**Optimal operation of novel hybrid** **district heating system driven by** **central and** **distributed variable speed pumps**

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**Highlights**

* A hybrid district heating system was proposed to reduce the system pressure level
* A hydraulic model was developed to simulate a hybrid district heating system
* Two cases were investigated under different operation control strategies
* Optimal pressure control strategy has advantages on saving pump energy

**Abstract**

The district heating system with distributed variable speed pumps can provide substantial energy savings, compared with the district heating system with conventional central circulating pump. However, for large-scale district heating systems, using distributed pumps at all substations leads to high pressures of the network terminals, which will increase the risk of pipe bursting and failure of heat supply. In this paper, the dilemma is overcome by combining the central circulating pump with distributed pumps to construct a novel hybrid district heating system, which can improve energy saving and reduce the network pressures of the district heating system. The optimal pressure control strategy for the new type of district heating network is developed to minimize the total pump power. In order to illustrate the feasibility and effectiveness of the proposed configuration, two cases were investigated regarding an existing district heating system with 1 heat source and 112 substations, including (I) varying the flow rate at all substations with the same relative rate, and (II) varying the flow rate at all substations with different relative rates. Analysis results show that compared with the conventional constant pressure difference control strategy, the hybrid system controlled by the optimal pressure control strategy ensures more stable operation conditions for the distributed pumps and can save 57% pump power when flow rate is 0.3.

**Keywords:** district heating network; distributed variable speed pumps; optimal operation; energy saving; zero pressure difference point

|  |  |
| --- | --- |
| **Nomenclature** | |
|  |  |
| ,, | coefficients of hydraulic characteristic curves of pump |
|  | basic incidence matrix of supply pipeline network |
|  | elementary row transformation matrix that extracted node pressure vector of substation from column vector of node pressures |
|  | final pump frequency after OPC strategy (Hz) |
|  | original pump frequency before OPC strategy (Hz) |
|  | column vector of volume flow rates of pipeline (m3/h) |
|  | flow rate of pump (m3/h) |
|  | flow rate of the central circulating pump of DH network (m3/h). |
|  | pressure head of pump (Pa) |
|  | pressure head of the central circulating pump of DH network (Pa) |
|  | pressure head at substation with a DVSP when the frequency of distributed variable speed pump is 50Hz (Pa) |
|  | pressure head at substation with a DVSP when the frequency of distributed variable speed pump is 20Hz (Pa) |
|  | column vector, of which elements are all ones |
|  | valve flow capacity |
|  | final operation number of pump after OPC strategy |
|  | original operation number of pump before OPC strategy |
|  | column vector of node pressures (Pa) |
|  | available pressure difference at each substations (Pa) |
|  | needed pressure difference at each substations (Pa) |
|  | needed pressure difference of substation without DVSP (Pa) |
|  | pressure difference of control valve in substation without DVSP (Pa) |
|  | column vector of flow rates of all nodes in the network (m3/h) |
|  | flow rate of substation without DVSP (m3/h) |
|  | range ability of control valve |
|  | column vector of pipeline hydraulic resistances (Pa·h2/m6) |
|  | hydraulic resistance of pipeline, plat heat exchanger as well as pipeline accessories except for control valve in substation without DVSP(Pa·h2/m6) |
|  | total pump power of network |
|  | valve opening |
|  | efficiency of pump |
|  |  |
| *Subscripts* | |
|  | substation without DVSP |
|  | substation with DVSP |
|  | central circulating pump of DH network |
|  |  |
| *Abbreviations* | |
| CCCP | conventional central circulating pump |
| CPDC | constant pressure difference control |
| DH | district heating |
| DVSP | distributed variable speed pump |
| OPC | optimal pressure control |

1. **Introduction**

As an indispensable infrustructure of urban facilities, the district heating (DH) system, which is considered as the most energy-efficient and environment-friendly technique for building space heating and domestic hot water supply, has been used for many years and dramatically developed over the past decades. There have been numerous and extensive researches focusing on the comprehensive performance improvement and optimization of the DH system.

In recent years, a new concept of the next generation DH network: the 4th generation district heating(4GDH), also regarded as the smart thermal grid, has been proposed, which enables the DH network to integrate more renewables to improve energy efficiency and environmental effects of the total system [1]. Lund et al. analyzed the important role of the 4GDH systems in smart energy systems. They also emphasized that the utilization of technologies, such as solar power, geothermal energy, industrial waste heat and thermal storage is essential for the transformation of 4GDH [2]. In addition to the preceding new trends of the DH techniques, the distributed variable speed pumps (DVSP) is the most promising technique to replace the conventional central circulating pump (CCCP) in the future DH network for reduction of the distribution energy and improvement of the distribution capacity [1].

Some researchers discussed the energy saving effect of the application of DVSPs in the DH network. Yan et al. established a hydraulic model to simulate the hydraulic behavior of a DVSP DH system, which was applied to a real DH network in Kuerle of China, their researches indicate that the DVSP DH system has a better performance of energy saving at least 30% than the CCCP DH system [3]. Ref. [4] shows that the average electrical energy saved by the DH system with the DVSP is 49.41% of the one saved by the DH system with CCCP. In addition to the better energy-saving, the DVSP DH system is more advantageous in improving the hydraulic balance of the DH system, compared with the CCCP DH system, so the application of DVSP is considered as a great advance in heating technology [5].

In order to further exploit the energy saving potential, great interests in engineering design and optimal operation on DVSP DH systems show in recent years. Sheng et al. developed a mathematical model of economic friction factor of the DVSP pipe network, and analyzed the influence of the cost of pump variations on the economic friction factor, which provided a reference for engineering design [6]. It is rather difficult to design or select DVSPs with appropriate capacities and hydraulic characteristics especially when there are fluctuating renewable heat sources in DH system, in order to sove this problem, Wang et al. proposed an optimization model to meet the hydraulic head demands of each substation and minimize the pump power simultaneously [7]. The optimal operation of DH system usually depends on the prediction of thermal demand of consumer, Guelpa et al. proposed a multi-level thermal request prediction method, which aims to evaluate the thermal request in the various sections of DH network with less computational resources [8]. In Ref.[9], a thermal simulation model was proposed to estimate heat losses of pipeline in the DH network, which can be very helpful to improve daily operation and maintenance to reduce heat losses in distribution as far as possible. In addition to the thermal condition, operation optimization techniques of the hydraulic conditions in DH system have also been extensively studied recently. Accurate hydraulic resistance of pipelines is essential for efficient hydraulic operation strategy. Based on a hybrid algorithm combining genetic algorithm and active set method, Wang et al. proposed a hydraulic resistance identification method to obtain more accurate and stable identification results [10]. By using the values of pressure and flow rate at the substations and heat sources under different operation conditions, a hydraulic resistance identification method was developed to obtain the hydraulic resistance of all the pipelines in the DH network accurately and effectively in Ref. [11]. In the multi-source DH system with the configuration of DVSP, the regulation is more complicated because of the strong coupling between distributed pumps, which means that all the distributed pumps need to be adjusted to their designated flow rates simultaneously. In order to solve this problem, Wang et al. proposed a hydraulic regulation method, which is based on a hydraulic model and a calibration model with genetic algorithm to achieve on-site hydraulic balance [12]. In Ref. [13], two associate co-operative optimization approaches for the DVSP DH system with multiple heat sources were established to meet the consumers’ heat demands with less operation cost and more fast regulation response. However, in these researches, the DVSP technique is only applied to small scale DH networks, due to the terminal pressure constraints. Applying the DVSP technique to all heating substations of large scale DH network will lead to high pressures of the network terminals, which may increase the harzards of pipe bursts and heating failures.

Recent studies of large scale DH networks have been focused on the hydraulic performances, since they are usually not at the optimum conditions, which may lead to high pumping cost [14]. Ref. [15] proposed a reduced model based on the proper orthogonal decomposition combined with radial basis functions, which allowed maintaining high level of accuracy despite reductions of more than 80% of the computational time compared with the CFD method to optimize the total pump power of the largest district heating network with multiple heat sources, in Turin, Italy. In Ref. [16], a tool for optimal management of large DH network is presented, which is applied to the reduction of the thermal peak request in order to minimize the total primary energy consumption. In Ref. [17], a method for modeling and simulating complex DH networks was proposed to optimize the total operating costs of a multi-source network, with constraints on the pressure and temperature levels in the user areas and on the heat generation characteristics at each production site. Most works available in literature are focused on optimal operation of existing large-scale DH network rather than its structure while planning for future expansions or transformation, so there is still a large potential for energy saving in further improvement of the large-scale DH network.

In this paper, a novel hybrid DH system driven by central and distributed variable speed pumps (hereinafter referred to as the hybrid system) was proposed in order to improve the energy efficiency and decrease the network pressures of the DH system, especially for the large-scale DH system. And the optimal operation for the new configuration of DH system was also presented, which can avoid frequent movement of zero pressure difference point of the hybrid system as well as minimize the total pump power of the whole network. The remainder of this paper is organized as follows: Section 2 compares the characteristic of three configurations of DH system. Section 3 introduces the operation control strategies. Section 4 develops a hydraulic model of optimal pressure control (OPC) strategy. Section 5 compares pump power consumption and stability about operation condition of the proposed operation control strategies. Finally, a summary is presented in Section 6.

1. **System description**

According to the configurations of the pumps within DH system, the DH system is mainly divided into three different kinds of systems, the CCCP system, the DVSP system, and the hybrid system. In the first part of this section, the configuration of the CCCP system, the DVSP system as well as the hybrid system are compared. In the second part, the hydraulic performance of the three kind of systems are analyzed.

## *System description*

The principle diagram of CCCP, DVSP and hybrid system was shown in Fig.1, Fig.2, Fig.3.

In the CCCP system, heat source pump is installed in the inlet of heat source, which is used to overcome the pressure loss of heat source itself; central circulating pump is installed in the outlet of heat source, which overcomes the pressure loss of the most unfavorable consumer, including pipeline and substation. Electric control valve is installed in each substation to consume the excessive available pressure head. By adjusting the valve opening, the needs of each consumer can be met. In order to ensure the flow stability of the heat source, hydraulic connector should be installed between the water supply and return main pipe in the heat source.

There are two different kind of pumps in the DVSP system, one is circulating pump, and the other is DVSP. The circulating pump is installed in heat source, which is used to overcome the resistance of heat source itself. Instead of electric control valve, the DVSP is located at each heating substation, which are used to overcome the pressure loss from outlet of heat source to the substation. By adjusting the frequency of distributed variable speed pump, the heat demand of each consumer can be met.

The hybrid DH system consists of three different kind of pumps, including the circulating pump of heat source, the central circulating pump of DH network and DVSP located at heating substations. The circulating pump of heat source only overcomes the pressure loss of heat source itself. The central circulating pump of DH network overcomes the pressure loss from outlet of heat source to the pressure difference control point of pipe network. The DVSP is installed in each substation after the pressure difference control point, which overcomes the pressure loss from the pressure difference control point to each substation correspondingly. Due to the available pressure head offered by the central circulating pump of DH network is larger than the required pressure head in some substations before the pressure difference control point, electric control valves should be installed in such substations.



1 heat source; 2 heat source pump; 3 hydraulic connector; 4 central circulating pump; 5 electric control valve; 6 substation heat exchanger;

**Fig. 1.** Principle diagram of CCCP system

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1 heat source; 2 circulating pump; 3 hydraulic connector; 4 DVSP; 5 substation heat exchanger;

**Fig. 2.** Principle diagram of DVSP system



1 heat source; 2 circulating pump of heat source; 3 hydraulic connector; 4 central circulating pump of DH network; 5 electric control valve; 6 substation heat exchanger; 7 DVSP;

**Fig. 3.** Principle diagram of hybrid system

## *Hydraulic performance*

The pressure diagram of the three types of DH systems was shown in Fig.4, Fig.5, Fig.6. The pressure level of the DH network is determined by the pressure peak of the whole network. In CCCP system and DVSP system, the maximum pressure of the network equals to the sum of the pressure loss of the supply pipeline, the return pipeline and the substation of the most unfavorable loop and the static pressure. While the maximum pressure of hybrid system is much lower than that of the CCCP and DVSP systems, because there is an intersection point in supply and return pressure line in Fig.6, which makes the maximum pressure of hybrid system equal to the sum of the pressure loss of the return pipeline, the substation of the most unfavorable loop and the static pressure.

As can be seen from Fig.6, the lift of the central circulating pump of DH network and DVSP is determined by the position of zero pressure difference point . The closer the zero pressure difference point is to the heat source, the smaller the lift of the central circulating pump of DH network will be, and the lift of each DVSP will increase. There is a point in the main pipeline of the hybrid system, when the zero pressure difference point set at this point, the available pressure head provided by the central circulating pump of DH network at substation 1 nearest to the heat source just meets the required pressure head of substation 1. In addition, the DVSPs should be installed at other substations except substation 1, because of that the available pressure head provided by the central circulating pump of DH network at other stations is smaller than the required pressure head of the station. Therefore, there is no need to install control valve to consume the excess available pressure head, then the zero pressure difference point is called the critical zero pressure difference point. The minimum total pump power and throttling loss can be achieved when the zero pressure difference point corresponding to the minimum lift of the central circulating pump of DH network is closest to the critical zero pressure difference point.



**Fig. 4.** Pressure diagram of CCCP system



**Fig. 5.** Pressure diagram of DVSP system



**Fig. 6.** Pressure diagram of hybrid system

From the perspective of pressure level of DH system, according to the pressure diagram of each system, the hybrid system has the lowest pressure level and the best safety. From the perspective of energy saving effect, because the power loss related to throttling is avoided, the pump power consumption of DVSP system is the least. That is to say, the energy saving effect of DVSP system is the best, followed by the hybrid system, and the CCCP system is the worst.

Table 1 gives an overview of the characteristics about these three kind of DH systems.

**Table 1**

The characteristics about CCCP system, DVSPs system and hybrid system.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Characteristic**  **System** | **Pump** | | | **Pressure level** | **power consumption** |
| **Type** | **Overcome pressure loss** | **Location** |
| **CCCP system** | Heat source pump | Heat source | Inlet of heat source | High | High |
| Central circulating pump | pipeline, substation | Outlet of heat source |
| **DVSP system** | Circulating pump | Heat source | Heat source | High | Low |
| DVSP | From outlet of heat source to substation | Each substation |
| **Hybrid system** | Circulating pump of heat source | Heat source | Heat source | Low | Medium |
| Central circulating pump of DH network | From outlet of heat source to the pressure difference control point of pipe network | Heat source |
| DVSP | From the pressure difference control point to substation | Each substation after the pressure difference control point |

1. **Operation control strategy**

Due to dramatic fluctuations in outdoor temperature, variation on heat loads happened in real time. In order to meet the heat demand of each consumer, mass flow control or supply temperature control should be taken into consideration. Compared to supply temperature control, the better optimal performance of less response time and distribution energy can be achieved simultaneously by mass flow control, especially for large-scale DH system. Therefore, constant supply temperature and variable flow regulation are adopted in the primary side of this DH system. The traditional operation control strategy is constant pressure difference control (CPDC) strategy, which maintains constant pressure difference in the pressure difference control point by varying rotation speeds of circulating pumps.

In order to further to improve the energy saving effect of the hybrid system, the authors proposed the optimal pressure control (OPC) strategy. The OPC strategy was addressed to minimize total pump power under the condition of meeting heat demand of each consumer, which consisted of the following steps. Moreover, the flow chart of OPC strategy was shown in Fig.7.

-According to fluctuant outdoor temperature, the real-time flow rate demands of each heat substation can be determined, which are the fundamental basis of next steps.

-In compliance with mass conservation equations, in the process of constant flow in the pipe network, the algebraic sum of the flow rates in all pipelines, which are associated with a node, is equal to the flow rate of that node. Hence, the flow rates of pipeline can be calculated as:

|  |  |
| --- | --- |
|  | (1) |

where is the basic incidence matrix of supply pipeline network; is the column vector of volume flow rates of pipeline (m3/h); is the column vector of flow rates of all nodes in the network (m3/h).

-With the value of column vector of volume flow rates of pipeline, the final frequency of the central circulating pump of DH network, the final frequency of distributed variable speed pump and valve opening can be obtained by hydraulic simulation, which would be presented in detail in the next section.

-Owing to the coupling between DVSP and control valves at each substation, the pump frequency and control valve opening should be adjusted to the final value at the same time by the means of Remote Control.



**Fig.7.** Flow chart of OPC strategy

1. **Model**

In the DH network, in order to provide required flow rates at each substations under certain condition, the available pressure difference should not be less than the required pressure difference. This can be represented as:

|  |  |
| --- | --- |
|  | (2) |

where denotes the available pressure differences of all substations (Pa), which is a column vector; is the required pressure differences of all substations (Pa), which is a column vector.

The available pressure difference of each substation can be calculated by the difference between the head provided by the central circulating pump of DH network and the pressure drop generated by overcoming the resistance of the supply and return pipeline, and the vector form can be expressed as:

|  |  |
| --- | --- |
|  | (3) |

where is the pressure head of the central circulating pump of DH network (Pa), which is a scalar; and is a column vector, of which elements are all ones; is the diagonal matrix of pipeline hydraulic resistances (Pa·h2/m6); is the diagonal matrix of the absolute value of volume flow rates of pipeline (m3/h); subscript stands for the central circulating pump of DH network. Due to the randomness of , elementary row transformation matrix is used in Eq. (3) to divide the column vector of pressure drop () into two block matrices, according to the principle that one block matrix is the column vector of pressure drop of the substation without DVSP, the other block matrix is the column vector of pressure drop of the substation with DVSP.

In a substation without DVSP, the required pressure difference can be derived as:

|  |  |
| --- | --- |
|  | (4) |

where is the required pressure difference of substation without DVSP (Pa); is the pressure difference of control valve in substation without DVSP (Pa); is the hydraulic resistance of pipeline, plat heat exchanger as well as pipeline accessories except for control valve in substation without DVSP(Pa·h2/m6); is flow rate of substation without DVSP (m3/h); subscript stands for a substation without DVSP. According to Ref [7], the pressure difference of control valve can be calculated as:

|  |  |
| --- | --- |
|  | (5) |

where is the range ability of control valve; is the valve opening; is the valve flow capacity. Combining Eqs. (2) - (4), the pressure head of the central circulating pump of DH network can be expressed as:

|  |  |
| --- | --- |
|  | (6) |

The available pressure difference of substation with DVSP should satisfy the following inequality:

|  |  |
| --- | --- |
|  | (7) |

where is the pressure head at substation with a DVSP when the frequency of distributed variable speed pump is 50Hz; is the pressure head at substation with a DVSP when the frequency of distributed variable speed pump is 20Hz; subscript stands for DVSP, subscript stands for a substation with DVSP. Let , , be the followings respectively:

|  |  |
| --- | --- |
|  | (8) |
|  | (9) |
|  | (10) |

Hence, the constrained optimization problem can be expressed as:

|  |  |
| --- | --- |
|  | (11) |

where is the maximum value of column vector element of and ; is the minimum value of column vector element of .

The pressure head of DVSP at substation can be calculated as:

|  |  |
| --- | --- |
|  | (12) |

The objective function can be expressed as:

|  |  |
| --- | --- |
|  | (13) |

where is the total pump power of network; is efficiency of pump, which can be approximated by a constant of 80%; is the flow rate of the central circulating pump of DH network (m3/h), which can be derived from the real time substation flow rate demands and Eq. (1). In Eq. (13), When the value of is determined, the objective function is a single variable linear function, so the optimal solution of must be obtained at the maximum or minimum value of . During operation of the DH system, the boundary value of can be derived from Eqs. (8) - (11) under the condition that the flow rate of each substation is known. Correspondingly, has two different values, and the smaller value is selected as the optimal solution of to decrease the total pump power of network.

With the pressure head of pump and flow rate, the pump frequency can be calculated as:

|  |  |
| --- | --- |
|  | (14) |

where is the pressure head of pump (Pa); is the original operation number of pump before OPC strategy; is the final operation number of pump after OPC strategy; is the flow rate of pump (m3/h); is the original pump frequency before OPC strategy (Hz); is the final pump frequency after OPC strategy (Hz); , and are the coefficients of hydraulic characteristic curves of pump. To protect the motor of pump at low heat load, the operation number of pump should be reduced when the calculated initial frequency of pump is less than 20Hz and then the final pump frequency can be determined by re-simulating. The flow chart of hydraulic simulation was shown in Fig.8.



**Fig.8.** Flow chart of hydraulic simulation

1. **Results and discussion**

To illustrate the feasibility and effectiveness of the proposed strategy, the hydraulic performances of OPC strategy as well as CPDC strategy were compared in a hybrid system. The DH system consists of 1 heat source and 112 substations, which are illustrated by a topology diagram in Fig.9. In this DH system, constant supply temperature and variable flow regulation are adopted in the primary side, and supply temperature control is adopted in the secondary side. In this system, the central circulating pumps of DH network are three in parallel. The pressure head as well as flow rate of each central circulating pump of DH network are 60m and 3500 m3/h, respectively. The total pressure level of the DH network is 1.0MPa. The substations with DVSP are all located on the left side of the *C-C* curve shown in Fig.5. The parameters of DVSPs are listed in Appendix A. The value of the coefficients of hydraulic characteristic curves of pump obtained by quadratic polynomial fitting are listed in Appendix B.



**Fig.9**. The topology diagram of hybrid system

Two cases were considered in this study. In case I, the flow rate of all substations varies simultaneously with the same relative rate, which may correspond to the same kind of consumers. In case II, the flow rate of all substations varies with different relative rate, which may correspond to different kinds of consumers. And in both cases, the pressure difference control point sets at the substation h11.

## *Case I*

In case I, the flow ratios of each substation vary from 0.3 to 1 simultaneously with the same degree. Under control of OPC and CPDC strategies, the power comparison and reduction rate of the central circulating pump of DH network were shown in Fig.10. It indicates that the OPC strategy can reduce the power of the central circulating pump of DH network at part load compared with the CPDC strategy. Meanwhile, the difference about the power of the central circulating pump of DH network controlled by OPC and CPDC strategies becomes smaller at the higher flow ratios. This is because of that with heat load increasing, operation conditions of network controlled by OPC and CPDC strategies gradually approach the design conditions. According to Fig.6, the pump power reduction rate of the central circulating pump of DH network controlled by OPC strategy is 65% when the flow ratio is 0.3.



**Fig.10.** Power and reduction rate of the central circulating pump of DH network under control of OPC and CPDC strategies

Fig.11 shows the power comparison and increasing rate of DVSP under control of OPC and CPDC strategies at different flow ratio. Contrary to the trend of the central circulating pump of DH network, the power of DVSP controlled by OPC strategy is significantly higher than that controlled by CPDC strategy when the flow ratio is greater than 0.4, which indicates that OPC strategy is more inclined to make full use of DVSP to meet the need of consumer. There is a maximum pump power-increasing rate of DVSP, when the flow ratio is 0.6.

Fig.12 shows the total power comparison and reduction rate of pump under control of OPC and CPDC strategies at different flow ratio. It is seen that the total pump power of the heating network is smaller than that of the CPDC strategy under control of OPC strategy. The difference about the total pump power of heating network becomes smaller at the higher flow ratios. When the flow ratio reaches 0.3, the total pump power of the heating network can save 57%.



**Fig.11.** Power and increasing rate of DVSP under control of OPC and CPDC strategies



**Fig.12.** Total power and reduction rate of pump under control of OPC and CPDC strategies

The lift as well as frequency comparison of the central circulating pump of DH network under control of OPC and CPDC strategies were shown in Fig.13 and Fig.14, respectively. It indicates that under the OPC strategy, the lift of the central circulating pump of DH network is smaller than that under the control of CPDC strategy. In addition, the difference about the lift of the central circulating pump of DH network controlled by OPC and CPDC strategies becomes smaller at the higher flow ratios. It can be seen that when the flow ratio is 0.3, the lift of the central circulating pump of DH network can save nearly 10m. According to Fig.15, under control of OPC strategy, the operation number of the central circulating pump of DH network decreases from three to two, when the flow ratio less than 0.4. Because of that, there is an interruption in frequency of the central circulating pump of DH network when the flow ratio is 0.4. Similarly, when the flow ratio is reduced to a value less than 0.35, the operation number of the central circulating pump of DH network is reduced from two to one. However, under control of CPDC strategy, the operation number of the central circulating pump of DH network is always three, while flow ratio is between 0.3 and 1. It can also be seen from Fig.13 that the CPDC strategy is more inclined to make full use of the central circulating pump of DH network to meet the need of consumer.



**Fig.13.** Lift of the central circulating pump of DH network under control of OPC and CPDC strategies



**Fig.14.** Frequency of the central circulating pump of DH network under control of OPC and CPDC strategies

## *Case II*

In real engineering, each substation may provide heat demand to different types of consumers. Hence, according to the variation of outdoor temperature, the heat demand of each substation changes in different proportion. In this case, the proportion of residential buildings and public buildings in the heating area of each substation is listed in Appendix C. Fig.15 shows the variation of outdoor temperature from 0 o’clock on January 1 to 24 o’clock on January 5. Correspondingly, according to the heat balance equation, the variation of total flow rate of network from 0 o’clock on January 1 to 24 o’clock on January 5 is shown in Fig.16.



**Fig.15.**Outdoor temperature from 0 o’clock on January 1 to 24 o’clock on January 5



**Fig.16.**Total flow rate of network

Fig.17 shows the power comparison of the central circulating pump of DH network when the DH network controlled by OPC strategy and CPDC strategy, respectively. Similar to the situation of case I, under the OPC strategy, the power of the central circulating pump of DH network is smaller than that under the control of CPDC strategy. Moreover, the pump power reduction rate of the central circulating pump of DH network controlled by OPC strategy was shown in Fig.18. It can be seen from Fig.16 – Fig.18, the power of the central circulating pump of DH network increases with the increase of total network flow rate. On the contrary, the pump power reduction rate is inversely proportional to the total flow rate. In other words, the pump power reduction rate of the central circulating pump of DH network decreases with the increase of total network flow rate.



**Fig.17.** Power of circulating pump of network controlled by OPC and CPDC strategies



**Fig.18.** Pump power reduction rate of circulating pump of network controlled by OPC strategy

Fig.19 shows the power variation of DVSP controlled by OPC and CPDC strategies. It indicates that the power of DVSP controlled by OPC strategy is larger than that controlled by CPDC strategy in most conditions. It can be seen from Fig.16 and Fig.19, the power of DVSP increases with the increase of total network flow rate. Fig.20 shows the pump power increasing rate of DVSP controlled by OPC strategy.



**Fig.19.** Power of DVSP controlled by OPC and CPDC strategies



**Fig.20.** Pump power increasing rate of DVSP controlled by OPC strategy

Fig.21 shows the total power comparison of pump under control of OPC and CPDC strategies while the flow rate of all substations varies with different relative rate. It can be seen that the total pump power increases with the increase of total network flow rate, and the energy saving effect of OPC strategy is more significant than that of CPDC strategy at lower flow rate.



**Fig.21.** Total power of pump controlled by OPC and CPDC strategies

The frequency and operation number of the central circulating pump of DH network controlled by OPC and CPDC strategies were shown in Fig.22 and Fig.23, respectively. Fig.22 indicates that the frequency of the central circulating pump of DH network controlled by OPC strategy is lower than that controlled by CPDC strategy. It can be seen from Fig.23 that when the flow rate is relatively low, the OPC strategy will reduce the operation number of the central circulating pump of DH network to reduce the power consumption, so as to make full use of the power provided by DVSP to meet the heat load.



**Fig.22.** Frequency of the central circulating pump of DH network controlled by OPC and CPDC strategies



**Fig.23.** Operation number of circulating pump of network controlled by OPC and CPDC strategies

The position movement of zero pressure difference point of the most unfavorable branch line under control of OPC and CPDC strategies was shown in Fig.24. With the change of outdoor temperature, the distance between the zero pressure difference point and the heat source will fluctuate correspondingly when the DH system controlled by CPDC strategy. This is because, when the outdoor temperature decreases, the increase of head load will lead to the increase of flow rate, and then the slope of the supply as well as return pressure line in pressure diagram will increase. In order to remain the pressure difference at the designed static pressure point, the zero pressure difference point will move towards the heat source and vice versa. Frequent movement of the zero pressure difference point will cause frequent adjustment of the DVSP, which is not conducive to the operation control of substation. However, under control of OPC strategy, the position of zero pressure difference point does not change much, which indicates that the central circulating pump of DH network can better adapt to the change of heat demand and enable the DVSP to operate under more stable conditions.



**Fig.24.** Zero pressure difference point of the most unfavorable branch line controlled by OPC and CPDC strategies

The comparison results obtained in this section are conducted by the well-developed numerical simulation approach of the network hydraulics, so the results are meaningful.

1. **Conclusions**

In this paper, a hybrid system was proposed to decrease the network pressures of the large-scale DH system. Then, an OPC strategy for optimal operation of the hybrid system was developed in order to decrease pump power consumption. Based on the simulation results, the following conclusions were drawn:

(1) Comparing with CPDC strategy, the hybrid system under the control of OPC strategy can reduce the total power of pump. The simulation analysis of case I indicate that the total pump power reduction rate reaches 57% under the control of OPC strategy when flow ratio is 0.3. However, with the increase of flow rate, the total pump power reduction rate gradually decreases.

(2) Comparing to the CPDC strategy, the OPC strategy can reduce the power consumption of the central circulating pump of DH network by reducing the frequency and operation number of the central circulating pump of DH network, but then the power of DVSP is increased. The result shows that the OPC strategy tends to make full use of DVSP to provide power to meet the need of consumers, and the CPDC strategy is more use of the central circulating pump of DH network to meet the need of consumers.

(3) Comparing to the CPDC strategy, the OPC strategy enables the DVSP to operate under a condition with more stable pressure difference. In other words, the OPC strategy enables more stable operation conditions for the DVSP.

With the new concept of smart thermal grid proposed, the large-scale DH networks are the trend of DH system, while the existing configuration of DH network with CCCP or DVSP will lead to high pressures of the network terminals, which may increase the harzards of pipe bursts and heating failures, especially for the large-scale DH networks. The hybrid system presented in this paper can solve the above problem effectively, and improve energy efficiency as well, which can help the transition of smart thermal grid. Operation optimization technique can further exploit the energy saving potential of DH system, which has become a hot spot in recent years. The OPC strategy proposed in this paper not only minimizes the total pump power of the whole network, but also avoids the frequent movement of zero pressure difference point of the hybrid system, which is conducive to the further application of the hybrid system.

**Appendix A. Flow rate and pressure head of DVSPs**

| Substation | Flow rate(m3/h) | Pressure head(m) | Substation | | Flow rate(m3/h) | Pressure head(m) |
| --- | --- | --- | --- | --- | --- | --- |
| h14 | 33.1 | 11.0 | h75 | | 107.7 | 10.3 |
| h15 | 33.1 | 11.0 | h76 | | 91.2 | 10.4 |
| h16 | 33.1 | 11.0 | h77 | | 66.3 | 10.9 |
| h17 | 41.4 | 10.5 | h78 | | 91.2 | 10.4 |
| h18 | 16.6 | 9.3 | h79 | | 66.3 | 10.9 |
| h19 | 16.6 | 9.3 | h80 | | 107.7 | 10.3 |
| h20 | 49.7 | 11.2 | h81 | | 107.7 | 10.3 |
| h21 | 33.1 | 11.0 | h82 | | 74.6 | 10.7 |
| h22 | 33.1 | 11.0 | h83 | | 91.2 | 10.4 |
| h23 | 24.9 | 10.6 | h84 | | 107.7 | 17.7 |
| h24 | 33.1 | 11.0 | h85 | | 74.6 | 18.3 |
| h25 | 16.6 | 9.3 | h86 | | 99.4 | 20.1 |
| h39 | 149.2 | 9.8 | h87 | | 49.7 | 20.1 |
| h40 | 182.3 | 9.9 | h88 | | 74.6 | 18.3 |
| h41 | 190.6 | 9.6 | h89 | | 132.6 | 16.6 |
| h42 | 62.2 | 9.6 | h90 | | 49.7 | 20.1 |
| h43 | 62.2 | 9.6 | h91 | | 124.3 | 22.0 |
| h44 | 207.2 | 8.9 | h92 | | 116.0 | 22.3 |
| h45 | 45.7 | 9.8 | h93 | | 207.2 | 18.1 |
| h46 | 140.9 | 10.1 | h94 | | 91.2 | 22.6 |
| h47 | 149.2 | 9.8 | h95 | | 41.4 | 21.5 |
| h48 | 149.2 | 9.8 | h96 | | 24.9 | 22.0 |
| h49 | 58.0 | 9.5 | h97 | | 132.6 | 21.7 |
| h50 | 49.7 | 12.6 | h98 | | 107.7 | 22.5 |
| h51 | 149.2 | 10.7 | h99 | | 99.4 | 26.1 |
| h52 | 16.6 | 13.7 | h100 | | 132.6 | 25.7 |
| h53 | 99.4 | 20.1 | h101 | | 33.1 | 25.8 |
| h54 | 82.9 | 17.2 | h102 | | 24.9 | 26.0 |
| h55 | 49.7 | 20.1 | h103 | | 116.0 | 25.8 |
| h56 | 16.6 | 20.1 | h104 | | 99.4 | 33.9 |
| h57 | 16.6 | 20.1 | h105 | | 132.6 | 33.7 |
| h58 | 124.3 | 17.1 | h106 | | 124.3 | 33.4 |
| h59 | 49.7 | 20.1 | h107 | | 74.6 | 37.0 |
| h60 | 74.6 | 23.4 | h108 | | 66.3 | 35.9 |
| h61 | 62.2 | 23.3 | h109 | | 66.3 | 33.4 |
| h62 | 58.0 | 23.1 | h110 | | 91.2 | 21.7 |
| h63 | 41.4 | 24.6 | h111 | | 74.6 | 18.3 |
| h73 | 132.6 | 10.9 | h112 | | 149.2 | 18.3 |
| h74 | 82.9 | 10.3 |  |  | |  |

**Appendix B. Coefficients of hydraulic characteristic curves of DVSPs**

| Substation | *A* | *b* | *c* | Substation | *a* | *b* | *c* |
| --- | --- | --- | --- | --- | --- | --- | --- |
| h14 | -0.0067 | 0.44 | 3.9 | h75 | -0.0001 | 0.01 | 10.0 |
| h15 | -0.0067 | 0.44 | 3.9 | h76 | -0.0001 | 0.01 | 10.0 |
| h16 | -0.0067 | 0.44 | 3.9 | h77 | -0.0006 | 0.06 | 9.8 |
| h17 | -0.0067 | 0.44 | 3.9 | h78 | -0.0001 | 0.01 | 10.0 |
| h18 | -0.0067 | 0.44 | 3.9 | h79 | -0.0006 | 0.06 | 9.8 |
| h19 | -0.0067 | 0.44 | 3.9 | h80 | -0.0001 | 0.01 | 10.0 |
| h20 | -0.0006 | 0.06 | 9.8 | h81 | -0.0001 | 0.01 | 10.0 |
| h21 | -0.0067 | 0.44 | 3.9 | h82 | -0.0006 | 0.06 | 9.8 |
| h22 | -0.0067 | 0.44 | 3.9 | h83 | -0.0001 | 0.01 | 10.0 |
| h23 | -0.0067 | 0.44 | 3.9 | h84 | -0.0006 | 0.09 | 14.2 |
| h24 | -0.0067 | 0.44 | 3.9 | h85 | -0.0037 | 0.45 | 5.5 |
| h25 | -0.0067 | 0.44 | 3.9 | h86 | -0.0037 | 0.51 | 6.0 |
| h39 | -0.0005 | 0.10 | 5.1 | h87 | -0.0067 | 0.43 | 15.0 |
| h40 | -0.0003 | 0.06 | 7.6 | h88 | -0.0037 | 0.45 | 5.5 |
| h41 | -0.0003 | 0.06 | 7.6 | h89 | -0.0006 | 0.09 | 14.2 |
| h42 | -0.0005 | 0.10 | 5.1 | h90 | -0.0067 | 0.43 | 15.0 |
| h43 | -0.0005 | 0.10 | 5.1 | h91 | -0.0006 | 0.10 | 18.0 |
| h44 | -0.0003 | 0.06 | 7.6 | h92 | -0.0006 | 0.10 | 18.0 |
| h45 | -0.0067 | 0.44 | 3.9 | h93 | -0.0004 | 0.19 | -1.6 |
| h46 | -0.0005 | 0.10 | 5.1 | h94 | -0.0006 | 0.10 | 18.0 |
| h47 | -0.0005 | 0.10 | 5.1 | h95 | -0.0067 | 0.43 | 15.0 |
| h48 | -0.0005 | 0.10 | 5.1 | h96 | 0.0072 | -0.64 | 33.6 |
| h49 | -0.0005 | 0.10 | 5.1 | h97 | -0.0006 | 0.10 | 18.0 |
| h50 | -0.0065 | 0.47 | 5.4 | h98 | -0.0006 | 0.10 | 18.0 |
| h51 | -0.0003 | 0.06 | 7.6 | h99 | -0.0051 | 0.66 | 10.3 |
| h52 | -0.0192 | 0.66 | 8.1 | h100 | -0.0007 | 0.17 | 15.6 |
| h53 | -0.0037 | 0.51 | 6.0 | h101 | -0.0088 | 0.49 | 19.1 |
| h54 | -0.0037 | 0.45 | 5.5 | h102 | -0.0088 | 0.49 | 19.1 |
| h55 | -0.0067 | 0.43 | 15.0 | h103 | -0.0007 | 0.17 | 15.6 |
| h56 | -0.1040 | 1.26 | 27.8 | h104 | -0.0055 | 0.70 | 18.7 |
| h57 | -0.1040 | 1.26 | 27.8 | h105 | -0.0007 | 0.21 | 18.4 |
| h58 | -0.0006 | 0.09 | 14.2 | h106 | -0.0007 | 0.21 | 18.4 |
| h59 | -0.0067 | 0.43 | 15.0 | h107 | -0.0011 | 0.29 | 21.4 |
| h60 | -0.0037 | 0.51 | 6.0 | h108 | -0.0011 | 0.29 | 21.4 |
| h61 | -0.0037 | 0.51 | 6.0 | h109 | -0.0015 | -0.02 | 41.2 |
| h62 | -0.0037 | 0.51 | 6.0 | h110 | -0.0037 | 0.51 | 6.0 |
| h63 | -0.0053 | 0.66 | 6.2 | h111 | -0.0037 | 0.45 | 5.5 |
| h73 | -0.0003 | 0.06 | 7.6 | h112 | -0.0005 | 0.12 | 10.9 |
| h74 | -0.0006 | 0.06 | 9.8 |  |  |  |  |

**Appendix C. The proportion of residential buildings and public buildings in the heating area of each substation**

| Substation | The proportion of residential buildings | The proportion of public buildings | Substation | The proportion of residential buildings | The proportion of public buildings |
| --- | --- | --- | --- | --- | --- |
| h1 | 0.24 | 0.76 | h57 | 0.22 | 0.78 |
| h2 | 0.75 | 0.25 | h58 | 0.77 | 0.23 |
| h3 | 0.55 | 0.45 | h59 | 0.65 | 0.35 |
| h4 | 0.47 | 0.53 | h60 | 0.18 | 0.82 |
| h5 | 0.19 | 0.81 | h61 | 0.49 | 0.51 |
| h6 | 0.26 | 0.74 | h62 | 0.76 | 0.24 |
| h7 | 0.56 | 0.44 | h63 | 0.37 | 0.63 |
| h8 | 0.39 | 0.61 | h64 | 0.35 | 0.65 |
| h9 | 0.57 | 0.43 | h65 | 0.27 | 0.73 |
| h10 | 0.35 | 0.65 | h66 | 0.36 | 0.64 |
| h11 | 0.23 | 0.77 | h67 | 0.55 | 0.45 |
| h12 | 0.2 | 0.8 | h68 | 0.45 | 0.55 |
| h13 | 0.38 | 0.62 | h69 | 0.68 | 0.32 |
| h14 | 0.52 | 0.48 | h70 | 0.26 | 0.74 |
| h15 | 0.62 | 0.38 | h71 | 0.81 | 0.19 |
| h16 | 0.75 | 0.25 | h72 | 0.31 | 0.69 |
| h17 | 0.2 | 0.8 | h73 | 0.82 | 0.18 |
| h18 | 0.57 | 0.43 | h74 | 0.63 | 0.37 |
| h19 | 0.24 | 0.76 | h75 | 0.38 | 0.62 |
| h20 | 0.79 | 0.21 | h76 | 0.22 | 0.78 |
| h21 | 0.74 | 0.26 | h77 | 0.32 | 0.68 |
| h22 | 0.46 | 0.54 | h78 | 0.14 | 0.86 |
| h23 | 0.34 | 0.66 | h79 | 0.43 | 0.57 |
| h24 | 0.14 | 0.86 | h80 | 0.51 | 0.49 |
| h25 | 0.43 | 0.57 | h81 | 0.56 | 0.44 |
| h26 | 0.46 | 0.54 | h82 | 0.55 | 0.45 |
| h27 | 0.85 | 0.15 | h83 | 0.64 | 0.36 |
| h28 | 0.64 | 0.36 | h84 | 0.5 | 0.5 |
| h29 | 0.48 | 0.52 | h85 | 0.25 | 0.75 |
| h30 | 0.65 | 0.35 | h86 | 0.18 | 0.82 |
| h31 | 0.49 | 0.51 | h87 | 0.16 | 0.84 |
| h32 | 0.57 | 0.43 | h88 | 0.36 | 0.64 |
| h33 | 0.25 | 0.75 | h89 | 0.62 | 0.38 |
| h34 | 0.76 | 0.24 | h90 | 0.18 | 0.82 |
| h35 | 0.77 | 0.23 | h91 | 0.47 | 0.53 |
| h36 | 0.61 | 0.39 | h92 | 0.65 | 0.35 |
| h37 | 0.77 | 0.23 | h93 | 0.61 | 0.39 |
| h38 | 0.58 | 0.42 | h94 | 0.36 | 0.64 |
| h39 | 0.54 | 0.46 | h95 | 0.45 | 0.55 |
| h40 | 0.1 | 0.9 | h96 | 0.38 | 0.62 |
| h41 | 0.24 | 0.76 | h97 | 0.41 | 0.59 |
| h42 | 0.51 | 0.49 | h98 | 0.27 | 0.73 |
| h43 | 0.49 | 0.51 | h99 | 0.65 | 0.35 |
| h44 | 0.66 | 0.34 | h100 | 0.53 | 0.47 |
| h45 | 0.1 | 0.9 | h101 | 0.77 | 0.23 |
| h46 | 0.63 | 0.37 | h102 | 0.16 | 0.84 |
| h47 | 0.78 | 0.22 | h103 | 0.77 | 0.23 |
| h48 | 0.22 | 0.78 | h104 | 0.78 | 0.22 |
| h49 | 0.62 | 0.38 | h105 | 0.29 | 0.71 |
| h50 | 0.75 | 0.25 | h106 | 0.73 | 0.27 |
| h51 | 0.59 | 0.41 | h107 | 0.56 | 0.44 |
| h52 | 0.31 | 0.69 | h108 | 0.69 | 0.31 |
| h53 | 0.68 | 0.32 | h109 | 0.31 | 0.69 |
| h54 | 0.54 | 0.46 | h110 | 0.57 | 0.43 |
| h55 | 0.41 | 0.59 | h111 | 0.14 | 0.86 |
| h56 | 0.35 | 0.65 | h112 | 0.36 | 0.64 |

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