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A Quasi-Feed-In-Tariff policy formulation in micro-grids: A bi-level multi-period approach

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HIGHLIGHTS

- We present a bi-level optimization problem formulation for Quasi-Feed-In-Tariff (QFIT) policy.
- QFIT dictates that subsidy prices dynamically vary over time depending on conditions.
- Power grid's physical characteristics affect optimal subsidy prices and energy generation.
- To maximize welfare, policy makers ought to increase subsidy prices during the peak-load.

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ABSTRACT

A Quasi-Feed-In-Tariff (QFIT) policy formulation is presented for micro-grids that integrates renewable energy generation considering Policy Makers' and Generation Companies' (GENCOs) objectives assuming a bi-level multi-period formulation that integrates physical characteristics of the power-grid. The upper-level problem corresponds to the PM, whereas the lower-level decisions are made by GENCOs. We consider that some GENCOs are green energy producers, while others are black energy producers. Policy makers incentivize green energy producers to generate energy through the payment of optimal time-varying subsidy price. The policy maker's main objective is to maximize an overall social welfare that includes factors such as demand surplus, energy cost, renewable energy subsidy price, and environmental standards. The lower-level problem corresponding to the GENCOs is based on maximizing the players' profits. The proposed QFIT policy differs from the FIT policy in the sense that the subsidy price-based contracts offered to green energy producers dynamically change over time, depending on the physical properties of the grid, demand, and energy price fluctuations. The integrated problem solves for time-varying subsidy price and equilibrium energy quantities that optimize the system welfare under different grid and system conditions.

1. Introduction

The objective in the paper is to develop a bi-level multi-period decision making formulation in micro-grids for energy markets that integrates renewable energy generation considering different Policy Makers'(PM) and Generation Companies'(GENCOs) objectives, while taking into consideration the effect of power line characteristics and the physical constraints in the system. The policy maker (or in some cases, the independent system operator) represents the governing and monitoring body of the grid, that is concerned with the welfare of the power grid, rather than the profitability. In the bi-level problem, the upper-level problem corresponds to the PMs, whereas the lower-level decisions are made by competing market players or GENCOs. The goal of the PM is to maximize an overall social welfare (OSW) measure which depends on overall system reliability, price stability, supply surplus, percentage of renewable energy generation, and other factors. On the other hand, GENCOs are profit maximizing entities. GENCOs' plants are subject to physical constraints in terms of line loading capabilities, Power Transfer Distribution Factors (PTDFs), as well as profitability considerations. We study the short-term (hourly, daily) planning and the interaction between the PM and GENCOs in a micro-grid, as well as the effect of different line

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parameters on the optimal generation, and the eventual price according to the demand. A better understanding of the interaction between PMs and GENCOs would enable the design of policies towards improved grid performance.

The formulation presented in this paper takes into account the integration of renewable energy standard (RES, also called Renewable Portfolio Standard) into the smart-grid infrastructure (Weisenmiller et al., 2012a). Through providing incentives for the green energy producers (GEPs), the PM targets achieving a certain level of renewable energy production. Feed-In-Tariff (FIT) and Tradable Green Certificate (TGC) are examples of policies that encourage GENCOs to invest in green energy production. A FIT is an energy-based policy that provides long-term incentives for GENCOs through payment of a regular subsidy price per unit of green energy generated (Couture et al., 2010). This policy accelerates the investment in green energy production. FIT policy's other objectives are job creation, decreasing electricity prices, growing the overall economy, building environment-friendly plants, managing waste streams, and attracting new investments (Couture and Cory, 2009). TGC policy is different than FIT policy in the sense that TGC GEPs are offered certificates proportional to the green energy produced. GENCOs utilizing TGC policy can trade these certificates independently of electricity (Tamas et al., 2010). FIT and TGC policies' common objective is to achieve a certain level of renewable energy production. Albeit policies like FIT and TGC have numerous advantages and benefits, some arguments could be raised against such policies. As discussed by Couture et al. (2010), difficulty controlling overall policy costs, near-term upward pressure on electricity prices, and distortion of wholesale electricity market prices are some of the disadvantages of FIT policy. In addition, shortage of capital leading to the exclusion of smaller participants from the market, price instability of TGCs when the system is near a target level and uncertainty in future energy prices are some potential TGC disadvantages (Poputoaia and Fripp, 2008).

The bi-level formulation developed in this paper utilizes the integration of these policies in the micro-grid economies. It also incorporates the impact of line parameters on the optimal power flow (OPF) in the system. The Quasi-FIT (QFIT) policy proposed in this paper is different from the usual FIT policy in the sense that the subsidy price-based contracts offered to green energy producers are varying over time, depending on the physical properties of the power-network (such as line-losses and minimum and maximum generation), demand, and energy price fluctuation, rather than being held constant over a long-term contract.

The paper is organized as follows. In Section 2, we present the relevant work and background in the area of computational modeling in energy markets. We also give an overview of OPF in micro-grids. Research gaps, price function, some underlying assumptions and preliminaries, and QFIT PM's and GENCO's optimization problem formulation are presented in Section 3. In Section 4, a solution strategy for the bi-level, multi-period problem is outlined. Simulation results for different system characteristics and scenarios are included in Section 5. Section 6 presents closing comments and conclusions.

2. Background

In this section we provide a succinct background on the relevant research areas covered throughout the paper. A simple model of the lower-level non-cooperative game and decision making problem for GENCOs is discussed in Section 2.1. The optimization methodology used to model constrained non-cooperative games along with an overview of tools used to solve the optimization problem is reviewed in Section 2.2.

2.1. GENCOs' interaction as a Nash–Cournot game

We model the lower-level problem as a non-cooperative, Nash–Cournot game where players make decisions independently. The Nash equilibrium of the non-cooperative games is generally used as a solution for problems associated with several players. The Nash equilibrium is a solution that guarantees that no player can individually improve their profits by changing their own strategies (Osborne and Rubinstein, 1994). The Nash–Cournot game (Hobbs, 2001; Han and Liu, 2013) is widely used in modeling non-cooperative games in energy markets. In this paper, we assume that the lower-level problem is modeled as Nash–Cournot game.

2.2. Bi-level problem formulation

In this paper, we develop a multi-period bi-level problem formulation in energy markets. The upper-level decision problem corresponds to the PM, while the lower-level optimization problem corresponds to the GENCOs. We first derive the equilibrium constraints on the lower-level problem. In the problem formulation, we assume various constraints for both the lower- and upper-level decision problems. Formulating the First Order Necessary Conditions (FONC) of optimality is the first step in finding the optimal solution to any non-cooperative constrained optimization problem. These optimality conditions are also called the Karush–Kuhn–Tucker (KKT) conditions. The FONC formulation results in a complementarity problem (Ferris and Pang, 1997). The complementarity problem is either a linear (LCP) or a nonlinear complementarity problem (NCP), depending on the nature of the constraints and the objective function. The solution can be found through methods developed for complementarity problems. Complementarity problems find the problem solution, as well as the optimization problem's multipliers (Murty and Yu, 1997). Murty and Yu (1997), Duan et al. (2010), and Gabriel et al. (2012) provide various algorithms that are used to solve both LCPs and NCPs.

In this paper, we formulate the nonlinear complementarity problem using the KKT conditions. These conditions, resulting from the lower-level optimization problem, are used as a set of constraints in the upper-level PM's decision making problem. This integration of the lower-level problem's optimality conditions results in a mathematical problem with equilibrium constraints (MPEC) (Pieper, 2001; Hawthorne and Panchal, 2012). Due to the lack of convexity and nonlinearity of MPECs, the solution derived for the upper-level problem can be combinatorial (Hawthorne and Panchal, 2012). The non-linearity of the problem and the non-convexity of the feasible space make the feasible space too small and hence the formulated problem a challenging one to solve. Efficient algorithms have been developed for solving MPEC problems. Penalty interior-point algorithm (PIPA), piece-wise sequential quadratic programming (PSQP), smoothing SQP, and some implicit function based methods are all algorithms that have been developed to solve such MPECs (Pieper, 2001). Gabriel et al. (2012) provided an extensive review on LCPs and MPECs, with applications modeling natural gas markets. In this paper, the MPEC's main objective is to solve for the time-varying optimal generation quantities and subsidy prices for the QFIT bi-level policy, considering price fluctuations, peak demand periods, and physical properties of the power-network.

2.3. Optimal power flow

The optimal power flow (OPF) problem seeks to control generation/consumption to optimize certain objectives such as minimizing the generation cost or power loss in the network. It is one of the fundamental problems in power system operation (Gan

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