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Hierarchical energy management system for multi-source multi-product microgrids☆

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ABSTRACT

This paper proposes a hierarchical energy management system for multi-source multi-product (MSMP) microgrids. Traditional energy hub based scheduling method is combined with a hierarchical control structure to incorporate transient characteristics of natural gas flow and dynamics of energy converters in microgrids. The hierarchical EMS includes a supervisory control layer, an optimizing control layer, and an execution control layer. In order to efficiently accommodate the systems multi time-scale characteristics, the optimizing control layer is decomposed into three sub-layers: slow, medium and fast. Thermal, gas and electrical management systems are integrated into the slow, medium, and fast control layer, respectively. Compared with wind energy, solar energy is easier to integrate and more suitable for the microgrid environment, therefore, potential impacts of the hierarchical EMS on MSMP microgrids is investigated based on a building energy system integrating photovoltaic and microturbines. Numerical studies indicate that by using a hierarchical EMS, MSMP microgrids can be economically operated. Also, interactions among thermal, gas, and electrical system can be effectively managed.

1. Introduction

1.1. Background

A multi-source multi-product (MSMP) microgrid integrates different energy sources (usually including natural gas and renewable energy) and loads in small-scale power grids [1]. Advantages of MSMP microgrids include supplying more reliable power to loads, providing lower cost power to remote areas, and integrating renewable and cleaner energy into a distribution network. The control system of MSMP microgrids is designed to optimize production and consumption of heat, gas, and electricity in order to improve overall efficiency [2]. However, the interactions among thermal (including heat and cooling), natural gas (NG), and electric networks can degrade the reliability and stability of MSMP microgrids. Until now, it is a common practice to manage electrical, natural gas, and thermal systems separately, without paying enough attention to interactions among different energy supply systems, such as the impact of natural gas network pressure fluctuation on the electric network, the influence of thermal load fluctuation on the electric network and natural gas network, etc.

Analysis of MSMP microgrids is challenging because of: 1) multi time-scale in the dynamics of energy demand and supply systems; 2) mutually interacting energy systems; 3) load/distributed generation (such as solar) fluctuation without accurate predictions; 4) the seamless mode switching processes should be considered in the control system.

Some theoretical modeling and optimization methods for production and consumption of heat, gas, and electricity have been proposed in order to ensure safety operating and improve overall efficiency of the interrelated energy systems [3]. To study the energy management system of the MSMP microgrid, the energy hub has been developed to describe the interrelationship among the three systems [4]. In the energy hub model, the electricity and gas from utilities are converted to heat and electricity and supplied to loads, which can be seen as a multi-source multi-product system [2]. Based on the energy hub model, the energy system is optimized incorporating energy network constraints and interactions between different energy networks [5].

☆ This document is a collaborative effort.

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A control-oriented approach to modeling and optimization of an energy hub is presented in Ref. [6]. Due to load and renewable energy uncertainty, technologies such as robust optimization is being studied to aid energy management [7,8]. As illustrated in Ref. [9], dynamic interactions between gas and electrical system has significantly impact on each other. Some studies have been conducted to consider dynamics interactions among various energy systems. In Ref. [10], a coordinated scheduling method is proposed for hybrid gas and electrical systems considering transient model for gas network. In Ref. [11], a control strategy is proposed to coordinate heating and electrical systems in an autonomous distributed generating system and dynamics of energy converters for heat and electricity are taken into account. The published studies are mostly focused on steady state analysis. However, the inherent complexity of the MSMP microgrid cannot be handled simply by controlling thermal, gas and electrical system separately. It is also inappropriate to consider the system as a steady state system, because of different time-scale of each energy system. Few discussions have been given to different energy system dynamic characteristics.

The hierarchical control scheme offers a mean to design the control structure of a multi time-scale system, which is a commonly used method in other applications. In the waste water treatment system [12], the hierarchical control structure is used to handle a full range of disturbance inputs. In the drinking water supply and distribution system [13], the control structure is proposed to incorporate various objectives, including optimizing the operational cost, meeting a demand on water of desired quality and maintaining the system constraints. In the greenhouse climate management [14], time-scale decomposition is employed to deal with different response time in the crop production process. Applying the hierarchical control structure to the MSMP microgrid gives rise to the following issues: 1) how to choose the number of control layers based on the time-scale characteristics; 2) how to design the structure of control systems used at each level of microgrid EMS; 3) how to design coordinating strategies for interactions among each control layer.

1.2. Proposed methodology

The theory of singularly perturbed systems [15] provides a way to tackle these issues and it produces a sound decomposition based on the differences in the response time occurring in microgrids. This technique has been used in various engineering applications considering different time scales [16]. In this paper, a hierarchical control structure is developed for MSMP microgrids based on the singular perturbation theory. The energy hub is integrated into the optimal control layer to follow the variation of loads and generate set-points for various energy management systems. The interactions among the three energy networks are coordinated in the hierarchical control structure in order to better coordinate different control sub-layers. In addition, significant and sudden changes of the system states, such as switching the operating mode, renewable output power fluctuation, start-up of the air-conditioner (AC) and the microturbine (MT), the demand response (DR) and the ESS saturation will also be handled by coordination the three energy system.

1.3. Technical contribution

The main contributions of this paper can be summarized as follows: 1) Transient characteristics of natural gas flow and dynamics of energy converter are integrated into the EMS; 2) A hierarchical EMS is proposed to integrate thermal and NG management system with conventional EMS considering interactions among the coupled energy systems; 3) A time-scale decomposition for MSMP microgrids is presented and shown that this decomposition yields a sub-control layers at each time-scale; 4) Based on the time-scale decomposition, a hierarchical control structure utilizing the existing control system for different energy systems is designed to coordinate the sub control systems.

1.4. Manuscript organization

The rest of this paper is organized as follows. In Section 2, the proposed MMSP microgrid configuration and models are described. In Section 3, time-scale decomposition and framework of the hierarchical EMS for MSMP microgrids is presented. In Section 4, performance analysis for the proposed hierarchical EMS is conducted. Section 5 summarizes the main findings and conclusions.

2. MSMP microgrid description

2.1. Configuration

MSMP microgrids can have diverse network topologies. In this paper, a building with integrated photovoltaic system which has shown both economic and ecologic aspects [17] is extended to a MSMP microgrid including the following main components, as shown in Fig. 1:

- A 25 kV infinite bus that is used to represent the utility;
- A low pressure NG network composed by three pipelines. The pipelines data is given in the Appendix and the gas company is represented by a 0.5 MPa constant pressure NG source;
- A 200 kW photovoltaic (PV) panels connected to the electric network. Solar energy is the only renewable energy source in this case[1];
- A 120 kW combined heating, and power (CHP) system that couples thermal, NG, and electric networks;
- A 160 kW AC that couples thermal and electrical systems;
- An electrical energy storage system (EESS) that smoothens the electrical system affected by PV panels and electric loads;
- A thermal energy storage system (TESS) that smoothens the thermal load.

2.2. Model description

This subsection introduces two types of MSMP microgrid components models depending on whether they couple energy networks.

2.2.1. Regular components

The output characteristic of a PV cell can be modeled as the PV model in Ref. [18]. Maximum Power Point Tracking (MPPT) is implemented in the boost converter using the so called Incremental Conductance + Integral Regulator technique [19].

A battery-supercapacitor hybrid EESS in Ref. [20] which takes advantage of these two complementary technologies is utilized to provide both large power and energy ratings for reducing both the PV power fluctuations and the system operating cost. The EESS integrated with the PV is connected to the microgrid via a DC-DC boost converter and a three-phase-three-level current-controlled

[1] In this paper, only PV panels are considered in the EMS for the MSMP microgrid. Other renewable energy sources, such as wind and biomass, will be the focus of future work.