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A linear programming model for power distribution with demand response and variable renewable energy ☆

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HIGHLIGHTS

- Introduce a linear programming framework to model distributed generation, flexible loads and distributed energy resources.
- Provide a closed loop infrastructure and energy asset investment model.
- It optimizes system costs considering dynamic response to marginal costs of energy and reserve.
- Provide a illustration based on a scenario of strong variable energy penetration in an EU region.

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ABSTRACT

A linear programming framework is proposed to model distribution network characteristics, and market clearing processes for flexible load and distributed energy resources providing reserve and reactive power compensation. One shows that the Nash equilibrium solution representing the interaction between utility and customers for demand response and distributed reserve transactions can be approximated by a linear program when the players (i.e. the customers) are numerous and tend to become infinitesimal. Then a linear program is shown to reveal the market prices, corresponding to the marginal cost for the utility. The goal in developing this model is to provide a new module for a regional long term model of development of smart energy systems. This module will then introduce in the modeling of energy transition, the new options and constraints that are provided by a penetration of renewables with the possibility of implementing distributed markets for demand response and system services permitted by the development of the cyber-physical layer. A case study of a potential smart urban distribution network in Europe is carried out and provides numerical results that illustrate the proposed framework.

1. Introduction

The goal of this paper is to introduce a linear programming framework to model distributed generation, flexible loads and distributed energy resources (DERs) along with the distribution grid topology and power flow in the context of smart energy systems in the presence of variable renewable energy. This modeling framework enables the “commoditization” of demand response, the introduction of decentralized markets for the optimal scheduling of secondary reserve, storage-like flexible loads and reactive power compensation through the dual use of volt/var control devices that accompany DERs.

This linear program has the potential to capture optimal adaptive operating costs, and, as such, provide the optimal dispatch module in a long-term optimal energy technology mix capacity expansion model such as ETEM-SG [1], that is capable of emulating the development of an efficient regional energy system with a planning horizon of 30–50 years.

The work reported in this paper is part of a larger research program that aimed at Modelling smart energy systems in long-term multi-energy models. The drive toward sustainable development will be facilitated by the transition to smart energy systems relying on the interface and co-optimization of the cyber and physical layers modeling the electricity cyber physical system. Increasing penetration of intermittent and volatile renewable energy sources connected at the transmission (e.g. wind farms) or the distribution

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networks (e.g. roof top photovoltaic (PV) panels) will impose new operational requirements. Fortunately, the advent of grid friendly Flexible loads and DERs including variable speed drive powered combined heat power micro-generators [2], heat pumps [3,4], and electric vehicles [5,6], provide new opportunities to optimize power systems by providing fast reserves and putting accompanying volt/var control devices (PV inverters, Electric Vehicle (EV) chargers and the like) to dual use for reactive power compensation. Under these circumstances, flexible loads and DERs can significantly improve operational and investment efficiencies. As indicated above, the aim of this work is to develop a linear programming approach permitting a representation of the constraints along with the significant degrees of freedom and capabilities of these new technology developments at distribution level in a regional long-term multi-service and multi-energy model. Linear programming models for regional energy systems analysis were introduced early on (see e.g. [7–9]) in conjunction with the development of the MARKAL/TIMES [10] family of models under the aegis of ETSAP,[1] a committee of the IEA. The interest for a regional or local energy modeling capability has been recently strengthened by the development of the smart grid and smart city concepts (see e.g. [11,4,12–14]). The representation of demand-response in the open-source energy model ETEM-SG[2] has been described in [1], and a similar development in TIMES has been proposed in [15], whereas a representation of smart grids has been introduced in the open-source energy modeling kit OSeMOSYS [16,17].

However, to our knowledge there does not exist yet a closed loop infrastructure and energy consuming and producing asset investment model that optimizes overall system costs by taking into consideration the anticipated dynamic response of grid-connected-asset behavior (i.e. intertemporal demand response and offering of reserves) to the prevailing dynamic spatiotemporal marginal costs of energy and reserve services. In fact, infrastructure investment optimization has been and continues to be addressed by open-loop avoided cost models [18–20] which select infrastructure investments based on predicted consumer behavior. For example, if transformers are expected to be overloaded for a certain number of hours and grid line losses to be high, additional transformer and grid line capacity is planned for. In contrast, the closed loop approach that we take, incorporates the response of Distribute Energy Resources (DERs) including flexible loads, EVs, renewable generation and the like, to dynamic marginal costs. The dynamic response of DERs results in the actual amelioration of high line losses and transformer overloading. More importantly, the behavior modification motivated by dynamic marginal cost based pricing results from the adaptation of the behavior of each individual DER to the behavior of all other DERs and lead to a mutually beneficial equilibrium. Hence, whereas state of the art avoided cost approaches determine an approximate economic life elongation of existing grid infrastructure for an estimated expansion of DERs, our closed loop model co-optimizes grid and DER expansion.

As such, our work builds on extensive past work on demand response in general [18,21–26] and EVs in particular [21,27–29]. In developing our closed loop model we have relied on recent work that captures the salient capabilities of detailed Alternating Current Optimal Power Flow (AC OPF) algorithms which rely on extended branch AC models [30,31] to solve for adaptive marginal cost based distribution locational prices (DLMPs) [32–39] while overcoming notorious non-convexities that hamper AC OPF and resorting to distributed models that deal with the complex intraday costs of DERs [18,26,33,40–50]. To further integrate DLMPs into a long term economic development energy model, we develop an iterative linear approximation of the non-linear extended branch AC OPF utilized by the distribution grid. The linearization converges in three or less iterations and allows us to deal with a multiyear energy development model. Each year is modeled by daily cycles that are selected and weighted appropriately to capture the uncertainty and volatility of renewable generation DERs. As such, our main contribution is the uniquely designed linear programming model.

Our proposed linear programming model takes into consideration the requisite options and constraints at the level of the distribution grid to provide a regional energy system with demand response and variable renewable energy sources. Hence the paper focuses on incorporating into a linear program, which would be compatible with the aforementioned regional long-term models, the ability of DERs to provide reserves, reactive power compensation and shift their operation over time so as to reduce losses, congestion, wholesale energy costs and distribution asset (particularly transformer) wear and tear.

The ultimate goal is to introduce distribution network costs, benefits and adaptability into a regional integrated energy systems analysis model that optimizes the transition costs to environmental sustainability of a grid that relies on variable energy generation, smart grid management and broadly construed demand response.

In summary this paper's contribution is the computationally efficient modeling of demand response and the associated reserves [40], as well as the reactive power compensation [51] that can be provided by DERs and flexible loads. Thus, sufficient introduction of DERs can act synergistically to mitigate the volatility of renewable generation [52] and enable its strong integration into the electricity grid. Moreover it is consistent with a game theoretic approach, as proposed, e.g. in [53], while it shows that the Linear Programming framework can be justified as a limit of Nash equilibrium solutions, when the players are numerous and tend to have infinitesimal influence on the price.

The paper is organized as follows: In Section 2 we show, that under appropriate conditions of grid cost convexity and small, price taker participants, a Linear Program leads to the usual competitive market equilibrium. In Section 3 we develop a linear program that represents accurately the market based mechanisms driving optimal demand response in smart grids. A similar approach is used for the representation of distribution network markets for reserves and reactive power, with all three products, real power, reactive power and reserves clearing simultaneously; in Section 4 a numerical illustration is given, based on a scenario of strong variable energy penetration in a european region. In Section 5 we conclude and discuss further developments envisioned in integrating this distribution grid sensitive model into regional integrated energy systems, like ETEM-SG or OSeMOSYS.

2. Modeling demand response in a linear program

The introduction of two-way communication between power retailers and customers that enables demand response based on real-time pricing defines a competitive framework involving the customers as agents having an influence on the price they are charged. This is illustrated in Fig. 1, which schematizes the exchange of information between the agents. In several papers dealing with smart grid and demand response modeling a nonzero-sum game paradigm is used - see e.g. [54] or [55]. So one has first to show that a linear program could also capture the essence of this relationship in certain circumstances, which are common to many smart grid operations. More precisely, the nonzero-sum game describing the relation between a cost minimizing retailer and the set of customers who individually optimize

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[1] http://www.iea-etsap.org.

[2] http://apps.ordecsys.com/etem.