Decentralized Energy Management with Profile Steering

Resource Allocation Problems in Energy Management

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Our energy supply chain is changing rapidly, driven by a societal push towards clean and renewable resources. However, these resources are often uncontrollable (e.g., wind and sun) and are increasingly being exploited on smaller scales (e.g., rooftop photovoltaic). This poses a reliability challenge for the operation of our energy supply chain, specifically for our electricity grid. In this grid, supply and demand must be matched at all times, since storage is virtually non-existent. Traditionally, the supply is controlled centrally and follows the load, where the latter is assumed to be uncontrollable. With the growing number of uncontrollable distributed renewable resources in the system, the centralized paradigm is quickly becoming infeasible.

To combat the decreasing flexibility due to loss of controllability on the generation side, often the exploitation of flexibility on the consumption side is considered. This flexibility comes from devices that can adapt their energy use, e.g., smart white goods or electric vehicles (EVs) with smart chargers. Such resources of flexibility on the consumer side are called distributed energy resources (DERs). With the expected growth of the number of DERs in future energy systems, their coordination offers potential to operate the grid more efficiently and allows the integration of more (uncontrollable) energy from renewables into the grid. Traditional steering approaches in the electricity grid do not scale well with the number of DERs and were not designed for the diversity (i.e., heterogeneity) of the envisioned DERs. Thus, new energy management approaches are required.

In this thesis we introduce and study such an energy management approach called profile steering. The profile steering approach decentralizes (part of) the computational effort to ensure scalability, making it a decentralized energy management approach. Profile steering relies on predictions and scheduling, meaning that it predicts the future system state and requirements and schedules the use of flexibility of the available DERs to best meet the system goals. We focus on the distribution grid, as a large part of the DERs are expected to be present in this part of the grid.

The profile steering approach influences the energy use of DERs using generic steering signals. We show that the approach can incorporate a broad class of such steering signals. This implies that the approach is flexible enough to be applied in many different situations. Furthermore, we exploit the hierarchical structure of the electricity grid to set up a corresponding hierarchical control structure. This structure allows us to incorporate local limitations into our approach, for instance maximum cable loading of the considered grid section.

As the developed approach is decentralized, we distribute (part of) the required computation to a local level, i.e., to a controller inside a home or embedded in a device. Such controllers often do not have large computational power. To ensure the computations can be feasibly executed on these local controllers with low computational power the resulting distributed scheduling problems have to be researched. We show that many of these problems fall into the class of resource allocation problems, which are well studied in literature. Several of these problems are extensions of known problems. Therefore, we apply some of the techniques found in literature and extend them to include common cases (current and futuristic) in residential energy settings.

In particular we consider buffering devices. Such buffering devices can utilize an internal buffer to decouple (part of) the time they require energy for their operation and the time this energy is taken from the grid. The first type of such a device we consider is the electric vehicle (EV). Scheduling the energy use of the EV is similar to a classical resource allocation problem if it can charge at any rate between zero and a given maximum. To solve this case we apply techniques from literature. However, if the EV can only be charged at a finite number of rates, the problem becomes NP -hard, even if we are only interested in obtaining feasible solutions. To circumvent this issue we consider an adaptation of the problem for which we develop an efficient solution method giving results that are nearly identical to feasible solutions to the original problem.

In a follow up chapter we extend the results found for the EV to devices that also allow discharging, e.g., residential stationary batteries and EV s with vehicle-to-grid capabilities. Furthermore, we study heating, ventilation, and air conditioning systems as a special case. In these systems the energy losses depend on the energy present in the storage (in this case the house itself). Next to developing a method to control such a device, we also study the effect of prediction errors on our approach and show that we can effectively deal with them in the case of heating, ventilation, and air conditioning systems using an approach inspired by model predictive control.

We use simulations to show the validity of profile steering using several cases. We show that profile steering can also be used to achieve near optimal results when minimizing the degradation of a power transformer. This indicates that the benefits that can be expected from using our approach are not limited to energy markets, but also include increased lifetime of grid assets resulting in reduced investment costs in these assets.

Summarizing, the introduced profile steering decentralized energy management approach promises to be a valuable approach in the future (smart) electricity grid where it can unlock the potential of many residential DERs and assist in an effective and efficient energy transition.