46755 – Assignment 1: System perspective

Deadline: March 18, 2024 (11:59pm)

February 4, 2024

Select a case study

Please select an electric power network. Potential options:

1. IEEE 24-bus reliability test system: link
2. The IEEE reliability test system: A proposed 2019 update: link
3. IEEE power systems test cases (different cases with 14, 30, 57, 118, and 300 buses): link
4. Several case studies are available in the open-source Julia platform PowerModels.jl: link

Please feel free to choose another case study. In case there is the lack of data for some items, **please select arbitrary (reasonable) values.** For the technical details of conventional generators and transmission lines, this link might be helpful (it corresponds to the IEEE 24-bus case study, but one can use similar data for other cases, too). Please assume the production cost of renewable units is zero. For the bid price of price-elastic demands, please consider comparatively high prices (compared to the generation cost of conventional units) such that the majority of demands will be supplied. For wind data, one potential data source is this link (you can normalize such data for your case study). For transmission lines, you can simply consider an identical reactance for all lines (e.g., 0.002 p.u. $\rightarrow$ susceptance = 500 p.u.).

Step 1: Copper-plate single hour

In lecture 2 you learn how to develop a market-clearing optimization model for a copper-plate power system (i.e., without modeling transmission network) and with a single hour. Please compute the values for the market-clearing price (uniform pricing scheme), the social welfare, the profit of every supplier (both types of conventional units and wind farms) and the utility of every demand. By utility for a demand, we mean her power consumption $\times$ [bid price - market price]. For the market price, please justify the value obtained using the KKT conditions.

Step 2: Copper-plate, multiple hours

This step is the extension of what you learn in lecture 2. Please extend the optimization model in Step 1 by including multiple time periods (here, 24 hours). This means you may need to define a new index, e.g., t, running from 1 to 24. Some input data are varying across hours, e.g., wind power and demand level. We are interested in enforcing new constraints that link hours, the so-called *inter-temporal* constraints. Please extend the market-clearing optimization model by incorporating at least 2 out of 3 types of inter-temporal constraints explained below:

1. **Ramp rates:** A very common inter-temporal constraint is the ramping up (down) limit of conventional generators, enforcing how much their power generation can be increased (decreased) in the current hour compared to that in the previous hour.

2. **Battery:** The inter-temporal constraint is the state of charge (SoC) of the battery, which is an equality constraint calculating the energy stored in hour t, accounting for the stored energy in the previous hour $(t-1)$ and charged/discharged energy in hour t. Potential reference for further reading: Section II of link. Please note that we are not interested in adding binary (0/1) variables to the model (to keep our optimization model convex). One simple solution is to consider an identical charging/discharging efficiency.

3. **Hydrogen demand:** Please consider at least two wind farms are equipped by their local electrolyzer. Each electrolyzer consumes wind power to electrolyze water and therefore produce hydrogen. Imagine the size of each electrolyzer is the half of the installed capacity of the corresponding wind farm. Assume each electrolyzer is always on, and produces 18 kg hydrogen by consuming 1 MW electricity. The only operational cost of the electrolyzer corresponds the power consumption, otherwise we ignore all other potential costs, e.g., the water cost. The inter-temporal constraint related to the hydrogen demand is that each electrolyzer should produce a certain amount of hydrogen (in tonnes) over the day (not hour), so this provides a degree of freedom how to meet the minimum daily hydrogen demand over 24 hours.

Considering a uniform pricing scheme, we are interested in deriving hourly market prices. How do inter-temporal constraints affect these prices?

Step 3: Optimization vs equilibrium

In step 2 you have added two types of inter-temporal constraints imposed by conventional generators (ramp rates), and/or storage (SoC), and/or electrolyzers (hydrogen demand). In lecture 3, you learn the market-clearing optimization model has a corresponding equilibrium model. Using KKTs, please discuss whether the market-clearing optimization model with inter-temporal constraint *still* has a corresponding equilibrium model. You are not expected to write the whole KKT conditions, but please find an elegant way (perhaps by writing a subset of KKTs) to support your argument.

Step 4: Network constraints

In lecture 4 you learn how to model power flow across network and enforce power transmission network limits. Please extend your market-clearing optimization model in Step 2. Please derive *nodal* market prices. Are nodal prices in every given hour necessarily identical? Please conduct a sensitivity analysis (by changing the capacity of one or more transmission lines) and discuss your results. Finally, switch to a *zonal* setting by splitting your power network to two or three (or more) zones. For different values of ATCs, derive zonal market prices. How different are they compared to nodal prices? What are the implications of nodal vs zonal frameworks to market participants (e.g., in terms of profit for generators)?

Step 5: Balancing market

In lecture 5 you learn about the balancing market. Pick one hour (out of 24 hours). While discarding network constraints and intra-day market (for simplicity), please assume there is an unexpected failure (outage) in one of conventional generators. The actual production of some wind farms is lower than their day-ahead forecast (e.g., 10%), while that of others is higher than their day-ahead forecast (e.g., 15%). All remaining conventional generators (but not demands) are potential balancing service providers. Each conventional generator as the balancing service provider offers the upward balancing service at a price equal to the day-ahead price plus 10% of her production cost. Similarly, she offers the downward balancing service (if she can, depending on her day-ahead schedule) at a price equal to the day-ahead price minus 13% of her production cost. The load curtailment cost is \$400/MWh. Please clear the balancing market for the given hour, and derive the balancing price. Finally, please calculate the total profit (in day-ahead and balancing) of conventional generators and wind farms in the given hour if the balancing settlement follows a *i*) one-price, and *ii*) two-price scheme.

Step 6: Reserve market

In lecture 6 you learn about the reserve market. Imagine, according to the TSO's quantification, the hourly upward reserve requirement in the reserve market is 15% and the hourly downward reserve requirement is 10% of the total demand in the corresponding hour. While discarding network constraints, please clear reserve and day-ahead markets *sequentially* (following the current practice in the European electricity markets) and report hourly market-clearing prices for reserve and electricity (for 24 hours).

Note: Please check the introduction slides presented on January 29, 2024, for the report template and page limit.