华南理工大学

South China University of Technology

博士留学生学位论文

基于能量枢纽模型的微能源网优化运行

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学　科　专　业　电力系统及其自动化

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Optimal operation of Micro energy networks based on energy hub model

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摘 要

在当今经济社会活动中，能源发挥着重要的作用。一方面，能源成本是产品价值的重要影响因素；另一方面，能源的安全和由能源利用所引发的环境问题也促使人类不断探索节能以及环保的新模式，促进了科学和技术的发展革新。当前针对能源危机和环境问题，全球科学家重点关注的一个解决方案就是构建能够综合不同类型能源的能源网络，即综合能源系统。通过综合能源系统增强用户用能的可靠性、减少环境污染、提高能源综合利用效率，推进社会资源环境的可持续性发展。

能量枢纽（Energy Hub，EH）是构建综合能源系统的一个重要基础。能量枢纽模型构建了一个可连接各种类型能量，并且可以灵活响应各种负荷需求的微能源系统模型，适用于居民区以及市中心等负荷集中区。如今，城市化的快速发展导致了负荷的激增以及负荷使用类型的多样化，同时，先进的可再生能源技术以及存储和转化技术在提高能源效率方面也取得了重大的进展。因此需要新的研究方案来改进能量枢纽的结构并且解决多个能量枢纽构建的微能源网模型的最优运行的问题。本文将在能量枢纽模型的基础上，对综合微能源网的优化运行问题进行分析，本文的主要内容分为以下三个部分：

1、为突破现有 EH 建模研究的局限性，本文提出了一种扩展 EH 模型，用于提高住宅区负荷的综合能源利用效率，降低能源使用成本。这个扩展模型考虑到了太阳能（包括太阳能的光电利用和光热应用）与电池储能系统(Battery energy storage system，BESS)相结合。在现有的能源价格及满足能源负荷需求的前提下，以一天能源使用总成本最低为目标，对 EH 中设备及外部供能的功率分配进行优化。约束条件包含了 EH 输入-输出的能量平衡，设备的容量限制以及 BESS 的荷电状态约束等。仿真算例对比分析了在不同 EH 结构的情况下，太阳能光电、光热利用和 BESS 对运行调度的影响。结果表明所提出的模型对优化用户综合用能具有较好的效益，并且，该 EH 结构和运行优化模型适用于住宅型园区的负荷。

2、EH 的结构特征和优化运行对园区供能特性和可靠性具有重大影响。为了更好地实现园区的优化供能，通过同时关注 EH 的结构特征和优化运行来协同园区的能源优化至关重要。由于目前对同时考虑 EH 系统结构及优化运行的联合优化问题缺乏研究，因此，本文研究着重于建立快速识别系统最优结构并同时满足最优运行两个目标的数学模型。具体地，本文提出了具有 12 个元件（包括能量输入、转化以及储存元件）的

EH 模型。在该优化问题中，采用二进制变量来表示元件使用与否的状态，当二进制变量为 0 时，代表该元件未被使用，而当二进制变量为 1 时，代表该元件处于使用的状态中。通过 12 个元件的组合，本文提出了 144 种具有不同能量枢纽结构的优化场景，并针对不同场景下的能量枢纽最优运行结果进行了比较。在对优化结果进行比较后可以发现，对结构和运行进行统一优化之后得到的能量枢纽的最优结构与 144 种不同结构中对运行进行优化后成本最低的结构是相同的。因此，本文所提的数学模型能够快速准确地同时解决结构和运行的最优化问题。

3、基于对含有多个 EH 优化运行研究的不足，并考虑到可再生能源和储能系统在微能源网中逐渐广泛应用的场景，本文提出了微能源网络（MEN）的协调优化运行的方法，该微能源网络包括了光伏、风电、电网和天然气传输网、以及多个 EH。本文引入了四种不同的运行方案（单纯考虑电力作用、考虑电能和天然气的作用、考虑电力天然气以及可再生能源的作用、考虑电力天然气可再生能源以及储能共同的作用）来评估能源类型和储能系统对微能源网性能的影响。求解的结果表明，与传统的单纯电力供应网络相比，在考虑太阳能，风能和储能系统的能量枢纽基础上构造的能量枢纽效率更高。

本文采用通用代数建模系统（GAMS）对所建立的数学模型进行求解，本文得到的结论对构建小规模多能量需求的能源管理模型具有重要的指导意义。

关键词：微能源网；能量枢纽；优化运行；GAMS；BESS；最优结构

Abstract

Energy plays an essential role in all social and economic activities with deep engagement. Energy cost is one of the key-driven factors contributing to industry manufactory and even other social areas such as culture and politics. Energy security and environmental issues have facilitated human beings to explore energy-efficient, economical and environment-friendly models. The energy network, combining various different energy categories, tends to be an innovative solution that attracts scientists' eyeball worldwide. Such energy network helps to enhance reliability, reduce environmental pollution, facilitate technology development in the energy system and promote energy sustainability. Hereby energy hub (EH) can be used to build up energy network model.

In terms of micro energy network (MEN), the multi-energy network operation optimization is analyzed based on the EH model. The solution is applied to the regions with highly intensive energy consumption, including residential areas, urban areas, etc. Besides, the rapid urbanization has led to load volume expansion and diversified energy consumption. The advanced technology of renewables integration, alongside with storage and conversion sections, has improved energy efficiency. The new research proposal is required to optimize EH structure and operations of MEN model built up by multiple EH. This dissertation especially aims to resolve the following key issues:

1/ This thesis presents an extended EH model to optimize total energy use costs for loads in residential areas, with the aim to fulfill the research gap in EH modeling and improving the operational efficiency of multiple forms of energy consumption. This extended model considering the involves solar energy (provided by PV and SHE) combined with Battery energy storage system (BESS). The optimization problem is set up based on daily load demand (such as electricity, heat, and cooling) and time-of-use (TOU) energy prices. A mathematical model is constructed with the objective of optimizing total energy cost during the day, including some constraints such as input-output energy balance of the EH, electricity price, capacity limitation of the system, and charge/discharge power of BESS. Four operational cases based on different EH structures are compared to assess the effect of solar energy applications and BESS on operational efficiency. The results show that the proposed

model predicts significant changes to the characteristics of electricity and gas power bought from utilities, leading to reduced total energy cost compared to other cases. They also indicate that the model is appropriate for the characteristics of residential loads.

2/ The structural and optimal operation of an energy hub has a tremendous influence on the hub's performance and reliability. In order to achieve the global optimum conditions for supplying energy, it is quite essential to develop the optimization research issues by focusing on hub system structure and operation simultaneously. Based on the lack of study about joint optimization problem, this research also concentrates on establishing a mathematical model to rapidly identify the optimal model structure that simultaneously satisfies two objectives: optimizing operating costs and selecting the optimal operating structure. The objective of the investigation is to penetrate into this joint optimization problem with a handy calculation method. This thesis envisions an innovative methodology that prominently increases the synergy between structural and operational optimization and targets system cost affordability. The generalized energy system structure is presented theoretically with all selective hub sub-modules, including electric heater (EHe) and solar sources block sub-modules. To minimize energy usage cost, an energy hub is proposed that consists of 12 kinds of elements (i.e., energy resources, conversion, and storage functions) and is modeled mathematically in a General Algebraic Modeling System (GAMS), which indicates the optimal hub structure's corresponding elements with binary variables (0, 1). Simulation results contrast with 144 various scenarios established in all 144 categories of hub structures, in which for each scenario the corresponding optimal operation cost is previously calculated. These case studies demonstrate the effectiveness of the suggested model and methodology.

3/ Previous peer research seldom addresses the problem of multiple EH optimal operations. Considering integration of renewables and storage systems, the dissertation proposes a method to coordinate optimal operations in MEN containing electricity and natural gas networks, based on EH model. The EH can be considered as the grand network node to contain various categories of energy. The demands for electricity, heat, and cooling load can be fulfilled with the application of conversion and storage devices. Four different operating scenarios are established to evaluate how energy sources and storage systems influence MEN. In comparison to traditional electricity supply, the simulation results indicate that MEN built

up by EH, with the integration of solar energy, wind energy and storage systems, is more efficient.

The General Algebraic Modeling System (GAMS) is applied to solve the optimal operating problems in this study. The dissertation research contributes to the modeling and calculation for flexible and efficient energy management, meeting the demand for small-scale loads with various energy engagement.

Keywords： Micro energy network; Energy Hub; Optimal operation, General algebraic modeling system (GAMS); Optimal structure.

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