FULL-SCALE EXPERIMENTAL INVESTIGATION OF A CHILLER PLANT IN ADAPTING OPTIMAL OPERATION STRATEGY FOR ENERGY CONSERVATION IN HI-TECH INDUSTRY

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ABSTRACT

In semi-conductor industry, the chiller plant is the major power consumption source of all supporting facilities. In this study, a chiller plant was selected to perform energy-efficient operation strategies to yield over 3% energy savings verified by the full-scale experiment. The development of the experimental model utilizes the ASHRAE Guideline 14-2002 as a tool, and integrated with the BEMS system to perform a remote real time online energy auditing system, on which intelligent operational strategy has been implemented.

1. INTRODUCTION

The SEMICON Conference held in Taiwan 2008, CEO Summit report indicated that during the past decade, power consumption of a typical semiconductor plant has been doubled from an average of 12.7 MW up to 23.6 MW, as shown in Fig. 1. Among them, production tool accounts for 50.1% of total power consumption, while the HVAC plant accounts for 20.1% of it. The production tools consume power after the manufacturing process and layout was fixed and cannot be changed easily. On the other hand, the chiller plant has acquired tremendous opportunity for energy-savings, due to its flexibility to meet the fluctuating load conditions.

Conventionally, a chiller plant was operated according to the return water temperature to judge whether a specific chiller should be put into or withdrawn from service to meet the fluctuating cooling load. The choice was made sometimes randomly, or in a rotational order, to make all chillers share loads evenly during their life spans.

Actually, each chiller has its own specific thermal performances which can be identified by the real time online auditing through the Building Energy Management System, or simply BEMS. If energy-efficient chillers can be put into service in a sequential order, power consumption of the chiller plant can be reduced significantly. The key point lies in that an experimental model should be developed first, to fit the operational data into a curve, which stands for the performance index of a specific chiller, and can be easily identified by the BEMS system. So that, during load fluctuating period, the better-performed chillers can be operated sequentially to meet the load and an intelligent operational strategy can be implemented.

In this study, this methodology has been exercised on an IC fab, followed by a full-scale experiment to validate its effectiveness.

2. DEVELOPMENT OF THE EXPERIMENTAL MODEL FOR THE CHILLER PERFORMANCES

A chiller thermal performance can be easily identified with its COP, or Coefficient of Performance. A high-COP chiller implies that it can be operated with less power consumption in generating a specific cooling capacity. In commercial HVAC industry, a typical 1000RT centrifugal chiller will have a COP value at around 6.0, or a specific power consumption of 0.58 to 0.6 kW per refrigeration ton. In Taiwan, the COP value of chillers has been regulated as a criteria and a requirement for the chiller manufacturers to meet, before their products can open to the market. Table 1 indicated this standard, issued by the Bureau of energy of Taiwan in 2005.

The predominant factors in affecting chiller thermal performances can be identified as the following, namely:

1. Chilled water supply temperature, T_{chsw} (°C)
2. Chilled water return temperature, T_{chwr} (°C)
3. Chilled water flow rate M1 (lpm)
4. Chiller power consumption, P1 (kW)
Fig. 1: Fab energy pie chart indicated that energy consumption in making a wafer has been doubled in the past decade

Table 1: Chiller COP criteria issued by the Bureau of Energy Taiwan

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<tr>
<th>Execution phases</th>
<th>First phase</th>
<th>Second phase</th>
</tr>
</thead>
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<td>Effective Date</td>
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<td>01.01.2005</td>
</tr>
<tr>
<td>type</td>
<td>(EER) kcal/h • w</td>
<td>(COP)</td>
</tr>
<tr>
<td>Water-cooled</td>
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</tr>
<tr>
<td>Pistons, and screws</td>
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<td>3.50</td>
</tr>
<tr>
<td></td>
<td>≥150RT ≤500RT</td>
<td>3.60</td>
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<tr>
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<td>4.00</td>
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<td>≥150RT ≤300RT</td>
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<td>4.77</td>
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<tr>
<td>Air-cooled</td>
<td>All units</td>
<td>2.40</td>
</tr>
</tbody>
</table>
These data are normally readily available and displayed on a BEMS system and can be shown in Fig. 2.

Fig. 2: The chiller plant operational data displayed on the BEMS system in this study

In addition, a chiller cooling capacity \( Q_{\text{evap}} \) can be calculated by the following equation:

\[
Q_{\text{evap}} = M_1 \cdot C_p \cdot (T_{\text{chwr}} - T_{\text{chwa}})
\]  

(1)

where \( C_p \) is the specific heat of water, and is 1 kcal/kg °C.

The cooling capacity can be further denoted in RT, or Refrigeration Tons, by unit conversions, where 1 RT is equivalent to 3.516 kW.

The ASHRAE Guideline 14-2002, provides a useful tool in correlating chiller COP value with the predominant parameters, and can be formulated as:

\[
1/\text{COP} = -1 + T_{\text{cwrt}} / T_{\text{chwr}} + [-A_0 + A_1 \times T_{\text{chwr}} - A_2 \times \left( T_{\text{chwr}} / T_{\text{chwa}} \right)] / Q_{\text{evap}}
\]

(2)

where \( A_0 \), \( A_1 \), and \( A_2 \) are coefficients to be determined [1].

The COP values obtained from the above equation results in better accuracy due to the fact that it was generated from experimental data. The deviation was normally kept within 5%, since the inaccuracy was mainly incurred during the curve-fitting process.

3. ESTABLISHMENT OF THE ENERGY-EFFICIENT OPERATION-AL STRATEGIES

Following the identification of energy efficiency of each chiller through the BEMS system, operational strategy can then be developed accordingly to reach optimization.

The BEMS system provides a real time online platform to audit energy efficiency of each chiller, so that a sequential order in operating higher efficiency chillers can be established. This procedure develops a default operational mode to meet the fluctuating cooling load. But this strategy is over-simplified in operating a group of chillers.

Chiller performance varies with its part load factor or PLF. Especially, different number of chiller units operating in tandem, can results in different PLF for each chiller, and thus results in total power consumption.

Therefore, further advanced operation model needs to be developed, in considering different combination of chiller units available, to reach a minimum total power consumption.

The specific operational curves generated earlier by the BEMS system for each chiller facilitated good tool in evaluating various combination matrix, and comes up with the optimal solution. This was not possible conventionally, even by the most-experienced HVAC engineer, to perform instantly on the jobsite manually.

4. FULL-SCALE EXPERIMENTAL INVESTIGATION

In this study, a chiller plant consisting of 14 centrifugal chillers, each with 1250 RT cooling capacity was selected for experiment. Two out of the fourteen chillers are spare units. In a typical summer day, eight chiller units were put into service as the base load, maintaining a redundancy capacity of 15%, to avoid a sudden interruption of cooling which might cause the cleanroom losing its stringent indoor environmental conditions. This excessive cooling capacity caused part of the chillers to operate under lower PLF and thus suffering from lower energy efficiency. With the eight units running and two units for spare, there still leaves four chillers to add on to meet the fluctuating load. This excessive cooling capacity will cause part of the chillers to operate under even lower PLF and thus suffering from lower energy efficiency. On the other hand, it also provided the opportunity to optimize its total power consumption by running with different chiller combinations.

Step 1 Establishing Chiller Operating Priorities

Based on the BEMS system operational data, each of the fourteen chillers performance curve was generated on site, enabling the default operating priority to be established. They are, in higher
energy efficiency order, CH-11, CH-2, CH-9, CH-12, CH-10, CH-5, CH-4, CH-1, CH-6, CH-7, CH-8, CH-13, CH-3 and CH-14, with their COPs listed in Table 2.

In a hot summer day, the cooling load in this plant is approximately 13,000RT. To meet this load, several combination of operating multiple chillers could be established resulting in different total power demands, as listed in Tables 3 to 6, named as strategy 1 to 4.

It indicated that the strategy 3, with the CH6, CH8 and CH3 running at 70%, 90%, and 80% PLF respectively, results in the lowest additive power demand of 2046 kW.

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<td>6.0</td>
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<td>5.4</td>
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<td>5.3</td>
</tr>
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<td>CH-3</td>
<td>4.9</td>
<td>4.6</td>
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</tr>
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Table 2: Ranking of the chiller energy COPs in this study

<table>
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<tr>
<th>Strategy 1</th>
<th>CH-6(100%)</th>
<th>CH-7(90%)</th>
<th>CH-8(50%)</th>
<th>CH-3(0%)</th>
<th>additive power demand (kW)</th>
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</thead>
<tbody>
<tr>
<td>0</td>
<td>803</td>
<td>804</td>
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Table 3: Simulation result of Operation Strategy 1, in adding on CH6, CH7, CH8 chillers
### Table 4: Simulation result of Operation Strategy 2, in adding on CH6, CH7, CH3 chillers

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<thead>
<tr>
<th>Strategy 2</th>
<th>CH-6</th>
<th>CH-7</th>
<th>CH-8</th>
<th>CH-3</th>
<th>additive power demand (kW)</th>
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### Table 5: Simulation result of Operation Strategy 3, in adding on CH6, CH7, CH8 and CH3 chillers

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<th>Strategy 3</th>
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<th>CH-7</th>
<th>CH-8</th>
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<th>additive power demand (kW)</th>
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Table 6: Simulation result of Operation Strategy 4, in adding on CH7, CH8, CH3 chillers

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</table>

5. SYSTEM COMMISSIONING

Strategy 3 was selected and operated for full-scale experimental investigation. The operational data indicated that the system chilled water flow was not balanced and needed further adjustment. The commissioning process began with adjusting the actual chilled water flow rate and compared with that of the BEMS readings. Whenever a deviation on the flow rates between the two happened, adjustment was needed until it fell into the tolerance ranges. Figure 3 and Table 7 indicated the result during this commissioning process.

After the completion of the commissioning process, strategy 3 was operated again, and compared with the conventional operational mode as the baseline. The total power consumption was 8470 kW vs. 8796 kW. An energy-savings of 3% has been realized. As the chiller plant is operating for 24 hours a day and 365 days a year, the total energy savings per annum amounts to 2,855,760 kWh, or an operational cost savings of 238,000 USD per year by adapting this operation strategy, without any capital investment.

Fig. 3: The commissioning process to balance chilled water flow rates among all chillers
Table 7: Chilled water flow rates, before and after the commissioning process

<table>
<thead>
<tr>
<th>Chiller Number</th>
<th>Operating Hertz Hz</th>
<th>Chilled water flow rate (before) LPM</th>
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<th>Chilled water flow rate (after)</th>
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6. CONCLUSIONS

In this study, an algorithm to operate multiple chillers has been established. It was further developed into an experimental model which can be readily operated on a BEMS system. In this study, the experimental model yields a deviation of 1% only, as compared with the simulation result as far as the chiller power consumption is concerned. The main reason is that these huge chillers were all operated on a 24 hours-a-day basis for manufacturing purposes under a steady load condition, which made the predominant factors in affecting system power consumption correlated well with the experimental model.

The optimal operational strategy was executed by a full-scale experiment to produce 3% energy savings, equivalent to 2,855,760 kWh, or an operational cost savings of 238,000 USD per year. This low cost and no cost strategy can be duplicated in similar central HVAC systems and has a great potential for further applications.

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REFERENCES