AN INTEGRATED APPROACH FOR ENERGY SAVING AND CONTROL OPTIMISATION OF CENTRALIZED AIR-CONDITIONING SYSTEM

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ABSTRACT

This paper presents an integrated approach for the energy saving, control optimization and BEMS/BMS application of centralized airconditioning systems. The approach is based on the field test/monitoring, building realistic performance simulation and emulation. The methods and their roles for improving the operation, the conúol optimization and EMCS/BMS application are discussed. Examples of utilization are presented.

INTRODUCTION

Hong Kong spent 23.18 billion HK dollars on building energy consumption (15.2 billions on electricity) in 1991, which represents around four percents of GDP in the same year. Commercial/office buildings using centralized air-conditioning system consume more than half of that energy. More than half of the energy in those buildings is used by their air-conditioning systems. In practice, it is observed that their operation is rarely optimized and many of them even have significant errors in operation. These cause large amount of energy waste.

BMS (Building Management System) has become an essential part of the commercial/office buildings in Hong Kong, which contributes significant energy saving potentials in the buildings as well as potentials of indoor environment improvement. Unfortunately, practice shows that many of the installed BMS systems in Hong Kong buildings are not well utilized. This is due to the lack of proper BMS (software and hardware) commissioning, well developed and tuned control strategy for particular applications, or well trained operators.

To solve those practical problems, an integrated approach is studied. This approach includes the realistic building performance simulation, emulation and field test/monitoring to optimize the operation and control of centralized air-conditioning systems, particularly the existing systems. It provides a commonly suitable method to answer two essential questions for the centralized air-conditioning system optimization:

- How much saving can be achieved by optimization and what are the optimal operation schedules and settings of an air-conditioning system under different conditions?

- How to achieve those optimal operation schedules and settings by on-line control systems (e.g. optimal control strategies)?

The integrated approach under study includes three comprehensive methods/steps: energy monitoring, realistic performance simulation, EMCS(Energy Management and Control System)/BMS emulation. This paper presents the approach, the methods and examples of utilization.

FIELD TEST/MONITORING, REALISTIC PERFORMANCE SIMULATION, EMCS EMULATION AND THE INTEGRATED APPROACH

The building energy monitoring method has been used to investigate the performance of HVAC long term on site, to identify the operation problems and to improve the energy efficiency [1,2].

To identify the optimal operation and control of an air-conditioning system, a large number of tests are often needed. This is hardly done in practice, due to the costs, interruption to scheduled services and the difficulties of repeating the test conditions. The building system simulation method has been developed to test the energy performances of the building system with different system configurations or under different operation/control schedules and therefore identify the optimal design or operation schedules [3,4,5].

Studies on the use of the building system simulation for testing the realistic (e.g. control and energy) performances of building HVAC systems under the control of EMCS/BMS have been performed [6,7]. The studies show that the realistic performance simulation is suitable to be used in assisting the HVAC control optimization and EMCS/BMS control software development.

The building emulation technique, which tests the real EMCS/BMS by linking them to the simulated building HVAC system via hardware interface, has been developed and proved to be a convenient, efficient and low cost testing method for real EMCS/BMS facilities [8,9,10,11,12].

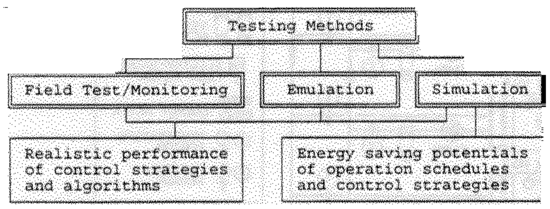

Figure-1 Testing approaches suitable for integrated building HVAC and EMCS systems

The performance testing methods (Figure-1) suitable for integrated building HVAC systems might be summarized as follows:

A. Field test/monitoring to evaluate the realistic performance;
B. Emulation method to test the realistic performance under EMCS/BMS control;
C. Simulation method to test the realistic performance of EMCS/BMS control strategies and algorithms;
D. Simulation method to evaluate the energy saving potentials of operation schedules and control strategies.

These methods are comprehensive, which can be considered as an integrated approach in the improvement and optimization of the building HVAC system.

The field test/monitoring evaluates the performance of the components and the operation of the integrated system. In the integrated approach under study, another objective of field test/monitoring is to collect sufficient data for model parameter identification and improve the model accuracy of the components. Two different approaches are employed for data collecting during field test/monitoring stage. The existing BMS in the building is one choice, if it can adequately monitor the system under investigation. A necessary step in this case is the calibration of the measuring instruments (sensors, transducers, meters) involved. Calibration itself, in fact, is also of interest to most building owners. Another alternative is to use special data acquisition facilities for the data collection. Currently in our case, a commercial software package 'Enerlyst' for energy monitoring is employed in some building monitoring projects.

The simulation for EMCS/BMS performance evaluation requires the simulation of building, air-conditioning systems and the EMCS/BMS as well. The simulation method for real control performance evaluation intends to represent whatever would happen in real situations. The realistic performance simulation is used as a test method to investigate the possibility of energy saving and the optimal control strategies, and to identify the optimal settings for particular systems in different conditions. On the base of the results, optimal control strategies can be developed/improved, tested, tuned and evaluated. Dynamic models of the building HVAC system components should only require the parameters which can be conveniently identified using easily available performance data (e.g. from the field monitoring), and the system construction data.

As the commissioning of BMS system after installed in field is strongly restricted due to the time limit, restriction of test conditions, interruption to the system operation and the difficulty of the problem reasoning, as many unexpected practical problems are mixed together. A building emulator provides an artificial but realistic environment to test the EMCS/BMS software and hardware. It reduces problems during the commissioning in field and the time consumption. It can also conveniently simulate different building conditions, which is important to evaluate the optimal control strategies.

EXAMPLES OF FIELD MONITORING

Case.1

A monitoring exercise was carried out on the central chilling system (Figure-2) in a forty-five story office building of a bank headquarters. A BMS system is installed for the plant, A/C and other building services systems. However its control function is not fully utilized and it is mainly used for monitoring. The central plant includes five 3150kW indirect seawater cooled centrifugal chillers over 10 years old. The condenser water pumps, primary chilled water pumps and secondary chilled water pumps are constant speed pumps. The sea water pump station employs three variable speed pumps, using frequency inverters.

The objectives of the study are to investigate the optimal settings (e.g. sea water pump speed or sea water flow rate, supply water temperature, sequencing, etc.) of the central plants at different conditions and to evaluate the proposed supervisory control strategies of the plant by simulation tests. Since the frequency inverters of the sea water pumps are newly installed and the centrifugal chillers are over ten years old, there are no reliable

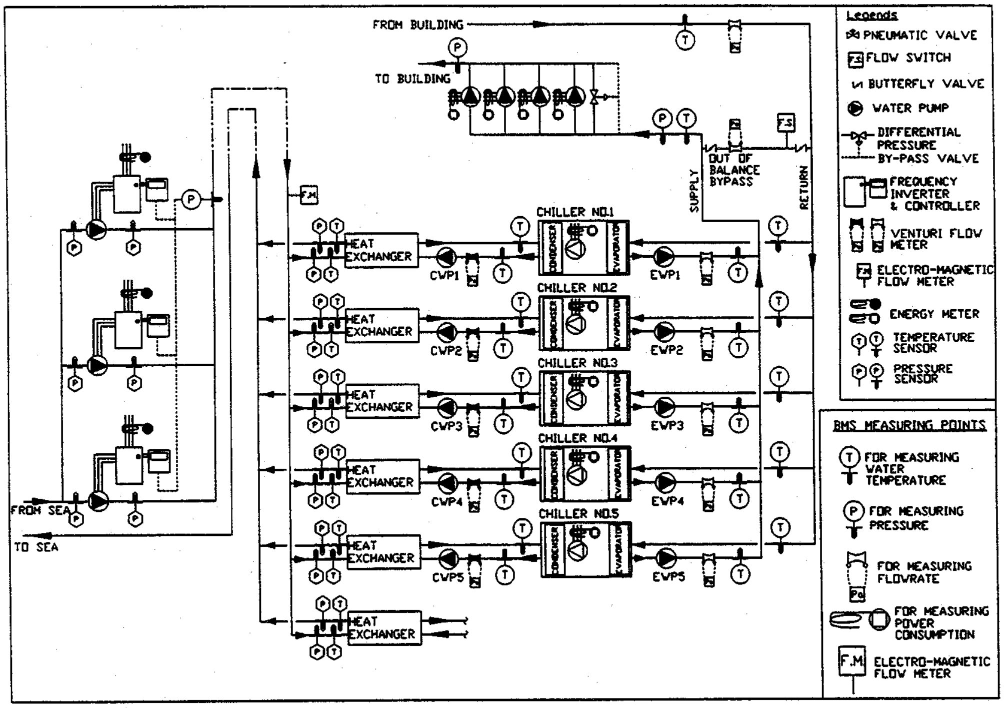

Figure-2 The measurement points for the central chilling system monitoring

performance data available. The objective of the test/monitoring exercise is to identify the performance of the plant.

Before the actual performance tests, the measurement points (e.g. temperature, flow, pressure and power points) of the central plant were calibrated. It is observed that significant errors occur in many of the temperature and flow rate measurement points. Correlations between the BMS measured values and the 'true values' manually measured by other meters of higher accuracy were obtained which were applied to modify the collected performance data of the plant after the performance tests.

Two sets of data were obtained to identify the performance of chillers. One set of data was obtained from the chiller test under controlled conditions. In the test case, one chiller (No.5) was tested at five different loads. Under each load, the chiller was tested under the combinations of three different condenser water inlet and three chilled water outlet temperatures. One test under one set of temperature settings was performed in a period varying from 30 to 60 minutes to get sufficiently long stabilized period. The BMS collects the data of the measured variables in every 2 minutes in the test case. The other set of data of five chillers was obtained from the regular BMS hourly data logging.

The pump consumption and pump head curves were tested at various flow rates (under different system resistance) at four frequency inputs. The pressure drop curves of the supply and return pipes were also obtained by measuring the pressure drop under different flow rates. The heat transfer coefficient and pressure drop of the heat exchanger were obtained by measuring the temperatures, the water flow rates (when only one chiller in operation) and pressures at sea water side. The secondary chilled water pump efficiency and pump curve were measured at different flow rates. The condenser and primary chilled water pump power consumptions were measure individually and considered to be constant.

Case.2

Figure-3 and Figure-4 present a part of monitoring system tested in the air-cooled central chilling plant of a commercial building. The monitoring system of chiller plant collects minute-by-minute data of the process variables by a computer data acquisition system operated by a specially designed energy monitoring software 'Enerlyst'. Those data provide fruitful information for evaluating the energy and operation performances of the chillers and pumps under various loads and operation conditions. The performances of the components are obtained by further identification of the collected data using a data analysis software 'Electric Eye'.

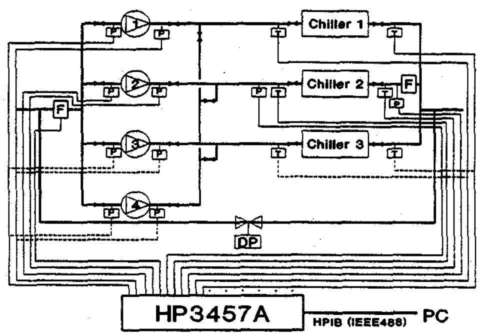

Figure-3 Schematic of water side measurement instrumentation of a central plant

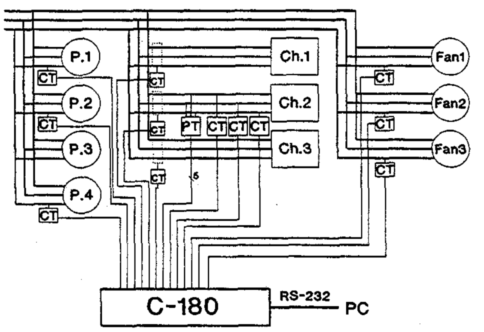

Figure-4 Schematic of power consumption measurement instrumentation of a central plant

The temperatures of chilled water are measured at the inlet and outlet of the chillers. The chilled water flow rate of the main pipe and one of the chiller are measured by magnetic flow meters. The differential pressures across a chiller and the pumps are measured to evaluate the hydraulic performance of the network. The power consumptions of the chillers, pumps and condenser fans are measured using current transducers. The inlet and outlet air temperatures at six different locations of a chiller are also collected by the same system.

EXAMPLES OF SIMULATION TESTS

Exercise.1

A simulation exercise was performed on an office building controlled by EMCS to study the simulation method for the building system realistic performance evaluation. Figure-5 shows the HVAC system of the building. The heating and chilling waters are generated by a fuel oil boiler and a chiller. The condenser cooling water of the chiller is chilled by a cooling tower using a two speed fan. The Air Handling Unit (AHU) includes a heating coil, a cooling coil, a supply fan and air dampers. Each zone has a VAV (Variable Air Volume) flow control and a reheating coil.

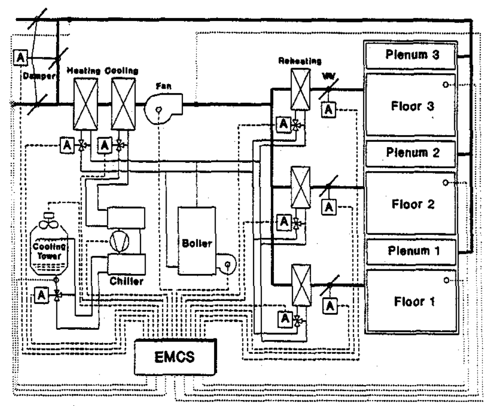

Figure-5 Schematic of the building and HVAC system used in simulation exercise

The EMCS control strategy implemented consists of eight controllers (control function routines) as shown in Figure-6. The zone controllers use a sequential control algorithm with 'zero energy band' (Both heating and cooling are turned off when the room temperature is located within a range specified by using different set-points for cooling and heating modes. The value of the 'zero energy band' is the difference between two set-points). Each zone controller also provides a signal to the supervisory controller indicating the heating/cooling demand of the zone.

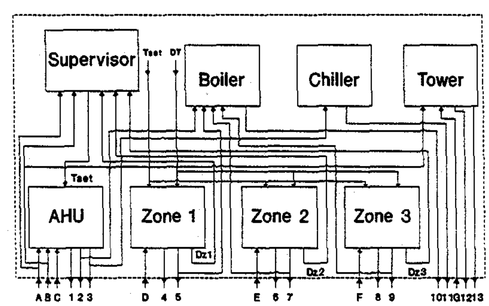

Figure-6 Schematic of the control strategies implemented in the simulation exercise

The supervisory controller generates the AHU temperature set-point according to the overall heating/cooling requirement of the zones, which is based on the zone heating/cooling demand signals, the ambient temperature and return air temperature. The AHU controller consists of an improved sequential control algorithm using three interrelated PID functions to control the heating/cooling coils and fresh air damper.

Ten hours simulation tests (TRNSYS was used as the solver) of a day were performed under the same external and internal loads. Different values of zero energy band of zone controllers were tested. Different PID settings of the local loop controllers were used to test the local loop control performance. Some of the test results are presented.

Figure-7 shows the energy cost and indoor thermal comfort index (PPD value) using different values of 'zero energy band'. The boiler energy consumption is converted into electricity consumption by using a factor of 6.7 to consider the difference of the prices (market prices were used to count the factor). The value of 'zero energy band' is selected from 0°C to 6°C. It can be found that the energy cost increases significantly when the zero energy band decreases. The indoor thermal comfort is improved significantly when the zero energy band decreases in case it is over 2 degrees in the test cases. When the zero energy band was below 2 degrees, no improvement of thermal comfort is achieved by reducing the zero energy band, whilst the energy cost increases. This can be explained by the fact that predicted neutral temperature (in PPD computation) notably differs from the room temperature control set-point (the mean value of two set-points in this case).

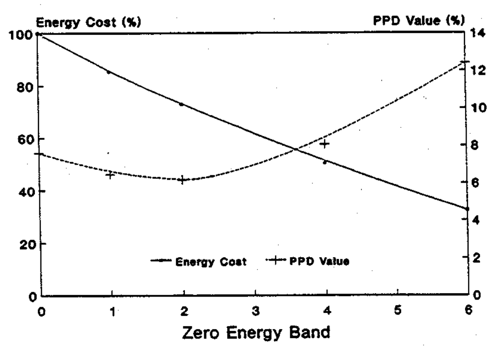

Figure-7 Energy cost and thermal comfort vs zero energy band

Figure-8 shows the AHU local control loop performance of the test using different (PID) proportional gains. The numbers in the X-axil are the proportional gains of the PID functions for AHU heating and cooling controls respectively. The integral time used by two PID is the same and remains unchanged in the tests. It can be observed that control activities (instability) increased as the proportional gains increased. Significant increase occurred when the gains used were over [4.0%/K,6.0%/K]. The average value of IAE (Integral Absolute Error) was high both when the gains were too high and too low. It was observed that too high gains causes the oscillation of the controlled AHU supply temperature and too low gains results large offset due to slow response to various changes.

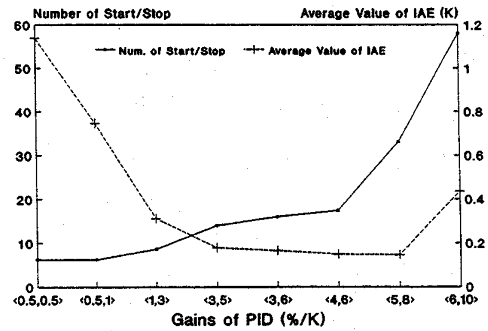

Figure-8 Number of start/stop and IAE value vs proportional gains

Exercise.2

The energy performance of the control strategy described in Exercise.1 was investigated by the tests under three weather conditions. The internal loads specified for the tests were the same. The outdoor air temperature (T_{atm}) range of these three conditions are listed in Table-1. To evaluate the performance of the AHU temperature reset control algorithm and the free cooling control capability of AHU control algorithm, two reference tests were performed in each of the three weather conditions. The fixed AHU set-points of 10°C and 14°C were selected in the reference tests respectively, and the fresh damper was fully open in both reference tests.

The energy costs and the average PPD values are listed in Table-1 *(The same conversion factor is used to convert the boil energy consumption into electricity consumption)*. In three conditions, significant energy saving and improvement on the indoor comfort is achieved by the EMCS using the above strategy which properly resets the AHU supply air temperature and well utilizes free cooling. Significant energy saving was achieved in 'Condition 1' and 'Condition 3'. Significant improvement of thermal comfort was achieved in 'Condition 1'. In 'Condition 1', the boiler energy increased as the set-point changed from 10°C to 14°C. It is due to higher room temperature was achieved when set-point was 14°C (also indicated by lower PPD value). The increase of boiler energy from 'Condition 2' to 'Condition 3' can be explained by that the ambient temperature in the early morning of 'Condition 3' (16°C) is lower than that of 'Condition 2' (17°C).

Table-1 Specifications and test results of strategy evaluation exercise

Condition	Condition 1			Condition 2			Condition 3		
Range of Tatm	1°C - 7°C			17°C - 24°C			16°C - 28°C		
Control Strategy	Tset 10°C	Tset 14°C	Tset Reset	Tset 10°C	Tset 14°C	Tset Reset	Tset 10°C	Tset 14°C	Tset Reset
Boiler (MJ)	2690	3041	1627	794	686	607	1097	995	886
Chiller& Tower (MJ)	0	0	0	647	529	552	973	839	776
Fan (MJ)	95	95	96	212	297	272	212	299	271
Total (MJ)	496	549	339	978	928	914	1349	1287	1179
PPD (%)	16	15	11	7.1	6.6	6.4	6.8	6.6	6.1

Building Emulation

Building emulation is an extension of building realistic performance simulation to test some real devices or system by replacing some part of the simulated system with the real devices (Figure-9). In the EMCS emulation test, the EMCS under test is connected to the simulated HVAC system via hardware interface. Studies on the emulation method, feasibility, the EMCS procedure and the reliability have been carried out by an IEA research project [8,9].

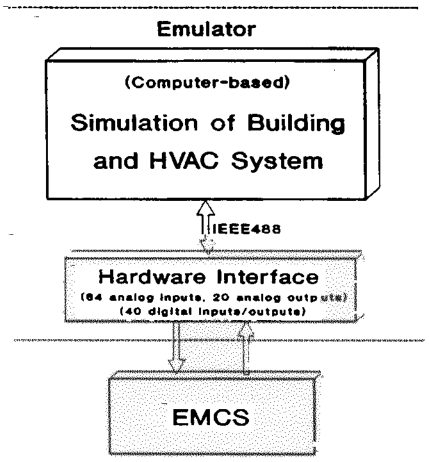

Figure-9 A building emulator developed in HKPU

In The Hong Kong Polytechnic University, a building emulator has been built in order to support the teaching, the research and application of Building Management Systems in Hong Kong. It is a single PC based building emulator using an integrated data acquisition and control system as the communication interface. The communication of the PC with the data acquisition and control system employs IEEE488. The interface of the emulator provides 64 single-ended (or 32 differential) analog inputs, 20 analog outputs.

The building and HVAC system simulation uses TRNSYS as the solver. The simulation software, real time simulation management, communication management and graphic display software are performed on the single computer. A simulation model package suitable for the typical building HVAC and central chilling plants in Hong Kong are under development.

CONCLUSIONS

The applications of the integrated approach in buildings is in progress with the support from site building service engineers. In a particular project for improving/optimizing the energy and control performance of a building HVAC and central chilling system, probably only some of the methods are necessary and helpful. For instance, the emulation method may not be helpful in the cases when the EMCS/BMS system is not used or the installed EMCS/BMS in the building cannot be interrupted.

The development of simulation software (component models) and the corresponding parameter identification programs is one of the tasks to be completed. Some of the component models are already available, but many of them need to be improved due to the lack of dynamic modelling. Currently, dynamic models of components of the central plant and the parameter identification programs are under developing and validating.

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