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Shanghai Tower's Versatile Energy Management System
上海中心大厦多能源管理系统


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Abstract

This paper will discuss the idea of controlling and managing the central air conditioning system of skyscrapers during the entire building life cycle. Taking the Shanghai Tower as a case study, this paper will use building load prediction technology, collect and analyze real-time operating data from the air conditioning systems and equipment. Improved algorithms have been applied based on the Swarm Intelligence to control and optimize the combination between multiple cooling systems, heating systems, and transmission equipment in order to achieve highly efficient operations for the central air conditioning system for the tower.

Keywords: Entire Building Life Cycle, Load Prediction, Energy Efficiency Assessment, Optimization Algorithms

摘要

本文论述了在建筑全寿命周期内，对高层建筑的中央空调系统进行控制和管理的想法。文章以超高层建筑—上海中心大厦为案例，介绍了利用建筑负荷预测技术，采集和分析空调系统及设备的实际运行数据，应用基于集群智能的改进算法，来完成各种情况下对多冷热源系统及输送设备的优化组合控制，实现大厦中央空调系统的高效运行。

关键词：建筑全寿命周期、负荷预测、能效评估、寻优算法

Introductory Thoughts

Modern architectural standards and thermal comfort requirements toward the internal environment is very high. These standards usually require a comprehensive central air conditioning system inside the building in order to guarantee thermal comfort. From a large number of mechanical and electrical equipment configurations to running on a high demand for energy and electricity, the central air conditioning system for a skyscraper has a power consumption that usually accounts for 40% to 60% of the entire building's electricity load. In respect to high energy consumption, skyscrapers operate at high costs as well. Therefore, a special concern in the industry is to figure out how to control the operation of the central air conditioning system in skyscrapers to improve the operating efficiency of the entire system, to maintain long-term energy efficiency through effective equipment management, and to minimize the energy demand for the central air conditioning system. The research on these issues is intended to achieve environmental protection and a rational utilization of energy.

思考

现代建筑对其内部环境的舒适性要求非常高，建筑内通常设有一套完备的中央空调系统。超高层建筑的中央空调系统，由于配置了大量的机电设备，其运行时对于能源的需求很大，尤其是电能，其电耗一般占整个建筑物用电负荷的40%~60%，这也使得超高层建筑的运行成本极高。于是，如何对超高层建筑的中央空调系统进行运行控制，来提高整个系统的运行效率，并通过对设备的有效管理，来保持设备长期的高能效，同时最大限度降低中央空调系统的能源需求，一直以来在业内都是一个重点关注的问题。并且对于这个问题的研究，要求在建筑的全寿命周期内，来实现对环境的保护和能源的合理利用。

上海中心大厦的冷热源系统

上海中心大厦位于上海浦东的陆家嘴功能区，大厦建筑总高度632米（请见图1）。大厦的建筑功能以办公为主，并附有酒店、会展、观光、商业等多种业态形式。上海中心大厦作为一幢具有综合功能的超高层建筑，设计时在大厦的地下二层和82层分别设置了低区和高区2个能源中心，来为整个大厦的供冷和采暖提供冷热源。其中低区能源中心供应大厦从1层~51层以及包括地下层在内所有建筑空间的空调系

Shanghai Tower's Heating and Cooling Systems

The Shanghai Tower is located in the Lujiazui financial district in Pudong, Shanghai, with a construction height of 632 meters (see Figure 1). The building is office-based with mixed-use programs incorporating functions such as hotel, exhibition, tourism, commerce, etc. Shanghai Tower is a super-tall building with integrated functions. During the design process, low and high zone energy centers are separately set up on the second underground floor and the 82nd floor to serve as the hot and cold sources for the entire building. The low zone energy center supplies the cold source for the air conditioning system for all architectural spaces from the first floor to the 52nd floor as well as the underground levels. Meanwhile, the low zone energy center also provides steam to supply the building's hot water system for A/C and domestic use through a heat exchanger. The high zone energy center supplies hot source for air conditioning systems for all architectural spaces of the 52nd floor and above. Taking into account the requirements for energy savings and environmental protection, the design of the building's cooling and heating systems adopts a variation of forms in terms of cooling and heating sources. This variety of forms include CCHP systems, ice storage systems, a conventional electric chiller system, ground source heat pump systems, cooling water, free cooling, steam boilers, etc. All the main engines of the heating and cooling systems can install equipment with a capacity of 10,000 kW along with all the devices that are set in the high- and low zone energy centers.

The owners of the Shanghai Tower predicted future running costs of the central air conditioning system of the tower and the results turned out to be quite alarming. Therefore, a multi-energy management system setup is desired in order to maintain a safe, efficient, and cooperative operation of central air conditioning system with the various forms of heating and cooling sources. In the end, the goal is to control the energy consumption of the central air conditioning system and to reduce future operating costs of the tower.

Air Conditioning Load Prediction

The maximum cooling load for air conditioning design in the Shanghai Tower is 47,479 kW. In fact, the building air conditioning loads are mainly affected by external meteorological parameters, the functional arrangement of the building, and pedestrian flow among other factors. During its actual runtime, the central air conditioning system often dynamically operates between the air conditioning seasons and transitional seasons, and most of time, runs in non-design conditions. Thus, only through an accurate prediction of the air conditioning load will the air conditioning can be reasonably distributed into different heating and cooling systems in order to maintain the operations in parts of high efficient loading zones. In the building, a large number of sensors are set up to monitor environmental parameters. Energy calculation devices are located in the hot and cold water mains of the air conditioning system in the high and low energy centers and partitions. These energy metering devices are setup to gather the actual operating parameters of the air conditioning system. In order to achieve the measurement, we need to establish a specialized database needs to be established utilizing specialized computer technology to calculate the hourly load of the building, the time distribution curve of the air conditioning load, and the load prediction models based on historical hourly load data. The database will be combined with constant adjustments of the measured data in order to achieve a day or a week of air conditioning load forecasts along with a basis for a rational arrangement of the heating and cooling systems.

Figure 1. Shanghai Tower. (Source: Gensler)
图1. 上海中心大厦（出自：Gensler）

统所需的冷源。低区能源中心同时还提供蒸汽，经换热后供应整座大厦的空调热水系统和生活热水系统的使用。高区能源中心为大厦52层及以上所有楼层建筑空间的空调系统提供冷源。考虑到节能环保的要求，大厦在空调冷热源设计上采用了多种形式，包括冷热电联供系统、冰蓄冷系统、常规电制冷机系统、地源热泵系统、冷却水免费供冷、蒸汽锅炉等。所有冷热源系统主机的设备装机容量约为10,000KW，所有设备分别设置在高、低区能源中心。

上海中心大厦的业主对其大厦中央空调系统今后的运行成本进行了预测，得出的结果非常惊人。于是，希望设置一套多能源管理系统，来保障其具有多种形式冷热源的中央空调系统能够安全、高效的联合运行，同时有效控制中央空调系统的能耗，降低大厦今后的运营成本。

空调负荷预测

上海中心大厦的空调设计最大冷负荷为47,479KW。事实上，建筑空调负荷主要是受外部气象参数、建筑内业态功能分布、以及人员流动等因素的影响而变化。中央空调系统在实际运行时，往往

Energy Efficiency Management

Hot and cold sources must be combined with the appropriate transmission and distribution system in order to achieve the efficient operation of the entire system. The Shanghai Tower's central air conditioning system is configured with various forms of cooling and heating equipment which includes the hot and cold water delivery system equipment for the entire building. All equipment selections in the design are concerned with the operational efficiency of the various devices under designed conditions. In fact, system processes in the actual run-time operate under non-designed conditions most of the time. It is necessary to analyze and evaluate the performance of the heating and cooling systems that are running. These systems include the air conditioning energy consumption per unit area, the cooling consumption per unit area, the energy efficiency ratio of the air conditioning system, the energy efficiency ratio of refrigeration coefficients, the transfer coefficients of chilled water, and the transfer of cooling water coefficients to adjust the equipment operation and improved energy efficiency for the system equipment.

Through assessment of differences in COP values caused by the time deviation in different heating and cooling system equipment, the normality of the running condition can be analyzed. With the same heating and cooling system equipment and time deviation of the COP values, the abnormalities of the running energy consumption condition, if there are any, can also be determined.

With the analysis comparing data of different assessment control effects at different time and special environments combined with mathematical models of energy consumption analysis based on time and environment, the generation and transformation process of the energy consumption can be described. The relationship between energy consumption and various influencing factors of energy can also be quantitatively interpreted in order to summarize the rules of energy consumption. Through the measured results of the mathematical models based on various parameters, the curve of the true efficiency of the cooling tower can be obtained. Based on the true efficiency of the cooling tower curve and the evaluation analysis of a new relationship curve between cooling energy consumption, loading rate of cooling, condensing temperature, and evaporation temperature, then the control policy of energy conservation at different times and different environmental atmospheres can be acquired. The establishment of multiple energy conservation analytical models is based on an air conditioning energy consumption target system and a combination of the itemization of energy consumption estimations will outline the energy conservation control policies. The evaluation of the system's electrical and mechanical equipment includes operating efficiency and the assessment of energy depletion.

Multi-Energy Management System

The Shanghai Tower's energy management system utilizes the application of optimization algorithms based on ideas derived from the Swarm Intelligence. After the improved system, the algorithms will work better for project applications and will have greater global optimization capabilities. The combination of the analysis of the air conditioning load prediction for the entire system and equipment energy efficiency analysis can solve the operations of the multiple heating and cooling systems (including CCHP system, ice storage system, a conventional electric chiller system, ground source heat pump system, etc.) and to optimize the multi-system composition. The optimized combination of heating and cooling systems is created to meet the premise of maximum predicted air conditioning load,

是在空调季和过渡季之间动态运行，并且大部分时间是处于非设计工况运行。因此只有通过对空调负荷的准确预测，才能够把空调负荷合理的分配给不同的冷热源系统，才能够控制冷热源设备包括输送系统设备，使之运行在部分负荷的高效区间。于是在大厦内设置了大量的传感器来对环境参数进行监测，并在高、低能源中心的空调冷热水总管和各分区冷热水总管上设置能量计量装置，来采集空调系统的实际运行参数。建立专门数据库，采用专业计算机技术来计算建筑物的逐时负荷，建立空调负荷的时间分布曲线和负荷预测模型，根据对历史的逐时负荷数据，结合实测数据的不断修正，来实现对未来一天或一周的的空调负荷预测，并以此为依据完成对冷热源系统的合理调度。

能效管理

合理的冷热源必须与合适的输配系统结合，才能实现整个系统的高效运行。上海中心大厦中央空调系统配置了多种形式的冷热源设备，包括整个冷热水输送系统设备。所有这些设备的选用，在设计时关注的是在设计工况下各种设备的运行效率。而系统在实际运行时，事实上大部分时间是处于非设计工况运行，因此有必要对冷热源系统运行的性能指标进行分析评估，包括单位面积空调能耗、单位面积耗冷量、空调系统能效比、制冷系数能效比、冷冻水输送系数、冷却水输送系数等，以此来调整设备的运行，提高系统设备的能效。

通过对不同冷热源系统设备于时间性偏差的COP值的差异性评估，来分析不同冷热源系统设备基于时间性偏差的运行状态是否正常；通过对同一冷热源系统设备于时间性偏差的COP值的差异性分析，来判断冷热源系统的运行及能耗状态是否异常。

分析不同评估控制效果于不同时间、不同环境空间的比较数据，并结合基于时间和环境的数学能耗分析模型，来描述能耗的产生、变化过程，定量解释能耗和各种影响因素之间的关系，得出能源消耗的规律。分析不同参数条件下数学模型的实测结果，得到冷却塔实际效率曲线，分析评估冷机能耗和负载率、冷凝温度、蒸发温度之间的关系曲线，得出冷却塔不同时间、不同环境空间的能效节能控制策略。建立以空调系统能耗指标体系为基础的多种节能分析模式，并与能耗分项计量相结合，得出节能控制策略。对于系统机电设备的能效评估包括运行效率评估、损耗效率评估。

多能源管理系统

上海中心大厦的多能源管理系统是应用了依据集群智能理论衍生的寻优算法思路，在进行改进后，得到具备全局寻优能力、并且更适合工程应用的算法。在基于对空调负荷预测以及对整个系统及设备的大量能效分析的基础上，来解决对多个冷热源系统（包括冷热电联供系统、冰蓄冷系统、常规电制冷机系统、地源热泵系统等）的运行进行优化组合。冷热源系统的优化组合是在满足最大预测空调负荷、能源成本、系统最大能效等约束条件的前提下，确定未来一段时间内冷热源设备投入运行的策略，实现按需供能，并且同时对整个输送系统的设备（冷却塔、冷水泵等）进行优化组合，来完成整个系统的高效运行。

上海中心大厦的多能源管理系统的运行，随着运行数据的不断积累，对大厦今后的运营将逐渐体现极大的价值。同时系统在运行过程中积累的各类数据和分析成果，对于现代建筑的节能控制技术的发展，具有重要的研究意义。

energy costs, and the system maximum energy efficiency among other premise constraints. These will determine an operational strategy for the cooling and heating equipment in the future. This operational strategy can achieve the demand for energy and the transporting equipment (cooling towers, chilled water pumps, etc.) which will also optimize the combination to achieve high-efficiency for the entire system.

With the operating data continuously accumulating, the future operations of the building will greatly benefit from the Shanghai Tower's multi-energy management system. The various types of data and result analyses acquired from the operation will have imperative research significance to the development of energy-saving technologies for modern architecture.