Investigating battery storage in combination with gas turbine generation for frequency regulation

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Abstract

Frequency regulation is an important grid ancillary service, which, currently, is mostly provided for by conventional generation. This study looks into the possible synergy of gas turbines with battery storage to provide a frequency regulation service. A model is built to describe how a grid's system frequency varies with power imbalances and to calculate the generation required to maintain system frequency between set limits, which is the frequency regulation requirement. A simple algorithm for deciding how the gas turbine and battery storage share the requirement is then presented. The overall model is run through a few times with the interaction between the gas turbine and the battery changing each time. Characteristics of the battery storage are calculated from the results and suggest that a lithium titanium oxide battery is the most suitable choice for the hybrid system studied.

Keywords: Frequency regulation; swing equation; gas turbine; battery storage.

1 Introduction

The increasing penetration of renewables exacerbate grid balancing issues due to their inherent intermittency. To balance generation and demand under normal conditions requires three methods: base energy, load following, and frequency regulation. Gas turbine plants play a crucial role in matching supply to demand. They can be used as base-load plants, peaking plants, and contingency reserves. To be able to provide grid support, as a spinning reserve for example, gas turbines must operate below their rated capacity, which compromises on efficiency. This, in turn, means that greenhouse gas emissions are higher per unit of electricity generated and maintenance costs tend to be higher. In a gas turbine and battery storage hybrid, the batteries can act as a virtual spinning reserve, and the gas turbine can operate at sub-optimal loads less frequently. In this way, the system becomes more efficient and less costly.

The work in this paper draws a lot from the work presented in [1] and [2]. In, [1] an OCGT and a lead acid battery system are compared for frequency regulation on a German grid. In [2], a gas turbine battery storage hybrid system is analysed with the aim to have the turbine working at constant speed or constant acceleration.

The report is structured as follows: in section 2, frequency regulation is explained. Next, in section 3, a model is built for describing how system frequency varies with power imbalances on the grid. In section 4, the behaviour of the gas turbine and battery storage hybrid system is discussed. The models built in the paper are then used in section 5 to analyse the hybrid system and to extract characteristics of the battery storage. Finally, conclusions and future work are presented in section 6.

2 Frequency regulation

2.1 Load profile components

The load profile of a power grid can be decomposed into three separate components: base load L_{b}, load following L_{lf}, and frequency regulation L_{fr} [3]. The total load can therefore be written as

$$L = L_{\mathrm{b}} + L_{\mathrm{lf}} + L_{\mathrm{fr}}. \tag{1}$$

The base load component is the minimum load in a load profile and is matched with base load generation: nuclear, CCGTs, hydroelectric, biomass, and coal. The base load can have seasonal variations but is considered constant on a daily basis. The load following component is the intra- and inter-hour variation in load and is matched by online generation units or storage to ensure the grid stays balanced [4]. Examples of load following generation are pumped hydro energy storage, hydroelectric, and gas peaking plants. External factors such as the weather, time of day, and day of week can affect the load profile in this time frame, and it's generally predictable. The frequency regulation component is the continuously fluctuating load on the order of seconds and is matched by fast-responding units so that system frequency is maintained at 50 Hz to prevent system damage. Frequency regulation is the name given to this balancing act, and it's one of the most important and lucrative grid ancillary services to provide for. Frequency regulation is achieved using power sources that are online, loaded, and on automatic generation control. In the time frame of seconds, the load profile fluctuates due to the random turning on and off of millions of individual loads [4]; its random, uncorrelated, and cannot be predicted.

Together, the load following and frequency regulation components of a load address its daily temporal variations. These components can be separated using the following method from [3]. The load following component is given by the rolling average of the load to smooth out the fast, random fluctuations. As an example, let's say we had a load profile containing data every 30 s, and we decide to take a 30 min rolling average. At time t, the load following component is given by the mean of the 29 earlier load values, the current load value, and the subsequent 30 values (in other words, taking the mean of all the data points within 15 min either side of the current one):

$$\begin{aligned} L_{\mathrm{lf}} &= \bar{L}_{30} \\ &= \mathrm{Mean}(L_{t-29} + \cdots + L_t + \cdots + L_{t+30}). \end{aligned} \tag{2}$$

In the above example, we took a 30 min rolling average, but this time interval is arbitrary. If the interval is too short, short-term fluctuations appear in the load following component and not enough as frequency regulation; if the interval is too long, long-term fluctuations appear in the frequency regulation component, which is then no longer random, and the load following component becomes too flat. Regardless of the time interval chosen, eq. (1) still holds and none of the load is lost. All the time interval does is allocate the fluctuations between L_{lf} and L_{fr}. In general, an X minute rolling average can be taken, with values of X ranging from 10 min to 90 min in [5, 3, 1].

As was mentioned before, the base load component is the minimum load in a load profile and is assumed constant (over the time scale of a day),

$$L_{\mathrm{b}} = L_{\mathrm{min}}, \tag{3}$$

and the load following component at time t is the X minute rolling average at t,

$$L_{\mathrm{lf}}(t) = \bar{L}_X(t), \tag{4}$$

so, using eq. (1), the frequency regulation component at t is given by

$$L_{\mathrm{fr}}(t) = L(t) - L_{\mathrm{min}} - \bar{L}_X(t). \tag{5}$$

2.2 Frequency regulation options

An energy storage system (ESS) is ideal for frequency regulation since it can act as a generator or load and switch between the two very rapidly. If the regulation component is successfully extracted from the load profile, it should be as close to net-zero energy as possible. This matches well with energy storage systems, which are, by definition, a net-zero energy resource. To be effective as a frequency regulation service, an ESS needs to be able to deal with the high ramp rates and high charge/discharge requirements without suffering from performance degradation. Batteries are one of the best suited ESSs for frequency regulation, with the lithium-ion chemistry being the most favourable at the moment.

Gas turbines are also used for frequency regulation because they can quickly ramp up and down their output power; however, they are not ideal for the job. In a report [6] that, among other things, examined the impact of storage on the California power grid, it was concluded that an ESS is up to two or three times as effective as a combustion turbine for providing frequency regulation services to the grid. In other words, a 100 MW ESS would be equivalent to a 200 MW to 300 MW combustion turbine for the purposes of frequency regulation. Using conventional generators to provide frequency regulation not only requires more MWs, but also causes indirect costs, such as additional maintenance cost, equipment wear and tear, and more greenhouse gases [1]. Also, an ESS has a faster response rate compared to conventional generators and can be precisely controlled.

2.3 Frequency regulation component used in this study

For this study, load profile data was not available, so the method described in section 2.1 for calculating L_{fr} was not used; instead, artificial data was created in Excel® to represent L_{fr}. In the artificial data, a value for L_{fr} was recorded at 5 s intervals, and 17,280 data points were created to represent a 24 hour day; fig. 1 shows L_{fr} plotted against time for the first hour of data. Over the 24 hours, the mean of L_{fr} is −0.04 MW and the standard deviation is 9.25 MW.

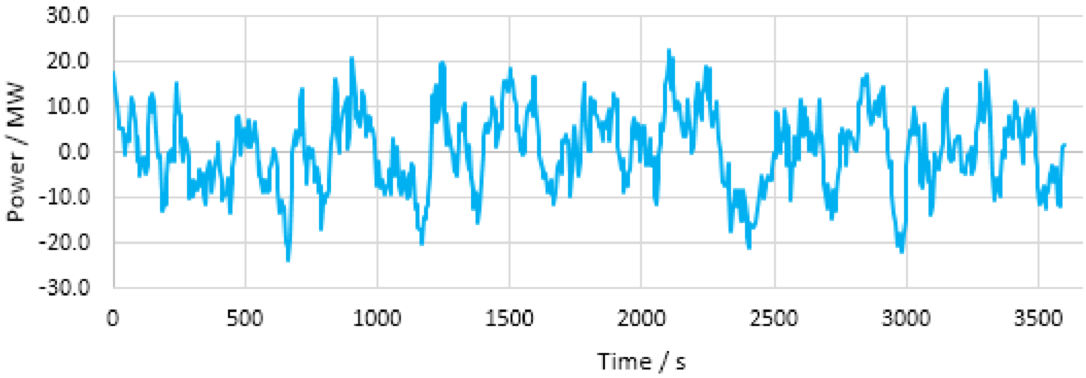

Figure 1: The frequency regulation component L_{fr} against time (for the first hour).

3 Frequency response to a power imbalance

In section 2.1, it was shown that a load profile can be broken down into three separate components. The same can be done for generation:

$$G = G_{\mathrm{b}} + G_{\mathrm{lf}} + G_{\mathrm{fr}}. \tag{6}$$

The power imbalance of a grid is the total load minus the total generation (ignoring losses), and if we assume that $G_{\mathrm{b}} = L_{\mathrm{b}}$ and $G_{\mathrm{lf}} = L_{\mathrm{lf}}$, then

$$\Delta P = L_{\mathrm{fr}} - G_{\mathrm{fr}}. \tag{7}$$

ΔP is constantly changing with time, and this affects the frequency of the grid. The relationship between power mismatch and frequency will be derived below. The derivation, up to eq. (12), is largely based on the one in [7].

The rotational kinetic energy stored in a synchronous generating machine is given by

$$E_{\mathrm{RKE}} = \frac{1}{2} J (2\pi f_{\mathrm{m}})^2, \tag{8}$$

with J being the moment of inertia of the synchronous machine and f_{m} the rotating frequency of the machine. The inertia constant H for a synchronous machine is defined by

$$H = \frac{E_{\mathrm{RKE}}}{S_{\mathrm{rated}}} = \frac{J(2\pi f_{\mathrm{m}})^2}{2 S_{\mathrm{rated}}}, \tag{9}$$

with S_{rated} being the rated power of the generator and H the time duration during which the machine can supply its rated power solely with its stored rotational kinetic energy.

The following equation describes how the rotational frequency f_{m} (or rotational speed $\omega_{\mathrm{m}} = 2\pi f_{\mathrm{m}}$) of the synchronous generator responds when there is a power imbalance, it is one of the many forms of the *classical swing equation*:

$$\dot{E}_{\mathrm{RKE}} = J(2\pi)^2 f_{\mathrm{m}}(\dot{f}_{\mathrm{m}}) = P_{\mathrm{m}} - P_{\mathrm{e}}. \tag{10}$$

P_{e} is the electrical power demand (load) and P_{m} is the mechanical power generated by the machine. Using eq. (9), adding a damping term to represent the self-stabilising properties of power systems, and replacing f_{m} with the rated frequency $f_0 = 50\,\mathrm{Hz}$ (frequency deviations are usually small excursions around the rated frequency) gives us

$$\dot{f}_{\mathrm{m}} + \frac{D}{2H} f_{\mathrm{m}} = \frac{f_0}{2H S_{\mathrm{rated}}}(P_{\mathrm{m}} - P_{\mathrm{e}}), \tag{11}$$

where D is a damping constant. Equation (11) gives us the relationship between a synchronous generator's frequency and the power imbalance at that generator. The equation for a whole grid system (containing numerous generators) is very similar:

$$\dot{\Delta f} + \frac{D}{2H} \Delta f = -\frac{f_0}{2H S_{\mathrm{B}}} \Delta P. \tag{12}$$

S_{B} is the system power base (the sum of all the rated powers of the generators), f is the system frequency, and ΔP is the power imbalance of the grid, which is given in eq. (7). If ΔP is independent of time then the general solution to eq. (12) is

$$\Delta f = K e^{-Dt/2H} - \frac{f_0 \Delta P}{S_{\mathrm{B}} D}. \tag{13}$$

For a constantly step changing ΔP, eq. (12) is very difficult to solve. My method was to effectively set t back to zero every time ΔP changed and then solve the equation again, with new initial conditions. If the step changes in ΔP occur at time steps of T, then the frequency at the n^{th} step change in ΔP, at $t = nT$, is

$$\Delta f(nT) = K_n e^{-DT/2H} - \frac{f_0 \Delta P\big((n-1)T\big)}{S_{\mathrm{B}} D}, \tag{14}$$

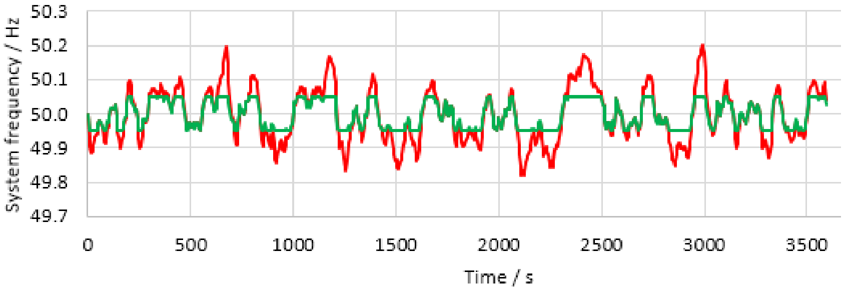

Figure 2: The system frequency against time (for the first hour) for two cases: without any frequency regulation (red), and with frequency regulation that maintains the system frequency between 49.95 Hz and 50.05 Hz (green).

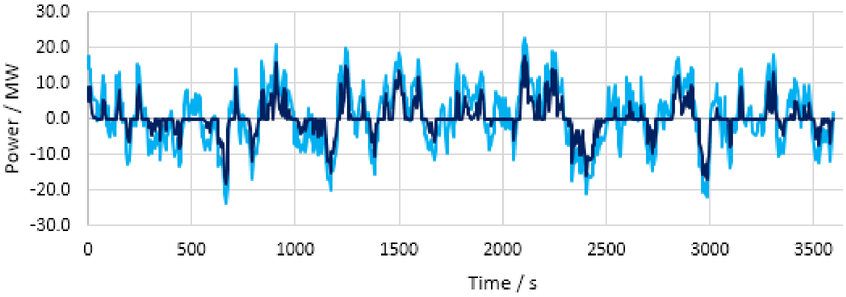

Figure 3: The frequency regulation component L_{fr} (light blue) and the frequency regulation requirement G_{fr} (dark blue) against time (for the first hour), when the system frequency limits are 49.95 Hz and 50.05 Hz.

where

$$K_n = \Delta f\big((n-1)T\big) + \frac{f_0 \Delta P\big((n-1)T\big)}{S_{\mathrm{B}} D}. \qquad (15)$$

The values of the parameters used in this study are as follows: $T = 5\,\mathrm{s}$, $D = 1$, $H = 5\,\mathrm{s}$, $f_0 = 50\,\mathrm{Hz}$, and $S_{\mathrm{B}} = 5000\,\mathrm{MW}$. The same values for D and H were used in [1], and 50 Hz is the grid system frequency of the UK (and other nations). The choice of value for S_{B} is somewhat arbitrary since the data for the frequency regulation component L_{fr} is artificial. The value chosen does give a sensible frequency variation.

3.1 Frequency regulation requirement

If G_{fr} is zero for all time (i.e. there are no frequency regulation services on the grid), then $\Delta P = L_{\mathrm{fr}}$. Using the data for L_{fr}, described in section 2.3, and eqs. (14) and (15), we get the variation of system frequency (without regulation) f over time, shown in fig. 2 as the red line.

The frequency regulation requirement is the amount of G_{fr} to keep the system frequency within set limits. In the model, a question is asked at the start of each time step: will the system frequency go outside the set limits by the next time step if $G_{\mathrm{fr}} = 0$ for the current time step? If the answer is no, then $G_{\mathrm{fr}} = 0$ for that particular time step. If the answer is yes, then a value for G_{fr} is calculated, using eqs. (14) and (15), so that the system frequency stays within the set limits. With the constraint that the system frequency cannot vary more than ±0.05 Hz, G_{fr} was calculated and is shown in fig. 3 along with L_{fr}. Note how the frequency regulation requirement G_{fr} is less than the frequency regulation component L_{fr}. Using $\Delta P = L_{\mathrm{fr}} - G_{\mathrm{fr}}$ and eqs. (14) and (15), we get the variation of system frequency (with regulation) f_{reg} over time, shown in fig. 2 as the green line.

4 Battery storage and gas turbine hybrid plant model

Now we have a frequency regulation requirement G_{fr}, it remains to split the power between a gas turbine and a battery. $G_{\mathrm{fr}}^{\mathrm{GT}}$ is the power delivered by the gas turbine, and $G_{\mathrm{fr}}^{\mathrm{B}}$ is the power delivered by the battery.

For each new value of G_{fr}, a decision is made. If the difference between the new value of $G_{\mathrm{fr}}(nT)$ and the previous power output of the gas turbine

$G_{\mathrm{fr}}^{\mathrm{GT}}\big((n-1)T\big)$ is greater than the gas turbine sensitivity parameter Q, then the gas turbine ramps up or down to try to meet the new value; however, it is limited by its max ramp rate. If the difference between the new value of $G_{\mathrm{fr}}(nT)$ and the previous power output of the gas turbine $G_{\mathrm{fr}}^{\mathrm{GT}}\big((n-1)T\big)$ is less than Q, then the gas turbine remains at its previous output power. The reasoning behind this is to avoid transitory inefficiencies by keeping the gas turbine's output as constant as possible: higher Q results in less variation. The battery makes up the difference between G_{fr} and $G_{\mathrm{fr}}^{\mathrm{GT}}$:

$$G_{\mathrm{fr}}^{\mathrm{B}} = G_{\mathrm{fr}} - G_{\mathrm{fr}}^{\mathrm{GT}}. \tag{16}$$

It is assumed that the battery has an infinite ramp rate, so can always meet the required power.

To calculate the battery variables, such as power and energy capacity, the following method is used. E_{R} is defined as the running total of $E(nT)$, which is defined as

$$E(nT) = G_{\mathrm{fr}}^{\mathrm{B}}(nT)T. \tag{17}$$

$E(nT)$ is the energy exchanged by the battery during the nth time step. The maximum and minimum of E_{R} during the whole 24 h period are recorded. Also, there is a limit set on the maximum and minimum state of charge (C_{max} and C_{min}). This is to protect the battery and to make sure that it can deliver its power capacity at all times. The battery's required energy capacity, power capacity, and initial energy can then be calculated using

$$E_{\mathrm{cap}} = \frac{E_{\mathrm{R}}^{\mathrm{max}} - E_{\mathrm{R}}^{\mathrm{min}}}{C_{\mathrm{max}} - C_{\mathrm{min}}}, \tag{18a}$$

$$P_{\mathrm{cap}} = \mathrm{Max}\left(\left|G_{\mathrm{fr}}^{\mathrm{B}}\right|\right), \tag{18b}$$

$$E_{\mathrm{i}} = E_{\mathrm{cap}}(C_{\mathrm{min}} - E_{\mathrm{R}}^{\mathrm{min}}). \tag{18c}$$

Also, another useful value can be calculated: the total energy exchanged E_{tot} by the battery during the 24 h period. It is given by

$$E_{\mathrm{tot}} = T\sum_{n=0}^{N}\left|G_{\mathrm{fr}}^{\mathrm{B}}(nT)\right|. \tag{19}$$

5 Results and discussion

In section 2.3, we discussed where the frequency regulation component L_{fr} came from. In section 3, we discussed how the system frequency changes when there is a power imbalance and the frequency regulation requirement G_{fr} to keep it within set limits. In section 4, the way the gas turbine and battery share the frequency regulation requirement G_{fr} was explained. In this section, some more results of the model that has been built up throughout this paper will be presented. The system frequency limits were set to ± 0.05 Hz from f_0 and the limits for the state of charge of the battery were set to $C_{\mathrm{max}} = 80\%$ and $C_{\mathrm{min}} = 20\%$. The rated capacity of the gas turbine was set to 300 MW with a maximum ramp rate of 10%, so $30\,\mathrm{MW\,min^{-1}}$. This means that in the 5 s time step between data points it can change its output by a maximum of 2.5 MW.

Figure 4 shows how the gas turbine and battery combine to match the frequency regulation requirement for the first half hour. As discussed in section 4, the hybrid system is designed to avoid transitory inefficiencies in the gas turbine. This is achieved through a sensitivity parameter Q: the higher Q is, the less the gas turbine is varying its output. In fig. 4a, the gas turbine operates with Q equal to 8 MW, which means that it remains at the previous power output unless the new value of G_{fr} is different to it by more than 8 MW. In fig. 4a, the sensitivity parameter Q is equal to 3 MW. In the 3 MW case, it's clear to see that the gas turbine is varying its output a lot more than in the 8 MW case.

Q affects how much the gas turbine contributes to G_{fr}, so it is likely to have an effect on the battery variables since the battery provides the difference. To investigate, Q was varied from 0 MW to 20 MW, and four battery variables were recorded from the model, shown in fig. 5. Figure 5a shows that the required energy capacity E_{cap} of the battery increases as Q increases. This makes sense because as Q gets higher, the battery is doing most of the frequency regulation work. In fig. 5b, the required power capacity P_{cap} remains relatively constant near 25 MW as Q increases. P_{cap} probably depends a lot more on the gas turbine ramp rate because even at low Q, the gas turbine struggles to meet G_{fr} if it jumps around a lot. The required initial state of charge of the battery follows a more complex relationship with Q. It can been seen in fig. 5c that the required initial state of charge is sometimes right at the SoC limits, which is certainly not ideal. In fig. 5d, we can see the total energy exchanged by the battery E_{tot} increasing up to $Q = 8$ MW but remaining constant thereafter. E_{tot} is an important parameter because it roughly relates to the number of cycles the battery undergoes and hence is related to the battery lifetime. Not shown in fig. 5, but still something to note, the maximum contribution from the gas turbine steadily decreases as Q increases. This means that the gas turbine can operate closer to its rated capacity as Q increases.

Table 1 shows the battery variables for the case

Variable	Value
E_{cap}	6.6 MW h
P_{cap}	26.1 MW
Initial SoC	55%
E_{tot}	102 MW h

Table 1: Battery variables when $Q = 8\,\text{MW}$.

when $Q = 8\,\text{MW}$. A possible lithium-ion chemistry that could match these characteristics is lithium titanium oxide. Lithium titanium oxide batteries are thermally stable, have a high cycle life, and can charge and discharge at high rates [8].

6 Conclusions

A model was built that can describe how system frequency varies with respect to power imbalances on the grid. A model for the interaction between a gas turbine and battery storage hybrid system providing frequency regulation services was also built. The models allow extraction of key battery characteristics.

Future work could include the following.

- The use of real load data and then following through the method in section 2.
- The variation of more parameters, such as the system frequency limits and the gas turbine rated capacity.
- A more comprehensive model for the interaction between the gas turbine and the battery storage.
- A battery lifetime model.
- A full optimisation of the hybrid system with a cost analysis.

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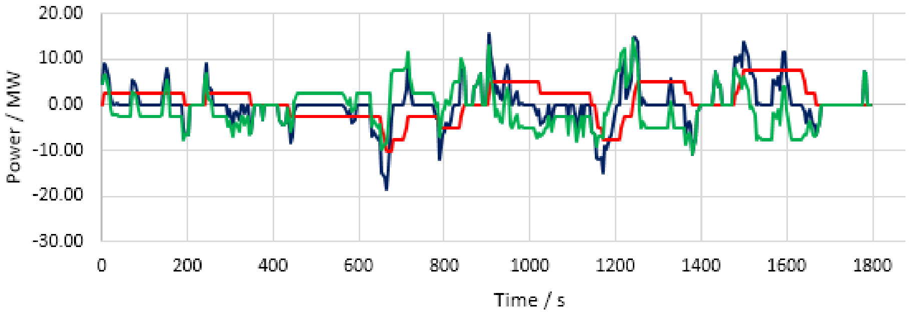
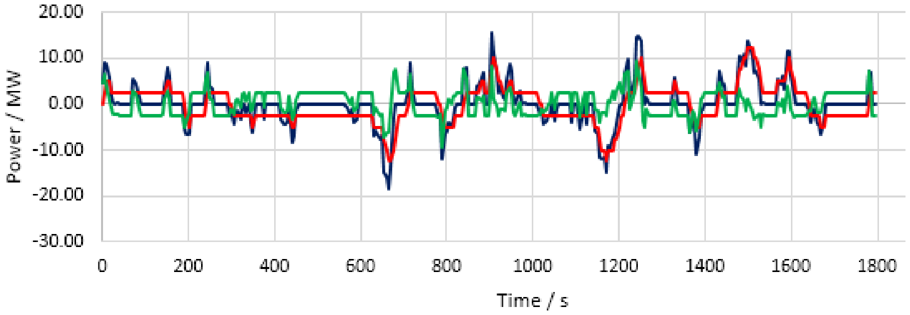
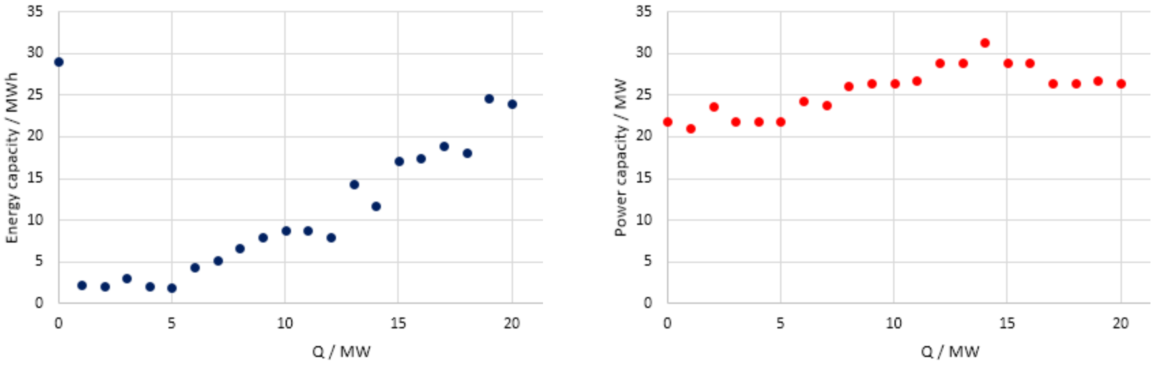


(a) $Q = 8\,\mathrm{MW}$



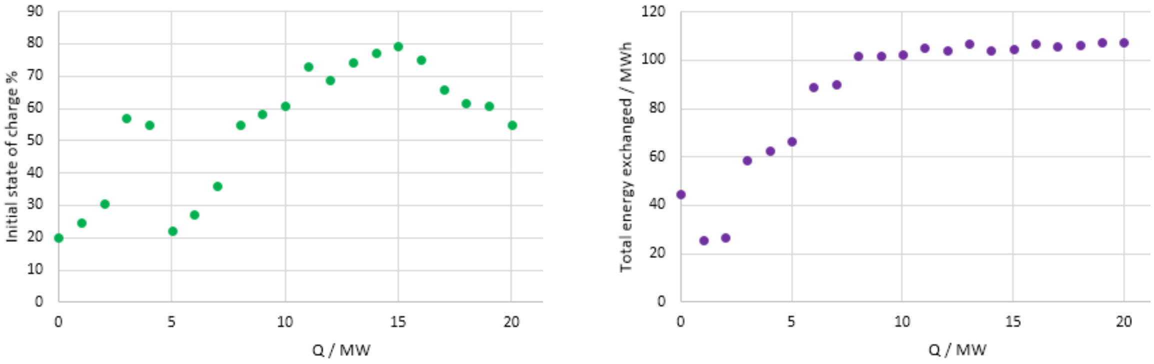
(b) $Q = 3\,\mathrm{MW}$

Figure 4: G_{fr} (dark blue), $G_{\mathrm{fr}}^{\mathrm{GT}}$ (red), and $G_{\mathrm{fr}}^{\mathrm{B}}$ (green) against time (for the first half hour).



(a) Energy capacity E_{cap}

(b) Power capacity P_{cap}



(c) The initial state of charge $E_{\mathrm{i}}/E_{\mathrm{cap}}$

(d) The total energy exchanged E_{tot}

Figure 5: Various battery variables plotted against the gas turbine sensitivity parameter Q.