Impacts of Large-scale Integration of Intermittent Resources on Electricity Markets: A Supply Function Equilibrium Approach

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Abstract—In this paper, the impact of large-scale integration of intermittent generation resources on electricity markets is studied through a supply function equilibrium model. A new formulation for determining supply function equilibria in uniform electricity markets is presented, where uncertainty of intermittent generation resources is taken into account. In the case of an unconstrained market model where generation limits are ignored, a closed form solution for market equilibrium is derived and its uniqueness is proved. In the case of a generation-constrained market model, an algorithm is proposed for determining supply function equilibria and the existence and uniqueness of the equilibrium is discussed. Case studies are presented for demonstrating the proposed approaches.

Index Terms—SFE under uncertainty, Scenario based EPEC, Large-scale wind power generation

I. INTRODUCTION

PRODUCING electricity using intermittent resources, such as wind- and solar-powered generators, is growing around the world [1]. The deriving factor in this trend is mainly the associated environmental benefits of these renewable energy sources. However, if integrated in large-scale, the non-dispatchable nature of intermittent resources imposes some technical and economical challenges on the operation of power systems [2]. In particular, market dynamics and prices could be influenced by such integrations [3]–[6].

In [3], it is shown that expected market price and loss of load probability decrease as wind power capacity increases in the electricity markets under perfect competition. It is shown in [4] that large-scale wind generation may lead to lower prices and higher supply reliability in the medium-term. According to [4], since large-scale wind generation decreases the capacity factor of dispatchable conventional generators, rate of installing dispatchable conventional generators will decrease in the long-term and consequently deteriorate reliability of supply. Impacts of intermittent technologies on the optimal generation mix in a perfect market is investigated in [5]. It is shown that high penetration of wind power capacity results in a decrease in the capacity of base load units and an increase in the capacity of intermediate units. Finally, in [6], the impacts of large-scale wind power generation on electricity prices are studied. It is concluded that several factors, such as wind share, supply function characteristics and variance of wind power, significantly influences the market value of wind power.

To model market dynamics, a perfectly competitive model is considered in [3], [6]. However, electricity markets are generally oligopolistic [7]. In [4], one base-load generator is assumed to be a dominant supplier in the market and a Cournot model is used to simulate the market. In this paper, it is assumed that all suppliers strategically participate in the market. A supply function equilibrium (SFE)-based approach is pursued; SFE-based models are believed to better represent the reality of electricity markets compared to either the Cournot and Bertrand models or a perfect competition model [8]–[10]. We use a scenario-based approach to model the uncertainty of intermittent supplies in the SFE. The main contribution of this paper is to present a new SFE-based approach for analyzing the market impacts of large-scale integration of intermittent resources.

The reminder of this paper is organized as follows: In Section II, available literature is reviewed and a framework for considering intermittent generation in SFE is presented. Some lemmas and theorems regarding uniqueness and existence of SFE in deterministic and probabilistic uniform electricity markets are presented in Sections III and IV, and an algorithm for determining principal SFE under intermittent generation is proposed. Impacts of large-scale wind generation on market price is assessed in Section V using the presented algorithm. Finally, conclusions are presented in Section VI.

II. BACKGROUND REVIEW AND METHODOLOGY

A. Supply Function Equilibrium (SFE) Model

A mathematical formulation of electricity markets based on the linear SFE model of [8] is considered in the present work. A multiple-firm supply function market model is employed where the transmission system constraints are ignored. Ignoring the transmission network constraints leads to a uniform price for the entire market footprint. Examples of uniform-price electricity markets are Alberta and Ontario electricity markets, where a province-wide price is determined for electricity for each planning interval.

Assume the cost of generating $Q_{S_i}$ by unit $i$ is $g(Q_{S_i}) = a_i Q_{S_i} + 0.5 b_i Q_{S_i}^2$ and the utility of consuming $Q_{D_j}$ by