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A bi-level optimization model for operation of distribution networks with micro-grids

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ABSTRACT

Active distribution grids (ADGs) consist of several distributed generations (DGs) and controllable loads (CLs). These resources are utilized in the form of several microgrids (MGs) which in turn facilitate managing of ADGs. Therefore, the problem of distribution company (DISCO) and MGs operation requires a hierarchical decision-making framework. An attempt is made in this paper to model such framework as a bi-level optimization problem. In the proposed bi-level model, the objective of the upper level (leader) problem is to maximize the profit of DISCO, and the objective of the lower level (follower) problems is to minimize the cost of MGs. The resulting model is a nonlinear bi-level problem which is transformed into a linear single-level problem through Karush–Kuhn–Tucker (KKT) conditions and dual theory. Since the proposed model creates a retail electricity market in distribution grid, two frameworks are considered for this market: various and uniform retail electricity prices. To illustrate the effectiveness of the model, a hypothetical distribution grid is considered as the case study. The impacts of the market price and various demand levels of MGs on the results are investigated in two scenarios.

Introduction

Motivation

Traditional power systems suffer from several crudities such as fossil fuel shortage, environmental issues of fossil fuel resources, and low energy efficiency in power delivery sector [1]. Moreover, electric power consumption is increasing due to the population growth, industrialization, and especially urban developments. Therefore, power system administrators try to supply the increasing demand in an efficient way. For this purpose, distributed generations (DGs) are penetrated in distribution grids to serve the load locally [1].

While conventional distribution grids, known as passive distribution grids, do not contribute in power generation, their main function is to provide consumers with the power from transmission grid. In the most passive distribution grids, distribution companies (DISCOs) purchase the required electrical energy from wholesale electricity market and sell it to the consumers with specified prices. Emerging DGs in distribution grids, referred to as active distribution grids (ADGs), enables the grids to produce power locally. In ADGs, due to presence of DGs, DISCOs have complex operation problems in comparison with passive distribution grids.

Generally, integration of DGs with local loads introduces a new concept called microgrids (MGs) [1]. From the technical point of view, a MG is a system with at least one DG and one demand which can be operated in both grid connected and standalone modes [2]. Usually, there are several MGs in ADG which may have independent operations. These MGs can be coordinated by the DISCO.

In ADGs, the decision making on the operation problem should be done in two levels. The early one is the DISCO and the latter is MGs as the upper and the lower levels decision makers, respectively. To operate the ADG in an optimal manner, these decision makers should be able to optimize their respective objective functions independently, and cooperate with each other simultaneously. Therefore, the operation problem requires a hierarchical decision-making framework. In this way, there are multiple decision makers with different objectives which the decision process has a structure on the order of levels [3]. As mentioned above, there are two levels of decision making in distribution grid for which the operation problem can be modeled as a bi-level optimization problem [4]. In a bi-level optimization problem, the decision makers optimize their respective objective functions independently. However, their decisions effect on the decision space of each other.

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Nomenclature

Indices

j index of MGs

Parameters

C_{DG}^{j} generation cost of DG ($/MW h)
C_{IL}^{j} load curtailment cost ($/MW h)
P_{demand}^{j} power demand (MW)
$P_{DG,\max}^{j}$ maximum DG capacity limit (MW)
$P_{DG,\min}^{j}$ minimum DG capacity limit (MW)
$P_{IL,\max}^{j}$ maximum load curtailment limit (MW)
$P_{\max}^{T_{up}}$ maximum limit for purchasing power from market (MW)
$P_{\max}^{T_j}$ maximum limit for power exchange between DISCO and MG j (MW)
ρ^{M} market price ($/MW h)
$\rho^{\max}$ maximum limit for price of power exchange between DISCO and MGs ($/MW h)

Variables

P^{M} power purchased from market (MW)
P_{D}^{j} power exchange between DISCO and MG j (MW)
P_{DG}^{j} power generation of DG (MW)
P_{IL}^{j} the amount of load curtailment (MW)
U_{i}^{j} binary variable used for linearization of the complementary slackness conditions for constraint i and MG j
λ_{i}^{j} dual variable for constraint i and MG j ($/MW h)
ρ_{D}^{j} price of power exchange between DISCO and MG j in framework 1 ($/MW h)
ρ^{D} price of power exchange between DISCO and all MGs in framework 2 ($/MW h)

Others

L^{j} lagrangian function

Literature review

The operation problem of DISCO, including DGs and controllable loads (CLs), is investigated in the literature. In [5], a two-stage hierarchical framework for operation of DISCO in day-ahead and real-time electricity markets is presented. In [6], the previous article is extended with consideration of uncertainty on real-time electricity prices and loads. Day-ahead scheduling of DISCO considering energy and reserve markets is addressed in [7,8].

The economic, environmental, and technical effects of MGs penetration on ADG are studied in different articles. In [9], multi criteria decision aid (MCDA) techniques are used for evaluating the impact of MGs on the ADG. To this end, five criteria including installation and operation costs, investment deferral, active power losses, environmental impact, and improving the distribution grid reliability are considered. In [10], three criteria including economic operation, active power losses, and environmental benefits are investigated to show the impacts of MGs on the ADG.

In some studies, distribution grid is considered as coupled MGs and operation of these MGs and cooperation among them is investigated. In [11], an optimal control algorithm for coupled microgrids is presented. In [12], energy resource scheduling of several microgrids in isolated distribution grid is investigated using multi-agent systems. In [13], energy consumption scheduling in distribution grids with coupled microgrids considering demand uncertainty is analyzed.

The operation problem of DISCO and MGs in ADG is modeled using system of systems framework in [14,15]. Although appropriate framework is addressed in these papers, the operation problem of DISCO and MGs is not modeled simultaneously. In other words, at first, the optimization problem is solved for MGs and then the problem is solved for DISCO. In each iteration, the required data for optimization is exchanged between these two systems. This iterative process is continued as long as the converge conditions are satisfied.

To model the optimal behavior of decision makers in two-level decision making, bi-level optimization model is proposed in literature. In [16], the bi-level optimization is used to model a demand response aggregator's behavior in offering strategy of a wind power producer. In the proposed model the wind power producer and demand response aggregator are considered as leader and follower, respectively. The proposed model in [16] is extended to model the day-ahead market clearing price in the optimal decision making of wind power producer in which wind power producer acts as leader and demand response aggregator's decision beside day-ahead market clearing process are considered as the followers [17]. In [18] a two-stage two-level model is proposed to model the optimal behavior of retailers in wholesale and retail electricity markets considering demand response. The optimal behavior of retailers in demand response market environment is modeled as bi-level optimization problem in [19] in which retailers and consumers are considered as leader and followers, respectively. Therefore, for modeling the operation problem of two-level of decision makers, i.e., Disco and MGs, a bi-level optimization approach is employed in this paper. In the proposed approach, the price and the amount of power exchange between DISCO and MGs are considered as two decision variables that link DISCO and MGs to each other. The proposed bi-level optimization problem is transformed into a single-level problem according to the Karush–Kuhn–Tucker (KKT) conditions. Then, nonlinear expression in the model is replaced with linear ones based on the dual theory.

Moreover, when the operation problem of DISCO and MGs is modeled as a bi-level optimization problem, a retail electricity market can be created in distribution grid that clears the electricity prices between DISCO and MGs. In this paper, two frameworks are considered for this market. In framework 1 (FM1), the price of power exchange between DISCO and each MG is determined. In framework 2 (FM2), the price of power exchange between DISCO and all MGs is determined as a uniform price. These two frameworks are compared with each other and remarkable differences are highlighted.

Although two frameworks are considered for retail electricity market, the proposed bi-level optimization models for these two frameworks are similar with small differences. Further details are discussed in the problem formulation section.