a pumping system depends not only on the design but also, even more, on its operation. Frequency converters are widely used with induction motor-driven pumps, enabling the pumps' speed variation to control the head and flow rate of pumps under different working conditions in an energy-efficient way. In real middle and large scale HVAC systems, several VSPs are usually parallel-connected into a pump group or station, with operation flexibility consideration.

Consequently, the control of pumping system is an important topic in HVAC optimal control area, where the loading/unloading and corresponding speeds of all operating VSPs need to be determined. It is essentially an optimization problem with the objective to minimize the total energy consumption of the entire pumping system, subject to the conditions that the whole pumping system should satisfy the required head and flow rate and operation limitations.

Extensive studies can be found related to optimal control of the pumping system. The majority of existing researches focus on adopting different kinds of numerical algorithms to solve such an optimization problem, such as genetic algorithm (Ma et al, 2011; Wang et al, 2012), evolutionary algorithm (Wang et al, 2009; Savic et al, 1997), Mixer Integer Nonlinear Programming (MINLP) algorithm (Westerlund et al, 1994; Yang et al, 2010a, 2010b), dynamic programming algorithm (E. da Costa et al. 2008), extreme value analysis method (Zhao et al, 2012) and so on. However, these algorithms are not straightforward and either require case by case development for different systems or require extensive data for the algorithm training. High implementation and computation costs prevent these algorithms from being adopted in real applications.

Some researchers tried to find analytical solution to this optimization problem to assist the straightforward control algorithm design (Fulai Y and Hexu S. 2011), and came to the conclusion that the optimal operation is to keep the speed ratio for each pump equal. Kallesøe (2011) and Karaca (2013) verified this conclusion by experimental study.

In real applications, the VSPs are controlled through a centralized method, as shown in Figure 1, which contains a centralized controller (DDC or PLC) collecting data from each VSP, calculating and making decisions based on the control algorithm and sending out control instructions.

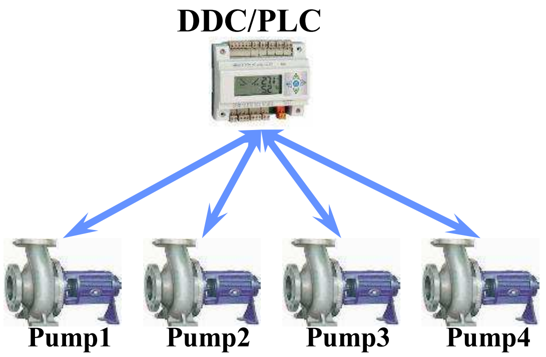

Figure 1. Centralized VSP control structure

While this paper presents a decentralized method for the optimal control of VSPs. The concept of decentralized control is introduced and explained by example. A decentralized optimal control algorithm is developed and validated through simulation by different cases using some real pump curves from published test data, and further demonstrated through hardware application.

DECENTRALIZED CONTROL

The basic idea of decentralized control is that local interactions between components of a system establish order and coordination to achieve global goals without a central commanding influence, meaning that the overall system is no longer controlled by one single controller but by several independent local controllers embedded inside each component.

The problem of controlling a team of many unmanned aircrafts formation, shown in Figure 2, is a typical example of decentralized control. Every aircraft is equipped with a decentralized controller with the ability of communication with neighbour aircrafts. Although each aircraft of the team only access limited information about its neighbour, they could still accomplish different formations through negotiation and coordination among neighbour aircrafts.

Figure 2. Unmanned aircrafts formation

In the decentralized VSP control system, as shown in Figure 3, each VSP is equipped with a decentralized controller and thus becomes a smart pump. The smart pumps within a group connect with each other through wire or wireless communication and could negotiate with neighbour pumps to work collaboratively to meet the control requirements and to be energy efficient.

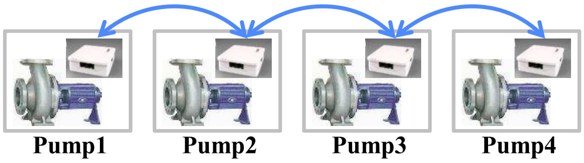

Figure 3. Decentralized VSP control structure

Some key features of this decentralized control structure are as follows:

1. With decentralized controller and decentralized control algorithm embedded inside, the VSPs are upgraded to smart products.
2. The decentralized control algorithm of each smart pump is identical, meaning every VSP follows the same rule.
3. The complicated onsite configuration and secondary development work is simplified to communication connection among smart pumps in the process of automation system construction.
4. The decentralized control structure enables the ability of plug and play, making the whole system flexible and scalable.

MODEL OF VSP

For centrifugal pumps, the operation curves at rated speed can be expressed as a set of static correlations among the pump head, flow rate and pump efficiency, which could be expressed as the following two polynomial equations:

$$H_0 = aQ_0^2 + bQ_0 + c \tag{1}$$

$$\eta_0 = jQ_0^2 + kQ_0 + l \tag{2}$$

where H_0, Q_0 and η_0 are the pump head, flow rate and mechanical efficiency at rated speed respectively; *a*, *b*, *c* and *j*, *k*, *l* are constants depending on the characteristics of a specific pump, which could be obtained from manufacturer data or experimental data at rated condition.

Pump operation curve at non-rated speed, on the other hand, could be scaled from the rated speed curve. According to the Affinity Laws of centrifugal pumps, the similarity working conditions of a VSP working at different speed could be described as:

$$\frac{Q_n}{Q_0} = \frac{n}{n_0},\ \frac{H_n}{H_0} = \left(\frac{n}{n_0}\right)^2,\ \frac{\eta_n}{\eta_0} = 1 \tag{3}$$

where n_0 is the rated pump speed, n is the pump speed at non-rated condition, H_0, Q_0 and η_0 are the pump head, flow rate and mechanical efficiency at non-rated speed respectively, i.e. at the speed of n. A new variable - pump speed ratio w ($0<w<1$), is introduced as:

$$w = \frac{n}{n_0} \tag{4}$$

Then, the pump operation curve at all working conditions (including rated and non-rated) could be expressed as:

$$H_n = aQ_n^2 + bwQ_n + cw^2 \tag{5}$$

$$\eta_n = j\left(Q_n/w\right)^2 + k\left(Q_n/w\right) + l \tag{6}$$

DECENTRALIZED ALGORITHM

The problem of pump group control is a multy solution problem. For a given working condition, there exists different pump combinations meeting the pressure and flow demand. For example, two pumps are running, both of which are working at 47Hz; or three pumps are running, all of which are working at 42Hz. So the control algorithm should find the optimized solution.

Problem analysis

In most practical situations, several VSPs are usually parallel-connected into a pump group, as shown in Figure 4, which leads to identical pressure difference of each parallel-connected VSP.

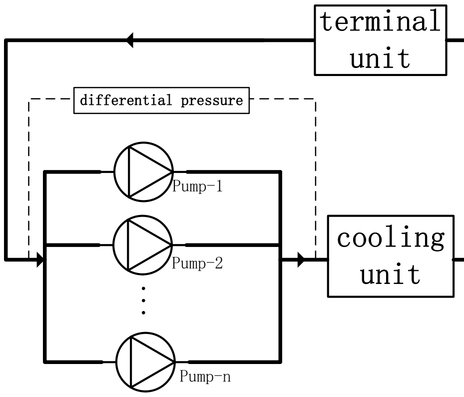

Figure 4. Schematic diagram of typical parallel-connected VSPs in HVAC system

In this circulation pumping system, a pressure difference setpoint is usually given by the upper control loop based on the terminal demands, which makes the regulation target for the VSP control algorithm. Under a certain pressure difference, the pump's flow rate and pump's efficiency could be expressed as the function of pump's speed according to the VSP model, as shown in Figure 6. And Figure 5 shows the fitting curves of a real tested pump at rated speed, which would be used for numerical simulation analysis in this paper.

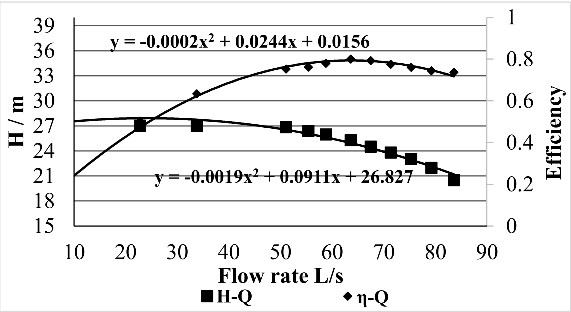

Figure 5. Fitting curves of a real tested pump

Figure 6 shows the variation of pump's flow rate and efficiency with different pump speed at the pressure difference of 18m. The VSP could supply different flow rate at different working speed, leading to different pump efficiency.

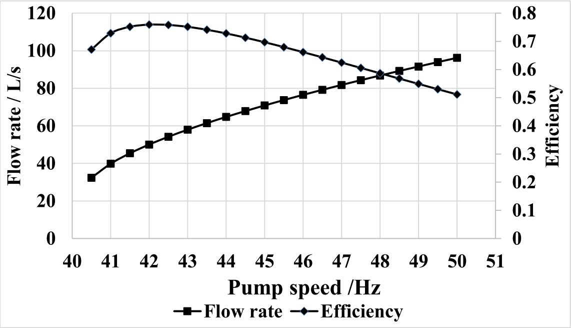

Figure 6. Flow rate and efficiency with different pump speed under 18m

There exists a highest pump efficiency, naming the pump's best efficiency point. The optimal control algorithm is to find the minimized power consumption solution, i.e. the maximized overall efficiency solution, which means each VSP's real working point should be closest to the its best efficiency point.

Algorithm description

In the decentralized algorithm, each VSP is a smart pump, with a decentralized control chip containing the decentralized algorithm and the pump's model embedded inside, which could calculate its own working point in real time. The goal of each smart pump is to lead its working point closest to its best efficiency point, and meanwhile satisfies the overall demand.

During the regulation process, the VSPs would communicate with each other and the information that they exchange includes expected relative efficiency (ε), the pump efficiency at its real working point over its efficiency at its best efficiency point, and flow rate difference (ΔG), the difference between current flow rate and flow rate demand.

When the system pressure difference comes out of range of pressure difference setpoint, the decentralized control system would make adjustment. Any running VSP could start the regulation, Figure 7 displays the basic decentralized regulation mechanism for each VSP. The VSP that starts up the regulation, sets its working point at the best efficient point, where the expected relative efficiency ε equals to 1 and calculates the flow rate difference with the flow demand accordingly, then passes this information, including ε and ΔG, to its neighbour VSP. The neighbour VSP receives the pump expected relative efficiency and makes comparison with its previous ε to judge whether to use this ε or to give a new ε, then calculates its own working point and the new flow difference ΔG on its selected ε, and finally comes to convergence judgement to compare the absolute value of ΔG with a given threshold value δ. If not meet the condition of convergence, the VSP would continue passing this new information to its neighbour VSP.

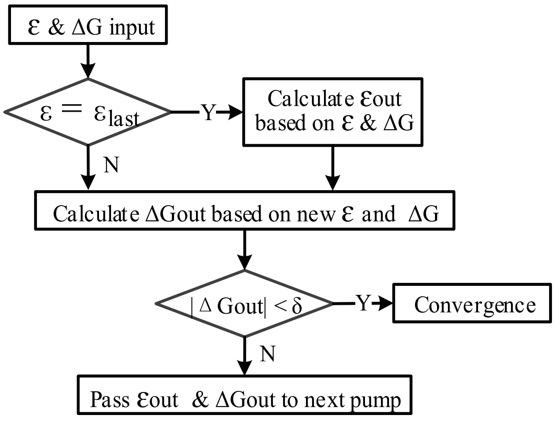

Figure 7. Flow chart of decentralized mechanism

The whole regulation process is an iterative process, each VSP follows the same rule and comes to convergence when the absolute value of flow difference is smaller than the given threshold value. And the pumps would work at the new condition, making the overall efficiency the highest.

Case study

Four identical VSPs are parallel-connected into a pump group, and the system pressure difference setpoint is 18m. At first, four VSPs are running and their initial working point lies on the left side of the best efficiency point, i.e. node 1 shown in Figure 8, which is far from the optimized solution. So, in this case, pump 2 starts the regulation and sets its working point at the best efficiency point, i.e. node 2 shown in Figure 8, where the expected relative efficiency equals to 1. The flow rate difference is -16.67L/s as its working point moves to node 2. And then pump 2 passes this information including ε and ΔG to its neighbour VSP, pump 3.

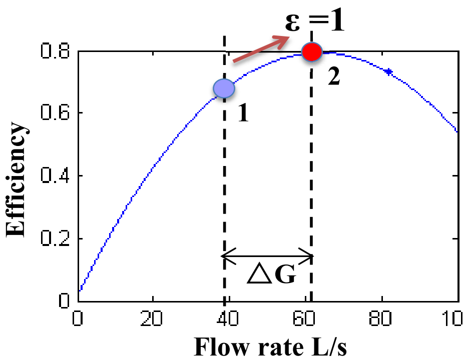

Figure 8. Initial working points of each VSP

Each VSP would follow the same rule, make the adjustments and pass the new information to its neighbour VSP, as shown in Figure 9, and the whole process is an iteration process.

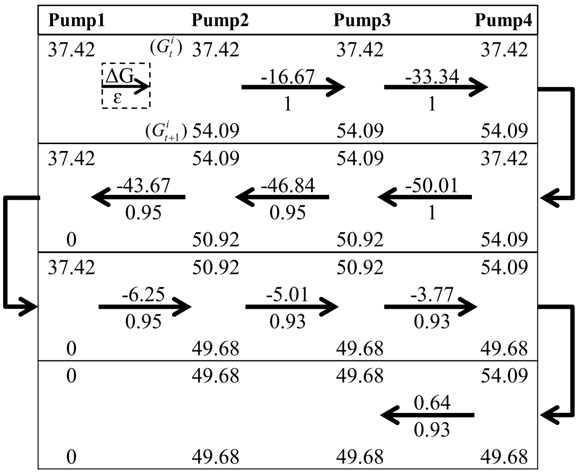

Figure 9. Iteration process of regulation

The negative ΔG means the current flow rate of all running VSP is larger than the flow rate demand and the running VSPs should move its working point to left side to reduce its flow rate. When a running VSP receives a negative ΔG and the sum of ΔG and its flow rate is smaller than zero, the VSP would turn off, which is just a flag during the iteration process and won't execute until convergence to avoid frequent on-off switch. On the other hand, when a standby VSP receives a positive ΔG, the VSP would turn on, which is also a computing flag during the regulation process.

And based on the decentralized mechanism, each VSP would compare the received ε with its previous ε on receiving new information. If the received ε equals to its previous ε, the VSP would make adjustment to give a new ε based on the ΔG. If the ΔG is positive, the VSP's working point should move right to take more flow rate and a new ε could be derived; otherwise, the VSP's working point should move left to take less flow rate and a new ε could also be derived. The regulating mechanism of ε could be constant step by changing ε 0.01 each time, or variable step by adopting some kind of descent method.

When the iteration process comes to convergence, pump 1 turns off and the other three VSPs' working poing move to node 3, shown in Figure 3, which is the optimized solution with the highest overall efficiency.

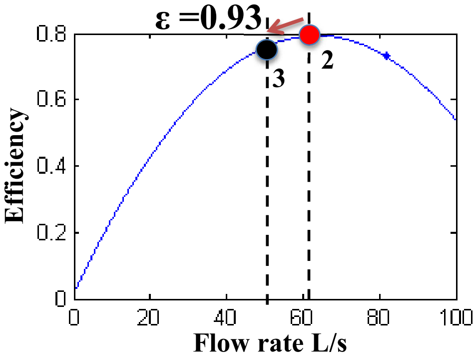

Figure 10. Final working points of each VSP

Four VSPs are running in the initial operation condition, and only three VSPs are left running while still meeting the requirments after the regulation of decentralized algorithm. The working status of each VSP of initial and final solution are shown in Table 1. The power consumption of final solution, which demonstrates the optimized solution, is reduced by 6.8%.

Table 1
Comparison of initial and final solution

	FLOW RATE L/S	PUMP EFFICIENCY	PUMP SPEED	ENERGY SAVING RATE
Initial	37.4	71.4%	40.8	6.8%
Final	49.7	75.9%	42.0	

SIMULATION AND EXPERIMENT

A continuous software simulation case based on the four parallel-connected VSPs is carried out for further validation of the decentralized algorithm. And an optimized method which could give the optimized solution for each working condition in a centralized method is also applied during the simulation to set a benchmark.

The optimized method could be described as follows: for a given working condition, list all the possible pump on-off status combination first; then solve the optimized pump speed for each pump on-off combination; finally select the optimized solution by comparing the power consumption of each combination.

Software simulation results

In the software simulation, the pressure difference setpoint is 18m, and different S value of water network is given to simulate the terminal demand variation, which is also the typical pumping load, i.e. cooling load variation within a day in real building operation condition. The results of decentralized algorithm and optimized algorithm are shown in Figure 11.

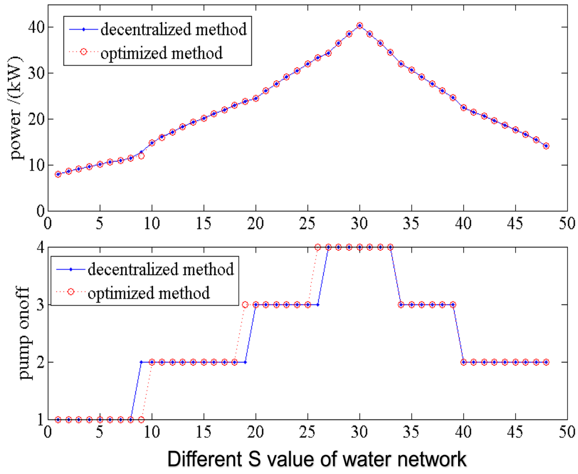

Figure 11. Continuous simulation results

The x-axis of Figure 11 represents different case or different working condition. The y-axis of the upper graph is the total power consumption and the y-axis of the lower graph shows the pump on-off combination, where 1 means one VSP is running and 2 means two VSPs are running, etc.

The results of decentralized algorithm and optimized method are almost coincide with each other. Only slight offset exists due to the given threshold acting as the convergence criteria during the iteration process. The continuous simulation results indicate that the decentralized algorithm is near optimal.

Hardware experiment

This decentralized algorithm is also applied to a hardware platform for further validation of its practicability.

Figure 12 shows the decentralized hardware platform, in which each circuit board represents a smart VSP with the pump model and decentralized algorithm embedded inside. Each circuit board is connected with its neighbour boards through ethernet communication.

Also each board has the ability of wireless communication, which enables them to receive wireless signal from sensors and send out inside information.

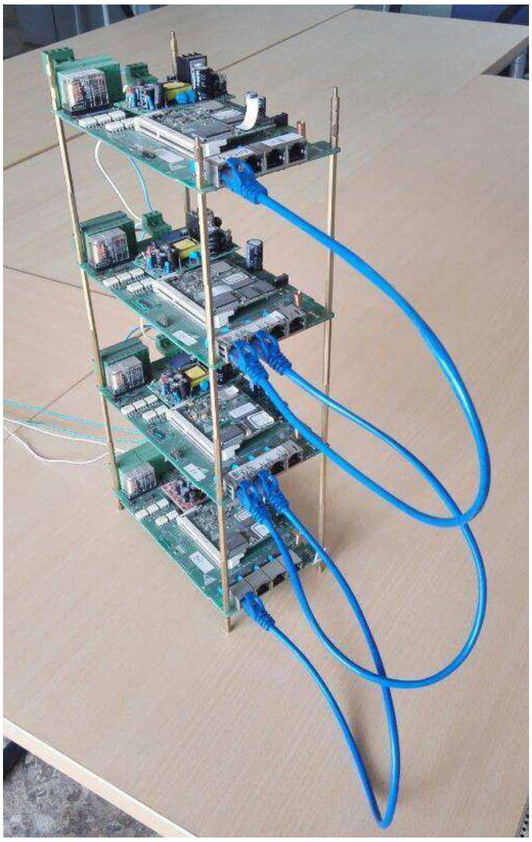

Figure 12. Decentralized hardware platform

To simulate the terminal system of water network, a software running on PC is developed to act as pressure difference sensor sending pressure difference signals wirelessly to the decentralized hardware platform. The same working conditions as software simulation are applied on this decentralized hardware platform and get the same results. The computing time of iteration process for each single case is less than 1s, which is quite short and could meet the control demand in real application.

It is also worth noting that the whole system is self-organised and plug-and-play, which means that no configuration or commissioning work is needed. Regardless of numbers or types of VSPs within the system, simply connect the neighbour VSPs through RJ45 jacks and they would communicate with each other to work collaboratively to meed the system requirements and to be optimized, as long as they are smart VSPs based on this decentralized hardware platform.

DISCUSSION

The basic idea of decentralized control method is proposed mainly to solve the engineering problems. Because in actual projects of a pumping station, the proprietor has to invite system integrator to instal automatic control system after purchasing of pump equipments. And the process of automation system construction is complex and time consuming as lots of secondary development work like configuration and commissioning is necessary onsite, which leads to high maintance and labor cost.

According to the vision of decentralized control method, the pump manufacturers could upgrad their traditional electromechanical device to smart device by embedding a decentralized control chip containing the decentralized algorithm and device model inside. The complicated onsite configuration and commissioning work could be simplified to wiring of communication connection betweenm neighbour smart devices in the process of automation system construction, because the smart devices could be self-organised and plug-and-play, making the whole system flexible and scalable.

Another important principle should be taken into consideration in real application is the constraint condition, including the lower and upper limits of the VSP’s working speed, the minimum running time before shutting down and the minimum time interval of starting up, which could be written into the decentralized controller. And each smart VSP knows its own working condition and wouldn't act while meeting the constraints.

CONCLUSION

This paper presents a novel idea of decentralized method for the optimal control of parallel-connected VSPs. The concept of decentralized control is introduced and explained through a simple example. In this decentralized control system, each VSP, which is equipped with a decentralized controller embedded with identical control algorithm, becomes a smart VSP and could communicate with each other to work collaboratively to meet the control requirements and to be energy efficient.

A decentralized optimal control algorithm is developed and validated through software simulation by different cases using some real pump curves from published test data. Comparing to the results of centralized optimized method demonstrates this decentralized control algorithm to be near optimal.

In addition, this decentralized algorithm is further demonstrated through hardware application on the decentralized hardware platform. Compared with the traditional centralized control method, this decentralized control method is much more flexible and scalable, and could avoid many engineering problems to reduce labor cost.

NOMENCLATURE

H = pressure difference
Q = flow rate
η = mechanical efficiency of pump
n = pump speed
w = speed ratio
ε = expected relative efficiency
ΔG = flow rate difference

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