Indirect control of electric vehicles for the provision of secondary frequency control

Semester Thesis

Department:
EEH – Power Systems Laboratory, ETH Zürich

Examiner:
Prof. Dr. Göran Andersson, ETH Zürich

Supervisors:
Marina González Vayá, ETH Zürich
Theodor Borsche, ETH Zürich

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Abstract

This semester thesis presents two indirect control concepts of electric vehicles for the provision of Load Frequency Control (LFC) by a vehicle aggregator. Each vehicle contracted with the aggregator is placed in a group after a grouping process. Each group defines whether the vehicle can offer LFC and also what type, positive or negative, given its end-use requirements.

Both controller concepts are based on the broadcasting of a probability signal to the vehicles. The probability signal is calculated according to the LFC signal transmitted by the Transmission System Operator (TSO) to the aggregator, and the number of vehicles that are placed in the groups which can provide the LFC service. The aggregator can measure only the aggregated response to that signal. Additionally, in the second concept a feedback loop recalculates the signal that is broadcasted at the next time step, based on the measured aggregated response.

The concepts are first evaluated by tracking the prequalification test of the Swiss TSO (Swissgrid) for generating units that provide secondary frequency control. After that, a real-time signal is tracked. Both simulations show that the two controller concepts are performing satisfactorily according to the requirement set by Swissgrid. Finally the effect of packet loss on the performance is examined.

Key Words: Indirect control of electric vehicle, Load Frequency Control (LFC), vehicle to grid, demand side management, Aggregator.
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1 Introduction

Today’s energy and climate change policy towards a more sustainable electricity system is causing a continuous increase in installed capacity of renewable generation with variable and uncertain production. This is leading to a growing amount of fluctuating infeeds into the transmission and distribution grids. Despite the improvement of the forecasting techniques, infeed prediction errors cannot be completely avoided. This is resulting in an increase of active power imbalances and therefore, a larger amount of control reserves is needed to balance the supply and demand in order to maintain the frequency at its target value. At the same time, the expansion of the smart grid and the Advanced Metering Infrastructure potentially offers the opportunity to manage large aggregated loads with precision equal to that of the supply side management.

In principle, any measure that can be taken by generating units has an equivalent measure that can be taken by loads (Demand Side Management). The primary characteristic of load control that distinguishes it from conventional generation-side approaches is that it must deliver a reliable resource to the power system while maintaining a level of end-use service that meets the customer’s expectations [3]. The use of loads for system services has several advantages such as:

I Although individual loads may become unavailable at any moment, the variability of the total contribution of a very large number of small loads is likely to be lower than that of a small number of large generators, for which a failure can have substantial impact on the ability to provide an ancillary service. Thus, many small responsive loads can provide greater reliability than a few large generators [10].

II Loads can often respond to operator requests instantaneously, whereas generators require some time to make output changes [10].

III Loads are distributed throughout the grid, so they give the opportunity to devise the spatially precise responses to contingencies [3].

The Transmission System Operator (TSO) is responsible for the procurement of all ancillary services [13]. Regarding frequency control, there are three levels of control that are generally used to maintain the balance between production and consumption: Primary, Secondary and Tertiary [14].

There are several studies that investigate the possibility to provide ancillary services by controlling loads such as thermostatically controllable loads or/and electric vehicles (EVs) [3], [7], [15], [1], [5], [4]. Specifically, the concept that parked electric vehicles are connected to the grid and can retrieve and inject controlled amounts of electric energy from/to the grid is referred as Vehicle to Grid (V2G) concept [15].
Studies have already argued that the most practical V2G service is regulation, since electric vehicles can most strongly compete in electricity markets when there is a capacity payment for availability apart from the payment when the power is utilized. This is the case of the ancillary services market, but not the case of the energy market for generation of bulk power. In the latter the cost of generated energy from vehicles is higher than the cost from centralized generators [8]. Therefore the upcoming introduction of electric and plug-in electric vehicles could potentially bring about a new source for ancillary services, such as frequency control. However, a single vehicle is too small to handle regulation service alone. Moreover, it is not possible for the TSO to coordinate a huge number of vehicles. Therefore, an aggregator which gathers the vehicle power and acts as an intermediary between the TSO and the EVs is proposed in [12].

The purpose of this semester thesis is to develop a controller for the provision of secondary frequency control by a vehicle aggregator. The features of the proposed controller are the following:

- It is based on the broadcasting of signals to the vehicles (indirect control).
- The aggregator can only measure aggregated response to that signal.
- A feedback loop recalculates the broadcasted signal depending on the aggregated response of vehicles.
- The vehicle requirements, such as the state of charge of the battery, are ensured locally.

This thesis is organised as follows. The second chapter gives an introduction to Load Frequency Control, investigates how it can be provided by electric vehicles and explains the evaluation procedure that is followed. The third chapter presents proposed concepts for the implementation of the targeted controller. The simulation results are presented and discussed in the fourth chapter. The fifth chapter contains the recapitulation and the conclusion of this thesis.

2 Load Frequency Control

2.1 General Aspects of Frequency Control Services

As it is mentioned in the introduction, maintaining the frequency at its target value requires that the active power produced and consumed is controlled to keep the load and the generation in balance. A certain amount of active power, called frequency control reserve, is kept available to perform this control. There are three control structures for frequency reserves: primary, secondary and tertiary. Usually the TSO tenders these three types
of control in specified quantities for each respective control area, both as positive (generation increase and load decrease) and negative (generation decrease and load increase) reserves. The amounts depend on the size and generation portfolio of the control area.

The automatic control system consists of the primary control and the secondary control (the latter can be also done manually, e.g. Nordel power system), while the tertiary control is activated manually in order to release the used primary and secondary control reserves after a disturbance. The primary control refers to control actions that are done locally (at power plant level) based on setpoints for frequency and power. It is activated by a proportional controller within the frequency-responsive governor of the generators and produces an output change proportional to the frequency deviation (speed-droop characteristic). In Continental Europe, the primary reserve has to be fully activated within 30 sec and has to be sustained for a maximum of 15 min. The frequency droop has to be such that the full reserve is activated before a frequency deviation of 200 mHz occurs. Thus, the control task is to bring the frequency back to acceptable values in short term. However there remains an unavoidable frequency control error because of the fully proportional control law. The control task is shared by all the generators participating in the primary frequency control irrespective of the location of the disturbance.

In the secondary frequency control, which is also called Load Frequency Control (or Automatic Generation Control), the power setpoints of the generators are adjusted in order to compensate for the remaining frequency error after the primary control has acted. Apart from that, it counters the effect of the change in the load flows on the tie-lines to other areas that is caused by the active power imbalances and primary control actions. So the goals of LFC are the following [2]:

- Release primary control.
- Keep the frequency in the interconnected power system close to the nominal value.
- Restore the scheduled interchanges between different areas.

Secondary control reserves are activated by a proportional-integral (PI) controller operated by the TSO. The LFC signal is transmitted by the TSO to the providing units in its control zone and it is dependent on the Area Control Error (ACE), which should be controlled to zero. The power reference values of the generators participating in the LFC in an interconnected area will be adjusted accordingly.
The ACE in Continental Europe is calculated according to Equation 1, where $P_{Ti}$ is the measured value of the total power exchange with the other control areas, $P_{T0i}$ is the scheduled power exchange with the other control areas, $B_i$ is the frequency bias factor of the controlled area, $f$ is the measured frequency and $f_0$ is the set value of the frequency:

$$ACE_i = P_{Ti} - P_{T0i} + B_i \cdot (f - f_0)$$  \hspace{1cm} (1)$$

A block diagram of such a controller is given in Figure 1. Tertiary control reserve is manually activated and is usually used to relieve the secondary control reserves. It must be fully activated after 15 minutes [4].

### 2.2 Provision of LFC by Electric Vehicles

The Vehicle to Grid (V2G) concept that is described in the introduction can be implemented when each vehicle has three required elements [9]:

I. A connection to the grid for electrical energy flow.

II. Control or logical connection necessary for communication with the aggregator.

III. Control and metering on-board the vehicle.
In order to achieve high penetration on the ancillary market, the V2G concept must satisfy not only the requirements of the TSO but also those of the vehicle owner. The system operator demands industry standard availability and reliability from the V2G system, while at the same time, the vehicle owner demands some minimum level of end-use and remuneration. These two dual objectives must be taken into account for effective approaches of load control. [3]

Methods for engaging loads in LFC system services can be distinguished based on the way that the loads are controlled. When direct control is applied, the system operator or another third party market player have the ability to increase or decrease the loads or can switch them on and off according to the system needs and the contracted amounts of LFC. The idea of indirect control management is to motivate consumers to align their energy consumption to factors like price signal [6].

Regarding the control architectures that can be applied, one can identify two types [12]:

I The centralized control architecture (Figure 2), where there is a central control station which has the ability to collect information and to directly control the vehicles. It is assumed that there exists a direct line of communication between the grid system operator and the vehicle so that each vehicle can be commanded by the grid system operator and it is allowed to bid and perform services while it is at the charging station.

II The aggregative architecture (Figure 3), where an intermediary, the aggregator, is inserted between the vehicles performing ancillary services and the grid system operator. This aggregator receives ancillary service requests from the grid system operator and issues power commands to contracted vehicles that are both available and willing to perform the required services. Under the aggregative architecture, the aggregator can bid to perform ancillary services at any time, while the individual vehicles can engage and disengage from the aggregator as they arrive at and leave from charging stations.

The aggregative architecture is more suitable for the participation in secondary control markets, because the minimum bid capacity is too large for a single EV. Therefore, many EVs must be pooled as one unit by an aggregator. From the viewpoint of the TSO, the aggregator will be responsible for delivering the promised control power, but the physical delivery is done by each EV.

Several studies examine the provision of LFC with load management schemes focused on centralized or decentralized approaches. For example, Almeida et al. [1] introduced modifications in the conventional AGC system in order to regulate the EV power consumption in response to changes in system frequency and tie-lines interchange scheduling. Aggregators act as
intermediaries between the AGC and the EV controllers. The TSO sends requests for EVs to change their power consumption via the AGC signal received by the aggregators. The aggregators distribute setpoints among the connected EVs and this way they directly affect their power consumption. Takagi et al. [17] proposed a charging power control scheme, based on the ACE and the frequency characteristic of PHEV $K_{PHEV}$ [W/Hz]. The latter is the change in charging power divided by the change in frequency and can be computed by analyzing the frequency spectrum of demand and system frequency. By applying the proposed method, the grid operator can control the charging power to the desired value by sending the same signal to all PHEVs. Koch et al. [11] developed a load modeling and control framework of aggregated heterogeneous Thermostatically Control Loads (TCL) for ancillary services. Their work is based on the indirect control approach, since a central controller collects information from the TCL population and transmits a control signal. The TCLs decide whether to react or not to this signal and if they react, they toggle on/off. The control signal is the switch probability that is calculated based on the number of loads that is needed to switch on/off, using the available state information about the TCLs. Galus et al. [4] proposed a method for tracking an LFC signal by groups of PHEVs, controllable thermal household appliances and a decentralized cogeneration unit. The control action is distributed among the units by an aggregator utilizing a Model Predictive Control strategy which allows the consideration of units’ and grid constraints. Finally, Kashyap et al. [7] explored several approaches to control distributed energy resources to support system operation and developed two control algorithms that effectively manage uncertainty in the state of the devices. More specifically, they developed an algorithm for situations where it is easy to send signals to and receive information from individual devices but broadcasting one signal to all devices cannot be done frequently enough to provide ancillary services. As a second step, they developed a control algorithm for conditions where
a common signal can be broadcasted to all devices quickly enough for ancillary services but there is limited capacity for retrieving information. The objective of this thesis is to build on the previous studies and to develop an indirect control scheme for tracking an LFC signal that can be applied by a vehicle aggregator. Indirect control means that the aggregator can only broadcast a common signal that is received by all EVs, and it is not able to address commands to specific vehicles. The vehicles decide if they will react to the signal sent. This approach is preferable from a communication point of view. The scheme takes into account constraints that are imposed by the end-use of the EVs and the quality of the delivered service to the TSO.

2.3 Requirements on Units Providing LFC - Evaluation Procedure

In order to be allowed to provide LFC, the generation units are subject to specific technical requirements that ensure the delivery of the control power demanded in real-time. The Transmission System Operator of Switzerland, Swissgrid, requires that all generating units that contribute to the market-based tenders of secondary control must be checked to ensure they meet the necessary technical conditions [16]. The appropriate test assesses the reaction of the generating unit to the test signal that is provided by Swissgrid (Figure 4). The actual power of the generating unit must be within the tolerance bands (Amplitude band: 5 %) of the secondary control power to be provided. All values in excess of the band are added together and applied across the entire signal. They must not be more than 1 % of the area covered by the signal. The following formula illustrates this process:

\[
\frac{\sum_{0}^{t} |P_{diff}| \cdot t_{t}}{P_{sec} \cdot t} \cdot 100\% \leq 1\% \quad (2)
\]

Where:

- Distance between maximum and minimum secondary control power: \( P_{sec} \)
- Values in excess of the band: \( P_{diff} \)
- Test duration: \( t \)
- Sampling rate: \( t_{t} \)
The proposed control scheme is evaluated with the above formula when tracking the Test signal, and also when tracking real daily data which are provided by Swissgrid.

3 Proposed Control Scheme

In this section two different concepts for the targeted controller are presented. Both controllers are performing indirect control of the electric vehicles and are implemented at the aggregator level. The aggregator is responsible for the bidding to the secondary control market for the provision of symmetrical control power and for the communication with the TSO on the one side and with the electric vehicles on the other side. The following two sections are valid for both concepts, whereas later a distinction is done between the two.

3.1 General Framework For The Control - Information Flows

Electric vehicles can provide symmetric control power by increasing or decreasing the load on the grid, i.e. start charging an idle EV for delivery of negative control and stop charging an EV for delivery of positive control. For positive control, there is also the additional possibility of discharging the batteries of the EVs and feed the energy into the grid.

When a symmetric bid is won by the aggregator, it is its task to ensure that the promised control power will be delivered if needed. In order to do that, the aggregator must know how many EVs can provide positive or negative control. Therefore, through a grouping process done at the EV
level, each vehicle is placed in a group according to specific constraints. These constraints are based on data like the current State Of Charge (SOC), the required SOC for the next trip and others, and they target to classify the EVs in such way, that not only the control power is delivered reliably, but also end-use requirements of the vehicle drivers are ensured.

The TSO is responsible for the transmission of the LFC signal to the aggregator. The aggregator, based on the aforementioned grouping and the LFC signal, calculates and broadcasts every control time step a probability signal to the EVs. The probability signal triggers the response of the electric vehicles that covers the need for secondary frequency control. The aggregator then measures the aggregated response of the vehicles, which should track the LFC signal. The information flow is depicted in Figure 5:

Figure 5: Hierarchical information flow between the actors.

Regarding the EVs and their connection points, it is assumed that there are pervasive and available connection points to the grid for charging and discharging, which allow EVs to connect throughout the day at any location. According to individual plans, the EVs can stay at the same or connect to a different connection point after a trip.

When the vehicles are connected, information is sent to the aggregator. This information includes the arrival time, the designated departure time, the SOC at arrival, the required SOC at departure, battery capacity and maximum connection power. Furthermore, the EVs have to communicate their group to the aggregator. Thus, the aggregator is able to calculate the
signal that is broadcasted correctly. For perfect knowledge, the grouping
information should be exchanged at the beginning of every control time
step. However this would result in a big communication burden. Therefore,
the more realistic case of information exchange in larger time intervals (e.g
every 15 minutes) is examined. The different time intervals of control and
information exchange are depicted in Figure 6.

Figure 6: Different time intervals of control and information exchange.

Finally, except for the aforementioned information about the connection
time and the next trip, every vehicle has a desired planned charging profile
for the whole period that the vehicle is connected to the grid. The vehicles
have to follow this schedule in parallel to the V2G service they offer. The
scheduled charging is usually the output of an optimization process.

3.2 Vehicle Representation

The tracking of the LFC signal refers to a short time step $\Delta t$ (10 sec), so
the State of Charge of each vehicle is calculated with respect to $t_d$, which
counts the steps. The relation between the consumed power, whether it is
the planned charging power or control power, and the SOC is given by the
following equation:

$$SOC(t_d + 1) = SOC(t_d) + \frac{P_{flow}(t_d) \cdot \Delta t \cdot \eta_{charge}}{C_{Batt}}$$

(3)
where $P_{\text{flow}}$ is the consumed power in [kW], $\eta_{\text{charge}}$ the charging efficiency, $C_{\text{Batt}}$ the capacity of the vehicle’s battery in [kWh] and $\Delta t$ the time step duration expressed in [h].

When the vehicle is providing control power, there is the possibility to discharge and feed power back into the grid. The relation between the control power that is fed into the grid and the SOC is given by the following equation:

$$SOC(t_d + 1) = SOC(t_d) + \frac{P_{\text{flow}}(t) \cdot \Delta t}{C_{\text{Batt}} \cdot \eta_{\text{dis}}}$$  

where $P_{\text{flow}}$ is the infeed power to the grid in [kW], $\eta_{\text{dis}}$ the discharging efficiency, $C_{\text{Batt}}$ the capacity of the vehicle’s battery in [kWh], $\Delta t$ the time step duration in [h].

The SOC is confined to a time-invariant battery specific range e.g. [20%, 100%] by the constraint:

$$0 \leq SOC_{\text{min}} \leq SOC(t_d) \leq 1$$  

Since the vehicles are modelled as loads, the power flow between a vehicle and the grid is positive when the vehicle is charging and negative when the vehicle is discharging:

$$P_{\text{flow}} = \begin{cases} < 0, & \text{when discharging} \\ > 0, & \text{when charging} \end{cases}$$  

To calculate the control power, the discharging power and the reduction of the consumed power are considered positive, while the increase in charging power is considered negative.

$$P_{\text{response}} = \begin{cases} < 0, & \text{when the charging power is increased} \\ > 0, & \text{when the charging power is decreased or discharging} \end{cases}$$  

The aggregated control power of all the electric vehicles that respond to the broadcasted signal of the aggregator is calculated as:

$$P_{\text{aggregate}} = \sum_{i=1}^{N} P_{\text{response}_i}$$  

where $N$ is all vehicles and $P_{\text{response}_i}$ is the control power that each vehicle provides at the current time step.

### 3.3 First Concept

In this proposed scheme the vehicles are reset to the planned charging profile after each control time step, regardless of whether they provided control power or not.
3.3.1 Groups

In this strategy every EV can have the following states prior to responding to the signal: (1) Disconnected, (2) Connected and Charging and (3) Connected and Idle. The planned charging profile for each vehicle determines whether the vehicle is charging or is idle. The specified groups determine the possible state of the EV at the next time step and therefore if it can provide positive or negative control power.

More specifically, in order to provide LFC service for the next time step, a connected vehicle that is charging is able to both stop charging or start discharging, is able only to stop charging or it cannot provide the service because it must charge. A connected but idle vehicle can both start charging or discharging, or perform only one of them. There is also the case that an idle vehicle cannot provide the V2G service. So the proposed groups according to the current state and the possibilities for the next control step are:

- Group 0: Disconnected
- Group 1: Stop charging
- Group 2: Must charge
- Group 3: Start charging/Discharge
- Group 4: Start charging/Not discharge
- Group 5: Discharge
- Group 6: Do nothing

3.3.2 Grouping process

It is determined that EVs can provide only a fixed amount of control power for secondary frequency control. That means that the discharging power is fixed, the charging power (for frequency control) is fixed and that only the EVs that are charging at least with the fixed power can reduce their charging by this amount of power. Thus, the EVs which are charging with power below this amount, cannot offer secondary control by stopping to charge. This is done in order to eliminate the error that would appear if every vehicle would respond with a random amount of control power (e.g. related to the charging power at the specific moment, see 3.3.5).

The grouping process is done, so as to ensure the end-use, namely the next trip, of the vehicle. For the subsequent grouping process the following variables are defined:

$P_{\text{charge}}$ is the charging power according to the planned charging profile
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\(SOC_{req}\) is the required State of Charge for the next trip

\[
SOC_{potential} = SOC(t_d) + \frac{(P_{max} \cdot T_{remain} - P_{fixed} \cdot \Delta t) \cdot n_{charge}}{C_{Batt}} \tag{9}
\]

where

- \(SOC_{potential}\) is the theoretical State of Charge that the vehicle can achieve by charging the whole remaining time till the departure, if the vehicle does not charge the current time step,
- \(P_{max}\) is maximum connection power of the vehicle in [kW],
- \(T_{remain}\) is the remaining time till the next trip expressed in [h],
- \(P_{fixed}\) is the fixed power in [kW],
- \(C_{Batt}\) is capacity of the vehicle’s battery in [kWh],
- \(\Delta t\) is one time step duration in [h],
- \(n_{charge}\) is the charging efficiency.

\[
SOC_{Charge} = SOC(t_d) + \frac{(P_{fixed} \cdot \Delta t) \cdot n_{charge}}{C_{Batt}} \tag{10}
\]

where \(SOC_{Charge}\) is the State of Charge that the vehicle would have after charging with fixed power during the current time step.

\[
SOC_{Discharge} = SOC(t_d) - \frac{(P_{fixed} \cdot \Delta t)}{C_{Batt} \cdot n_{dis}} \tag{11}
\]

where, \(SOC_{Discharge}\) is the State of Charge that the vehicle would have after discharging with fixed power during the current time step.

The grouping process is done according to the following constraints:

- If the vehicle is not connected to the grid it is placed in group 0.
- If \(P_{charge} > 0\) AND \((SOC_{potential} < SOC_{req} OR P_{charge} < P_{fixed})\) the vehicle is placed in group 2.
- If \(P_{charge} > 0\) AND \(SOC_{potential} \geq SOC_{req}\) AND \(P_{charge} \geq P_{fixed}\) AND \(SOC_{Discharge} \geq SOC_{req}\) the vehicle is placed in group 1.
- If \(P_{charge} > 0\) AND \(SOC_{potential} \geq SOC_{req}\) AND \(P_{charge} \geq P_{fixed}\) AND \(SOC_{Discharge} < SOC_{req}\) the vehicle is placed in group 1.
- If \(P_{charge} = 0\) AND \(SOC_{chargel} \geq 1\) AND \(SOC_{Discharge} < SOC_{req}\) the vehicle is placed in group 6.
• If $P_{\text{charge}} = 0$ AND $SOC_{\text{charge}} \geq 1$ AND $SOC_{\text{Discharge}} \geq SOC_{\text{req}}$ the vehicle is placed in group 5.

• If $P_{\text{charge}} = 0$ AND $SOC_{\text{charge}} < 1$ AND $SOC_{\text{Discharge}} \geq SOC_{\text{req}}$ the vehicle is placed in group 3.

• If $P_{\text{charge}} = 0$ AND $SOC_{\text{charge}} < 1$ AND $SOC_{\text{Discharge}} < SOC_{\text{req}}$ the vehicle is placed in group 4.

At the end of the time step, every EV returns to the state that is determined by the planned desired charging profile, but depending on whether it provided service or if there is a change in the planned charging profile, it may belong to a different group.

### 3.3.3 Grouping at Aggregator level

Vehicles have to communicate their planned desired charging profile day-ahead to the aggregator, as well as their planned trips and required SOC for them. Thus the aggregator knowing this information can run the grouping process already described and group the vehicles. With that knowledge it can place its bid in the load frequency control market.

### 3.3.4 Grouping at vehicle level

Every control time step, the vehicles receive the probability signal that is broadcasted by the aggregator which is determined based on the load frequency control signal transmitted by the TSO (see Sect. 3.3.5). Each vehicle will either respond to the signal or will continue to act according to the day-ahead desired plan. Afterwards, every vehicle classifies itself into a group, which determines if it will be able to act and how (positive or negative control) in the next control time step.

### 3.3.5 Probability signal

The load frequency control signal is transmitted by the TSO to the aggregator every control time step. Therefore, the aggregator knows the power control that must be delivered according to the bid it has placed. Based on the fixed connection power ($P_{\text{fixed}}$) that a EV can deliver, the aggregator calculates the number of EVs needed for the delivery of the required control power:

$$N_{V2G} = \frac{LFC}{P_{\text{fixed}}}$$

(12)

where $N_{V2G}$ is the amount of EVs that must respond in order to provide the load frequency control needed and $LFC$ is the frequency control power needed in [MW].
When positive control is needed, the frequency control signal is positive, while for negative control the frequency control signal is negative. According to the knowledge the aggregator has about the number of the EVs in each group, a probability signal is produced by the aggregator every control time step. This probability signal is broadcasted to the EVs.

For positive control only the EVs in groups 1, 3 and 5 can provide control power, therefore the probability signal is defined:

$$p_{signal} = \frac{N_v 2G}{U_p}$$  \hspace{1cm} (13)

where $U_p$ is the sum of EVs in groups 1, 3 and 5.

For negative control the EVs in groups 3 and 4 can respond, thus the probability signal in this case is calculated:

$$p_{signal} = \frac{N_v 2G}{D_{own}}$$  \hspace{1cm} (14)

where $D_{own}$ is the sum of EVs in groups 3 and 4.

If the grouping information exchange from the vehicles to the aggregator is not realized at every control time step, a grouping error is introduced in the resulting probability signal that is broadcasted. This is due to the fact that the vehicles that act and provide control power at a time step, may move to another group in the next time steps as a result of the action. So the aggregator would have an outdated estimate of the sum of vehicles in the respective groups, until it is updated again with the correct grouping. In order to limit this error, the aggregator makes a simplified estimation by calculating the number of vehicles that actually responded and subtracting the amount of the respective sum ($U_p$ or $D_{own}$). More specifically:

$$U_{p_{new}} = U_{p_{old}} - V_{responded}$$  \hspace{1cm} (15)

where $U_{p_{new}}$ is the amount of vehicles available for positive control after response, $U_{p_{old}}$ is the amount of vehicles available for positive control before response and $V_{responded}$ is the amount of vehicles that responded.

$$D_{own_{new}} = D_{own_{old}} - V_{responded}$$  \hspace{1cm} (16)

where $D_{own_{new}}$ is the amount of vehicles available for negative control after response, $D_{own_{old}}$ is the amount of vehicles available for negative control before response and $V_{responded}$ is the amount of vehicles that responded.

$$V_{responded} = \frac{P_{aggregate}}{P_{fixed}}$$  \hspace{1cm} (17)
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3.3.6 Power response

The probability signal is broadcasted to the EVs. Regarding whether it is positive or negative control, the EVs in the respective group will respond to the signal with probability equal to the signal that is sent. Such a success/failure experiment is called Bernoulli trial, and it is similar to the assumption that each vehicle that can respond (namely it belongs to the proper group) “flips a coin” with the signal probability as probability of success. The resulting aggregated control power is the sum of the control power of the individual vehicles that respond (see eq. 8). Due to the use of the random process for the determination of the actual number of vehicle that respond, a random error is infiltrated in the output.

The EVs that respond to the signal offer secondary frequency control, while those that do not respond act according to the desired charging plan. Here it should be mentioned that if an EV in group 4 is responding, it is starting charging when negative control is needed, while it is discharging in the case of positive control. Moreover, if an EV in group 1 is responding, although it could potentially discharge, it prefers to stop charging because discharging is not preferable due to the following reasons [15]:

- Energy already bought and stored in the battery is discharged.
- Losses due to non perfect charge/discharge efficiencies
- Costs due to battery degeneration by increasing the amount of cycles

3.4 Second Concept - The Aggregated response of the vehicle is based on a feedback loop

In this scheme the vehicles do not reset their response after each control time step to the desired charging profile like in the previous strategy. Therefore, only the difference between the aggregated response of the vehicles at the previous time step and the control power requested for the current time step has to be covered. The vehicles are reset to the desired planned charging profile after a specified longer time interval \( T_{\text{reset}} \), e.g. 15 minutes.

This time a connected vehicle can be in one of the following states at the beginning of a time step: charging, discharging or idle (having no power exchange with the grid) (in comparison with the two possible states, charging and idle, of the first strategy). A vehicle that is charging is able to stop charging or it will stay as it is because it must charge. A vehicle that is idle can start charging, can start discharging or will stay idle. Finally a vehicle that is discharging, as a result of an action of a previous control time step within the same \( T_{\text{reset}} \) time interval, can stop discharging and stay idle. Therefore, seven different groups are determined:

- Group 0: Disconnected
3 PROPOSED CONTROL SCHEME

- Group 1: Must charge
- Group 2: Stop charging
- Group 3: Start charging
- Group 4: Start discharging
- Group 5: Not charging/Not discharge
- Group 6: Stop discharging

Figure 7 depicts the different groups and the way a vehicle can move from one group to the other.
3.4.1 Grouping constraints

Again, for the same reasons as in the first strategy, it is determined that EVs can provide only a fixed amount of control power for secondary frequency control. For the subsequent grouping process the following variables are defined: $P_{\text{state}}$ is the power flow between the vehicle and the grid. $SOC_{\text{req}}$ is the required State-Of-Charge for the next trip.
3 PROPOSED CONTROL SCHEME

\[
SOC_{\text{Charge}} = SOC(t_d) + \frac{(P_{\text{fixed}} \cdot T_{\text{rem}}) \cdot \eta_{\text{charge}}}{C_{\text{Batt}}} \quad (18)
\]

where

\(SOC_{\text{Charge}}\) is the State of Charge that the vehicle will have after charging with fixed power for the remaining time till the end of the \(T_{\text{reset}}\), \(T_{\text{rem}}\) is the remaining time steps till the end of \(T_{\text{reset}}\) expressed in [h], \(P_{\text{fixed}}\) is the fixed power in [kW], \(C_{\text{Batt}}\) is capacity of the vehicle’s battery in [kWh] and \(\eta_{\text{charge}}\) is the charging efficiency.

\[
SOC_{\text{Discharge}} = SOC(t_d) - \frac{(P_{\text{fixed}} \cdot T_{\text{rem}})}{C_{\text{Batt}} \cdot \eta_{\text{dis}}} \quad (19)
\]

where,

\(SOC_{\text{Discharge}}\) is the State of Charge that the vehicle has after discharging with fixed power for the remaining time till the end of the \(T_{\text{reset}}\) and \(\eta_{\text{dis}}\) is the discharging efficiency.

The grouping is done according to the following constraints:

1. If the vehicle is not connected to the grid it is placed in group 0.

2. if \(P_{\text{state}} > 0 \text{ AND } (P_{\text{state}} < P_{\text{fixed}} \text{ OR } SOC(t_d) < SOC_{\text{req}})\) then is placed in group 1

3. if \(P_{\text{state}} \geq P_{\text{fixed}} \text{ AND } SOC(t_d) \geq SOC_{\text{req}}\) is placed in group 2

4. if \(P_{\text{state}} = 0 \text{ AND } SOC_{\text{Charge}} \leq 1\) is placed in group 3

5. if \(P_{\text{state}} = 0 \text{ AND } SOC_{\text{Charge}} > 1 \text{ AND } SOC_{\text{Discharge}} > SOC_{\text{req}}\) is placed in group 4

6. if \(P_{\text{state}} = 0 \text{ AND } SOC_{\text{Charge}} > 1 \text{ AND } SOC_{\text{Discharge}} < SOC_{\text{req}}\) is placed in group 5

7. if \(P_{\text{state}} < 0\) is placed in group 6

3.4.2 Probability signal

In this implementation, the required number of vehicles that have to respond in order to provide the LFC power is calculated based on a feedback loop, which is the difference between the aggregated response at the previous time step and the LFC signal of the current time step:

\[
N_{V2G} = \frac{LFC(t_d) - P_{\text{aggregate}}(t_d - 1)}{P_{\text{fixed}}} \quad (20)
\]
where $N_{V2G}$ is the amount of EVs that must respond in order to provide the required change in the aggregated power response of the vehicles.

Positive control means in this case, that the difference between $LFC(t_d)$ and $P_{\text{aggregate}}(t_d - 1)$ is positive and not necessarily that the frequency control signal is positive. Negative control means that the difference and not exclusively the frequency control signal is negative. According to the knowledge the aggregator has about the number of the EVs in each group, a probability signal is produced by the aggregator every control time step. This probability signal is broadcasted to the EVs.

For positive control only the EVs in groups 2 and 4 can provide control power, therefore the probability signal is defined:

$$p_{\text{signal}} = \frac{N_{V2G}}{U_p} > 0$$  \hspace{1cm} (21)

where $U_p$ is the sum of EVs in groups 2 and 4.

For negative control the EVs in groups 3 and 6 can respond, thus the probability signal in this case is calculated:

$$p_{\text{signal}} = \frac{N_{V2G}}{Down} < 0$$  \hspace{1cm} (22)

where $Down$ is the sum of EVs in groups 3 and 6.

Also in this case, if the grouping information exchange from the vehicles to the aggregator is not realized at every control time step, a grouping error is introduced in the resulting probability signal that is broadcasted. As it is mentioned, this is due to the fact that the vehicles that act and provide control power at a time step, may be placed into another group within the next time steps, as a result of that action. So the aggregator would have an outdated estimate of the sum of vehicles in the respective groups, until it is updated again with the correct grouping. For the limitation of this error the same concept is applied as before (see 3.3.5).

### 3.4.3 Grouping at Aggregator level

The concept that is presented in the first strategy is also valid here (see 3.3.3).

### 3.4.4 Grouping at vehicle level

Each vehicle runs the grouping process every time step and it is possible to provide control power even if it is already providing (e.g. reducing the charging power). In any case, the grouping process makes sure that the battery does not get emptied to a point where charging at an unscheduled time is needed. Charging is possible only because of planning (day ahead) or as a response to a negative control request.
3.4.5 Power response

The probability signal is broadcasted to the EVs. Regarding whether it is positive or negative control, the EVs in the respective group will respond to the signal with probability equal to the signal that is sent (random output of a Bernoulli trial - success/failure experiment). In this concept, the amount of control power that is activated at each control time step is usually less than the one in the first concept, because only the number of vehicles that are needed to cover the difference from the response of the previous time step is activated. Therefore this number is usually much smaller than the number in the first strategy. Thus the random effect in the output, due to the random process is smaller. The latter is not valid in the case that there is a change in control power needed (from positive to negative or from negative to positive), where the number of vehicle needed is larger.

4 Simulation Results - Discussion

In this section the results of the two controller concepts implemented in Matlab according to different simulation scenarios are presented and discussed. More specifically, the following scenarios are simulated and studied:

- Tracking the test signal of Swissgrid,
- Tracking real time data of a whole day assuming perfect information with 20MW bid of the aggregator,
- Tracking real time data of a whole day assuming 15-minute exchange of information and various bids sizes,
- Effect of packet loss.

The evaluation procedure is described in 2.3, while the resulting error is analyzed and classified into the two sources that have been mentioned namely the (1) random error and (2) grouping error. The aforementioned simulations are realized when the control time step is 10 seconds. Finally, the real time data are provided by Swissgrid, the swiss TSO.

4.1 Error Sources

In general two sources of error between the aggregated response of the vehicles and the desired response that is the LFC signal can be identified: (1) the random error due to the Bernoulli process that every vehicle runs (implemented by the function binornd() in Matlab) and (2) the grouping error due to incomplete information of the aggregator on the groups that the vehicles belong to. In the simulated scenarios these two errors are decoupled and are presented on the respective figures. The calculation of the errors is
done according to the following equations:

\[ E_g = \frac{P_{fixed} \cdot (N_{V2G} - N_{oV})}{0.5 \cdot P_{sec}} \] (23)

where

\( E_g \) is the grouping error in [\%], \( N_{oV} \) is the number of vehicles that should respond based on the probability signal sent and assuming perfect information. \( N_{V2G} \) is the desired number of vehicles that must respond in order to provide the change in the aggregated power response of the vehicles. \( P_{sec} \) is the distance between the maximum and minimum secondary power (thus \( 0.5 \cdot P_{sec} \) is equal to the bid size).

\[ E_r = \frac{P_{fixed} \cdot (N_{oV} - N_{oV_{actual}})}{0.5 \cdot P_{sec}} \] (24)

where,

\( E_r \) is the random error in [\%], \( N_{oV} \) is the number of vehicles that should respond based on the probability sent and assuming perfect information, \( N_{oV_{actual}} \) is the number of vehicles that actually responded to the broadcasted signal.

Based on the aforementioned, the total error is due to the difference between the number of vehicles necessary to cover the requested control power and the number of vehicles that respond to the signal and offer control power. \( E_{tot} \) in [MW] is calculated by the following equation:

\[ E_{tot} = P_{fixed} \cdot (N_{V2G} - N_{oV_{actual}}) \] (25)

The random error is caused by the random output of the decision process of each vehicle, thus it cannot be predicted and cannot be completely avoided. On the other hand, grouping error is related to the knowledge about the grouping of vehicles that the aggregator has. Based on that information, the aggregator calculates the probability signal that sends to the EVs. If this information is wrong, the probability that is sent is not the appropriate one and therefore the aggregated response will be different from the desired one. This error can be eliminated when the vehicles send their groups to the aggregator at each control step. Otherwise, a grouping error will be present and its magnitude will be related to the number of vehicles that will have moved from their groups between two consecutive information updates.

4.2 First Concept’s Simulation Results

In order to demonstrate the first control approach, simulations are conducted for all the scenarios presented in the beginning of Chapter 4. Table 1 presents the numerical values of the system:
Table 1: Parameters of the system

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control time step</td>
<td>10 seconds</td>
</tr>
<tr>
<td>$P_{fixed}$</td>
<td>3 kW</td>
</tr>
<tr>
<td>$P_{max}$</td>
<td>15 kW</td>
</tr>
<tr>
<td>$SOC_{min}$</td>
<td>0.2</td>
</tr>
<tr>
<td>$\eta_{charge}$</td>
<td>0.9</td>
</tr>
<tr>
<td>$\eta_{dis}$</td>
<td>0.9</td>
</tr>
<tr>
<td>$C_{batt}$</td>
<td>16 kWh</td>
</tr>
<tr>
<td>Vehicle fleet</td>
<td>1000000 vehicles</td>
</tr>
</tbody>
</table>

4.2.1 Tracking the test signal

Figure 8 shows the aggregated response of the vehicles to the Test signal:

![Figure 8: Str 1 - Tracking the test signal: aggregate response and error](image)

The output of the evaluation procedure is that all values in excess of the band added together result in 0.15% which is less than the required 1%. Thus the proposed scheme would pass the prequalification test.
4.2.2 Assuming perfect information

In this case it is assumed that the EVs are sending their groups to the aggregator at the end of each control time step. Therefore the aggregator has perfect information about the state of the vehicles, so the probability signal that is broadcasted is calculated based on the actual grouping situation. Thus, any existing error is related to the random error of the binomial function. It is assumed that the aggregator wins a 20 MW symmetric control bid and the simulation covers 24 hours. The Figure 9a presents the output of the simulation and Figures 9b and 9c show the random error and the grouping error.

The output of the evaluation procedure is that all values in excess of the band added together result in 0.26% which is less than the required 1%.

4.2.3 15 minutes information update

In this more realistic scenario perfect information is no longer assumed. The vehicles send their groups to the aggregator every 15 minutes, that is at the beginning of the 1st, 91th, 181th and 271th time step of each hour. Again the simulation covers 24 hours. The result of the simulation assuming that the aggregator has won a 20 MW bid is presented in Figure 10a, while Figures 10b and 10c show the random error and the grouping error.

The output of the evaluation procedure is that all values in excess of the band added together result in 0.68% which is less than the required 1%. The peaks in the resulting error between the 5000 and 6000 time steps are due to the bigger grouping error during this period. This grouping error can be explained by the LFC signal requests for a large amount of control power (close to or at the maximum of 20 MW). Therefore, a lot of vehicles respond at each time step and for that reason, many can change groups (after the grouping process at the end of each time step). Thus, till the next information update, the aggregator has outdated knowledge about the number of available cars for V2G which deviates a lot from the actual amount of vehicles and therefore calculates a wrong probability signal.

Figure 11a presents the simulation result, assuming this time that the aggregator has won a 50 MW symmetrical bid. The output of the evaluation procedure is that all values in excess of the band added together result in 0.63% which is less than the required 1%. The Figures (11b and 11c) show the random error and the grouping error.

The random error, as a percentage of the LFC signal, is less than the one of the 20MW bid. Since the power that can be offered by one vehicle is fixed, a larger number of vehicles are needed to cover the bigger bid of 50 MW. Therefore, the deviation from the desired amount of vehicles ($N_{V2G}$) due to the Bernoulli process has less impact on the aggregated response (i.e. 3kW is smaller percentage of 50 MW than of 20 MW).
4 SIMULATION RESULTS - DISCUSSION

(a) Str 1 - Simulation with perfect information - 20MW bid: aggregate response and error

(b) Str 1 - Perfect information - 20MW bid: random error

(c) Str 1 - Perfect information - 20 MW bid: grouping error

Figure 9: Str 1 - Perfect information - 20MW bid
4 SIMULATION RESULTS - DISCUSSION

(a) Str 1 - with 15 minutes exchange - 20MW bid: aggregate response and error  

(b) Str 1 - 15 minutes exchange - 20MW bid: random error  

(c) Str 1 - 15 minutes exchange - 20MW bid: grouping error  

Figure 10: Str 1 - 15 minutes exchange - 20MW bid
Figure 11: Str 1 - 15 minutes exchange - 50MW bid
4.2.4 Packet loss effect

In this section the effect of packet loss on the quality of control is examined. Three cases are studied, the first one assumes no packet loss, the second one that 10% of the vehicle fleet do not recieve the broadcasted signal and the last one assumes that 50% of the fleet do not recieve the probability signal. In all three cases, perfect information is assumed, namely, the vehicles send their groups to the aggregator at every control time step. The simulation duration is 1 hour.

1) The simulation is run without any packet loss and the output is presented in Figure 12a. The output of the evaluation procedure is $0.18\% < 1\%$. Figures 12b and 12c show the random error and the grouping error that are present in this scenario. As expected, since there is perfect information, there is no grouping error, only random.

2) Packet loss 10% is assumed (Figure 13a). The output of the evaluation procedure is $2.11\% > 1\%$, so this scenario failed to pass the evaluation procedure. The packet loss can be interpreted as an increase of the random error, as it is shown from the Figure 13b. It can be observed that the 10% packet loss causes a decrease of 10% (and therefore an error increase) between the aggregated response and the LFC signal. This is explained because the system has no memory, so the probability signal that is sent must trigger the exact amount of vehicles to cover the LFC. Therefore, when 10% of the vehicle that have to respond are not receiving the signal, this is directly translated to a 10% less aggregated control power.

3) The following scenario assumes 50% packet loss and the result is presented in Figure 14a. The output of the evaluation procedure is $19.5\% > 1\%$. Figures 14b and 14c show the random and grouping errors.

As it is expected, the concept failed also in this scenario. The larger packet loss percentage has bigger impact in the aggregated response of the vehicles.
4 SIMULATION RESULTS - DISCUSSION

(a) Str 1 - Perfect information - no packet loss: aggregate response and error

(b) Str 1 - Perfect information - no packet loss: random error

(c) Str 1 - Perfect information - no packet loss: Grouping Error

Figure 12: Str 1 - Perfect information - no packet loss
(a) Str 1 - Perfect information, 10% loss: aggregate response and error

(b) Str 1 - Perfect information, 10% packet loss: random error

(c) Str 1 - Perfect information, 10% packet loss: grouping error

Figure 13: Str 1 - Perfect information, 10% loss
(a) Str 1 - Perfect information, 50% packet loss: aggregate response and error

(b) Str 1 - Perfect information, 50% packet loss: random error

(c) Str 1 - Perfect information, 50% packet loss: grouping error

Figure 14: Str 1 - Perfect information, 50% loss
4.3 Second Concept’s Simulation Results

In order to demonstrate the second presented control approach, simulations are conducted for the aforementioned scenarios. Table 2 presents the numerical values of the system:

Table 2: Parameters of the second control system

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control time step</td>
<td>10 seconds</td>
</tr>
<tr>
<td>$T_{reset}$</td>
<td>15 minutes</td>
</tr>
<tr>
<td>$P_{fixed}$</td>
<td>3 kW</td>
</tr>
<tr>
<td>$P_{max}$</td>
<td>15 kW</td>
</tr>
<tr>
<td>$SOC_{min}$</td>
<td>0.2</td>
</tr>
<tr>
<td>$\eta_{charge}$</td>
<td>0.9</td>
</tr>
<tr>
<td>$\eta_{dis}$</td>
<td>0.9</td>
</tr>
<tr>
<td>$C_{batt}$</td>
<td>16 kWh</td>
</tr>
<tr>
<td>Vehicle fleet</td>
<td>1000000 vehicles</td>
</tr>
</tbody>
</table>

4.3.1 Tracking the test signal

Figure 15 shows the aggregated response of the vehicles to the test signal:
4 SIMULATION RESULTS - DISCUSSION

4.3.2 Assuming perfect information

In this case it is assumed that the EVs are sending their groups to the aggregator at the end of each control time step. Therefore, the aggregator has perfect information about the state of the vehicles and the probability signal that is broadcasted is calculated based on the actual grouping situation. Thus, any error that exists in this case is related to the random output of the Bernoulli function. The aggregator wins a 20 MW symmetric control. Figure 16a presents the output of the simulation. The output of the evaluation procedure is that all values in excess of the band added together result in 0.02% which is a lot less than the required 1%. Figures 16b and 16c show the random error and the grouping error that exist in this scenario.

As expected, since there is perfect information, there is no grouping error. In addition, the random error in this concept is smaller, in comparison with the first one. As the state is kept by the vehicles, only the difference in the requested control power (between two time steps) has to be compensated.
(a) Str 2 - Simulation with Perfect information - 20MW bid: aggregate response and error

(b) Str 2 - Perfect information - 20MW bid: random error

(c) Str 2 - Perfect information - 20 MW bid: grouping error

Figure 16: Str 2 - Perfect information - 20MW bid
Thus the signal for the current time step is calculated through the feedback loop.

4.3.3 15 minutes information update

In this case perfect information is no longer assumed. The vehicles send their groups to the aggregator every 15 minutes as in the scenario of the first strategy, namely at the beginning of the 1st, 91st, 181st and 271st time step of each hour. First the aggregator wins a bid for 20 MW. Figure 17a presents the output of the simulation.

The output of the evaluation procedure is that all values in excess of the band added together result in 0.10% which is less than the required 1%. From Figures 17b and 17c can be observed that a bigger error can occur when there is a change in control power (from positive to negative or reverse) or when there is a big change between two control steps. This is expected because in such cases, a larger amount of vehicles must respond in order to cover the change. Another point that should be mentioned is that the grouping error and therefore the total error, is bigger close to the end of 15-minute period between two consecutive information exchanges, because the information that the aggregator has about the grouping of vehicles is outdated. Thus, the probability that is broadcasted is not the appropriate one. This is clear from Figure 17c. Finally, when the LFC signal is constant, the resulting error is almost zero, because the aggregated power of the previous time step is also sufficient for the next one.

2) It is assumed now that the aggregator wins 50 MW symmetrical bid (Figure 18). On the one hand, the random error is smaller due to the weaker effect of the random output of the Bernoulli trial for each vehicle. Since in every step a higher amount of vehicles is needed, any difference between the desired amount of vehicles and the amount that responded, results in smaller deviation from the LFC signal. On the other hand, the grouping error is bigger due to the faster change in the actual grouping, since more vehicles are needed to provide the control power. The average total error in this case is 0.55%, while in the case of 20 MW bid size was 0.48%. The output of the evaluation procedure is that all values in excess of the band added together result in 0.11% which is less of the required 1%.

4.3.4 Packet loss effect

In this section the effect of packet loss in the quality of control is examined. The same three cases are studied, firstly with no packet loss, secondly with 10% packet loss and thirdly with 50% packet loss.

At the beginning, perfect information is assumed, namely, the vehicles send their groups to the aggregator every control time step. The simulation time is 1 hour.
Figure 17: Str 2 - 15 minutes exchange - 20MW bid
Figure 18: Str 2 - 15 minutes exchange - 50MW bid
A) Perfect information.
1) The simulation without any packet loss is presented in Figure 19a. As expected, since there is perfect information, there is only random error, as shown in Figures 19b and 19c. The evaluation process gives: 0.006% < 1%.
2) Now a packet loss 10% is assumed and the results are presented in Figures 20a, 20b and 20c. The evaluation process gives: 0.02% < 1%.
3) Finally, the following scenario assumes 50% packet loss. Figures 21a, 21b and 21c show the results. The evaluation process gives: 0.38% < 1%.

Comparing the two strategies, it is clear that the second concept is not affected by the packet loss. This is explained from the fact that the feedback loop recalculates the signal, based on the aggregated response of the previous time step. Thus only a small change in control power is usually needed from the previous time step to the current step. Therefore the packet loss does not have a big impact and the error is reduced. The effect is present only when the system is reset, so the aggregated response of the previous time step is considered zero. In this case, the same explanation as that of the first strategy’s is valid. That is, due to the packet loss only a reduced amount of vehicles are receiving the signal, which is calculated based on the complete amount of vehicles in the groups, therefore there is a reduced response.

B) Information exchange every 15 minutes.
1) Simulation without any packet loss (Figures 22a, 22b and 22c). The evaluation process gives: 0.06% < 1%.
2) Now packet loss 10% is assumed (Figures 23a, 23b and 23c). The evaluation process gives: 0.02% < 1%.
3) Finally, the following scenario assumes 50% packet loss and the results are shown in Figures 24a, 24b and 24c. The evaluation process gives: 0.41% < 1%.

From the simulation results it is clear that the packet loss affects the response only at the time steps where the system is reset, therefore the aggregated response of the previous time step is zero. Otherwise, even 50% packet loss has minimum impact on the response due to the recalculation of the signal every time step.
4 SIMULATION RESULTS - DISCUSSION

(a) Str 2 - Perfect information, no packet loss: aggregate response and error

(b) Str 2 - Perfect information, no packet loss: random error

(c) Str 2 - Perfect information, no packet loss: grouping error

Figure 19: Str 2 - Perfect information, no packet loss
4 SIMULATION RESULTS - DISCUSSION

(a) Str 2 - Perfect information, 10% packet loss bid: aggregate response and error

(b) Str 2 - Perfect information, 10% packet loss: random error

(c) Str 2 - Perfect information, 10% packet loss: grouping error

Figure 20: Str 2 - Perfect information, 10% packet loss
4 SIMULATION RESULTS - DISCUSSION

(a) Str 2 - Perfect information, 50% packet loss: aggregate response and error

Figure 21: Str 2 - Perfect information, 50% packet loss

(b) Str 2 - Perfect information, 50% packet loss: random error

(c) Str 2 - Perfect information, 50% packet loss: grouping error
4 SIMULATION RESULTS - DISCUSSION

(a) Str 2 - 15-minute update, no packet loss: aggregate response and error

(b) Str 2 - 15-minute update, no packet loss: random error

(c) Str 2 - 15-minute update, no packet loss: grouping error

Figure 22: Str 2 - 15-minute update, no packet loss
4 SIMULATION RESULTS - DISCUSSION

(a) Str 2 - 15-minute update, 10% packet loss bid: aggregate response and error

(b) Str 2 - 15-minute update, 10% packet loss: random error

(c) Str 2 - 15-minute update, 10% packet loss: grouping error

Figure 23: Str 2 - 15-minute update, 10% packet loss
4 SIMULATION RESULTS - DISCUSSION

(a) Str 2 - 15-minute update, 50% packet loss: aggregate response and error

(b) Str 2 - 15-minute update, 50% packet loss: random error

(c) Str 2 - 15-minute update, 50% packet loss: grouping error

Figure 24: Str 2 - 15-minute update, 50% packet loss
4.4 Overview of the results

Table 3 presents the evaluation results of the two control concepts for the different scenarios that were examined:

Table 3: Simulation results overview

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Strategy 1</th>
<th>Strategy 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test signal</td>
<td>0.15%</td>
<td>0.15%</td>
</tr>
<tr>
<td>Perfect knowledge 20 MW</td>
<td>0.26%</td>
<td>0.02%</td>
</tr>
<tr>
<td>15-min update 20 MW</td>
<td>0.68%</td>
<td>0.10%</td>
</tr>
<tr>
<td>15-min update 50 MW</td>
<td>0.63%</td>
<td>0.11%</td>
</tr>
<tr>
<td>Perfect knowledge, 0% packet loss</td>
<td>0.18%</td>
<td>0.006%</td>
</tr>
<tr>
<td>Perfect knowledge, 10% packet loss</td>
<td>2.11%</td>
<td>0.02%</td>
</tr>
<tr>
<td>Perfect knowledge, 50% packet loss</td>
<td>19.5%</td>
<td>0.38%</td>
</tr>
<tr>
<td>15-min update, 0% packet loss</td>
<td>-</td>
<td>0.06%</td>
</tr>
<tr>
<td>15-min update, 10% packet loss</td>
<td>-</td>
<td>0.02%</td>
</tr>
<tr>
<td>15-min update, 50% packet loss</td>
<td>-</td>
<td>0.41%</td>
</tr>
</tbody>
</table>

Figure 25 presents the number of vehicles in each group over the day according to the planned charging profile, while Figure 26 shows the grouping situation each hour after the provision of 20 MW LFC with the second control strategy (information is updated every 15 minutes).

Figure 25: Grouping over the day based on the planned charging
5 Conclusion and Outlook

This semester thesis focused on the development of an indirect control approach for the provision of load frequency control (LFC) by a vehicle aggregator. Two concepts were presented and were implemented in Matlab environment. Both concepts are based on the following features:

I A grouping process places the electric vehicles in groups according to constraints that ensure a satisfactory end-use by the vehicle owner.

II The broadcasted signal is a probability signal that is calculated based on the amount of vehicles in each group and on the LFC signal that is transmitted by the TSO to the aggregator.

III The vehicle in a group that is able to respond, chooses whether it will respond or not according to the output of a success/failure experiment, with probability of response equal to the broadcasted signal.

IV The aggregator measures the aggregated response.

Additionally, in the second concept, a feedback loop recalculates the broadcasted signal depending on the aggregated response of the previous time step and therefore only the difference in the requested control power between two consecutive control steps need to be covered. Thus the error is reduced.

The evaluation procedure that is used to confirm the concepts is the one required by the Swiss TSO for the provision of LFC from generating units. Simulation scenarios were examined for the tracking of the prequalification test signal and also for the tracking of a real-time signal. The results show...
that both concepts, in all cases, pass the requirement that it is set by Swiss-grid. The performance of the second concept is better than that of the first one, due to error reduction as a result of the feedback loop.

Furthermore, the effect of packet loss on the performance was examined. The output of the first concept is greatly affected from the packet loss, where even 10% loss is leading to unsuccessful tracking of a signal. On the other hand, the second concept is robust and it is not significantly affected by the packet loss even assuming a 50% loss.

Finally, a further improvement to the concepts presented in this thesis can be the design of an estimator for the calculation of the amount of vehicles that remains in each group after the completion of each time step.
References


