buildings

MDPI

Article

Variable Differential Pressure Control Strategy for Variable Water Flow Air Conditioning Systems

Haoyi Zhufang, Yu Huang, Yulong Dai and Changzhi Yang *

College of Civil Engineering, Hunan University, Changsha 410082, China
* Correspondence: czyang@hnu.edu.cn

Abstract: In large-scale air conditioning water systems, variable water flow (VWF) control strategies are frequently utilized to conserve energy. This paper presents a variable differential pressure (DP) set-point control strategy for VWF air conditioning systems based on the pipeline characteristic curve. This strategy bifurcates the most unfavorable loop into two segments: the equivalent main pipe (EMP) and the most unfavorable terminal branch pipe (MUTBP). Initially, the impedance of the EMP is obtained by curve fitting the measured values of the water supply and return main pipes (WSRMP), as well as the MUTBP. Subsequently, by calculating the disparity between the DP of the actual pipeline and the DP of the EMP, and comparing it with the DP of the MUTBP, the optimal working condition point for pipeline operation can be identified. Finally, a theoretical calculation is conducted on a typical air conditioning water system. This adjustment strategy achieves an energy-saving rate of 15.27%, 12.10%, and 11.50%, respectively, under the three adjustment conditions of closing the nearest terminal, the middle terminal, and the most unfavorable terminal, as compared with the constant DP set-point control strategy of WSRMP. This strategy boasts fewer control devices, a simple control system, and better operability and engineering applicability than other strategies.

Keywords: chilled water pipe network; energy-saving; differential pressure set-point; variable water flow; control strategy

check for updates

Citation: Zhufang, H.; Huang, Y.; Dai, Y.; Yang, C. Variable Differential Pressure Control Strategy for Variable Water Flow Air Conditioning Systems. *Buildings* **2023**, *13*, 903. https://doi.org/10.3390/buildings13040903

Academic Editor: Francesco Nocera

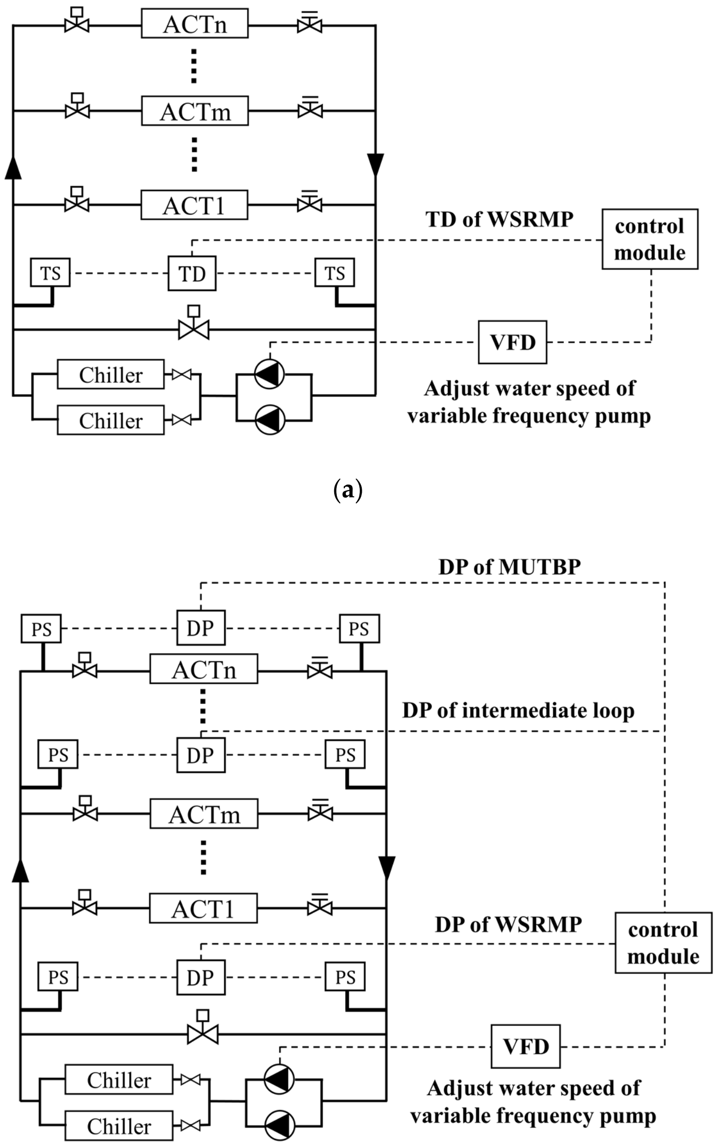
Received: 22 February 2023
Revised: 24 March 2023
Accepted: 27 March 2023
Published: 29 March 2023

1. Introduction

In public buildings that utilize central air conditioning, the energy consumption of air conditioning comprises between 50% and 60% of the building's total energy consumption [1]. In load conditions ranging from 40% to 80% [2], a substantial amount of energy is wasted. Within the air conditioning systems of public buildings, the chilled water system is responsible for roughly 15% to 20% of the total air conditioning energy consumption [3]. Consequently, decreasing the energy usage of the overall air conditioning water system carries great significance in building energy preservation.

In a conventional central air conditioning water system, the underlying cause of high energy consumption can be attributed to issues such as "large flow and small temperature difference (TD)" stemming from mismatches in cooling water demand amongst branch users and partial load conditions [4]. In light of this, numerous scholars have introduced the concept of an air conditioning variable water flow (VWF) system, which has been theoretically analyzed and experimentally tested, proving its feasibility [5–8]. As variable flow technology becomes increasingly commonplace, scholars place greater emphasis on the control strategy of VWF systems.

In engineering, common VWF control strategies can be categorized into two groups based on their control objects: the TD set-point control strategy and the DP set-point control strategy. As illustrated in Figure 1a, TD control regulates the flow rate of the water pump by driving variable frequency drivers (VFD) to ensure that the TD between the water supply and return main pipe (WSRMP) matches the set value. When this set value remains constant, it is referred to as constant TD control. A straightforward control principle and strong operability characterize this strategy. Compared to conventional fixed air volume control strategies, it boasts a higher energy-saving rate [9–11]. Some researchers have proposed variable TD control by varying the TD set value [12,13]. Compared to constant TD control, this strategy is more energy efficient. Nevertheless, this type of TD control strategy of VWF systems cannot reflect the load demand of each terminal, and the hysteresis of water temperature change results in suboptimal control effects. Therefore, it is only suitable for users without regulating valves and in air-conditioned areas with low individual requirements [14].



(**a**)

(**b**)

Figure 1. Common VWF control strategies in engineering: (**a**) the TD set-point control strategy; and (**b**) the DP set-point control strategy. ACT represents the air conditioner terminal; VFD represents variable frequency drivers; TD represents temperature difference; TS represents temperature sensor; DP represents differential pressure; and PS represents pressure sensor.

In light of these problems, DP set-point control strategy has emerged as the preferred control strategy due to its sensitive response capability and reliable controllability. As depicted in Figure 1b, DP set-point control drives the VFD to regulate the flow rate of the water pump by ensuring that the DP at the relevant position within the pipeline system is maintained at the desired level. Typically, the WSRMP, the intermediate loop, and MUTBP are selected as control positions, and the water pump is adjusted by fixing the DP setting value [15–17]. In separate studies, Zeng [18] and Zhao [19] analyzed the three constant DP set-point strategies across different locations. Their findings indicate that the constant DP set-point control strategy for the WSRMP has the highest energy consumption. In contrast, the intermediate loop constant DP set-point control strategy has slightly lower energy consumption. The constant DP set-point control strategy for the MUTBP has the smallest energy consumption. While this constant DP set-point control strategy boasts improved control effect and universality compared to TD set-point control, the DP setting value must consider various factors, such as load distribution on the user side and the position of the DP sensor. These factors directly impact the level of energy consumption in the VWF air conditioning system and the efficacy of the control effect.

In contrast to the abovementioned approaches, numerous scholars have explored avenues for further optimizing energy consumption in water systems by collecting terminal information and algorithmic optimization. For instance, He et al. [20] proposes a strategy for variable flow and variable DP control which is based on valve position. This approach enables the control of flow and DP by collecting information on the opening of the terminal valve. This strategy is characterized by its stability in control and, when compared with conventional constant DP control strategies, can achieve significantly greater energy savings. In another study, Zhao et al. [21] identifies the most unfavorable thermodynamic loop by implementing an optimal DP reset strategy, and subsequently controls the position of the end valve within the optimal valve position range by collecting information on the terminal valve position. This results in greater energy savings for water pumps. Additionally, Yu et al. [22] proposes a distributed iterative optimization algorithm based on a novel distributed control architecture and the alternating direction strategy of multipliers with regular term. This strategy requires the installation of only one distributed controller in each piece of equipment, and the results indicate that the proposed algorithm can save up to 28.54% of energy when compared with strategies that are not optimized, while simultaneously realizing dynamic hydraulic balance in the pipe network.

This control methodology offers greater flexibility in its control mode and is more energy-efficient than the constant DP set-point control technique. Nevertheless, it typically requires more sensors to gather terminal information, resulting in a complex control system. The extended information transmission loop also presents difficulties, such as information loss during the callback process.

The preceding analysis reveals that the current VWF control methodologies exhibit their respective merits, while also suffering from numerous limitations in practical applications, including the existence of many control elements, complex control systems, and the vulnerability of control information loss, as demonstrated in Table 1. Accordingly, this paper advocates for a simplistic control approach that utilizes variable DP set-point control strategy, thereby guiding the frequency conversion of water pumps with fewer measurement instruments and a simplified control system, ultimately attaining energy conservation objectives.

Table 1. Advantages and disadvantages of traditional VWF strategies.

Traditional VWF Control Strategies	Advantages	Disadvantages
The constant TD set-point control strategy	Simple control principle	Significant latency Low control precision
The constant DP set-point control strategy for the MUTBP	High reliability	Long control circuit Information callback is easy to lose
The constant DP set-point control strategy for the WSRMP	Simple system Easy to maintain and operate	Insufficient potential for energy-saving
The variable DP set-point control strategy based on valve position and others	Maximum energy saving	A large number of detection points Control system is complex

This strategy shares a common concept with the conventional constant DP set-point control strategy for the MUTBP, which guarantees the equitable flow distribution of the entire water system by ensuring the DP control value at the MUTBP. However, unlike the constant DP set-point control strategy for the MUTBP, this strategy employs measurement and control units installed on the WSRMP rather than at the farthest terminal from the chiller room. This removes the issues related to information loss during callback and control system failure caused by the lengthy control line. Additionally, calculations indicate that this approach results in more significant energy conservation than the installation of measurement and control devices in the constant DP of the WSMRP. Thus, for most VWF systems currently in mainland China that do not control or utilize the constant DP set-point control strategy for the MUTBP and the WSRMP, this technique can be utilized to effect energy-saving retrofits.

2. Control Strategy

2.1. Control Theory

The relationship between the resistance loss of the pipe network and the volume flow of the pipe network in the air conditioning water system typically conforms to the following equation [23]:

$$\Delta P = SQ^2 \tag{1}$$

where the ΔP is pipe network resistance loss, mH_2O; S is pipe network impedance, s^2/m^5; and Q is volume flow of pipe network, m^3/s.

Within the formula mentioned above, S represents a coefficient that comprehensively characterizes the resistance features of the pipe network, known as pipeline impedance, and is only related to the intrinsic characteristics of the pipe network, such as the pipe's diameter, length, and material. Pipeline impedance remains unchanged if no modifications are made to the pipeline itself. In practice, valve aperture is typically adjusted to modify the size of pipeline impedance S and, as a consequence, regulate the flow of the pipeline network. The larger the valve aperture, the greater the S value, and the steeper the curve; conversely, a smaller valve aperture results in a reduced S value and a milder curve.

Figure 2 illustrates a schematic diagram of a typical variable flow air conditioning water system. ACT represents the air conditioner terminal, PS denotes the pressure sensor, and FS represents the flow sensor. It is assumed that the loop containing the farthest terminal ACTn represents the most unfavorable loop. In practical operation, the user may adjust the terminal due to varying requirements, causing the pipeline impedance S to increase. Nonetheless, there is no change on the main pipe's inherent characteristics because of no modifications. Thus, the water system pipeline is divided into two distinct parts: the equivalent main pipe (EMP) depicted in red and MUTBP illustrated in blue. Under any working condition, the impedance, S_m, of the equivalent main pipe essentially remains constant.

The differential pressure, ΔP_p, on WSRMP and the corresponding differential pressure, ΔP_t, at the fully opened least favorable terminal valve, are obtained through pressure sensors. In contrast, the flow rate, Q_p, of the WSRMP is measured using flow sensors. A functional relationship, denoted as $\Delta P_p = f\left(S_m {Q_p}^2, \Delta P_t\right)$, relates the three variables as per Formula (1). Once this functional relationship and S_m are known, the flow rate Q_p and pressure difference ΔP_p measured on the WSRMP can be utilized to infer the DP at the terminal. This information can then guide the frequency conversion adjustment of the water pump based on the concept of determining the DP at the most unfavorable terminal.

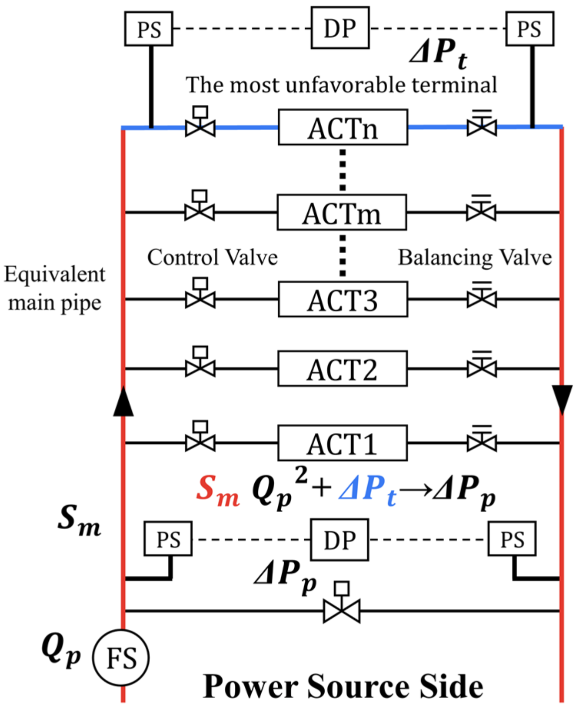


Figure 2. A typical air conditioning water system. ACT represents the air conditioner terminal; DP represents differential pressure; PS represents pressure sensor; FS represents the flow sensor; Q_p represents the flow rate of the supply and return main pipeline; S_m represents the impedance of equivalent main pipe; ΔP_p represents the differential pressure of the water supply and return main pipe; and ΔP_t represents the differential pressure of the most unfavorable terminal branch pipe.

It is important to note that during the actual process, the flow rate of each section of the main pipeline will vary once it is divided into each terminal. Hence, the "EMP" referred to in this context does not pertain to the actual main pipeline. Rather, it can be comprehended as the section of the most unfavorable loop, excluding MUTBP. The flow rate of the equivalent main pipe corresponds to the total flow rate, Q_p, on the WSRMP.

2.2. Control Strategy

The relationship mentioned above is represented in the form of a characteristic pipeline curve, which is utilized to elucidate the control strategy further. Figure 3 depicts C_d as the characteristic curve of the pipeline under design conditions, C_m as the characteristic curve of the EMP, and C_H as the dynamic characteristic curve of the pipeline, reflecting the interdependence between pipeline power and flow. The curves' resemblance is to the pump's performance. The operating state point of the pipeline under design working conditions is denoted by point a. At this juncture, the pipeline's flow rate is Q_a, the pipeline's DP is ΔP_{pa}, and the DP of MUTBP is ΔP_t. Upon the user adjusting the terminal, the pipeline's total impedance will increase, resulting in a steeper curve and assuming the actual pipeline characteristic curve becomes C′. Based on the functional relationship, the optimal operating point, c, can be identified, subject to ensuring DP of the most unfavorable terminal by ensuring that the difference ΔP_t between the curve C_m and the curve C′ remains unaltered.

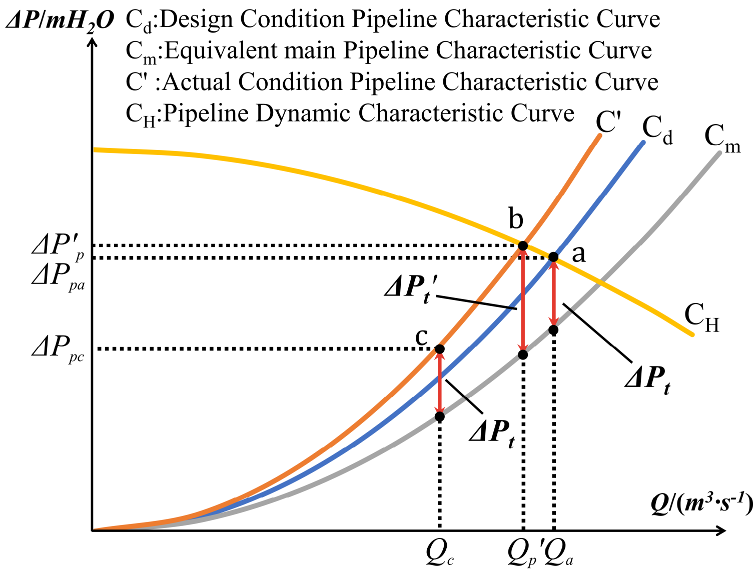


Figure 3. Measurement control system diagram. *a* represents the operating state point of the pipeline under design working conditions; *b* represents the operating state point of the pipeline with the user adjusting the terminal; and *c* represents the operating state point of the pipeline utilizing this strategy.

Figure 2 demonstrates that in the absence of water pump adjustment, the characteristic curve of pipeline power will remain unaltered, resulting in the actual operating point shifting from point *a* along the curve C_H to point *b*. At this stage, the pipeline's resistance will increase to $\Delta P_p{}'$, and the energy consumed by the pipeline will be $E' = \Delta P_p{}' \times Q_p{}'$ (represented by the rectangular area at the upper right vertex with point *b* as its boundary). However, upon adopting this adjustment strategy, the energy consumed by the entire pipeline will reduce to $E_c = \Delta P_{pc} \times Q_{pc}$ (represented by the rectangular area at the upper right vertex with point *c* as its boundary). This strategy guarantees that the resource pressure head at MUTBP is maintained under the design working conditions, naturally meeting the pressure head requirements of other loops. Moreover, the energy consumed in the pipeline using this strategy (E_c) is lower than that consumed by the unadjusted water pump (E'), guiding further frequency conversion adjustment.

2.3. Measurement Control System

The implementation of the control strategy mentioned above in an actual engineering system is discussed in detail below. Figure 4 illustrates the measurement control system for this strategy, which involves two stages. In the initial preparation stage, it is necessary to install measuring equipment at MUTBP of the VWF air conditioning system and the power source side for on-site commissioning. Under design conditions, ensure the valve at MUTBP is fully open. Measure the differential pressure ΔP_{p1} and flow rate Q_{p1} of the WSRMP. Simultaneously, measure the differential pressure ΔP_{t1} at MUTBP. The first set of data represents the parameters of the design operating point. Subsequently, the water flow rate of the WSRMP is changed through a series of means, such as frequency conversion of the water pump. The measured values of multiple data sets are obtained and included in Table 2. The differential pressure ΔP_m of the EMP is equal to the measured WSRMP differential pressure ΔP_p minus the most unfavorable terminal differential pressure ΔP_t. Based on Formula (1), quadratic regression is performed on the pipeline flow Q_p and the equivalent differential pressure ΔP_m to obtain the characteristic regression parameter S_m of the equivalent main pipe. The preparation phase is over.

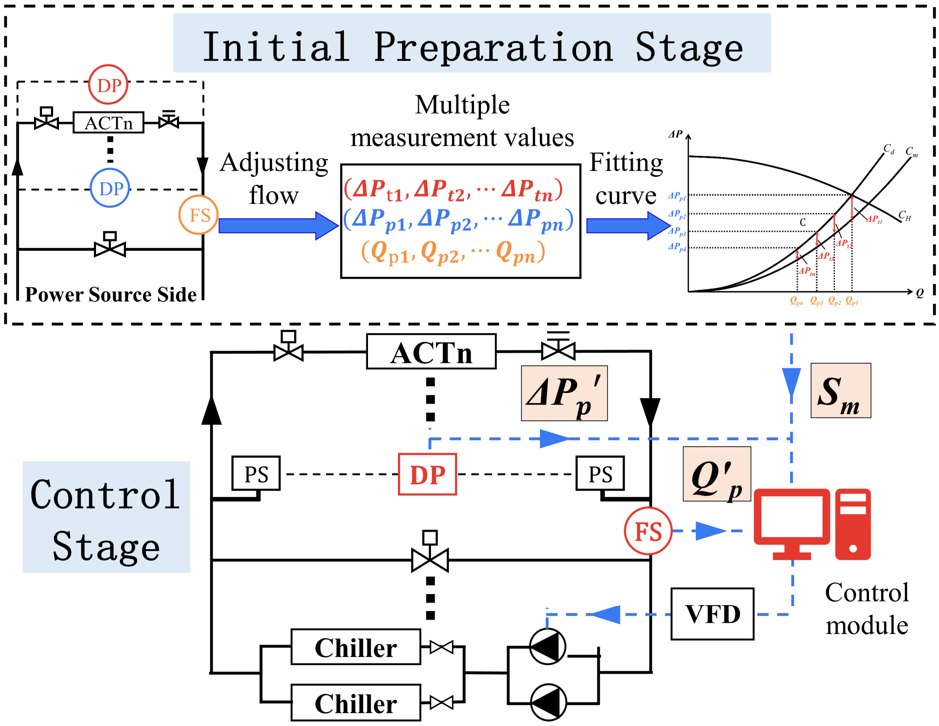


Figure 4. Measurement control system. In this process, three parameters are fed into the control module, namely the impedance of equivalent main pipe (S_m), obtained during the initial preparation stage, the real-time flow rate ($Q_p{}'$), and the real-time differential pressure ($\Delta P_p{}'$), measured, respectively, by the flow sensor and the pressure sensor during the control stage. The control module generates the corresponding inverter command in accordance with the control logic to guide the pump inverter.

Table 2. Measured value during preparation.

Measurement Parameters	Parameter Source	1	...	n
WSRMP flow	Flow meter	Q_{p1}	...	Q_{pn}
DP of WSRMP	Differential pressure meter	ΔP_{p1}	...	ΔP_{pn}
DP of MUTBP	Differential pressure meter	ΔP_{t1}	...	ΔP_{tn}
DP of EMP	$\Delta P_m = \Delta P - \Delta P_t$	ΔP_{m1}	...	ΔP_{mn}

During the control stage, flow and differential pressure sensors will be installed on the water WSRMP. Real-time differential pressure $\Delta P_p{}'$ and flow rate $Q_{p1'}$ measurements from the sensors will be inputted along with the previously calculated equivalent main pipe impedance S_m into the flow regulation control module. The specific control logic is depicted in Figure 5, which can be used to adjust the water pump accordingly. The control logic begins by assessing whether any changes have occurred in the working conditions based on the flow rate. If the difference between the measured flow rate $Q_p{}'$ and the set flow rate Q_{p1} falls outside the allowable accuracy range ε_1, then, the module compares the measured pipeline differential pressure $\Delta P_p{}'$ with the product of EMP resistance S_m and $Q_p{}'^2$ as well as the set differential pressure ΔP_{t1} at the most unfavorable terminal. If the difference between the two is outside the allowable accuracy range ε_2, the pump flow rate is adjusted and re-measured until the optimal operating point is achieved. The specific values of ε_1 and ε_2 need to be determined according to the particular engineering conditions.

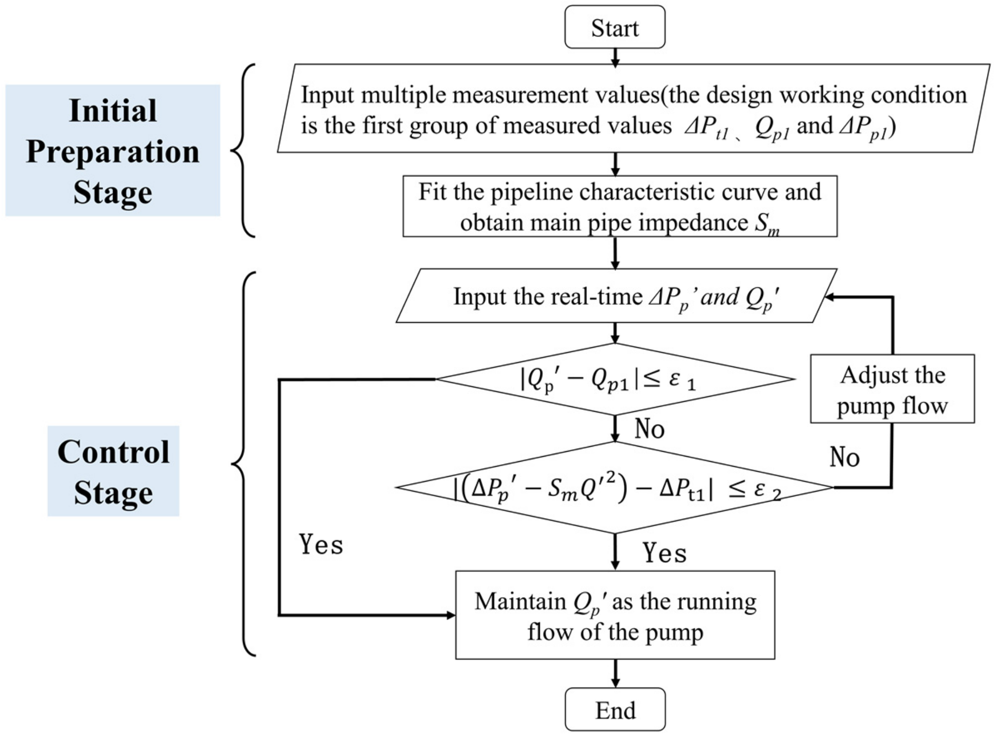


Figure 5. Control logic diagram.

3. Computational Analysis

3.1. Basic Information of Typical Pipe Network System

To underscore the strategy's performance in a VWF system, we will integrate calculations and analyses with a representative pipe network system. Figure 6 illustrates the schematic diagram of a typical primary pump VWF system's pipeline network configuration. Notably, the system comprises ACT1 to ACT9, which are air conditioner terminals, and $L_{1g} \ldots L_{1h}$, which constitute the water supply and return branch pipes. Prior to conducting a theoretical analysis, we propose the following assumptions:

(1) Except for ACT9, each terminal has a balancing and a regulating valve. The hydraulic adjustment of the balancing valve has been completed during design, and the regulating valve can be adjusted as per user needs.
(2) ACT9 represents the most unfavorable terminal, as the hydraulic balance adjustment is calibrated with it as a reference. Hence, it lacks a balancing valve, with the regulating valve set to its maximum capacity.
(3) The pressure drop of each water supply and return branch pipe is identical, and the pressure drop of each terminal is equivalent, satisfying the hydraulic balance requirements during the design phase, thereby enabling convenient calculation.
(4) The supply pressure on the power source side fully complies with the differential pressure regulation requirements, with each terminal operating under the designed working conditions.
(5) Upon terminal closure, the default impedance becomes infinite.

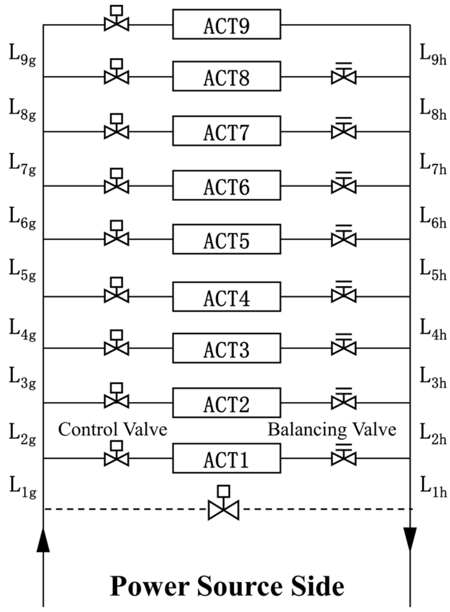


Figure 6. Composition of typical pipe network system. ACT represents the air conditioner terminal; L_g represents water supply pipe; and L_h represents water return pipe.

According to the five assumptions above, Table 3 illustrates the initial conditions based on engineering cases and design experience. The table shows that the pressure drop at the most unfavorable terminal is ΔP_t = 7mH$_2$O, the pressure drop of the loop in which it is located is 10.6 mH$_2$O, and the flow rate of WSRMP is Q_{p1} = 90 m^3/h. Thus, the designed operational point of the pipeline is A(90,10.6).

Table 3. Control system measurements.

Pipeline Object	Rated Flow Rate /(m^3·h^{-1})	Rated Pressure Drop /(mH$_2$O)	Impedance /(s^2·m^{-5})
L_{1g}, L_{1h}	90	0.2	320
L_{2g}, L_{2h}	80	0.2	405
L_{3g}, L_{3h}	70	0.2	529
L_{4g}, L_{4h}	60	0.2	720
L_{5g}, L_{5h}	50	0.2	1037
L_{6g}, L_{6h}	40	0.2	1620
L_{7g}, L_{7h}	30	0.2	2880
L_{8g}, L_{8h}	20	0.2	6480
L_{9g}, L_{9h}	10	0.2	25,920
ACT1–9	10	7	907,200
Balancing Valve1	10	3.2	414,720
Balancing Valve2	10	2.8	362,880
Balancing Valve3	10	2.4	311,040
Balancing Valve4	10	2	259,200
Balancing Valve5	10	1.6	207,360
Balancing Valve6	10	1.2	155,520
Balancing Valve7	10	0.8	103,680
Balancing Valve8	10	0.4	51,840

The constant DP set-point control strategy for WSRMP represents a VWF control strategy that sustains the DP on the WSRMP at the specified value. Similar to the strategy mentioned above, it incorporates a measuring device on the WSRMP. Both strategies exhibit low failure rates and are amenable to information collection, thereby warranting a comparative assessment of their energy consumption across three working conditions, specifically, the closure of the most unfavorable terminal, ACT9, the middle terminal, ACT5, and the nearest terminal, ACT1.

3.2. Determination of Working Condition State Point

As this case study is based on theoretical analysis without real-time measurements from relevant sensors, determining the working condition point is a relatively intricate task. Therefore, the calculation and analysis diagram are illustrated in Figure 7. In Figure 7, C_m, C_d, and C′ represent the characteristic curves of the EMP, the design working condition pipeline, and the actual working condition pipeline, respectively. Moreover, the diagram illustrates the dynamic characteristic curves C_{H1} of the pipeline in design working conditions, the dynamic characteristic curve C_{H2} of the constant DP set-point strategy for WSRMP, and the pipeline dynamic characteristic curve C_{H3} of this strategy. A, B, and C denote the operating points of the pipeline under design conditions, the operating points of the constant DP set-point strategy for WSRMP, and the pipeline operating point of this strategy, respectively.

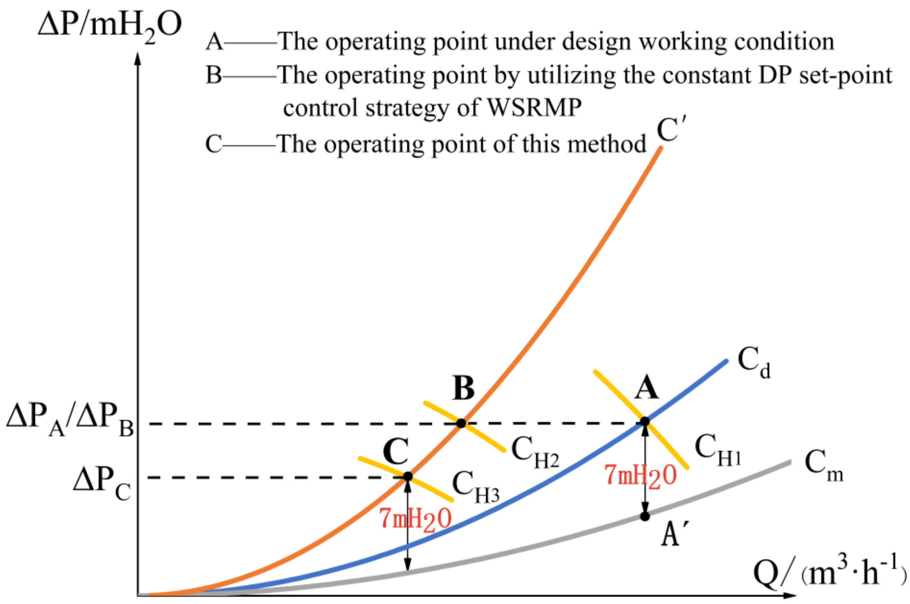


Figure 7. Schematic diagram of analysis process. C′ represents the characteristic curves of the actual working condition pipeline; C_d represents the characteristic curves of the design working condition pipeline; and C_m represents the characteristic curves of the equivalent main pipe.

Following the control principle described in Section 2, determining the pipeline operating point using this strategy involves establishing the design working conditions and the characteristic curve of the EMP. To obtain the characteristic pipeline curve C_d for the design working condition, point A can be regressed based on Formula (1). As for the EMP characteristic curve C_m, keeping the flow rate constant at point A, the pressure drop can be obtained by reducing ΔP_t = 7mH_2O. Point A′ can also be obtained using regression fitting based on Formula (1) and point A′.

Subsequently, when the user adjusts the terminal due to mismatching requirements, the pipeline impedance S_0 will change to S'. In fluid mechanics literature [24], the pipeline network impedance for a pipeline system satisfies the following relationship during the process of series–parallel connection:

$$S_C = \sum_{i}^{n} S_i \tag{2}$$

$$\frac{1}{\sqrt{S_b}} = \sum_{j}^{m} \frac{1}{\sqrt{S_j}} \tag{3}$$

where S_c is the total impedance of series pipes, s^2/m^5; S_i is impedance of each series pipe section, s^2/m^5; n is number of pipe sections in series; S_b is total impedance of parallel pipelines, s^2/m^5; S_j is impedance of each parallel pipe section, s^2/m^5; and m is total impedance of series pipes.

The above formula enables the calculation of the total pipeline impedance S' under actual working conditions through multiple series–parallel iterations. The specific calculation formula is presented in Table 4.

Table 4. Impedance calculation formula. The unit of the impedance is s^2/m^5.

Calculation Object	Calculation Formula
The impedance of branch pipe where ACT9 is located	$S_9 = S_{ACT9} + S_{L_{9g}} + S_{L_{9h}}$
The impedance of branch pipe where ACT1–8 is located	$S_n = \left(\frac{1}{\sqrt{S_{n+1}}+\sqrt{S_{ACTn}}}\right)^2 + S_{L_{ng}} + S_{L_{nh}} (n = 1\sim8)$
Total pipeline impedance	$S' = S_1 + S_{L_{1g}} + S_{L_{1h}}$

Once the three curves have been determined, the state points for each working condition can be identified. The design condition point A has already been obtained, and the pipeline operation point B corresponding to the constant DP set-point strategy for WSRMP should be defined by searching for the pressure drop of the main pipe where the most unfavorable loop is located under the design condition is used as the DP setting value, which is 10.6 m.

To determine the pipeline operating point C for this strategy, it is necessary to maintain a difference of $7mH_2O$ between the curves S' and S_0, as per the corresponding relationship mentioned previously.

Two points in the above process are worth explaining:

(1) In the actual control process, the C_d and C_m curves should be fitted based on multiple sets of measured values described in Section 2.3. In this example, only one set of values is used for regression to compare the energy-saving performance of the two strategies.

(2) The above parameters are all derived from fluid mechanics formulas, which can be relatively complex. In practical engineering, it would be more convenient to measure and control the system through various sensors according to the control logic and process.

3.3. Calculation Results

Following the calculation ideas and strategies described in Section 3.2, the pipeline operating points for the three working conditions of closing the most unfavorable terminal ACT9, the middle terminal ACT5, and the nearest terminal ACT1 were calculated and are listed in Table 5.

Table 5. Calculation results of three working conditions.

Working Conditions	Impedance of C_m ($s^2 \cdot m^{-5}$)	Impedance of C′ ($s^2 \cdot m^{-5}$)	Energy Consumption at Point B (w)	Energy Consumption at Point C (w)	Energy-Saving Rate
1	5760	21,925	2286	1937	15.27%
2	5760	20,662	2355	2070	12.10%
3	5760	20,321	2374	2101	11.50%

Table 3 reveals that, in all three operating conditions, an increase in distance between the adjustment terminal and the power source side leads to a decrease in actual pipeline curve impedance and, consequently, a reduction in energy consumption. This finding is consistent with the conclusion reached by Chi et al. [25] in their established model. Compared to the constant DP set-point strategy for WSRMP, this approach delivers energy-saving rates of 15.27%, 12.10%, and 11.50%, respectively, yielding remarkable energy-saving benefits.

4. Conclusions

Given the complexity of the existing VWF control strategy for air conditioning water systems and the potential for information callback loss, a novel control strategy for the variable DP set-point of VWF air conditioning systems is proposed. The principal findings are as follows:

(1) The proposed control strategy divides the hydraulic loop most susceptible to unfavorable conditions into two parts: EMT and MUTBP. During the preparation stage, the equivalent main pipe impedance S_m is measured. During the actual control stage, the measured supply and return main pipe flow Q_p and differential pressure ΔP_t are input into the flow control module to guide frequency conversion adjustment of the water pump.

(2) This paper's proposed control strategy only requires the installation of a flow sensor and a differential pressure sensor in WSRMP of the water system to guide the frequency conversion adjustment of the water pump. Compared to the constant DP set-point strategy for MUTBP, the control line is closer to the chiller room, and information collection is easier. Furthermore, compared to existing strategies, it requires fewer sensors and results in a simpler control system, making it more operable for VWF air conditioning systems.

(3) Based on the theoretical calculation of a typical pipe network system with nine ACT terminals, this proposed control strategy achieved energy-saving rates of 15.27%, 12.10%, and 11.50% under the three working conditions of closing the most unfavorable terminal, the middle terminal, and the nearest terminal, respectively, when compared to the traditional constant DP set-point strategy for WSRMP. These results demonstrate significant energy-saving benefits.

Theoretically speaking, although the adjustment of the main pipe is not considered, it may impact the resistance characteristics of the corresponding three-way valve on the main pipe's closed terminals. Hence, the impedance of EMP is not strictly constant. This effect can be deemed negligible in engineering and hence, not considered in this study. Furthermore, the research objective of this manuscript is to address the issues associated with the conventional control approach of VWF air conditioning systems, which is characterized by a complex control system and a propensity for information feedback loss. As for the hydraulic stability of each user branch, caused by pipe network adjustments [26–28], and the optimization of the water system, considering the efficiency of frequency conversion pumps and chiller units, these aspects are beyond the scope of this paper. Further research will explore these areas.

Author Contributions: Conceptualization, Y.H., Y.D. and C.Y.; Methodology, C.Y.; Formal analysis, H.Z., Y.H. and C.Y.; Writing—original draft, H.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

ACT	Air conditioning terminal
a	The operating state point of the pipeline under design working conditions
A	The operating point of designing working
b	The operating state point of the pipeline with the user adjusting the terminal
B	The operating point of the main pipe constant pressure difference control strategy
c	The operating state point of the pipeline utilizing this strategy.
C	The operating point of this strategy
C_d	Design Condition Pipeline Characteristic Curve
C_H	Pipeline Dynamic Characteristic Curve
C_m	Equivalent main pipeline characteristic curve
C'	Actual Condition Pipeline Characteristic Curve
DP	Differential pressure
FS	Flow sensor
E'	The energy consumed by the pipeline without control
E_c	The energy consumed by the pipeline with control strategy of this article
EMP	The equivalent main pipe
L_g	Water supply branch pipes of the pipeline
L_h	Water return branch pipes of the pipeline
L	Water branch pipes of the pipeline
m	Total impedance of series pipes
MUTBP	The most unfavorable terminal branch pipe
n	Number of pipe sections in series
PS	Differential pressure sensors
ΔP	Pipe network resistance loss(mH_2O)
ΔP_a	Differential pressure at point a(mH_2O)
ΔP_c	Differential pressure at point c(mH2O)
ΔP_m	Differential pressure of the equivalent main pipe (mH2O)
ΔP_p	Differential pressure of the supply and return main pipeline (mH_2O)
$\Delta P'_p$	Real-time Pressure difference of the supply and return main pipeline (mH_2O)
ΔP_t	Differential pressure of the most unfavorable terminal (mH_2O)
Q	Volume flow of pipe network(m^3/s)
Q_a	Volume flow at point a(m^3/s)
Q_m	The Equivalent main pipe flow(m^3/h)
Q_p	The flow rate of the supply and return main pipeline (m^3/s)
Q'_p	Real-time flow rate of the supply and return main pipeline (m^3/s)
Q_{pc}	The flow rate of the supply and return main pipeline at point C(m^3/s)
S	Pipe network impedance (s^2/m^5)
S_b	Total Impedance of Parallel Pipelines(s^2/m^5)
S_c	Total impedance of series pipes(s^2/m^5)
S_i	Impedance of each series pipe section(s^2/m^5)
S_j	Impedance of each parallel pipe section(s^2/m^5)
S_m	Impedance of the equivalent main pipe (s^2/m^5)
TD	Temperature difference
WSRMP	The water supply and return main pipe
VFD	Variable frequency drivers
VWF	Variable water flow
ε	Accuracy range

References

1. Jiang, Y. Trend of building energy consumption in our country and key points of energy saving. *Constr. Sci. Technol.* **2006**, *7*, 10–15.
2. Lu, Y.Q. *Practical Heating and Air Conditioning Design Manual*, 2nd ed.; China Architecture & Building Press: Beijing, China, 2015; pp. 2015–2016.
3. Sun, Y.J. Variable water flow control in air conditioning systems for energy efficiency. *Heat. Vent. Air Cond.* **2001**, *6*, 5–7.
4. Zhao, T.Y. Optimal Control with Variable Differential Pressure Setpoint in Air Conditioning Chilled Water System. Ph.D. Thesis, Harbin Institute of Technology, Harbin, China, 2009; p. 10.

5. Sun, Y.J. Variable Water Flow Control in Air Conditioning Systems for Energy Efficiency (continued one): Effect of Water Flow Variation on Operation. *Heat. Vent. Air Cond.* **2004**, *7*, 60–69.
6. Sun, Y.J. Variable Water Flow Control in Air Conditioning Systems for Energy Efficiency (continued two): Appropriate Application of Variable Frequency Pumps. *Heat. Vent. Air Cond.* **2005**, *10*, 90–113.
7. Li, Z.S.; Zhang, G.Q.; Liu, J.L.; Li, D.M.; Mei, S. Performance Test and Fault Diagnosis for Chillers based on Chilled Water Flow Rate Variation. *Heat. Vent. Air Cond.* **2006**, *8*, 108–112.
8. Jia, J.; Yuan, C.J.; Liu, K. Optimization Proposal of Chilled Water System and Energy Conservation Technology of Centrifugal Chiller. *Fluid Mach.* **2006**, *6*, 82–86.
9. Luo, J.Z. Research on Control Strategy of Variable Primary Flow System. Master's Thesis, Chongqing University, Chongqing, China, 2015; p. 5.
10. Liu, X. Characteristics of Hydraulic Pipe Network and Optimal Control Strategy Study for Chilled Water System. Master's Thesis, Tongji University, Shanghai, China, 2007; p. 3.
11. Du, F.H.; Liang, D.D.; Li, F.L. Research on Energy Saving of Air Conditioning System Based on Terminal Constant Temperature Difference Control. *Technol. Innov. Appl.* **2021**, *11*, 139–141.
12. Li, B.H. Research on Energy Saving Optimization of Air Conditioning Chilled Water System Based on Load Forecast. Master's Thesis, Xi'an University of Architecture and Technology, Xi'an, China, 2021; p. 6.
13. Chai, S. *Feedforward Variable Temperature Difference Control of Central Air Conditioning Refrigerated Water System Based on Load Forecasting*; Beijing University of Civil Engineering and Architecture: Beijing, China, 2019; p. 6.
14. Li, S.L. Energy Saving Control of Variable Chilled Water Flow in Primary Pumps Systems. *Heat. Vent. Air Cond.* **2006**, *7*, 72–75.
15. Bahnfleth, W.P.; Peyer, E. Comparative analysis of variable and constant primary-flow chilled-water-plant performance. *Heat./Pip./Air Cond. Eng.* **2001**, *4*, 41.
16. Hartman, T. Packaging DDC networks with variable speed drives. *Heat./Pip./Air Cond.* **1998**, *11*, 70.
17. Rishel, J.B. Control of Variable-Speed Pumps on Hot-and chilled-water systems. *ASHRAE Trans.* **1991**, *97*, 746–750.
18. Zeng, W. Selection of variable frequency control strategy and consumption of water pump in variable flow system. *Build. Energy Environ.* **2022**, *41*, 45–48.
19. Zhao, W.C. *Design of Energy Efficiency and Automatic Control System for Central Air Conditioning*; China Architecture & Building Press: Beijing, China, 2018; pp. 30–34.
20. He, X.H. Optimization Control of Chilled Water System of HVAC. Master's Thesis, Hunan University, Changsha, China, 2012; p. 4.
21. Zhao, T.Y.; Ma, L.D.; Zhang, J.L. An optimal differential pressure reset strategy based on the most unfavorable thermodynamic loop on-line identification for a variable water flow air conditioning system. *Energy Build.* **2016**, *110*, 257–268.
22. Yu, J.Q.; Liu, Q.; Zhao, A.J.; Chen, S.Y.; Gao, Z.K.; Wang, F.; Zhang, R. A distributed optimization algorithm for the dynamic hydraulic balance of chilled water pipe network in air-conditioning system. *Energy* **2021**, *223*, 120059. [CrossRef]
23. Gong, G.C. *Fluid Transmission and Distribution Network*; China Machine Press: Beijing, China, 2013; pp. 297–298.
24. Cai, Z.J.; Long, T.Y. *Fluid Mechanics Pump and Fan*; China Architecture & Building Press: Beijing, China, 2009; pp. 145–147.
25. Chi, G.L. Exploitation of Simulator on Air-Conditioning System Automatic Control Based on TRNSTS. Master's Thesis, Dalian University of Technology, Dalian, China, 2010; p. 12.
26. Jiang, Y. Adjust Ability and Stability of Hydraulic Networks. *Heat. Vent. Air Cond.* **1997**, *27*, 1–7.
27. Cho, H.; Cabrera, D.; Patel, M.K. Identification of criteria for the selection of buildings with elevated energy saving potentials from hydraulic balancing-methodology and case study. *Adv. Build. Energy Res.* **2022**, *16*, 427–444. [CrossRef]
28. Cholewaa, T.; Balenb, I.; Siuta-Olcha, A. On the influence of local and zonal hydraulic balancing of heating system on energy savings in existing buildings—Long term experimental research. *Energy Build.* **2018**, *9*, 156–164. [CrossRef]