 doi:10.20944/preprints201803.0249.v1

Article

Chilled station optimization operation based on TRNSYS simulation of an existing public building

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Abstract: Taking an existing public building as an example, on the basis of the measured data, the mathematical model of each equipment module of the chilled station and the TRNSYS custom module are established. The mathematical model of "chilled station cooling capacity—equipment power" is proposed and established. The full-frequency control strategy based on device contribution rate is proposed and established to set up the Matlab control module of the chilled station. The TRNSYS simulation platform is used to simulate a public building chilled station in cooling season. The result shows that the season energy efficiency rate of the public building air-conditioning system is 2.15 times the original after applying the new control strategy.

Keywords: chilled station, TRNSYS, control strategy, operational energy efficiency

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1. Introduction

32 domestic public buildings are researched only to find that the current air-conditioning system's chilled station equipment is mostly controlled by artificially changing the number of operating devices. The air-conditioning terminal is not adjusted and the automatic control system is in a paralyzed state actually.A small number of public buildings using automatic control systems still have the problem of low energy efficiency in air-conditioning projects.

Some scholars have conducted research on this, and research shows that the energy saving of a single device does not mean that the system is energy-efficient. The full conversion of the chilled station can significantly increase the energy efficiency of the system[1-5]. The Hopfield neural network (HNN) can be used to predict the chilled water supply temperature[6-8], simulated annealing algorithm, BP algorithm, and Sub-models and other optimization algorithms can solve the optimization problem of multidimensional nonlinear constrained central air conditioning systems, and thus obtain the set values of the most supervised control strategy control variable[9-16]. TRNSYS simulation platform can be used to calibrate experimental data and energy simulation of air-conditioning systems, and optimize control Strategy[17-22].

This article takes one of the public buildings used the automatic control system as the research object for analysis and calculation and the air conditioning system's terminal regulation is not considered. The optimal control strategy for the chilled station is studied in this article.

2. Research object

2.1. Basic information

This article examines an existing public building (hereinafter referred to as test building) in Dalian. The nameplate parameters of the air-conditioning system's equipment are shown in Table 1.

It is equipped with an air-conditioning automatic control system, a direct digital control system (DDC system), and chilled water. A flow bypass valve is provided between the inlet and outlet pipes, and the water supply amount is changed according to the set supply and return water temperature difference so as to adapt to changes in the system load. The cold season is from July 1 to September 30, a total of 92 days, and the operation time is 8:30 to 17:30 with the daily operation of 9 hours.

Table 1. The nameplate parameters of each equipment of the air condition system

Device name	Nameplate parameter
Chiller	Q=1383.2kW；N=265.7kW
Cooling water pump	G=319m³/h；H=27m；r=1450r/min；N=37kW
Cooling tower	G=320m³/h；cooling water37/32℃；N=5.5kW*2
Chilled water pump	G=262m³/h；H=33m；r=1450r/min；N=37kW
Fan coil	Total 280.32kW
VRV	Total 435.25kW

400 sets of operation data for the summer of 2017 were selected in order to analyze and calculate the operating characteristics of the building chilled station.

2.2. Operating characteristics

The operating characteristics of the air-conditioning system include the energy efficiency of a single device and the energy efficiency of the system. This article uses the chiller energy efficiency rating and the Season Energy Efficiency Rate in air-conditioning system(SEER) as the operating characteristic parameters. In order to test whether the SEER meets the design requirements, the air-conditioning engineering design energy efficiency ratio is introduced.

2.2.1. Chiller energy efficiency rating

The energy efficiency rate of chillers[23] is determined based on the coefficient of performance and the overall partial load performance coefficient, which are in turn divided into three levels of 1, 2, and 3, with the first level representing the highest energy efficiency. "Energy efficiency limit values and energy efficiency grades for chillers" (Chinese standard GB19577-2015) stipulates that the test value and labeling value of coefficient of performance (COP) and IPLV of water-cooled chillers should not be less than specified value corresponding to the energy efficiency class in Table 2.

Table.2. Water-cooled chiller energy efficiency rating

Nominal cooling capacity（CC） kW	Energy efficiency rate					
	1		2		3	
	（COP） W/W	（IPLV） W/W	（COP） W/W	（IPLV） W/W	（COP） W/W	（IPLV） W/W
CC≤528	5.60	7.20	5.30	6.30	4.20	5.00
528＜CC≤1163	6.00	7.50	5.60	7.00	4.70	5.50
CC＞1163	6.30	8.10	5.80	7.60	5.20	5.90

The nameplate calibration COP of the chiller unit is 5.20. The actual COP of the chiller at different host load rates during the test is shown in Fig.1.

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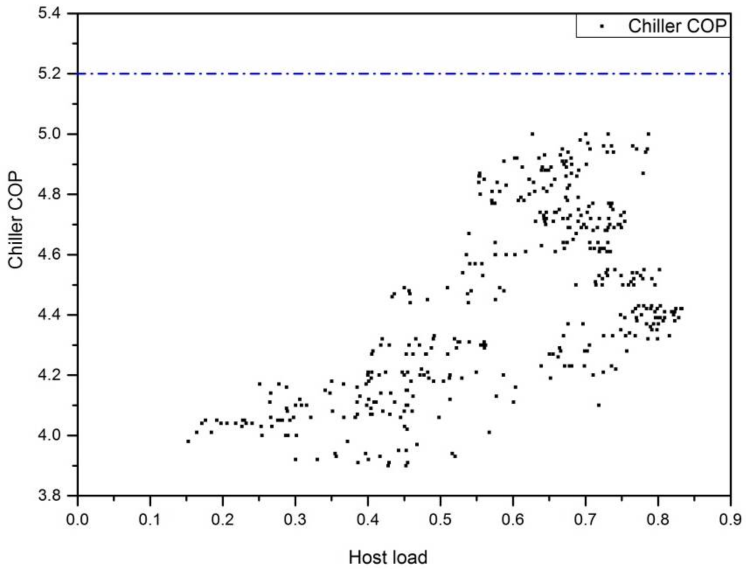

Figure 1. Chiller COP at different host load rates

- On the whole, the chiller COP increases with the increase of the host load rate, but there is no obvious relationship between the changes, and the operation energy efficiency of the chiller is not stable.
- The average COP of the chiller is 4.44, with a maximum value of 5.00, which does not reach the nameplate calibration value.
- The host runs 32.25% of the time below 50% load.

2.2.2. Design energy efficiency rate of air conditioning engineering(DEER)

The formula for DEER[24] is as follows:

$$DEER = \frac{\sum Q}{\sum N} \quad (1)$$

where $\sum Q$ is the design cooling load for air conditioning(kW), $\sum N$ is the total power consumption of air conditioning(kW).

"Limit of DEER" refers to the average of the design energy efficiency ratio of air-conditioning engineering for various types of cold source, and is the bottom line of the air-conditioning engineering design energy efficiency ratio. At present, there is no study on the DEER limits of office buildings in Dalian, but some scholars have studied the DEER limits of office buildings in Chongqing, as shown in Table 3.

Table.3. The DEER limits of office buildings in Chongqing

Cold source	Air-cooled heat pump chiller	Screw chiller	Centrifugal chiller	Variable frequency VRV air conditioning system	LiBr absorption chiller
DEER limits	2.40	2.89	3.25	2.20	2.60

Chongqing has high daytime temperatures in summer, the nighttime temperatures are hot and the outdoor environment is less comfortable. Research shows that DEER limits are higher in areas with higher outdoor comfort[24]. During the day in Dalian, the land temperature is high and the ocean is blowing wind from the sea to land; the nighttime wind blows from the land to the sea, and the comfort of the outdoor environment is higher. Therefore, the DEER limit in Dalian is higher than that in Chongqing.

The design cooling load of test building is 2350kW, so its DEER is equal to 1.66 according to formula (1) and Table 1, which is obviously does not meet the requirements of DEER limits for office buildings in Dalian.

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2.2.3. Seasonal energy efficiency rate of air conditioning engineering(SEER)

The formula for SEER[24] is as follows:

$$SEER = \frac{Q_n}{N} \quad (2)$$

where Q_n is the cold load at different partial load rates(kW), N is the total power consumption of air-conditioning works under partial load(kW).

The SEER is shown in Fig.2. after calculating.

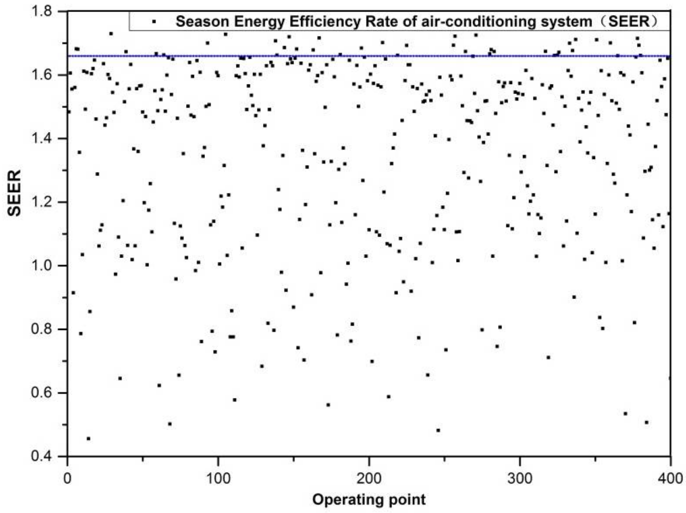

Figure 2. SEER of test building

The average SEER of the test buildings is 1.34, and it does not reach the design energy efficiency ratio at 90.25% of the operating conditions.

From the above analysis, it can be seen that the chiller has unstable operation energy efficiency, the DEER is lower than the limit value, and SEER cannot reach the design energy efficiency ratio. In the following, the mathematics model of equipment is established and the optimization strategy is proposed for the problems existing in existing public buildings. Simulations are performed using the TRNSYS simulation platform.

3. Mathematical models of chilled station equipment

According to the measured data, parameters of the equipment model can be identified. Parameter identification determines a set of parameter values based on the experimental data and the established model, so that the numerical results calculated by the model can best fit the test data so that the unknown process can be predicted. When the predicted results match the measured results, this model can be considered to have high credibility. The parameter identification of the model requires the least square estimation of the model parameters. The basic idea is as follows.

Find an estimate of θ defined as $\hat{\theta}$ so that the sum of the squares of the difference between the actual measurement Zi (i=1,..., M) and the measurement estimate which is $\widehat{Z_1} = H_i\hat{\theta}$ determined by the estimate is minimized.

3.1. Mathematical model of single equipment

Some scholars have studied the MP model of the chilled station equipment[25]. In this paper, the parameters of the equipment model are identified based on the measured data. The selected 400 sets of data are preprocessed, 250 sets of data are used to identify the parameters of the equipment model using Origin software, and 150 sets of data are used to test the accuracy of the model.

Taking the chiller as an example, the selected 250 sets of measured data are input into Origin to identify the parameters of the chiller model. After many iterations, the parameter estimation reaches the convergence criterion, and the obtained parameter value retains three significant digits are as follows.

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$$A = -0.00614,\ B = 0.856,\ C = -30.1,\ D = 477$$

So the chiller model obtained is:

$$N_1 = -0.00614k_1^3 + 0.856k_1^2 - 30.1k_1 + 477 \tag{3}$$

where N_1 is the chiller actual power(kW), k_1 is the chiller motor operating frequency(Hz).

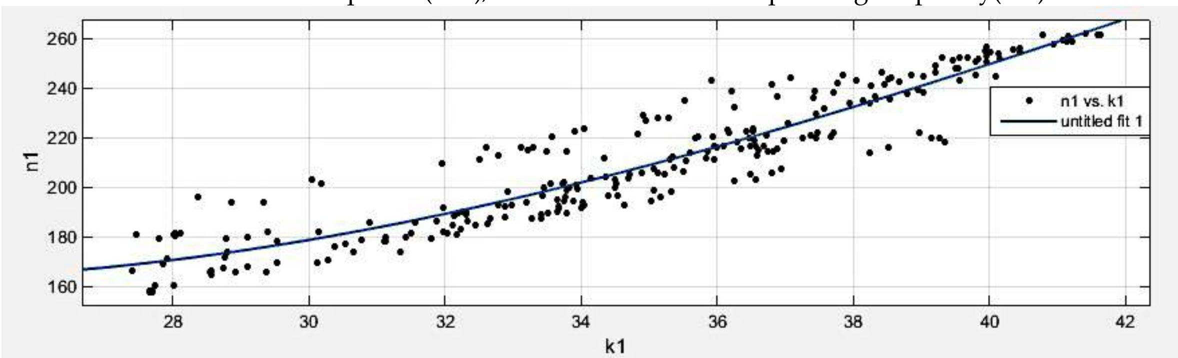

Figure 3. Chiller model fitting results graph

In order to further verify the accuracy of the model, the remaining 150 groups of measured data are used to predict and verify the chiller model that has completed parameter identification.

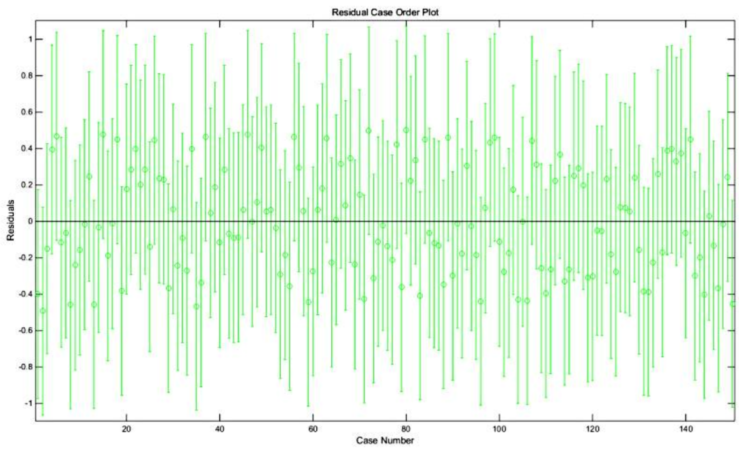

Figure 4. Chiller model fitting residual map

As can be seen from the figure,the relative error between the measured value and the predicted value can be kept within 5% in 150 sets of data. The error variance of the identified model is 0, and the correlation coefficient is 1, indicating that the identified model can accurately predict the measured data. Therefore, the identification model can be used in the subsequent study.

After the simulation and test, the residual values of the predicted values and actual values of other equipment models are all within 5%, and each equipment model is as follows.

$$H_2 = 0.00138k_2 + 0.00289G_2k_2 \tag{4}$$

$$\eta_2 = 0.0663k_2^{-2}G_2^2 - 0.247k_2^{-1}G_2 + 0.552 \tag{5}$$

$$N_2 = -4.46 \times 10^{-4}k_2^3 + 0.0874k_2^2 - 3.81k_2 + 55.0 \tag{6}$$

$$H_3 = 0.00819k_3^2 + 0.00173k_3G_3 - 0.000168G_3^2 \tag{7}$$

$$\eta_3 = -0.0561k_3^{-1}G_3 + 0.00192G_3 + 0.520 \tag{8}$$

$$N_3 = -6.10 \times 10^{-5}k_3^3 + 0.0124k_3^2 + 0.439k_3 - 11.8 \tag{9}$$

$$N_4 = \left(\frac{k_4}{k_{ct}}\right)^3 N_{ct} = 8.8\times10^{-5}k_4^3 \tag{10}$$

where H_2 is the chilled water pump head(m), G_2 is the chilled water pump flow(m^3/h), k_2 is the motor operating frequency of chilled water pump(Hz), η_2 is the chilled water pump efficiency(%), N_2 is the chiller water pump actual power(kW), H_3 is the cooling water pump head(m), G_3 is the cooling water pump flow(m^3/h), k_3 is the motor operating frequency of cooling water pump(Hz), η_2 is the

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cooling water pump efficiency(%), N_3 is the cooling water pump actual power(kW), N_4 is the cooling tower actual power(kW), k_4 is the motor operating frequency of cooling tower(Hz), k_{ct} is the motor rated frequency of cooling tower which is equal to 50(Hz).

3.2. Mathematical model between chilled station output cooling capacity and equipment power

This article proposes and establishes the "output cooling capacity - equipment power" (hereinafter referred to as "Cooling capacity - Power") model of the chilled station. It is assumed that the MP model is as follows.

$$Q = AN_1^B + CN_2^D + EN_3^F + GN_4^H + I \tag{11}$$

where Q is the output cooling capacity(kW), N_1 is the chiller actual power(kW), N_2 is the chiller water pump actual power(kW), N_3 is the cooling water pump actual power(kW), N_4 is the cooling tower actual power(kW), A/B/C/D/E/F/G/H/I is the model identification parameters.

Using the 400 sets of measured data to identify the parameters of the "Cooling capacity-Power" model, the results are as follows.

$$A = 672.228,\ B = 0.190,\ C = 473.245,\ D = -0.021,\ E = 724.859$$

$$F = 0.139,\ G = -987.326,\ H = -0.134,\ I = -1480.762$$

Thus the "Cooling capacity - Power" model is as follows.

$$Q = 672.228N_1^{0.19} + 473.245N_2^{-0.021} + 724.859N_3^{0.139} - 987.326N_4^{-0.134} - 1480.762 \tag{12}$$

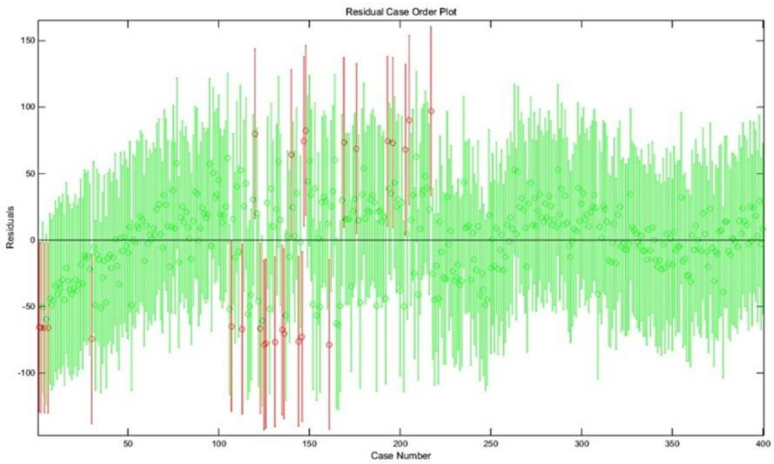

Figure 5. "Cooling capacity - Power" model fitting residual map

3.3. Chilled station optimization control strategy

At present, the air-conditioning engineering automatic control system is mostly PID control mode which structure is simple and stable. The PID control of the primary pump variable flow system makes the chilled station have a certain self-adaptive capacity for changes in the building load, but the central air conditioning system is nonlinear and has strong hysteresis. The system is in low control effectiveness when the building load changes greatly. A optimized control strategy is established based on the device contribution rate according to the "Cooling capacity - Power" model.

The device contribution rate is the ratio of the amount of change in cooling capacity to the amount of power change in a device when the cooling capacity changes. Taking a single chiller as an example, the rated cooling capacity is 500kW and the rated power is 300kW. When the cooling

 doi:10.20944/preprints201803.0249.v1

capacity reduces from 500kW to 480kW, the power of the chiller reduces from 300kW to 290kW. The contribution of the chiller is $\frac{500-480}{300-290}=\frac{20}{10}=2$.

Matlab is used to find the minimum power value of each device at a given cooling capacity.

The samples of the chilled station equipment are checked to obtain the input power variation range of each equipment. Simulation is done in the TRNSYS platform using the cold load module and the chilled station equipment module to output the temperature of the chilled water in and out of the chiller, the cooling capacity, the input power of each equipment, and obtain the temperature difference variation range of chilled water in and out of the chiller.

FunctionG is set in which the chilled water pump power, frequency, and flow are input. When using, N_2 is input and k_2 can be calculated according to equation(6), then functionG is called out to output the value of chilled water pump flow G_2.

Cooling capacity is represented by Q_{cc}, chiller power N1, chilled water pump power N2, cooling water pump power N3, cooling tower power N4, and the temperature difference of chilled water in and out the chiller is △t. Objective function $\min N = \min(N_1 + N_2 + N_3 + N_4)$.

The constraints are as follows.

$$\begin{cases} Q_{cc} = c\rho G_2 \Delta t \\ N_2 = -8.32\times10^{-4}k_2^3 + 0.122k_2^2 - 4.66k_2 + 58.8 \\ 3.12 \le \Delta t \le 5.46 \\ 119.16 \le N_1 \le 217.98 \\ 12.56 \le N_2 \le 24.01 \\ 14.68 \le N_3 \le 25.32 \\ 2.52 \le N_4 \le 8.42 \end{cases}$$

Under the condition of one chiller to one water pump to one cooling tower and no control module, the cooling capacity of the chilled station reduces from 1220kW to 1200kW. The cooling capacity and power of each device are shown in the table below.

Table.4. The cooling capacity and equipment power change of chilled station

Cooling capacity(kW)	**Actual input power of chilled station equipment(kW)**			
	Chiller	**Chilled water pump**	**Cooling water pump**	**Cooling tower**
1220	213.39	19.28	24.60	6.60
1200	209.52	18.97	24.50	5.96
Device contribution rate	5.17	65.13	190.56	31.37

It can be seen that when the cooling capacity is 1200 kW, the ratio of the cooling capacity to the total input power of the chilled station equipment (chilled station COP) is 4.63. The chiller has the lowest contribution rate, and the cooling water pump equipment has the highest contribution rate. Therefore, increase the input power of the chiller and reduce the input power of the cooling water pump to find the minimum total input power with cooling capacity of 1200kW.

Matlab is used to find the optimal value and the result is shown in table. 5. When the input power of the device is as follows, the cooling capacity is guaranteed to be 1200 kW and the total input power of the device is the minimum.

Table.5. The minimum input power of chilled station equipment under the same cooling capacity of 1200kW

Device	**Chiller**	**Chilled water pump**	**Cooling water pump**	**Cooling tower**
Input power(kW)	211.52	17.41	22.73	4.73
Device contribution rate	10.70	10.71	10.69	10.71

The chilled station COP is 4.74 after optimization, which is 1.00% higher than before. It can be seen that the device contribution rate of each equipment is basically the same. In order to test whether the optimal value of device contribution rate is always the same or not under different cooling capacity, cooling capacity from 1220kW to 1180 kW, 1160kW and 1140kW are verified and the results are as follows.

Table.6. Device contribution rate under different cooling capacity

Cooling capacity(kW)	**Actual input power of chilled station equipment(kW)**					**Chilled station COP**
	Chiller	Chilled water pump	Cooling water pump	Cooling tower	Total power	
1180 before fixing	207.24	18.87	24.48	5.90	256.49	4.60
Device contribution rate	6.50	98.36	330.49	57.34		
1180 after fixing	210.41	16.30	21.62	3.62	251.95	4.68
Device contribution rate	13.42	13.44	13.42	13.43		
1160 before fixing	206.96	18.66	23.97	5.98	252.58	4.59
Device contribution rate	9.33	97.30	95.08	194.29		
1160 after fixing	209.96	15.86	21.19	3.18	250.19	4.64
Device contribution rate	17.49	17.56	17.59	17.56		
1140 before fixing	205.59	18.32	23.92	5.09	252.58	4.51
Device contribution rate	2.44	144.93	90.84	106.75		
1140 after fixing	209.59	15.48	20.61	2.81		4.59
Device contribution rate	21.05	21.07	20.04	21.12	248.49	

It can be seen that the optimal value of device contribution rate is the same and the chilled station COP increases by 1.80%, 0.96%, and 1.65% with the cooling capacity 1180kW, 1160kW, and 1140kW at this condition. Thus it can be concluded that the chilled station COP is the highest when the freezing plant device contribution rate is the same in the case of a certain amount of cooling capacity, and the optimal control strategy is established base on this.

Taking the seasonal energy efficiency ratio (SEER) as the objective function, a new chilled station control strategy based on the device contribution rate is established combined with the "Cooling capacity-Power"model.

According to the known "Cooling capacity-Power" model, the device contribution rate of each equipment is as follows.

Table.7. Device contribution rate of chilled station equipment

Device	**Device contribution rate**
Chiller	$\frac{\partial Q}{\partial N_1} = 52.805 N_1$
Chilled water pump	$\frac{\partial Q}{\partial N_2} = 839.640 N_2$
Cooling water pump	$\frac{\partial Q}{\partial N_3} = 20.628 N_3$
Cooling tower	$\frac{\partial Q}{\partial N_4} = 47.607 N_4$

The device contribution rate is the same which is $\frac{\partial Q}{\partial N_1} = \frac{\partial Q}{\partial N_2} = \frac{\partial Q}{\partial N_3} = \frac{\partial Q}{\partial N_4}$, so that

$$52.805 N_1 = 839.640 N_2 = 20.628 N_3 = 47.607 N_4 \tag{13}$$

The chilled station control strategy is as follows

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- The cooling load changes when the outdoor weather conditions change, so that the cooling capacity is known.
- In conjunction with function (12) and (13), the input power of chilled station equipment can be obtained.
- According to the "power-frequency" model of the equipment obtained in 3.1., the equipment frequency can be calculated.
- Adjust the device frequency according to the calculation result.

After obtaining the equipment mathematical models, a device customization module can be set up in the TRNSYS simulation platform. In combination with the control strategy based on the device contribution rate, the TRNSYS simulation platform is used to simulate the energy consumption of the chilled station.

4. TRNSYS simulation platform of chilled station based on device contribution rate

Chilled station model is established in the TRNSYS simulation platform which includes a building cooling load module, a device customization module, a Matlab control module, a weather file input module, and a result output module.

4.1. Building cooling load module

Walls, windows and internal heat source are edited in the Type56 module to build a building cooling load model.

4.1.1. Architectural basic information

The test building is an office building, in which the offices and meeting rooms are air-conditioned areas and the corridors, elevator rooms are non-air-conditioned areas. The building is 84m high, the roof heat transfer coefficient is 1.96W/(m^2 • K), and the external wall heat transfer coefficient is 1.18W/ (m^2 •K). The window-wall ratio is 0.29 in the north, 0.37 in the south, 0.06 in the west, 0.06 in the east, and the heat transfer coefficient of the external window is 4.8 W/(m^2 • K). The external wall area of air-conditioned and non-air-conditioned areas is shown in Table 8.

Table.8. External wall area in each orientation

Area	External wall area（㎡）			
	North	South	West	East
Air-conditioned area	2066.4	2688	1142.4	1411.2
Non-air-conditioned area	621.6	0	705.6	436.8

4.1.2. Architectural related parameters

The chilled station opening time of test building is from July 1st to September 30th each year for a total of 92 days. It runs 5 days a week and the daily operation time is 8:30-17:30.

The USE Weekly Planning Mode is used to set the schedule in the TRNSYS model in which Monday to Friday are the working days, and Saturday and Sunday are the rest days. The initial temperature of the air conditioning zone is set at 20℃ and the initial relative humidity is set at 50%.

The number of people, labor intensity, equipment, lighting, and lighting density are set according to actual conditions.

4.1.3. Temperature and load analysis of the building cooling load module

Only cooling season is simulated in this article so the TRNSYS simulation time of the chilled station is 4344h to 6552h. Assembly-Control cards are selected in the TRNSYS operation interface to change the simulation time and the output interface display temperature is changed from 0 to 40℃.

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The temporary change graphs of temperature and cooling load can be output after connecting the online plotter.

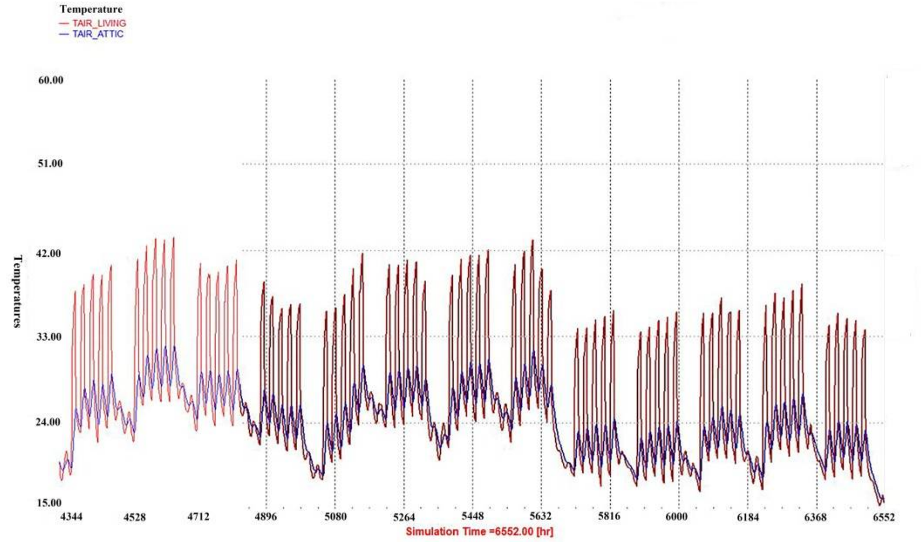

Figure 6. Temperature temporary change without cooling

Fig. 6 shows the temperature temporary change of the room in the cooling season when the air is not cooled. Red is the air-conditioned area and blue is the non-air-conditioned area.

- The average temperature of 4344h-5632h is higher than the average temperature of 5632h~6552h, because the outdoor temperature in July and August is higher than the outdoor temperature in September.
- The temperature in the air-conditioned zone is higher than that in the non-air-conditioned zone. There are people and equipment loads in the air-conditioned zone, so the internal heat sources is more than that in the non-air-conditioned zone.
- The temperature curve has obvious regularity that two wavelet peaks and five large wave peaks are repeated for one cycle. Two wavelet peaks are the hottest in the afternoon on Saturday/Sunday and the five big crests are the hottest days in the afternoon from Monday to Friday. The peaks from Monday to Friday are significantly higher than that on Saturday/Sunday. The reason is that there is no personnel and equipment load on Saturday/Sunday, and the temperature is low, which is consistent with the USE plan set in the Schedule.

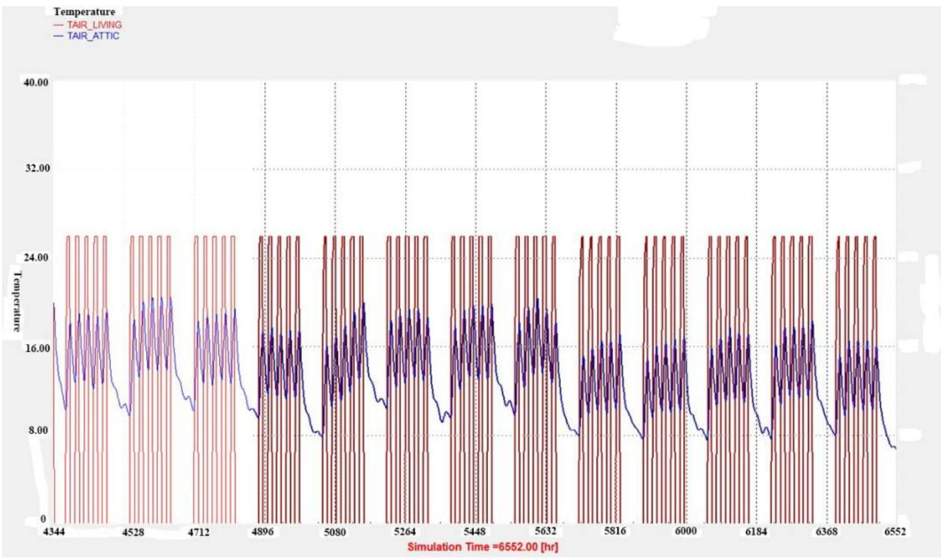

Figure 7. Temperature temporary change with cooling

Figure 7 shows the temperature temporary change of the room temperature in the cooling season during the cooling period. The room temperature in the air-conditioning area is 26℃ during the day and the room temperature decreases at night, which meets the USE plan in Cooling.

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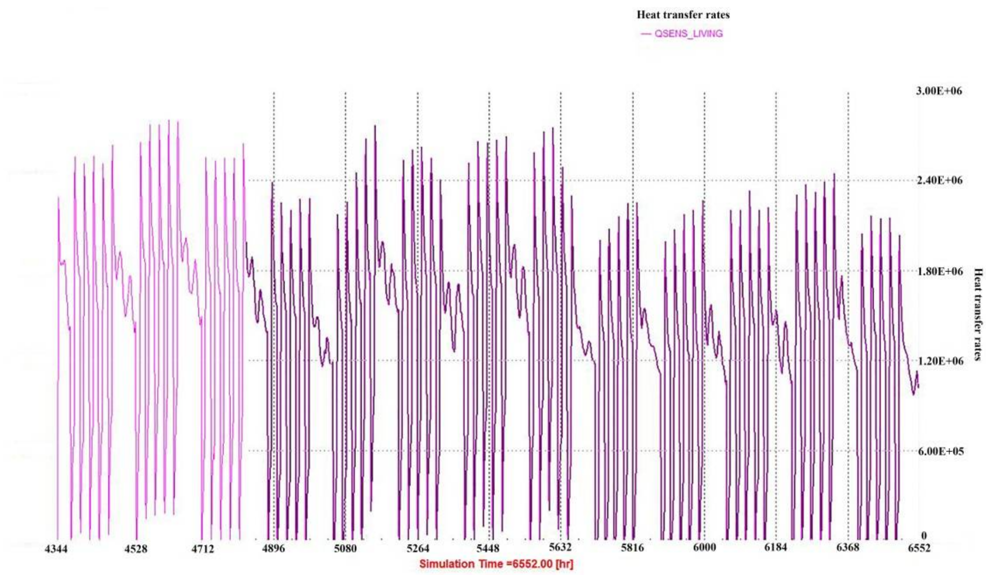

Figure 8. Cooling load temporary change in air-conditioned area

Figure 8 shows the cooling load temporary of the air-conditioned zone during cooling season. The cooling load in the air-conditioned zone in July and August is greater than that in September.

It can be concluded that the simulation results are in line with the actual situation from the above analysis, indicating that the building model in Type56 is well established.

4.2. Chilled station equipment customization module

The established mathematical model of the freezing station equipment was used to replace the model contained in the software when establishing a chiller module in the TRNSYS simulation platform. The model was programmed to create a custom module embedded in the TRNSYS simulation platform.

4.2.1. Chiller module

The operation parameters of chiller include chilled water inlet unit temperature T_{chi}, chilled water outlet unit temperature T_{cho}, chilled water flow G_{ch}, cooling water inlet unit temperature T_{ci}, cooling water outlet unit temperature T_{co}, cooling water mass flow G_c, chiller operation energy efficiency COP, operating power $P_{chiller}$, cooling capacity Q_e, rated cooling capacity Q_{ch}, and cooling load Q_{load}. In addition, the chiller also includes a model identification parameter k1 and a chiller control signal S_c.

Custom module in TRNSYS includes three tabs that must be set: model parameters, input parameters and output parameters, which are as shown in Table.9.

Table.9. Custom chiller module parameters

Model parameters	N、Q_{ch}、k_1
Input parameters	T_{chi}、T_{ci}、G_{ch}、G_c、Q_{load}、S
Output parameters	T_{cho}、T_{co}、G_{ch}、G_c、COP、Q_e、$P_{chiller}$

- Modeling steps

A chiller module Type250 that can be used for TRNSYS simulation is established after determining the various parameters required for a custom chiller module. The steps are as follows.

1. All variables are set according to the analysis results of the chiller operating parameters and the module is saved as "Type250.tmf".
2. The C++ program framework is exported and the calculation program is established for the chiller module. The flow chart is shown below.

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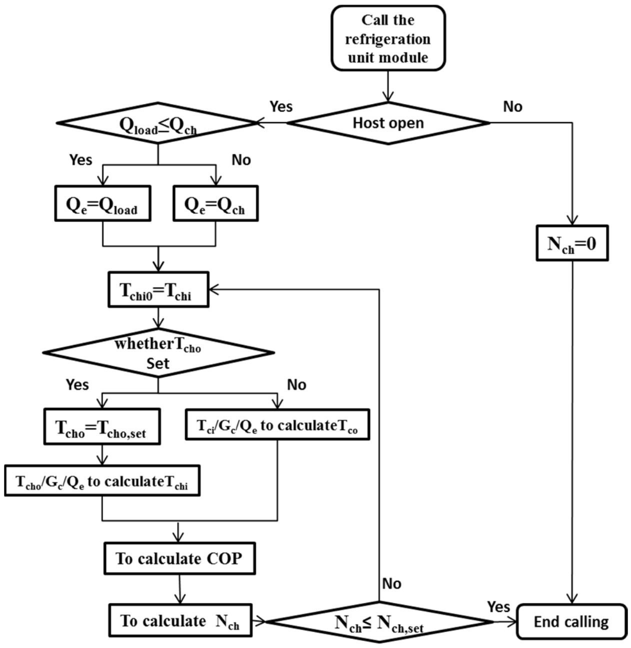

Figure 9. Custom chiller module program flow chart

3. After changing the source program, "Type250.dll" is generated under the "./Trnsys/UserLib" directory, and TRNSYS loads the file here. Update "Direct Access/Refresh tree" to make it appear in the component module tree on the right side of the interface. At this point, the chiller module is established and can be directly called during simulation.

- Module accuracy verification

Taking a single chiller as an example, the cooling load, the flow rate of chilled/cooling water, and the return temperature of chilled/cooling water were given as input parameters. The chiller module is used to predict the COP and other parameters of the chiller. Select 109 sets of operation data on July 23, 2017 to verify the accuracy of the chiller module.

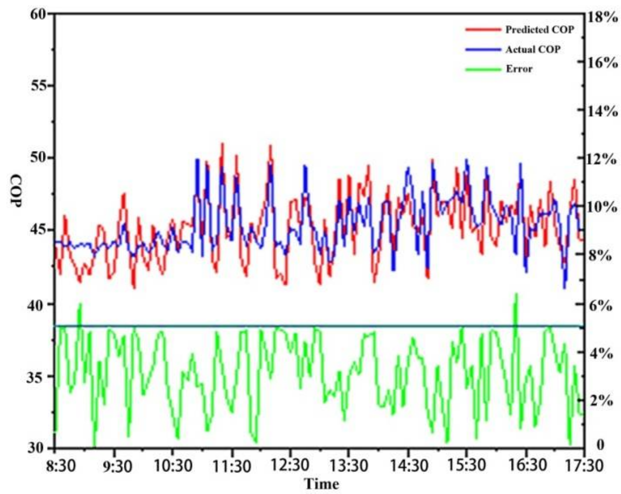

Figure 10. Chiller module prediction COP

There are only 2 points where the module prediction COP and the actual COP error are greater than 5%. That is, the COP prediction accuracy of the chiller module is above 95% with a probability of 98.16%.

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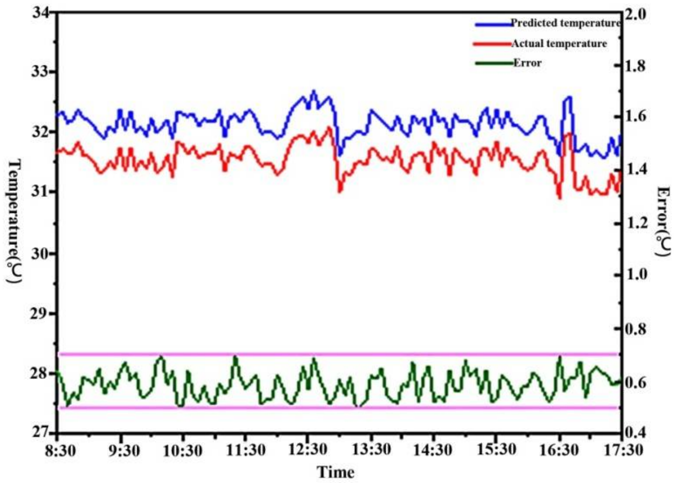

Figure 11. Chiller module prediction cooling water outlet temperature

The module predicts that the cooling water outlet temperature of the chiller is lower than the actual temperature, cause the cooling water does not absorb heat from the outside during modeling, and the actual condensing heat of the chiller is greater than the sum of the chiller power and cooling capacity, so the actual outlet water temperature is high. The cooling water outlet temperature error between the predicted and actual values of the module is between 0.5 and 0.7℃.

It can be concluded that the accuracy of the chiller module is high enough and can be used for the following simulation from the above analysis results.

4.2.2. Chilled water pump module

The method of establishing the water pump module is almost the same as that of the chiller. The required parameters are shown in the Table.10.

The relevant operation parameters of water pump include inlet water temperature T_i, outlet water temperature T_o, flow rate G, frequency k, head H, efficiency η, power N, model identification parameters k, G and control signal S.

Table.10. Custom chilled water pump module parameters

Parameters	Chilled water pump	Cooling water pump
Model parameters	Rated power N_{ch}、rated flow G_{ch}、rated head H_{ch}、model identification parameters	Rated power N_c、rated flow G_c、rated head H_c、model identification parameters
Input parameters	G_2、k_2、S	G_3、k_3、S
Output parameters	N_2、η_2、H_2	N_3、η_3、H_3

4.2.3. Cooling tower module

The relevant operation parameters of cooling tower include tower inlet temperature T_{co}, outlet tower temperature T_{ci}, cooling water flow rate G_c, fan frequency k, model identification parameter k, and control signal S.

Table.11. Custom cooling tower module parameters

Model parameters	Rated power N_{ct}、rated flow G_{ct}、rated frequency k_{ct}、model identification parameters
Input parameters	G_3、k_4、S
Output parameters	N_4

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4.2.4. Matlab control module

According to the chilled station control strategy based on the device contribution rate, the Matlab control module is programmed, and the communication between TRNSYS and Matlab is realized through the COM interface. Matlabt compiles the m file into a COM component, and TRNSYS can directly call the m file. At the beginning of the TRNSYS simulation, TRNSYS will read the simulation start time, end time, and simulation step size of the input file; when calling the m file, TRNSYS simulation pauses and waits for Matlab to process the result. Matlab simulation stops at the end of Matlab processing, and TRNSYS reads the simulation results and continues to simulate. It is done alternately until the end of the simulation.

4.3. Chilled station TRNSYS simulation platform

Create an empty project, add the selected component to the project, set the parameters of each component according to the previous requirements, connect the components, and establish a simulation platform based on the joint operation of TRNSYS and Matlab.

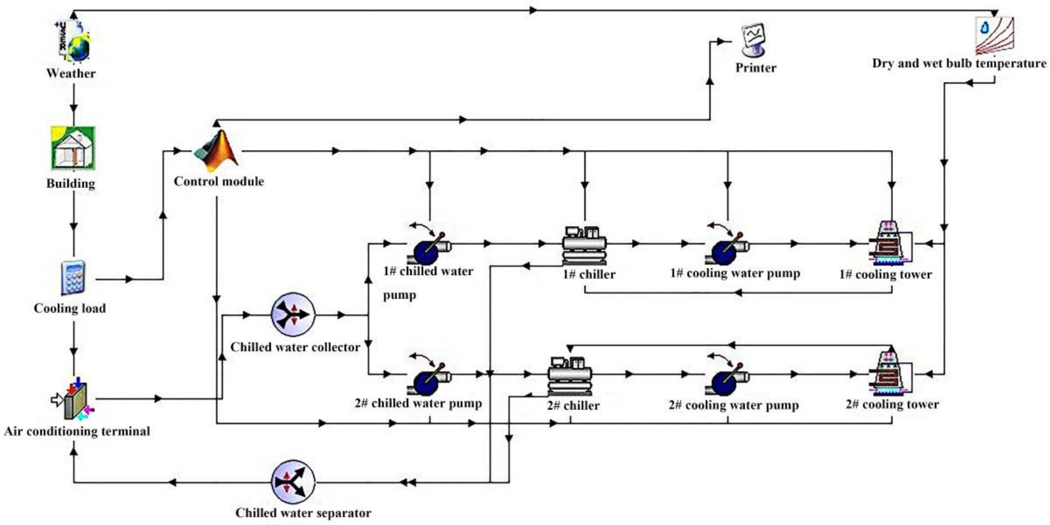

Figure 12. Chilled station TRNSYS simulation platform

The chilled station TRNSYS simulation platform has been established which can be used to simulate the energy consumption of the chilled station and calculate the SEER based on the optimal control strategy.

5. Optimization effect analysis of chilled station based on SEER

The chilled station TRNSYS simulation platform was used to simulate the energy consumption of the freezing station from July 1 to September 30 (corresponding to the TRNSYS simulation platform 4344h~6552h), and the SEER based on the device contribution rate was calculated.

Temporary cooling load of the test building is shown below.

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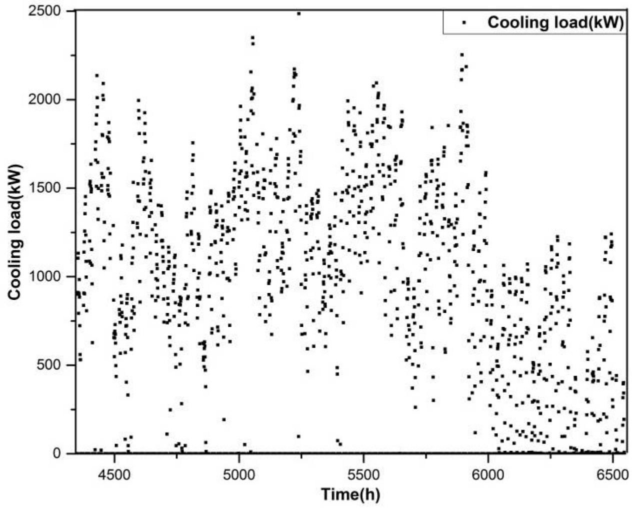

Figure 13. Temporary cooling load simulation result of the test building

Temporary energy consumption of the air-conditioning system is shown below.

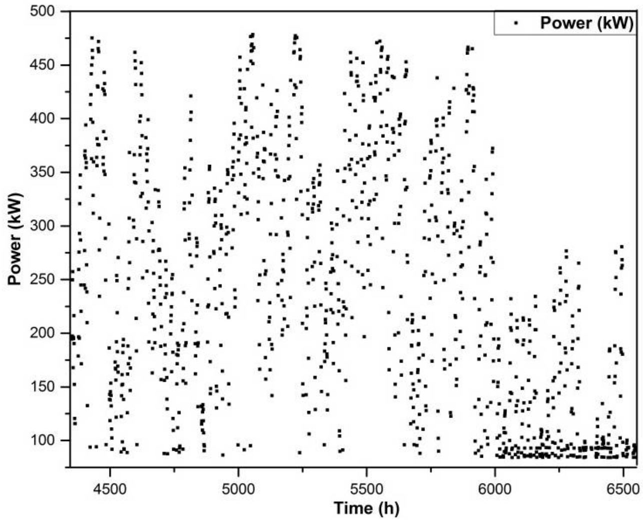

Figure 14. Temporary energy consumption of the air-conditioning system

The temporary SEER is shown below.

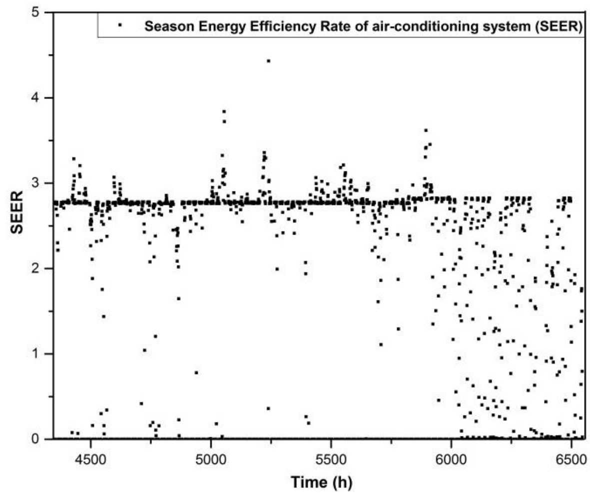

Figure 15. Temporary energy consumption of the air-conditioning system

It can be seen that the SEER is around 2.75 in July/August and fluctuates stably. In September, the SEER is not stable as that in July/August, which results in a decrease in the average SEER value.

According to the simulation results of the chilled station, the monthly SEER distribution based on the control strategy of device contribution rate of the test building is shown in the following figure.

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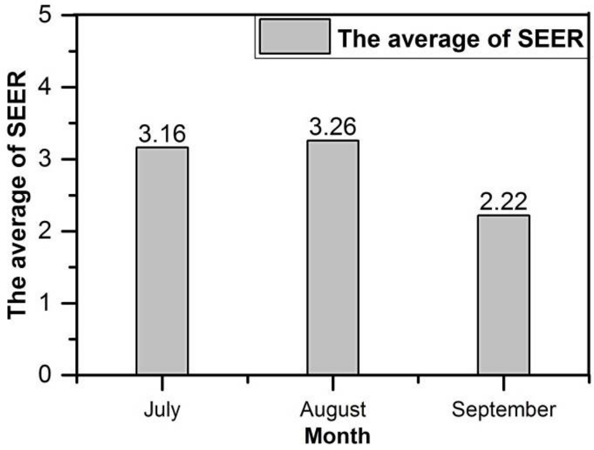

Figure 16. Monthly SEER based on the control strategy of device contribution rate

The test building is simulated using a control strategy based on device contribution rate and the results show that the average SEER during the cooling season is 2.88. The highest average SEER is 3.26 in August, and the lowest is 2.22 in September. The value of SEER based on the device contribution rate is 2.15 times of the current SEER, indicating that the control strategy is effective and worthy of further research and promotion.

6. Conclusions

A new chilled station control strtegy is proposed in this article which is based on the device contribution rate and its TRNSYS model is established to simulate energy consumption. SEER is used as an evaluation index to verify the effectiveness of the control strategy.

- A mathematical model of "chilled capacity - equipment power" of the chilled station is proposed and established with a correlation coefficient of 0.9917 which is
$$Q = 157.157N_1^{0.336} - 351.167N_2^{-2.391} + 26.278N_3^{0.785} - 750.897N_4^{-0.0634} + 342.692$$
- Matlab is used to find the power value of each device that minimizes the total power input of chilled station in the case of a given cooling capacity. The optimal value of device contribution rate is the same and the chilled station COP increases by 1.80%, 0.96%, and 1.65% with the cooling capacity 1180kW, 1160kW, and 1140kW at this condition. The energy consumption of the chilled station is the smallest when the device contribution rate is the same and the SEER is the highest in the case of a certain amount of cooling capacity.Based on this, the whole frequency conversion control strategy of the chilled station based on the device contribution rate is proposed, and the Matlab control module is loaded into the TRNSYS simulation platform to simulate the test building.
- The actual SEER of test building is 1.34 during the cooling season. The whole frequency conversion control strategy of the chilled station based on the device contribution rate is applied to TRNSYS platform to simulate energy consumption. The simulation result shows that the average SEER is 2.88 which is 2.15 times of the current value.

Acknowledgments: The authors gratefully acknowledge the National Natural Science Foundation of China (numbered 51638003) and the Fundamental Research Funding for Central Universities (numbered DUT17RW118) for the cost of research.

Author Contributions: Baogang Zhang contacted the site survey. Chang Sun carried out the mathematical models of equipment and the "cooling capacity – power", established the chilled station TRNSYS platform. Ming Liu checked and revised the manuscript. Lin Lv participated in field tests.

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

References

1. Liu G.D.; Ma W.W.; Liu Q.Y. Energy consumption analysis of air conditioning cooling water pumps by variable frequency speed regulation. National HVAC Refrigeration 2010 Annual Conference Proceedings, 2010.
2. Shuang L. Full-frequency conversion and energy-saving analysis of cold station system. *Refrigeration and air conditioning* **2015**, *35(12)*, 48-51.
3. Bahnfleth W.P.; Peyer E.B. Energy Use and Economic Comparison of Chilled-Water Pumping System Alternatives. *ASHRAE transactions* **2006**, *112(2)*.
4. Fangyuan L. Cooling Tower Fan Frequency Control and Energy Saving. *Fan technology* **2007**. *2*, 57-59.
5. Thomas Hartman. P.E. New 'LOOP' chiller plant uses advanced technologies to achieve big cost reductions. Joint ASHRAE/AEE Technical Seminar, Edmonton, Alberta November, 1999.
6. Yang Q.; Zhu J.; Xu X., et al. Simultaneous control of indoor air temperature and humidity for a chilled water based air conditioning system using neural networks. *Energy and Buildings* **2016**, *110*, 159-169.
7. Chang Y.C.; Chen W.H. Optimal chilled water temperature calculation of multiple chiller systems using Hopfield neural network for saving energy. *Energy*, **2009**, *34(4)*, 448-456.
8. Yang Q.; Zhu J.; Xu X., et al. Simultaneous control of indoor air temperature and humidity for a chilled water based air conditioning system using neural networks. *Energy and Buildings*, **2016**, *110*, 159-169.
9. Wenping C.; Changzhi Y. and Yuansheng Y. Central air-conditioning water system optimization control based on chiller performance curve. *Fluid machinery* **2008**, *36(8)*.
10. Houjian H. Research on Modeling and Optimization of Central Air Conditioning Water System. Master, Shenyang University of Technology, Shenyang, 2005.
11. Zimmer H. Chiller control using on-line allocation for energy conservation]. ISA Annual Conference, Houston, USA, 1976.
12. Cho C.H.; Norden N. Computer optimization of refrigeration systems in a textile plant: a case history. *Automatica* **1982**, *18(6)*, 675-683.
13. Braun J.E. Methodologies for the design and control of central cooling plants. Master, University of Wisconsin-Madison, Wisconsin, 1988.
14. Braun J.E; Klein S.A.; Beckman W.A. Methodologies for optimal control of chilled water systems without storage. *ASHRAE transactions* **1989**, *95*, 652-662.
15. Chen C.W.; Chang Y.C. Support Vector Regression and Genetic Algorithm for HVAC Optimal Operation. *Mathematical Problems in Engineering* **2016**.
16. Ahn B.C.; Mitchell J.W. Optimal control development for chilled water plants using a quadratic representation. *Energy and Buildings* **2001**, *33(4)*, 371-378.
17. Chen D.D. Study on Real-time Optimization Control Strategy of Central Air Conditioning Variable Water System. Master, Shanghai Jiao Tong University, Shanghai, 2007.
18. Zhang L. Research on Energy Saving Reform of a Central Air Conditioning System. Master, Harbin institute of Technology, Harbin, 2013.
19. Gao J.; Huang G.; Xu X. An optimization strategy for the control of small capacity heat pump integrated air-conditioning system. E*nergy Conversion and Management* **2016**, *119*, 1-13.
20. Wu S.H. Design and Implementation of Group Control System of Freezing Room. Msater, East China University of Science and Technology, Shanghai, 2014.
21. Bursill J.; Cruickshank C.A. Heat Pump Water Heater Control Strategy Optimization for Cold Climates. *Journal of Solar Energy Engineering* **2016**, *138(1)*, 011011, 10.1115/1.4032144
22. Ahn B.C.; Mitchell J.W. Optimal control development for chilled water plants using a quadratic representation. *Energy and Buildings* **2001**, *33(4)*, 371-378.
23. Jia P. Brief Analysis of GB19577-2015 "Cold Energy Efficiency Limit Value and Energy Efficiency Grade of Chillers". *Air conditioning HVAC technology* **2016**, *4*, 32-33.
24. Yang L.N. Research on Energy Efficiency Ratio of Air Conditioning Projects in Public Buildings. Master, Chongqing University, Chongqing, 2007.
25. Zhang B.G.; Wang T.X.; Liu M. Establishment of chilled water system model based on monitoring data. *Low-temperature building technology* **2017**, *39(8)*, 148-151.