Dynamic Capacity Control and Balancing in the Medium Voltage Grid

(Doctoral Consortium)

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ABSTRACT

Renewable power sources such as wind and solar are inflexible in their energy production, which requires demand to rapidly follow supply in order to maintain energy balance. Promising controllable demands are air-conditioners and heat pumps which use electric energy to maintain a temperature at a setpoint. Such Thermostatically Controlled Loads (TCLs) have been shown to be able to follow a power curve using reactive control. In this project we investigate the use of planning under uncertainty to pro-actively control an aggregation of TCLs to overcome temporary grid imbalance. We model the planning problem under consideration using the Multi-Agent Markov Decision Process (MMDP) framework.

Since we are dealing with hundreds of agents, solving the resulting MMDPs directly is intractable. Instead, we propose to research ways to decompose the problem by decoupling the interactions.

Keywords

Planning under uncertainty, scalability and heuristics, MMDPs, smart energy networks

1. PROBLEM STATEMENT

Our current electricity network is designed to transmit electricity from a small number of large power supplying companies to a large group of consumers, and industry and commerce. The organization of electricity networks follows this function through its division into three voltage levels. Produced power is transmitted across long distances using the high voltage transmission network, until it reaches the local medium voltage distribution networks. There the power is either delivered to large consumers such as major industry or handed off to the low voltage feeders connecting several households.

This topology has served us well until now, but it is expected that future changes in grid utilization will put the networks under increased pressure. Increased use of types of large electric consumer loads such as electric vehicles and electric heating and cooling threaten to overload the rated maximum load of distribution transformers. And increased distributed generation through consumer operated solar panels, industrially operated micro-CHP, and wind farms increases the volatility in the supply of electricity. Addressing these problems using traditional grid reinforcement and back-up supply generators is considered too expensive and inefficient, and therefore researchers have looked into techniques to make the electricity network intelligent; so called smart-grid solutions.

This research project aims to develop advanced algorithms for managing the consumption of electricity within the available capacity, in order to keep future electricity networks stable.

2. THERMOSTATICALLY CONTROLLED LOADS

An ideal mechanism for balancing fluctuations in production and bridging periods of restricted capacity would be a storage device. Storage devices are widely considered to not be feasible for the future electricity network because of their cost and their relatively low capacity and short lifespan. Therefore people have been looking for alternative mechanisms that behave somewhat like storage without these drawbacks. One promising type of storage-like device is a thermostatically controlled load.

A thermostatic load is any device that is able to consume (electric) power for the heating or cooling of a body in relation to the outdoor temperature, such as refrigerators or central heating systems. The goal of the thermostat is to operate the device such that the temperature of the body remains as close as possible to a given setpoint at all times.

A Markov chain model of thermostats controlled by hysteresis controllers was presented by [5]. In their model, the temperature of the body in the next time step $\theta_{i,t+1}$ is deduced from the current temperature $\theta_{i,t}$, the current outside temperature θ_t^{out}, a temperature input from the device θ_i^{pwr}, and a random temperature shift $\theta_{i,t}^{\text{rnd}}$ modeling exogenous actions such as opening a door. The hysteresis controller operates to keep the temperature within a deadband surrounding temperature setpoint $\theta_{i,t}^{\text{set}}$.

We use a similar model in our papers [2, 3] to make on/off decisions $m_{i,t}$ for every TCL i and for every discrete time period t. The length of such a period Δ, together with the thermal constants R_i (thermal resistance, °C / kW) and C_i (thermal capacitance, kWh / °C) determine how quickly the current temperature responds to the external factors

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through the fraction $a_i = \exp \frac{-\Delta}{R_i C_i}$, resulting in the model:

$$\theta_{i,t+1} = a_i \theta_{i,t} + (1 - a_i) \left(\theta_t^{\text{out}} + m_{i,t} \theta_i^{\text{pwr}} \right) + \theta_{i,t}^{\text{rnd}}. \qquad (1)$$

In [3] we show how a large aggregation of TCLs can be modeled using a Multi-Agent Markov Decision Process, in order to plan the activation times of the devices to stay below a maximum power consumption curve. The objective of each TCL is to keep its temperature as close as possible to its temperature setpoint without jointly exceeding the amount of available power at any time step.

3. FUTURE RESEARCH DIRECTIONS

This section describes a number of promising directions for extending the current work on TCLs.

3.1 Generalizing the Power Constraints

In the TCL problem, agents are collectively resource constrained. Without this constraint coupling them together, individually optimal plans would always combine into a globally optimal plan. The coupling constraint originates from the shared infrastructure for supplying the TCLs with the power they need to operate. There are other domains where planning problems with this type of constraint exist, such as taxi planning (using the available fares as resources). If we can generalize the power constraint to some type of model construct, we can leverage the solution techniques designed on the TCL problem in other domains.

3.2 Heterogeneous Agents

Agents in the TCL problem are highly similar, which makes it in a sense easy to combine them. Taken to its logical extreme, this similarity allows for control mechanisms that only consider the agents as an aggregate with one control action and one output signal. Given sufficient modeling detail it becomes possible to control such an aggregate using a closed loop feedback controller. In the domain of TCLs, early aggregation techniques for nearly homogeneous groups of TCLs were developed by Callaway [1]. More recently, Soudjani and Abate [6] proposed an abstraction procedure to generate a formalized stochastic model of a population of completely homogeneous TCLs with guarantees on the error in the response of the model. Another application of aggregation to the wider energy domain can be found in the works of Meyn et al. [4], who design an aggregation for *very* large groups of pool pumps.

Compared to the aggregate control approaches, modeling TCLs as MMDP has the advantage of allowing it to plan policies for the states of individual agents. Additionally, a key advantage of the MMDP model also allows us to model individual agent properties. This becomes more valuable the more heterogeneous the agent population under control becomes. In the other direction, the more heterogeneity the model is able to absorb, the more useful it will become relative to other approaches.

3.3 Hierarchical Decomposition of Resource Constraints

In the described TCL problem there is only a single constraint, which is a global maximum on the power consumption. In real networks there are constraints at multiple levels. At the highest level, the total production should match the total consumption. But additionally, power flows should not exceed the load capacities of any of the transformers in the network. At the lowest level, individual TCLs are connected to a feeder cable, and their actions influence not only power but also voltage levels. Unlike power, voltage has a sequential behavior. Suppose we are given three TCLs p_1, p_2, p_3 connected sequentially to the same feeder, with p_1 sitting closest to the transformer. Then activating p_1 lowers the voltage for both p_2 and p_3, while activating p_2 only affects p_3.

Adding all these additional constraints to the original MDP formulation increases the coupling between agents. Because we rely on the originally loose coupling of the problem to perform the decoupling and arbitrage heuristics, additional coupling threatens the heuristic solution quality. On the other hand, the structure of these additional constraints also provides opportunities to exploit structure to solve the problem. Because the electricity grid is hierarchical, constraints at a low level may obscure those at a high level. We can exploit this property to try to split the problem into several subproblems that only rarely affect each other. Even when it is not required to consider these additional constraints, hierarchical decomposition can help with the scalability of the problem.

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