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The influence of distributed generation penetration levels on energy markets

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HIGHLIGHTS

- DG affects energy markets depending on technologies, penetration and infrastructure.
- Energy prices vary when the market moves from centralized to several suppliers.
- Variational inequalities are presented to simulate a market under such transitions.
- The increase of DG penetration level may present different energy prices variation.
- If technical and political issues of smart grids are not improved, markets may crash.

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ABSTRACT

Planning of national energy policies brings new dilemmas with the introduction of distributed generators (DG). Economic theory suggests that a perfectly competitive market would lead to efficient pricing. In the absence of competition, regulators play a fundamental role in attracting reasonably priced finance in order to maintain, refurbish and increase the infrastructure and provide services at a reasonable cost. Energy market price equilibrium is mainly dependent on suppliers, generators, energy sources and demand, represented by conventional utility grid users. Its behavior is similar to that of other commodities. As generation becomes less centralized with the increasing economic viability of renewable energy sources, new suppliers are being connected to the grid. Such evolution means the transition from a monopolistic market to a broader and more open environment, with an increasing number of competitors. We make use of variational inequalities to model a hypothetical DG market in different scenarios, from monopoly, to oligopoly, to open market. Such an approach enables different equilibrium outcomes due to different DG penetration levels. Based on these findings, we argue that energy policies for such markets must be developed according to each specific stage of the grid's lifecycle. We show how energy policies and market regulations may affect such a transition, which may be catastrophic if not managed properly, and which is dependent on the energy mix.

1. Introduction

Modern societies face an ever growing energy demand, which implies several challenges, including the forecasted shortage of traditional fossil energy resources and the consequences of environmental pollution. The development of micro-energy power generation technologies, distributed generation (DG) technologies, and storage energy technologies require that the power infrastructure and the information infrastructure of intelligent micro-grids achieve two-way power flows and multi-stakeholder interactions (Sun and Zhang, 2012). These developments are bringing radical changes to the traditional model of generation and supply, as well as to the business model of the energy industry (Houwing et al., 2008).

For Krajacic et al. (2011), future energy systems will be based on four pillars: Renewable Energy, Buildings as Positive Power Plants, Energy Storage and Smart Grids in combination with Plug-in Electric Vehicles and V2G (Vehicle-to-Grid). Investments on hydro, nuclear, wind and photovoltaic (PV) power generation, as well as other new energy generating technologies are growing continuously. However, the rapid development of the power industry has revealed some weaknesses on the security, stability and vulnerability of power networks (Houwing et al., 2008).

An effective way to solve these problems is planning and developing distributed supply micro-grid systems in conjunction with the traditional centralized power supply systems. Compared with large and conventional electrical networks, micro-grids can be composed of the loads and micro-power generators (i.e. DG can

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be contained in the micro-grid, such as wind or photovoltaic power generation), which can provide electricity, and often heat simultaneously (Daoutis and Dialynas, 2009). Both the siting and the capacity of a DG source have different influences on the short-circuit currents, bus voltages and power flows in distribution grids (Jardim et al., 2008; Rüther et al., 2008; Rüther and Braun, 2009; Molina and Mercado, 2010; Braun and Rüther, 2010; Urbanetz et al., 2012).

The deployment of distributed generation faces several technical barriers as penetration level increases. We argue that planning distribution energy grids with increasing DG also requires incremental economic policy changes. As penetration level increases, different economic scenarios and outcomes shall be dealt with.

We have modeled a distribution grid as an energy market, transitioning from a monopolistic structure to a scenario with an increasing number of competitors, in order to simulate a grid considering the transition from centralized to distributed supply. This study allows for the evaluation of possible economic scenarios that may appear in future energy networks.

This article aims at comparing energy market characteristics, such as price and quantity (MWh), considering distributed and centralized generation, also taking into account the increasing penetration levels of renewables. In Section 2 we present a literature review on DG's characteristics, which were considered in the model development. In Section 3, we present the general characteristics of energy markets, followed by a description of the influence of deregulation and DG penetration on such markets. In Sections 4 and 5, we propose a mathematical model using variational inequalities for energy markets with DG. In Section 6 we present the results of the simulations using the proposed model, based on three different DG technologies (PV, wind and biomass) and on market structures.

2. Distributed energy generation

Distributed generation generally means a small power generation unit based on new energy and renewable energy, which is located near the load (Ackermann and Knyazkin, 2002). New energy and renewable energy include hydropower, wind energy, solar energy, biological energy, geothermal energy and ocean energy (Sun and Zhang, 2012). In the Brazilian energy context, the National Agency for Electric Energy—ANEEL (2010) includes other sources of energy in a DG system even if they are not from renewable sources, defining DG broadly as small-scale generators distributed along the grid.

Micro-grid is a small distribution network which is composed of distributed generation (DG), load, distributed storage (DS), power conversion equipment and control system, and can realize flexible energy management (Obara et al., 2011a, 2011b; Houwing et al., 2008). A typical micro-grid model is shown in Fig. 1.

DG in micro-grids involves a variety of energy forms, such as PV, wind power, micro-gas turbines and CCHP (Combined Cycle Heat and Power). A DG can supply electric power to the local load and feed surplus electric power back to the utility grid. Through energy management, it can adjust the output energy of distributed generation to meet demands for heating and cooling (Lasseter, 2002).

The ability of a micro-grid system to withstand disturbances is relatively small, especially in islanding operation mode. Considering the randomness and intermittency of wind and solar energy supply availability, the security of the system may face a higher risk than when supplied by conventional sources. Thus effective operation control for micro-grids is one key technology challenge in order to overcome such faults (Sun and Zhang, 2012).

The difference between micro-grids and DG is that micro-grids can run connected to the bulk power grid, or run independently,

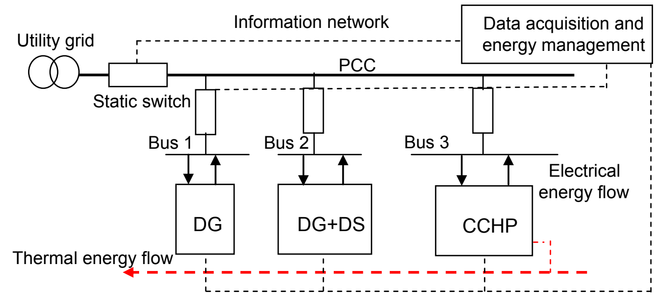

Fig. 1. Micro-grid, distributed energy generation and storage. . Adapted from Lasseter (2002)

disconnected from a large grid in the case of a large grid fault. In order to eliminate the impact on the large power grids, improvement of the micro-grid structure, configuration parameters and the control strategy is needed (Obara et al., 2011a).

Renewable energy generation systems are weak in terms of stability of power supply since the sources are mostly dependent on weather conditions. However, some of them, like solar irradiance and wind speed, have complementary profiles. Therefore, the Distributed Hybrid Energy System (DHES), composed of several new energy power generation sources, is the future development direction in new energy grid power generation systems. The DHES is a new power supply system combining distributed energy and distributed energy storage technology (Krajacic et al., 2011). The characteristics of hybrid energy systems is to overcome the instability of a single energy supply, achieve the complementary advantage and efficiency improvement of different energy sources by using different characteristics of various micro-sources, rationally allocate micro-sources and energy storage systems, and at the same time enhance electricity supply reliability and power quality at connection/isolation operating states by load leveling control strategies and the power electronic devices (Sun and Zhang, 2012).

The anti-peaking characteristic of wind power poses a challenge to power flow control, short circuit current control and power quality (Wu et al., 2010; Hedegaard and Meibom, 2012). At present, there is significant uncertainty of operational levels due to the imperfection of the forecasting system of wind power. Without the help of basic data and accurate forecasting, a power company's operation mode is uncertain (Obara et al., 2011a). For this matter, battery banks are used to supply power to fast load transients, ripple and spikes in stand-alone applications (Nirmal-Kumar and Niraj, 2010), and may as well be suitable for distributed storage systems.

As an example of how new technologies can overcome such issues for renewables, Du and Lu (2011) proposed a battery-integrated boost converter utilizing the distributed maximum power point tracking (DMPPT) configuration for a PV system, where each PV module has its own battery and DC/DC converter. In such topology, the MPPT function is not affected by the load demand and input power from PV. Application of the proposed converter to DMPPT configuration can save the voltage amplification stage and maintain PV voltage during partial shading. Thus, energy planning methodologies that use smart energy storage systems can assist the integration of energy flows, at the location of the energy end-use or close to it (Krajacic et al., 2011).

3. The energy market

There are several types of regional energy markets, including commercial trading in several levels (Caamaño et al., 2007; Chao, 2011; Chao and Wilson 2004): private bilateral agreements