Master thesis description

Real-time load control for enabling high penetration of renewable energy

The need of switching from a power production based on fossil fuel towards a more sustainable one has become evident during the last decades. The link between greenhouse emissions due to fossil fuel consumption and global warming is now widely accepted and it is reasonable to expect that the progressive shrinkage of the fossil fuels and uranium reservoirs will lead to increasing costs of thermoelectric and nuclear energy and geopolitical instability. The generation capacity of renewable energy is constantly growing, with 178 GW production added globally in 2017. In the same year, the increase in photovoltaic capacity alone was greater than the natural gas, coal and nuclear power capacity increase combined. Some countries, such as Norway, Iceland, Albania and Paraguay, are already close to producing 100% of the consumed electricity from renewable sources, mostly thanks to their hydroelectric power capacity. Many other countries, including China, USA, India and the EU, have set important goals for replacing fossil fuels energy sources with renewable energy generation in the near future. While the debate about the feasibility of a global 100% renewable electrical energy production with current technology is still ongoing, it is clear that renewable energy sources are experiencing a fast growth which is going to accelerate in the coming years.

In the electric power system, **the supply and demand of electricity must be balanced at all times** and there is very little opportunity to store energy. This balance is achieved today thanks to the traditional fossil fuel generators and hydroelectric plants, which can control their energy output to meet the energy demand in real time. **Wind and solar** power are the fastest growing renewable sources and they **pose a serious threat because of the inherently unpredictable and uncontrollable nature of their power generation**. One solution to this problem is to increase battery storage systems, which is inefficient, expensive and anyway limited in its capacity. Furthermore, the grid frequency stability is guaranteed by the mechanical inertia of synchronous rotating generators, which is almost null in the wind and solar power generation systems. The consequence is that an increased share of renewable energy will lead to a faster variating, unpredictable system which has limited control capabilities.

Recently, the possibility of **balancing the grid by adapting the user power consumption over time** has emerged as a research field. The main challenge is to **devise a scheme that allows to coordinate the power consumed by so-called deferable loads** such as heat pumps, refrigerators, water heaters and electric vehicles under charge to accommodate the load curve to the grid generation variability, **with minimal impact on the end users but maximal effect at the grid level**. The consumption of these types of loads can be shifted in time (within limits) without really impacting the quality of service offered to the user. Furthermore, given the pervasive presence of small (potentially) controllable loads, it is expected that they would be able to respond with the required speed and precision to balance the grid in real time.

Another challenge posed by the high penetration of solar energy is the so-called “duck curve”, as illustrated in Figure 1. **The ramp-rate required to supply the required power when the sun sets will soon exceed the ability of the gas turbines, which are the fastest ramping available generators**. A faster responding system would better track the power production, thus reducing the frequency and voltage variation across the grid. Large-scale control of deferrable loads is expected to be able to react much faster than gas turbines, **thus enabling the increase of solar penetration beyond the constraints currently imposed by ramping rates**.

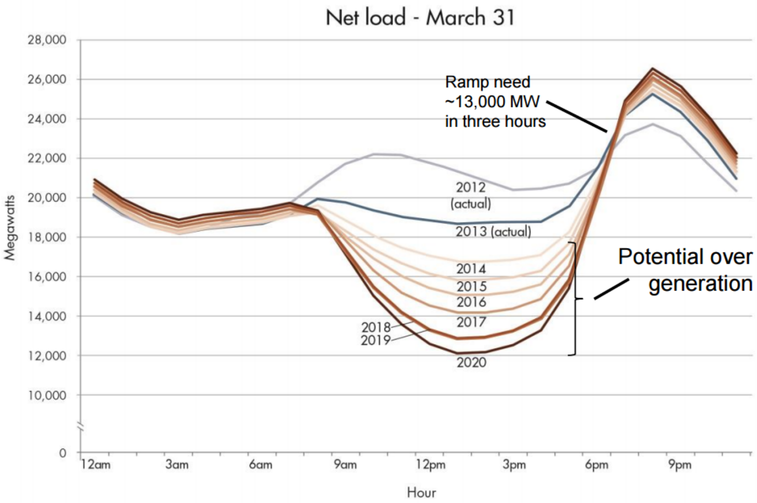

Figure 1: The “duck curve” in California: with the increase of solar production, that covers most of the load during daytime, traditional generators need to activate really fast to supply power when the sun sets. It is forecasted that the ramp-rate required will soon exceed the physical limits of gas turbines, which are the fastest available power generators. Source: US Department of Energy
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Finally, the distributed nature of this control would allow for a locally focused control, thus avoiding large rerouting of power and overcharge of lines connecting different areas (tie lines) in case of a generator fault.

The **aim of this thesis** is to formulate the problem of controlling a large population of deferrable loads with minimal impact on the end user as a **tractable optimization** problem and (i) analyze the feasible space of solutions in order to **characterize the degree of controllability of the system** and (ii) provide a practical tool to **systematically interface controllable loads with real-time grid optimization** (i.e. coordinate both loads and generators in the scheduling of power production taking into account the tight voltage and transmission constraints in the networks)

The need for real-time power balance

To develop a better understanding of the issues raised by an increase in the amount of renewable energy production share, let us develop a simplified model of the frequency of an AC power system in steady state. The AC frequency of the grid is approximated by the differential *swing equation*

$$M\frac{\mathrm{d}\omega}{\mathrm{d}t} \approx P_g - P_l, \tag{1}$$

where ω is the deviation of the system frequency from the rated value (50 Hz in Europe, 60Hz in the USA), P_g is the total generated power, P_l is the power absorbed by the loads (households, industries, etc.) and M is directly proportional to the total mechanical inertia of the turbines in the synchronous generators (nuclear, coal, gas and hydroelectric plants). A stable frequency is essential for the correct functioning of the connected machines and it has to be kept under constant control. From (1) we notice that, if there is a sudden power imbalance ($P_g \neq P_l$), the frequency in the systems starts to deviate from the nominal value. Corrective mechanisms measure the frequency and modify the generated power P_g to restore balance. The rate of change of the frequency is directly proportional to the available inertia M. High penetration of wind and solar has two detrimental effects to the grid:

- It reduces the value of M as wind and solar do not operate with turbines and thus provide no mechanical inertia
- It reduces the ability of controlling P_g as wind and solar plants cannot choose their power outputs.

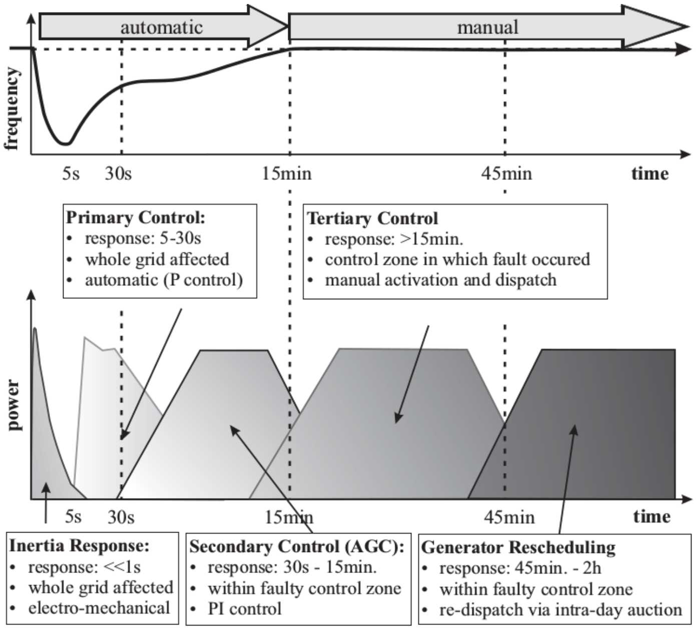

Figure 2: Frequency control response time. Source: ETH Zürich

As it can be seen in Fig 2, it takes minutes before the turbines can increase their generated power to balance a disturbance and the stability of the grid initially relies only on inertia. To better stabilize the system without relying on synchronous generation, large energy storage plants have recently been tested, such as the Hornsdale Power Reserve in Australia, which was able to react faster and more efficiently than traditional systems to the fault of a coal generator on December 2017. The aim of this thesis is to explore whether similar results can be obtained without such large battery installations, by posing a control on the power consumption P_l instead of the power generation P_g.

Controllable loads model

Deferrable loads can be controlled by shifting their consumption with minimal impact on the end user, because they are able to store energy. Some examples are given by thermal loads (heat pumps, water heaters, air conditioners and refrigerators) and charging electric vehicles. Each of these loads has then an internal state dynamics that has to be taken into account. However, accounting for thousands of single load dynamics is computationally infeasible. Therefore, it is convenient to build a single aggregate evolution model for a population of controllable loads.

Let's take as an example a population of thermal loads, whose model is depicted in Fig. 3. By defining as $\boldsymbol{x} \in \mathbb{R}^{N_{bin}}$ a vector where each element is the ratio of loads in a particular bin, we can define a matrix $\boldsymbol{A}$ where the element $\boldsymbol{A}_{ij}$ represents the probability of a load to transition from the bin i to the bin j. The control input alters this probability, thus increasing or decreasing consumption. By the Law of Large Numbers, if the number of controllable loads is large enough, we expect extremely accurate power tracking. The evolution of the system at a time step t can be written as:

$$\boldsymbol{x}_{t+1} = \boldsymbol{A}(\boldsymbol{u}_t)\boldsymbol{x}_t$$

The structure of the matrix $\boldsymbol{A}$ is determined by the nature of the load and by the control input $\boldsymbol{u}_t$. The model here described is a Controlled Markov Chain. The tracking problem can be formulated as a

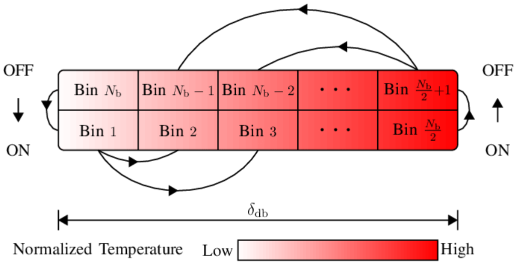

Figure 3: Transition model for a thermal load: each load has to maintain a temperature within a given range. This range of temperatures can be discretized into $N_{bin}/2$ temperature intervals and each load in a certain temperature interval can be either ON or OFF. Each load can transition to a different interval depending on disturbances such as the ambient temperature, while the controller can influence the transition to the ON or OFF state. When exceeding the temperature limits, the load will automatically turn either ON or OFF and cannot be controlled until it returns within the acceptable range. Source: IEEE transactions on Smart Grids

constrained optimization problem over a finite time horizon $t = 1, ..., N$ of the form

$$\begin{aligned} \min_{\boldsymbol{u}_{1:t} \in \mathcal{U}} \quad & \textstyle\sum_{t=1}^{N} g(\boldsymbol{u}_t) && \text{minimize discomfort to the users} \\ \text{s.t.} \quad & P(\boldsymbol{x}_t) = \bar{P}_t && \text{while tracking the power consumption reference } \bar{P}\text{...} \\ & \boldsymbol{x}_{t+1} = \boldsymbol{A}(\boldsymbol{u}_t)\boldsymbol{x}_t && \text{...and satisfying the physics of the system} \end{aligned} \tag{2}$$

First we will reformulate (2) in a way that is tractable, i.e. a convex optimization problem that can be easily solved using established numerical algorithms. Then we will study the set of *feasible references*, i.e., which classes of power references $\bar{P}$ can be tracked by such a system. This will give us an idea of the potential capabilities of load-side control for frequency balancing. Finally, we will explore embedding Problem (2) within the bigger Optimal Power Flow (OPF) problem, which is solved every 15 minutes by the transmission utilities in order to schedule generators effectively. All results will be validated both in theory and numerical simulations.

Supervision

This Master Thesis will be conducted at the Colorado University at Boulder, CO, USA, an institution with an outstanding reputation in the field of power systems optimization and control; and with the collaboration of the National Renewable Energy Laboratory (NREL) in Golden, CO, USA: the leading renewable energy research center of the US Department of Energy. The project will be supervised by Prof. E. Dall'Anese (CU Boulder) and by Dr. M. Colombino (NREL). At ETH Zürich, the project will be advised by Prof Florian Dörfler, a leading expert in complex control for power systems. The proposed project will also benefit from the advise of Prof. M. Almassalkhi (U. Vermont), who is a leading researcher in the field of controllable loads and co-founder of the "Paketized Energy" company that aims at bringing this idea to the market.

Yours sincerely,
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