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Power supply–demand balance in a Smart Grid: An information sharing model for a market mechanism

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ABSTRACT

In the future, global energy balance of a Smart Grid system can be achieved by its agents deciding on their own power demand and production (locally) and the exchange of these decisions. In this paper, we develop a network model that describes how the information of power imbalance of individual agents can be exchanged in the system. Compared to existing network models with hierarchical structures, our developed model, together with a market mechanism, achieve the power balance in the system in a completely distributed way. Additionally, dynamics, constraints and forecasts of each agent can be conveniently involved.

1. Introduction

The Smart (Power) Grid is the most promising solution for the problems presented by increased electrification, and the large-scale introduction of distributed power generation in the power system.

The Smart Grid offers a number of significant advantages. First, the Smart Grid allows for two-way communication, which enables demand response. Secondly, domestic power generation is a key component, which makes the end-user both a producer and a consumer, or a prosumer, of electric power [1]; in a Smart Grid, prosumers are both incentivized and empowered to contribute to the balance of power supply and demand in the system. Thirdly, by producing power locally, Smart Grids also minimize transportation costs. A problem with the transportation of electricity is found in the fact that energy is lost in the power network transmission lines. Matching supply and demand at a local level therefore can be used to better minimize the losses from transportation; a feature of the Smart Grid which offers both economic and environmental gains.

Another important feature of the Smart Grid is found in the fact that if local matching lowers the fluctuations in the power system, Smart Grids will ease the control effort of the overall power system [2]. However, because the end-user decides when to use his electric devices, a major question that arises here is: how do we coordinate the decisions of a large number of end-users? In the power system, the end-users can have a large variety of electric power demand and production devices, such as washing machines, freezers and micro combined heat and power systems, which can be controlled even if they are subject to operational constraints. The rest of the power demand, that cannot be controlled, can, to some extent, be predicted. This means that the decisions have to be coordinated on two levels. Firstly, the end-user has to anticipate on the forecasted power profile. Secondly, since power is shared in the network, the end-user must also anticipate on how neighbors decisions will influence the power profile. Therefore, in order for the end-users to contribute to the system in

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an optimal way, a difficult control problem has to be solved to coordinate the decisions. As the network grows in the number of end-users, a large number of decision variables has to be included in the optimal control problem.

It is widely agreed that a centralized solution scheme for the so-called optimal control problem is too time consuming, because of the computational complexity [3]. Therefore, a host of scalable control methods have been proposed in the Smart Grid setting. Current models, proposed by the literature for device coordination, have a centralized component in the fact that there is one decision-making agent, see e.g. [4]. In the PowerMatcher game [5] for example, an agent for each device broadcasts a bidding curve for his willingness to pay for electricity. One agent at the top of a hierarchical structure, then determines the equilibrium price. The PowerMatching concept was implemented in Groningen, in the Netherlands, as a demonstration project of a future energy-infrastructure called PowerMatching city, see [6]. Twenty-five households with smart appliances, such as micro-combined-heat-power systems that match their energy use in real time based upon the available energy generation, were connected. The project was generally perceived as a big success, however a number of short-comings were observed. In particular, predictions of power is not yet taken into account, and since the prices are the same everywhere in the network, there is no preferred location for the production in the network.

This observation motivates us to consider a fuller model, with a distribute information structure for scalability, as well as including predictions on the power demand. In [4] a methodology combining forecasts, planning and real time control, that is capable of distinguishing position in the network, is described. However, the planning is centralized. Probably the most related to the results presented in this paper is the work presented in [7], where a multi-agent Model Predictive Control (MPC) approach is presented. However, the method is applied to load frequency control, which is a different type of problem than what we treat and, most importantly, an information sharing structure has not been considered. In particular, we address the challenge to match local supply and demand real time anticipating on the future behavior and only base decisions on local information. Further, we will avoid a hierarchical network structure.

In this paper, and to avoid a centralized structure, we propose an information network where each agent has local (imbalance) information about the system when they make their decisions. Further, in order to anticipate on future behavior, and to incorporate constraints from the electric devices, we work in a MPC framework. In the MPC framework we include predictions about the end-users future power demand, and technical constraints from the devices that need to be controlled, see e.g. [8–10]. We propose an information-sharing network, and dynamically couple the end-users information to coordinate decisions in the network. The information at an end-user is a mixture of personal imbalance, and the connected neighbors imbalances. In a large network, the distance between suppliers and consumers also plays a role: it is more energy efficient to buy from a close-by end-user, than a far-away end-user. An end-user cannot exchange imbalance information with everybody, but bargains directly with a subset of all end-users in the network. This motivates the choice of information network topology. The idea is that the system, as a total, reaches the same balance as if it could bargain with all end-users directly, but now there is an ordering by information distance to neighbors of who an end-user buys his power from: if the power is available at the direct neighbors, the end-user will buy from this neighbor, and the power coordination is done locally. In the case that an end-user needs to buy from a neighbor that is not a direct neighbor, he must bargain through his neighbors neighbor connections until an end-user wants to sell.

The information network which the proposed model models, is made up by a subset of the end-users in the power network, which is connected to the overall power system. This means that there is also a power exchange between the sub-network and the external network. However, this exchange is not modeled explicitly, but the objective is formulated as if the members of the information network are forming a closed grid, minimizing the imbalance, meaning that the power exchange with the external network is minimized. Then, after the actions are taken, we assume that the excess or shortage of power is taken care of by the external network. The control goal is the supply demand balance at a market level within the information network. We stress that the end-users are virtually connected to the information network, while they are physically connected to the power network. Therefore, the information network does not need to have the same topology as the power network, but it can have any desired topology.

In this way, it is clear that coordinating decisions in the information network will influence the control of central power plants. In the literature, the Optimal Power Flow (OPF) problem is solved to find the optimal power generation given line power constraints. This is a steady state optimal control problem. In contrast to our formulation, the objective of the OPF is to minimize generation cost while the balance problem is included as a hard constraint. In [11], a dynamic feedback controller for an optimal real-time update was designed. However, predictions and anticipation on the future situation in the network can not easily be included.

Our proposed information sharing model facilitates distributed decisions of dynamically coupled prosumers in a Smart Grid with input constraints. We take into account forecast about future behavior when the decision is made. If the end-user receives local real time information concerning the systems status, possibly in the form of prices, he can make decisions for when to turn on or off his demand, production or storage of electric power such that both the end-users and the overall system benefits. Such a control strategy using a price mechanism is described in [12,13] where it has been applied to a vehicle formation example. The strategy is based on dual decomposition and sub-gradient iterations, and [14] describes a distributed model predictive control (d-MPC) version of the method. This way, the end-user can make his control decision based on price incentives from virtually connected neighbors, local imbalance information predictions, his own constraints and his own predictions. In [15], which focuses on the control aspects of this approach for Smart Grids, the positive effect of the scalability of the distributed algorithm was shown, and in general distributed grids are more robust to topological failures [16].