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Emissions control via carbon policies and microgrid generation: A bilevel model and Pareto analysis

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ABSTRACT

Economic models are needed to analyze the impact of policies adopted for controlling carbon emissions and increasing distributed renewable generation in microgrids (green penetration). The impacts are manifested in performance measures like emissions, electricity prices, and electricity consumption. This paper presents an economic model comprising bi-level optimization and Pareto analysis. In the bi-level framework, the upper level models the operation of the microgrids and the lower level deals with electricity dispatch in the grid. The economic model is applied on a sample network in two steps. In step1, the bi-level model yields operational strategies for the microgrids and the corresponding values of the grid performance measures. In step2, a statistical analysis of variance combined with Pareto optimization attains guidelines for setting policies for emissions reduction and green penetration without adversely impacting electricity prices and demand. We conclude that renewable generation from microgrids can significantly reduce the negative impacts of the policies. Our economic model is novel as it 1) integrates operational strategies of microgrids and the grid under an emissions control regime, 2) explicitly considers social cost of carbon in the electricity dispatch, and 3) balances multiple objectives of emissions reduction, green penetration, and electricity consumption using a Pareto analysis.

1. Introduction

Many countries around the world have adopted stricter carbon emissions reduction targets. For instance, the EU has established an emissions trading system (EU ETS) that seeks to reduce the GHG (greenhouse gas) emissions by 21% by 2020 from the 2005 level. In a recent declaration, the EPA (Environmental Protection Agency) in the U.S. has set carbon emissions reduction targets for each state with an overall goal of reducing 30% below 2005 level by 2030 [1]. Among the various means of emissions reduction, implementation of a carbon cap, assessment of the true social cost of carbon, and transformation of the power grid to a smart grid to allow distributed renewable generation via microgrids will play key roles. The U.S. DOE (Department of Energy) envisions that by 2030 many of the current electricity grids will upgrade their operations into smart grids [2]. It is anticipated that part of the distributed renewable (green) generation will be provided by a growing number of microgrids operating under the smart grids. Microgrids (with renewable generation, storage devices, and smart meters) will develop cost efficient operating strategies, which will determine their interactions with the smart grid including buy and sell decisions of electricity. Economic models need to be developed to assess the true impact of carbon cap, SCC (social cost of carbon), and green penetration via microgrids on grid performance measures such as carbon emissions reduction, electricity prices, and electricity consumption. This paper presents such an economic model, part of which accounts for the interaction between the microgrids and the ISO (independent system operator) of a smart grid using a bi-level optimization framework. The remaining part of the model processes the results of the bi-level optimization using a statistical analysis of variance and Pareto analysis to develop policy guidelines that attain a desirable balance among emissions reduction, green penetration, and electricity price and consumption.

Literature contains a number of models that address the issue of operational planning of microgrids (e.g., [3–6]) without accounting for the dispatch by the main (smart) grid. These microgrid models consider the main grid as a buffer, i.e., a microgrid can buy or sell electricity from or to the grid at any time and in any quantity. This assumption may not hold as the number and sizes of the microgrids grow in a network resulting in an increase in the proportion of grid electricity produced and consumed by the microgrids. Therefore,

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the ISOs must consider microgrids' influence on the optimal dispatch of electricity. The need for such joint control of operations of microgrids and smart grid was emphasized in Ref. [7].

Commonly expected benefits of microgrids in smart grids, such as reduction of congestion and transmission losses, efficient utilization of electricity and heat, and reduction of emissions, were studied in Ref. [8]. Since microgrid energy production is associated with high uncertainty, incorporation of efficient and large scale energy storage facilities, for a large deployment, was recommended in Ref. [9]. It was also suggested in Ref. [10] that the efficiency of microgrid operation strongly depends on the battery scheduling process. A microgrid-based planning model considering the power system reliability and economic criteria has recently appeared in Ref. [11]. A multi-objective intelligent energy management system for microgrids to minimize their operation cost and the environmental impact is proposed in Ref. [10]. A bi-level model in Ref. [12], similar in spirit to our model, examined the competition between microgrids and a large central generation unit. The societal impact of carbon emissions is known as the SCC (social cost of carbon). A detailed discussion and various definitions of SCC can be found in Ref. [13]. Estimation of SCC suffers from uncertainties associated with the future levels of green house gas emissions, the monetized effects of past and future emissions, and methods of translating the environmental effects into economic measures [14]. An IWG (interagency working group), in the U.S., has suggested setting the SCC to \$21/tCO_2 [15]. It is asserted in Ref. [16] that consideration of the monetary effects of emissions via SCC will increase the development and deployment of green technologies. In the remaining part of this section, we provide a brief outline of the network topology, assumptions and approach for the bi-level optimization model, result of which are further analyzed using a statistical and Pareto analysis technique for developing policy guidelines.

It is considered that the electricity network is a smart grid and it is controlled by an independent system operator. Microgrids are grid-connected and are widely distributed among different buses. The smart grid covers a large area such that the microgrids are likely to be subjected to different solar, wind, and demand patterns. Microgrids are considered as distributed green energy resources with storage, which produce and trade electricity to satisfy demand. The microgrids develop efficient operational strategies over a planning horizon (say, 24 h) and participates in the hourly market with supply bid only. An operational strategy includes green energy production quantity, charge/discharge of batteries, and electricity buy or sell quantity bids to ISO. Microgrids are assumed to be price takers. To obtain operational strategies, microgrids consider forecasted values of solar irradiance, wind speed, electricity demand, and the LMP (locational marginal price). The ISO develops the optimal hourly dispatch via DC OPF considering the microgrids' bid, environmental constraints (e.g., emissions cap and SCC), supply functions of the other generators, demand curves of the consumers, and network system constraints.

The objectives of the microgrids and the ISO are attained via a bi-level optimization model where the upper level model minimizes the operation (production) cost of the microgrids and the lower level model develops an optimal electricity dispatch. The solution of the bi-level model also yields the carbon emissions level, green energy penetration, electricity price, and electricity consumption. Thus, the optimization model offers a tool to asses overall impact of microgrids on the smart grid. It is known that network performance measures (emissions level, green penetration, price, and consumption) are negatively correlated. For example, a consumers concern is price increase, a generators concern is profit/revenue reduction, and a policy makers concerns include inadequate emissions reduction and reduced electricity consumption. A high reduction in emissions (environmentally desirable) is likely to increase the cost of electricity (hurting consumers), reduce electricity consumption (lowering economic activity), and reduce market share and profits of fossil fuel generators [13]. Hence, we develop a designed statistical experiment to first measure the effects of cap, SCC, and green penetration via microgrids on the market performance measures. Results of the statistical study are used to develop a Pareto analysis, which yields choices for emissions cap, SCC, and microgrid generation capacities to support policies for emissions reduction, green penetration, and economic activity (electricity consumption).

The contributions of this paper can be summarized are as follows. 1) We model the game between microgrids and the ISO to obtain operational equilibrium strategies. 2) We analyze the impact of microgrid generation, SCC, and carbon cap on carbon emissions, electricity prices, electricity consumption, and green penetration. 3) We develop a statistical sensitivity analysis using analysis of variance to study the true impact of SCC, carbon cap, and microgrid penetration. 4) Finally, we develop policies for emissions control and green penetration by balancing multiple objectives of emissions reduction, green penetration, and electricity consumption using a Pareto analysis.

The rest of the paper is organized as follows. Section 2 presents the details of the bi-level model. Section 3 presents the model solution approach. Section 4 provides the details of the bi-level model implementation on a sample electricity network with 82 buses and 37 microgrids. Section 5 describes the results obtained from the mode implementation. Section 6 presents the designed experiment and the Pareto analysis. The concluding remarks are given in Section 7.

2. Microgrid and smartgrid interaction: a bi-level model approach

Our adoption of a bi-level modeling framework is motivated by its common use in modeling interaction among participants in deregulated electricity markets (e.g., [17–19]). The bi-level framework (leader-follower or Stackelberg game) allows us to study how the ISO (lower level model) reacts to the microgrids decisions (upper level model) and, consequently guides the operational strategies of the microgrids. Fig. 1 shows a schematic of the interaction between the microgrids and the smart grid.

The upper level model considers all microgrids in the network, and obtains their individual operational strategies. It considers the current values of the hourly forecasts for electricity prices, electricity demand, and weather conditions for all hours of the planning horizon. These forecasts are specific to each microgrid location. Literature contains several microgrid operational models that are based on forecasted parameters with no uncertainty (e.g., [9,12,20,21]). We also do not consider forecast uncertainties in our model. However, if uncertainties are to be accommodated, a stochastic bi-level model will have to be developed. The stochastic model will consider a set of forecast scenarios and their probabilities. The upper level model will minimize the expected operational cost of the microgrids, where, for each scenario, a lower level model

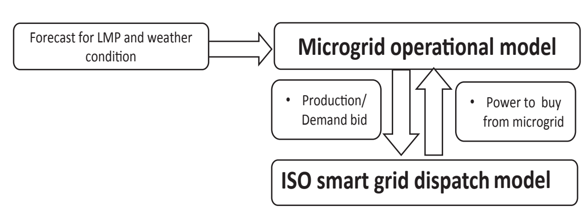

Fig. 1. A bi-level optimization framework for smartgrid with microgrids.