Electric vehicle fleet strategies for smart participation in primary frequency reserves

The objective of this project is to model a fleet of electric vehicles participating in primary frequency regulation. You may use any programming language you prefer, Python is recommended.

So-called "Reserve Entities" (REs), such as aggregators of electric vehicles (EVs), that are participating to Frequency Containment Reserves (FCR) must answer to the following regulation signal as stated by the Transmission System Operator (TSO):

$$P_{RE}(t) - P_c = k \cdot P_{bid} \cdot (f(t) - f_n)$$

Where:

- $P_{bid} = \frac{P_{max}}{1.1}$ where P_{bid} (kW) is the power capacity bid by the RE for a time settlement (typically a block of 4 hours) and P_{max} (kW) the maximum withdrawal/injection power from/to the grid. The factor 1.1 is defined by rules emanating from RTE (French TSO)
- P_c is the command power (kW). It can only be changed every 15 minutes, and is limited to the following maximum value: $P_{max} - P_{bid}$. It is used to correct the trajectory of the state-of-charge (SOC) battery-based assets participating in FCR, but most often $P_c = 0$.
- $P_{RE}(t)$ (kW) is the instantaneous regulating power of the RE in receiver convention (i.e. $P_{RE} > 0$ means charging the batteries)
- $f(t)$ the instantaneous grid frequency (Hz)
- $k = 5$ Hz^{-1}

Grid frequency data

Q1. Using the website https://power-grid-frequency.org/database/, download grid frequency data for a month (location: anywhere in continental Europe). Assuming that $P_c = 0$, plot the distribution of the reduced regulating power $\frac{P_{RE}(t)}{P_{bid}}$ expected by the TSO from an aggregator that would have acted as a reserve entity over the whole period (expressed in reduced units p.u. or percentage %). We assume that the aggregator would have had a negligeable impact compared to the summed contributions of other

REs, hence the grid frequency is not affected by this simulated additional contribution to FCR.

Q2. What observation can you make regarding the magnitude of the regulating power?

Q3. We consider a singular vehicle participating to FCR. Plot the state-of-charge (SOC) deviation induced by primary frequency regulation for the following rolling windows: 4 hours, 8 hours, 12 hours, 24 hours. We assume no energy losses of any kind. SOC is expressed in % and is simplified by the following definition, with E_{batt} the useful energy capacity of the battery in kWh. We assume that $E_{batt} = 46$ kWh and the maximum power of bidirectional transfers between the vehicle and the grid is (both positive and negative) $P_{max}^{1EV} = 7$ kW (corresponds to rounded single-phase AC EVSE).

$$\frac{d\ SOC}{dt}(t) = 100\ \frac{\eta(P_c) \cdot P_c(t) - \dfrac{1}{\eta(P_d)} P_d(t)}{E_{batt}}$$

Q4. Under these conditions, is it reasonable for an EV to participate in FCR for these consecutive periods (4 hours, 8 hours, 12 hours, 24 hours)?

Smart dispatch strategy

We consider a fleet of N bidirectional vehicles. During FCR participation, the aggregator may choose to dispatch the regulating power evenly across the fleet (i.e. each vehicle receives a power setpoint of $\frac{P_{RE}(t)}{N}$). We call this dispatch strategy the "uniform" strategy. We consider on-board charger AC-DC conversion losses (see file `data/obc_efficiency.csv`). Bidirectional losses are considered symmetrical (DC-AC).

Q5. Considering the uniform strategy, compute the average efficiency $\eta_{uniform}$ of a fleet of vehicles performing primary frequency regulation.

Q6. What alternative dispatch strategy could limit conversion losses? What is the limit of the average efficiency with this "smart" strategy when $N \rightarrow +\infty$, denoted η_{smart}^{∞}? What is the (minimum) number of EVs N_0 for which $\eta_{smart}^{N_0} \geq \eta_{uniform} + \frac{90}{100}\left(\eta_{smart}^{\infty} - \eta_{uniform}\right)$? (i.e. what is the fleet size for which 90% of quantitative benefits are achieved?)

Q7. The smart strategy also reduces the average operation time of OBCs, which is a critical metric of power converter degradation. Express the average operation time t_{op}^{N} of OBCs in reduced units (p.u., relative to the FCR participation time), as a function of N, k and $\langle |f - f_n| \rangle$ (with $\langle |f - f_n| \rangle$ the time-average of the absolute value of frequency deviations). Compute the limit of t_{op} when $N \to +\infty$, denoted t_{op}^{∞}. What is the (minimum) number of EVs N_0 for which $t_{op}^{N_0} \leq 1 - \frac{90}{100}\left(1 - t_{op}^{\infty}\right)$? (i.e. what is the fleet size for which 90% of quantitative benefits are achieved?)

Driving and charging behaviour

A handful of EVs were monitored throughout the year 2021. Historical driving sessions are referenced in `data/driving_sessions.csv`. These vehicles were not bidirectional, but we aim to model bidirectional EVs based on this monitored data, i.e. EVs that display the same availability during charging sessions and the same trips.

Q8. Infer charging sessions from driving sessions. Arbitrate for each charging session if they were performed in AC (slow charging) or DC (fast charging), assuming OBC power level was 7 kW for every vehicle.

We assume that simulated bidirectional EVs are available for V2G operations during their AC charging sessions, during which we assume they are plugged to their 7-kW bidirectional EVSE.

Q9. Plot the coincidence factor over time of the fleet for blocks of 1 hour and 4 hours (12pm to 1am, 1am to 2am, etc. for 1-hour blocks and 12pm to 4am, 4am to 8am, etc. for 4-hour blocks). The coincidence factor is the minimum number of EVs simultaneously plugged in AC over a period of time.

Q10. Based on the coincidence factors at the beginning and end of the year, what limitation comes with inferring charging sessions from driving sessions?

Revenues from FCR participation

Q11. Using the database of the website https://www.regelleistung.net/, find how much an aggregator managing the fleet constituted by the driving sessions data can earn over a month of your choosing based on a) the 1-hour and b) 4-hour coincidence factor. Coincidence factors set the maximum bid of the aggregator. Express the results in €/EV. *Note: the minimum FCR participation block duration is 4 hours but may change in the future to be reduced to 1 hour, hence the two proposed hypotheses.*

Q12. Using frequency deviation data, compute the induced average virtual mileage per vehicle for the considered coincidence factors (1-hour and 4-hours). It does not matter that the month of frequency deviation data does not match the month of the considered coincidence factors, because frequency deviations share very similar behaviour all year long.

Q13. Considering the loss of residual value for the average EV due to virtual mileage, how much are reduced the revenues of V2G? Simulate mileage from 5,000 km to 75,000 km with steps of 5,000 km. Refer to `data/residual_value.csv`, and consider a driving consumption of 0.2 kWh/km.

Simulation framework

Q14. The objective of this section is to model, over a month, individually the vehicles of the fleet, controlled by an aggregator. The simulation should be made with the two different aggregator dispatch strategies: uniform and smart, and for the two coincidence factor timeseries (1-hour and 4-hour). The expected outputs are SOC and power profiles for each vehicle. You should be wary of:

- Respecting the user's mobility requirements: the simulated vehicles should reach the SOC listed in driving sessions data before any trip,
- Ensure emergency mobility needs: the SOC of any vehicle should never drop below 20%.
- Not all charging sessions are V2G-compatible, some are DC charging sessions and impact the SOC profile in a similar fashion to driving sessions.
- Managing the various power capacities available to the aggregator:
    - The instantaneous maximum power (number of plugged-in EVs multiplied by 7 kW),
    - The power capacities reserved for FCR P_{max}: coincidence factor multiplied by the size of the fleet multiplied by 7 kW. P_{max} is split between:
        - The power bid P_{bid} (power capacities reserved for FCR P_{max} divided by 1.1)
        - The maximum command power $P_{max} - P_{bid}$

For the smart dispatch strategy, you may use a sequential activation of EVs based on their SOC: if $P_{RE}(t) < 0$, EVs with the highest SOC may be discharged in priority, whereas if $P_{RE}(t) > 0$, EVs with the lowest SOC may be charged first. By defining a sorted order, ascending or descending depending on the sign of the frequency deviation, the number of vehicles saturated at SOC = 100% or SOC = 20% will be limited, as they will tend to converge towards the average SOC of the fleet.

Advice: work with two timesteps: 15 minutes for dispatch decisions, 10 s for actual power dispatch.

This is the most open question and should take significantly more time than the others.

Battery degradation

The battery may be modelled by a Thevenin generator with an open-circuit voltage (OCV) of $360 + 0.85 \cdot SOC[\%]$, expressed in V.

Q15. Express the battery current I as a function of the input/output battery power P, internal resistance R and OCV.

For the next question, we neglect the internal resistance such that $I = \frac{P}{OCV}$. We propose to use the following battery degradation model, with $\Delta t = 1$ hour.

- Cycling:
  - When charging/discharging in mode 3: $\Delta L_{cyc} = 2 \cdot 10^{-7} \cdot |I| \cdot 10^{0.003\,|I|} \cdot \Delta t$ expressed in reduced units (temperature is assumed constant hence does not influence cycling ageing).
  - For driving sessions and mode 4 charging sessions: we approximate $\Delta L_{cyc} = 5 \cdot 10^{-5}\,|\Delta SOC|$ where ΔSOC is the SOC difference of the driving/charging session
- Calendar: $\Delta L_{cal} = 2 \cdot 10^{-4} \cdot 10^{0.004 \cdot SOC[\%]}\, \alpha\, t^{\alpha-1}\, \Delta t$ where $\alpha = 0.75$ and t the age of the battery in seconds (assume 3 to 5 years old battery).

Q16. Assess the fleet average battery degradation based on SOC/power profiles computed in Q14. Modify the code to one additional scenario in which vehicles do not participate in FCR at all. Compare the different scenarios.