# Optimal EV Charge Scheduling Considering FCR Participation and Battery Degradation

*2023 IEEE International Conference on Energy Technologies for Future Grids*
*Wollongong, Australia, December 3-6, 2023*

# Optimal EV Charge Scheduling Considering FCR Participation and Battery Degradation

Rahmat Khezri, *Senior Member, IEEE*, David Steen, and Le Anh Tuan, *Member, IEEE*
*Department of Electrical Engineering*
*Chalmers University of Technology*
Gothenburg, Sweden
rahmatollah.khezri@chalmers.se, david.steen@chalmers.se, tuan.le@chalmers.se

***Abstract*— Emerging vehicle-to-grid (V2G) technology gives more flexibility to electric vehicles (EVs) for participating in ancillary service markets. This paper presents an optimal charge scheduling model for EVs by considering V2G, frequency containment reserve (FCR), and battery degradation, to investigate the profitability of FCR participation for an individual EV. The model considers the EV owners' preferences for desired energy at the departure times while participating in FCR. The total scheduling cost of the EV is minimized through a mixed integer linear programming (MILP) problem. The outputs of the MILP model are the EV's charge/discharge pattern and the amount of power for each scheduling horizon. It is found that FCR participation is quite profitable for EV owners.**

***Keywords*— *battery degradation, electric vehicle, frequency containment reserve, optimal operation, vehicle-to-grid.***

## NOMENCLATURE

### *A. Abbreviations*

| | |
|---|---|
| DSO | Distribution system operator |
| EV | Electric vehicle |
| FCR | Frequency containment reserve |
| FCR-D | Frequency containment reserve - disturbance operation |
| FCR-N | Frequency containment reserve - normal operation |
| SOC | State-of-charge |
| TSO | Transmission system operator |
| V2G | Vehicle-to-grid |

### *B. Sets*

| | |
|---|---|
| $\mathcal{T}$ | Set of time intervals (simulation horizon) |
| $\Xi$ | Set of decision variables |

### *C. Parameters*

| | |
|---|---|
| $d$ | Day number |
| $D^{range}$ | EV's driving range (km) |
| $\underline{f}/\overline{f}$ | Minimum/maximum frequency bounds for FCR-N (Hz) |
| $\mathcal{H}^{EV}$ | EV's battery capacity (kWh) |
| $\mathcal{O}^{EV}_{min}/\mathcal{O}^{EV}_{max}$ | Minimum/maximum SOC of EV's battery (%) |
| $\mathcal{O}^{EV}_{initial}$ | Initial SOC of EV's battery (%) |
| $\mathcal{O}^{EV}_{des}$ | Desired SOC of EV's battery by the user (%) |
| $P^{EV}_{min}/P^{EV}_{max}$ | Minimum/maximum allowable power of EV (kW) |
| $t$ | Index for time |
| $t_{sF}/t_{eF}$ | Start/end time to participate in FCR (hr) |
| $t_{aH}/t_{dH}$ | Arrival/departure time to/from Home (hr) |
| $t_{aW}/t_{dW}$ | Arrival/departure time to/from Work |
| $V$ | Voltage of battery pack (V) |
| $\pi^{sp}$ | Spot market price of electricity (€/kWh) |
| $\pi^{gu}$ | Grid utilization price (€/kWh) |
| $\pi^{W}$ | Extra fee for EV charging at workplace (€/kWh) |
| $\pi^{bs}$ | Present value of EV's battery (€) |
| $\rho^{agg}$ | EV owner's portion of capacity reimbursement (%) |
| $\eta^{ch}/\eta^{ds}$ | Charge/discharge efficiency of EV's battery (%) |
| $\xi$ | Battery's retained capacity at end-of-life (%) |

### *D. Variables*

| | |
|---|---|
| $P^{\Theta}$ | Power bid of EV based on agreement with aggregator (kW) |
| $D^{p}$ | Trip distance of EV (km) |
| $f$ | Measured frequency (Hz) |
| $F^{ch}$ | Charging cost of EV (€) |
| $F^{dg}$ | Degradation cost of EV's battery (€) |
| $F^{EV}$ | Operation cost of EV (€) |
| $G^{ds}$ | Revenue from discharging EV (€) |
| $G^{FCR}$ | Revenue from FCR participation by EV (€) |
| $\mathcal{K}$ | Temperature (K) |
| $\mathcal{O}^{EV}$ | State of charge of EV's battery (%) |
| $P^{EV}_{ch}/P^{EV}_{ds}$ | Charge/discharge power of EV (kW) |
| $P^{EV}_{req}$ | Requested power during FCR participation (kW) |
| $\mathscr{b}^{ch}/\mathscr{b}^{ds}$ | Binary variables |
| $\pi^{dg}_{x}/\pi^{dg}_{y}$ | Calendar/cycle ageing cost of battery (€/kWh) |
| $\pi^{FCR-N}$ | Capacity reimbursement for FCR participation (€/kWh) |
| $\pi^{reg}$ | Up/down-regulation cost during FCR participation (€/kWh) |
| $\theta_x/\theta_y$ | Calendar/cycle ageing of battery (%) |

## I. INTRODUCTION

Driven by environmental challenges and legislation, as well as the ascending energy cost and descending availability of fossil fuel, electro-mobility is gaining momentum globally. Electric vehicles (EVs) are the most efficient and cleanest way to decarbonize the transport sector. The number of EVs is rapidly increasing in the world by selling more than 120,000 EVs in each week of 2021 which was more than the total year selling in 2012 [1]. Considering such a high number of EVs, it

978-1-6654-7164-0/23/$31.00 ©2023 IEEE

is important to explore new services from EVs for the grid and new value streams for EV owners [2].

Integration of EVs in electricity network can be considered as an opportunity to support the power systems for energy balance. The majority of cars are parked around 95% of the time [3]. This is a great opportunity to develop efficient EV scheduling programs. On the other side, introduction of vehicle-to-grid (V2G) technology for EVs has gained considerable attention to use stored energy of the vehicle for grid support [4]. The core of V2G is having a bidirectional charger to bring the discharging capability to EVs. However, battery degradation should be considered for V2G operation to achieve a cost-efficient EV discharge [5].

Due to long-term availability and V2G technology, EVs can be used for ancillary services in power systems. Frequency containment reserve (FCR) is one of the greatest value ancillary services that can be driven from the EV [6]. FCR has the task of stabilizing the frequency in case of frequency deviations and is fundamental to be able to keep the power balance in the network [7]. It is activated automatically if the frequency changes within the frequency range it is going to support.

Minimizing EV scheduling cost is addressed by some studies. Smart charging of EVs under different electricity tariffs is investigated in [8] without V2G. In [9], a rule-based energy management is developed for smart homes with a fast-charging EV. Optimal scheduling for two cases of unidirectional and V2G is developed in [10] without battery degradation. In [11], an iterative approach is used to optimize the EV scheduling by considering battery degradation. However, EV's participation in FCR markets is not investigated by the existing works. The profitability of FCR participation for individual EVs rather than aggregators should be investigated.

The main contribution of this work is to optimize V2G scheduling for an EV by FCR participation and applying battery degradation cost. The worst-case scenario for FCR participation is identified and two FCR cases, i.e., FCR-N and FCR-D, are examined. The battery degradation cost involves two components of calendar ageing and cycle ageing. The optimal V2G scheduling is formulated as a mixed integer linear programming problem and it is solved for a sample week in winter by considering historical data of electricity price, FCRs capacity reimbursement, and temperature.

## II. Frequency Containment Reserve

There are two different FCR products, namely FCR-N and FCR-D. FCR-N is the frequency reserve used in normal operation. FCR-N is a symmetrical product, that is, refers to up and down regulation with automatic activation for frequency deviation within 49.90 - 50.10 Hz [12]. The capacity included in the bid for FCR-N must stay available to the ancillary service, if there is available capacity on top of that, which is not included in the bid, the EV user may utilize the remaining capacity on the grounds that it does not affect the availability or the activation of the FCR-N capacity. The capacity bids which are procured for FCR-N will be reimbursed by "pay-as-bid" rule at the day-ahead stage, while capacity activation at the delivery stage is priced according to the downregulation and upregulation electricity prices on Nord Pool [12]. The activated capacity for upregulation will be reimbursed by the upregulation price of the market that is at least the day-ahead price. The activated capacity for downregulation is purchased by the downregulation price of the market that is at most equals the day-ahead price [12].

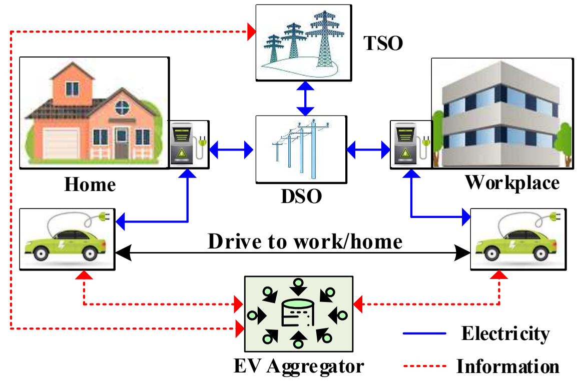

Fig. 1. System configuration for EV connected to the grid.

FCR-D up is one of two frequency holding reserves used in case of disturbance. Since FCR-D is an unsymmetrical product, it has two different markets known as FCR-D up and FCR-D down. In this study, we examine FCR-D up which refers only to upregulation with automatic activation in the frequency range 49.90-49.50 Hz [13]. It is notable that the volume requirement for FCR-D up depends on current dimensioning faults (e.g., a largest generating unit or an interconnection) in the system and can therefore vary during the year. The maximum volume requirement is based on Oskarshamn 3 being in full operation, which then means that the dimensioning fault in the Nordics is 1450 MW [13]. The bids procured for FCR-D will be reimbursed by "pay-as-bid", while there is no reimbursement or cost for activation [13].

## III. EV Charge Scheduling Model

It is assumed that the EV's battery system operator is the EV owner and employs the scheduling model to achieve an economic battery dispatch by energy arbitrage and FCR participation. The EV can be connected to a bidirectional charger as soon as arrives at home or workplace as shown in Fig. 1. The aggregator participates to the ancillary service markets in connection with transmission system operator (TSO). Then, the aggregator transmits the FCR signals with the EV.

### *A. Objective Function*

The EV scheduling model seeks to minimize the battery's operation cost as follows:

$$f = \min_{\Xi} F^{EV} \tag{1}$$

$$F^{EV} = F^{ch} - G^{ds} + F^{dg} - G^{FCR} \tag{2}$$

where $\Xi$ represents the set of decision variables. $F^{ch}$ is the cost of EV's charging, $G^{ds}$ is the revenue from discharging, $F^{dg}$ is the cost of battery ageing, and $G^{FCR}$ is the revenue from EV's participation in FCR.

The charging and discharging costs are divided in two cost terms for home and workplace. The charging cost is calculated based on the charged energy at home and work, spot market price, constant grid utilization cost ($\pi^{gu}$), and extra fee for using charger at work ($\pi^{W}$), as follows:

$$F^{ch} = \sum_{t=t_{eF}}^{t_{dH}} \left( (\pi^{sp}(t) + \pi^{gu})\, P_{ch}^{EV}(t) \right) \Delta t + \sum_{t=t_{aW}}^{t_{dW}} \left( (\pi^{sp}(t) + \pi^{gu} + \pi^{W})\, P_{ch}^{EV}(t) \right) \Delta t \quad (3)$$

The EV's revenue from discharging is calculated by spot market price at home, and spot price minus extra fee at work.

$$G^{ds} = \sum_{t=t_{eF}}^{t_{dH}} \left( \pi^{sp}(t)\, P_{ds}^{EV}(t) \right) \Delta t + \sum_{t=t_{aW}}^{t_{dW}} \left( (\pi^{sp}(t) - \pi^{W})\, P_{ds}^{EV}(t) \right) \Delta t \quad (4)$$

The cost of battery ageing is calculated based on the calendar ageing and cycle ageing costs of the EV at each time slot.

$$F^{dg} = \sum_{t=1}^{\mathcal{T}} \left( \pi_x^{dg}(t) + \pi_y^{dg}(t) \right) \Delta t \quad (5)$$

In this study, two cases of FCR are investigated. In the first case, the revenue of EV for participating in FCR-D is calculated. The revenue for FCR-D consists of one payment term which is the capacity reimbursement ($\pi^{FCR-D}$) according to "pay-as-bid" [13]. The FCR-D capacity is considered as the power bid ($P^{\Theta}$) of the EV. It is assumed that the EV owner only receives a portion of the capacity reimbursement ($\rho^{agg}$) from the aggregator.

$$G^{FCR-D} = \sum_{t=t_{sF}}^{t_{eF}} (\rho^{agg} \times \pi^{FCR-D}(t)\, P^{\Theta})\, \Delta t \quad (6)$$

The revenue from EV's participation in FCR-N includes two terms of payment. The first payment term is capacity reimbursement ($\pi^{FCR-N}$) according to "pay-as-bid". The FCR capacity is considered as the power bid ($P^{\Theta}$) of the EV. Similar to FCR-D, it is assumed that the EV owner only receives a portion of the capacity reimbursement for FCR-N. The second payment term is for the energy compensation which is paid based on up- or down- regulation price.

$$G^{FCR-N} = \sum_{t=t_{sF}}^{t_{eF}} \left( \rho^{agg} \times \pi^{FCR-N}(t)\, P^{\Theta} + \pi^{reg}(t)\, P_{req}^{EV}(t) \right) \Delta t \quad (7)$$

## B. EV Model

The model of EV contains the constraints for charging and discharging of the EV's battery as well as constraints for its state of charge (SOC). The following constraints are considered to avoid EV for charging/discharging at the same interval and also to apply the minimum and maximum power to be charged or discharged.

$$\mathcal{b}^{ch}(t)\, P_{min}^{EV} \leq P_{ch}^{EV}(t) \leq \mathcal{b}^{ch}(t)\, P_{max}^{EV} \quad (8)$$

$$\mathcal{b}^{ds}(t)\, P_{min}^{EV} \leq P_{ds}^{EV}(t) \leq \mathcal{b}^{ds}(t)\, P_{max}^{EV} \quad (9)$$

$$\mathcal{b}^{ch}(t) + \mathcal{b}^{ds}(t) \leq 1 \quad (10)$$

The SOC of EV's battery ($\mathcal{O}^{EV}$) is calculated based on its previous value, charging/discharging power, requested power for FCR, and the trip distance if any. The SOC should not violate its minimum and maximum ranges at any time. The SOC at departure times should be greater than the desired SOC of the EV owner. The SOC at the end of scheduling horizon should be greater than initial SOC of the EV.

$$\mathcal{O}^{EV}(t) = \mathcal{O}^{EV}(t-1) + \eta^{ch} \frac{\left( P_{ch}^{EV}(t) + P_{ch,req}^{EV}(t) \right) \Delta t}{\mathcal{H}^{EV}} - \frac{\left( P_{ds}^{EV}(t) + P_{ds,req}^{EV}(t) \right) \Delta t}{\eta^{ds}\, \mathcal{H}^{EV}} - \frac{D^{p}(t)}{D^{range}} \quad (11)$$

$$\mathcal{O}_{min}^{EV} \leq \mathcal{O}^{EV}(t) \leq \mathcal{O}_{max}^{EV} \quad (12)$$

$$\mathcal{O}^{EV}(t_{dH}) \geq \mathcal{O}_{des}^{EV}, \quad \mathcal{O}^{EV}(t_{dW}) \geq \mathcal{O}_{des}^{EV} \quad (13)$$

$$\mathcal{O}^{EV}(\mathcal{T}) \geq \mathcal{O}_{initial}^{EV} \quad (14)$$

## C. FCR Contribution by EV

This study investigates the worst-case scenario for participation of the EV in FCR market. In the worst-case scenario, the EV needs to participate in the FCR for the whole period with the power bid (maximum power) in downregulation or upregulation. So, the power bid and FCR period can determine the required energy of the EV for participation in the worst-case scenario without any penalty. For example, if the power bid is 5 kW and the FCR period of EV is 6 hours, the available energy of the EV, at the starting time of FCR, should be around 30 kWh to be able to contribute to downregulation with 5 kW for the whole period. Hence, a compromise is required between the power bid, period of participation in FCR, and the SOC of EV at arrival time to home.

$$E_{req}^{max} = \sum_{t=t_{eF}}^{t_{dH}} P^{\Theta}\, \Delta t \quad (15)$$

$$\mathcal{O}_{req}^{EV}(t_{aH}) = \frac{E_{req}^{max}}{E^{EV}} \times 100 \quad (16)$$

In this study, since it is assumed that the EV should not arrive home with less than 50% SOC, starting time for FCR participation ($t_{sF}$) and its end time ($t_{eF}$) are selected as arrival time to home and 12 am.

For the case of FCR-D, it is assumed that all the capacity is activated when the frequency drops below 49.9 Hz. However, for the case of FCR-N, the requested power from EV ($P_{req}^{EV}$) can be calculated based on the measured frequency of the system for each time interval as follows:

$$P_{req}^{EV}(t) = \begin{cases} P^{\Theta}, & if \quad f(t) > \overline{f} \\ \dfrac{2P^{\Theta}.\left(f(t) - \underline{f}\right)}{\overline{f} - \underline{f(t)}} - P^{\Theta} & if \quad \underline{f} \leq f(t) \leq \overline{f} \\ -P^{\Theta} & if \quad f(t) < \underline{f} \end{cases} \tag{17}$$

where $\underline{f}$ and $\overline{f}$ are the minimum and maximum frequencies for FCR-N activation.

### D. Battery Ageing Cost

The calendar and cycle ageing costs of the EV's battery are formulated as follows:

$$\pi_x^{dg}(t) = \frac{\pi^{bs}}{100\% - \xi(\%)} \theta_x(t) \tag{18}$$

$$\pi_y^{dg}(t) = \frac{\pi^{bs}}{100\% - \xi(\%)} \theta_y(t) \tag{19}$$

where $\pi^{bs}$ is the present value of battery value, $\theta_x$ and $\theta_y$ are the calendar and cycle degradations, and $\xi$ is the battery's retained capacity at end-of-life (EOL).

The battery degradation model for calendar and cycle ageing are taken from [14], where a Lithium-Nickel-Manganese-Cobalt oxide (NMC) + Lithium-Manganese oxide (LMO) was experimentally investigated in terms of degradation. The linearized model of the extracted calendar ageing is given by:

$$\theta_x(t) = \mathcal{Q}(t)\, e^{\left(\frac{\mathrm{E_a}}{\mathrm{R}\,\mathcal{K}(t)}\right)} d^{-0.5}\, \Delta t \tag{20}$$

$$\mathcal{Q}(t) = \begin{cases} a_1\, \mathcal{O}^{EV}(t) + a_2 & 0 \leq \mathcal{O}^{EV} \leq 50 \\ \ell_1\, \mathcal{O}^{EV}(t) + \ell_2 & 50 < \mathcal{O}^{EV} \leq 70 \\ c_1\, \mathcal{O}^{EV}(t) + c_2 & 70 < \mathcal{O}^{EV} \leq 100 \end{cases} \tag{21}$$

where $\mathrm{E_a}$ is the activation energy for the reaction in kJ mol$^{-1}$, and R is the universal gas constant in J mol$^{-1}$ K$^{-1}$. $\mathcal{K}$ is the battery's temperature in Kelvin which changes by time. $\mathcal{Q}(t)$ is a function of SOC for three intervals, where $a_1, a_2, \ell_1, \ell_2, c_1$, and $c_2$ are the coefficients for SOC integration in calendar ageing.

The linearized form of the extracted cycle ageing model is given by:

$$\begin{aligned} \theta_y(t) = R(t)\Big(g_1\left(P_{ch}^{EV}(t) + P_{ch,req}^{EV}(t)\right) \\ + g_2\left(P_{ds}^{EV}(t) + P_{ds,req}^{EV}(t)\right) \\ - g_3\Big)\left(\mathscr{b}^{ch}(t) + \mathscr{b}^{ds}(t)\right)\frac{10^3}{V\,\mathcal{H}^{EV}}\,\Delta t \end{aligned} \tag{22}$$

$$R(t) = z_1\, \mathcal{K}^2(t) + z_2\, \mathcal{K}(t) + z_3 \tag{23}$$

where $g_1$, $g_2$, and $g_3$ are the coefficients for cycle ageing model. $R(t)$ is a quadratic function of battery's temperature with $z_1$, $z_2$, and $z_3$ as the coefficients. In this study, since the cycle ageing is assumed due to charge and discharge of battery for energy exchange, the cycle ageing model is multiplied by $\left(\mathscr{b}^{ch}(t) + \mathscr{b}^{ds}(t)\right)$ to not calculate it during storage conditions.

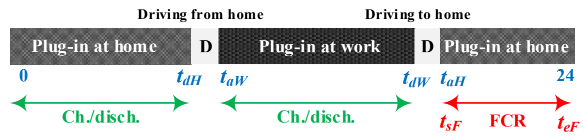


Fig. 2. Timeframe of EV availability and driving.

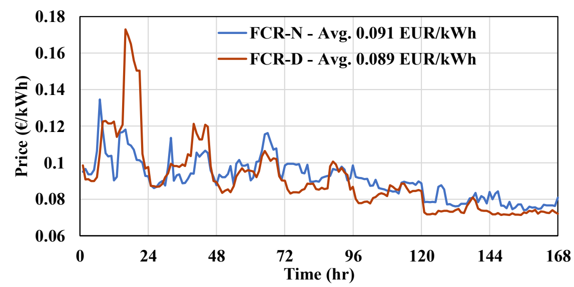


Fig. 3. Capacity reimbursement for FCR-N and FCR-D for a sample week in winter.

TABLE I
CHARACTERISTICS OF THE SYSTEM AND EV

| Characteristic | Value |
|---|---|
| **Grid utilization cost** | 0.083 €/kWh |
| **Fee for charger usage at workplace** | 0.01 €/kWh |
| **Discount rate** | 5% |
| **EV owner's portion for capacity reimbursement ($\rho^{agg}$)** | 80% |
| **Battery capacity** | 64 kWh |
| **Driving range** | 344 km |
| **Energy consumption per km** | 0.186 kWh/km |
| **Charger's power limits** | $P^{min}$ = 0.5 kW, $P^{max}$ = 7 kW |
| **Replacement cost of battery** | €137/kWh |
| **State of charge (SOC)** | $\mathcal{O}_{min}^{EV}$=10%, $\mathcal{O}_{max}^{EV}$=90% |
| **Charge/discharge efficiency** | $\eta^{ch} = \eta^{ds}$ = 93% |
| **Power bid** | 7 kW |
| **Total hours for FCR contribution** | 6 hours |

## IV. CASE STUDY

The developed scheduling model with FCR participation is investigated for a case study in Sweden. For this purpose, the spot market price, FCR-N and FCR-D capacity reimbursement, frequency data, and temperature are collected for a sample winter week in 2021 in Sweden.

Fig. 2 shows the timeframe of the EV availability. Starting from 12 am, the EV is plugged-in at home. Driving from home to work means departing at $t_{dH}$ and arriving to work at $t_{aW}$. The EV will be plugged-in at workplace between $t_{dH}$ and $t_{aW}$ before leaving the work. Then, departing from work at $t_{dW}$ and arriving to home at $t_{aH}$, the EV will be again plugged-in at home for the rest of the day. It is assumed that the EV participates at FCR between 6 pm and 12 am. It is notable that the uncertainties related to departure time, trip distance, and arrival time are generated using stochastic functions as discussed in [15].

The characteristics of the considered system and EV are

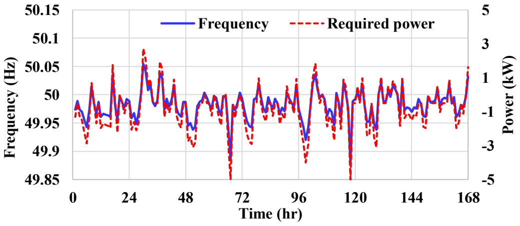


Fig. 4. The measured frequency and associated activated power for EV by considering a power bid of 5 kW.

presented in Table I. It is assumed that the maximum power of the charger is 7 kW where the inverter cannot support less than 0.5 kW as the minimum power.

Fig. 3 shows the capacity reimbursement price for FCR-N and FCR-D in a sample week in winter of 2021. As shown, the average prices for FCR-D and FCR-N, for the selected week, are almost the same. But the peak value for FCR-D is higher than the peak price for FCR-N. Spot market price of electricity for the same week is taken from [16].

Fig. 4 shows the measured/actual frequency and resulted power request (considering 5 kW power limit and equation (17)) for the sample winter week of 2021. Frequency violates 49.9 Hz two times during the considered week which means FCR-D is activated only two times and the whole 5 kW should be discharged for those moments.

## V. Results and Discussions

The developed optimization model is coded in Python software [17] and solved by Gurobi solver [18]. The optimization is solved for three cases for one week scheduling in winter. The examined cases are: FCR-D, FCR-N, and without participation in FCR market. Table II lists the economic results of the optimization for all three cases. As shown in the table, participating in the FCR markets is profitable for the EV owner compared to the case without participation. Of the two FCR markets, the FCR-D has more revenue for the EV owner compared to FCR-N. So, the lowest scheduling cost is achieved for the FCR-D participation. The charging cost of EV is higher for FCR-N due to frequent changes of frequency between 49.9 – 50.1 Hz, and hence more charging request from the EV. The calendar ageing cost is the highest for the FCR-D due to limited activation of charging/discharging for participation. As shown in Fig. 4, there are only two hours during the week that the frequency drops to less than 49.9 Hz. But cycle ageing cost is the highest for the case without FCR participation due to more frequent charging/discharging in this case.

The battery degradation in terms of cycle, calendar, and total ageing is shown in Fig. 5(a) for all three cases. The FCR-D has the lowest cycle ageing due to lower charge/discharge activation. However, the calendar ageing is the highest for FCR-D. Fig. 5(b) shows the total charging energy and discharging energy for all three cases for one week operation. Due to energy arbitrage, the case without FCR has the highest charge and discharge during the week. This is the reason that the highest degradation occurs for the case without FCR as

TABLE II
Economic Results of Different Models for the Winter Week

| Model | Total cost (€) | FCR rev. (€) | Charg. cost (€) | Disch. rev. (€) | Cyc. age. cost (€) | Cal. age. cost (€) |
|---|---|---|---|---|---|---|
| **FCR-D** | -6.59 | 15.87 | 29.76 | 27.51 | 2.13 | 4.89 |
| **FCR-N** | -4.43 | 32.60 | 46.73 | 25.31 | 2.82 | 3.93 |
| **w/o FCR** | 5.38 | - | 55.79 | 57.70 | 3.34 | 3.94 |

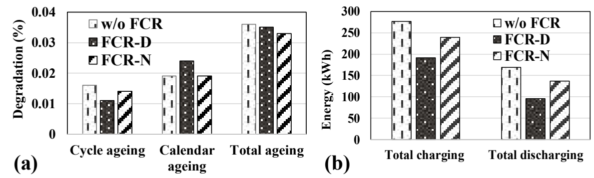


Fig. 5. Comparison of two models in terms of: (a) exchanged energy with the network, and (b) battery degradation.

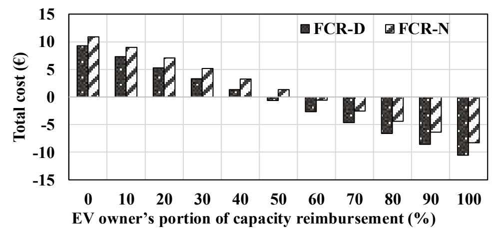


Fig. 6. Effect of EV owner's portion of capacity reimbursement ($\rho^{agg}$) on total cost of EV scheduling.

shown in Fig. 5(a). In total, it can be inferred that FCR participation decreases the battery ageing slightly.

In most of the cases, it is not clear what portion of the capacity reimbursement ($\rho^{agg}$) will be paid to the EV owner by the aggregator. Hence, it is important to investigate the effect of $\rho^{agg}$ on total cost of EV scheduling. In this part, the assumption is that it is considered the EV participates in the FCR no matter it is economic or not. Fig. 6 shows the sensitivity of the total cost of EV scheduling for FCR-N and FCR-D when the EV owner's portion of capacity reimbursement changes between 0% (no payment for FCR participation) and 100% (full payment of capacity reimbursement for FCR participation).

## VI. Preparation for V2G Demonstration

The optimal scheduling model developed in this paper is planned to be demonstrated on a real case study at Chalmers. The demonstration will include the V2G compatible car, an AC wallbox for bidirectional on-board AC charger, an off-board DC bidirectional charger, and internal server for running the optimization algorithm. Fig. 7 shows a schematic of the suggested real-time optimal scheduling of EV in which the decision variables can be updated each 5-min or 15-min.

First, an online platform should be prepared such that the EV owners could enter their departure time, estimated next arrival time, estimated trip distance, desired SOC for the departure, EV's battery capacity, and the battery age. Then, this data along with temperature, spot electricity market price, frequency measures using a frequency measurement device and capacity bids are used as the input data for the optimization

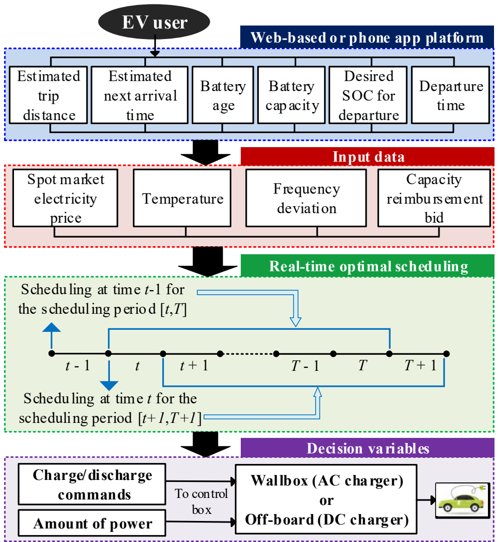


Fig. 7. Schematic of the suggested real-time optimal scheduling of EV in which the decision variables can be updated each 5-min or 15-min.

model. Since the optimization should be run in a real-time system, a rolling-horizon approach must be used to update the decision for each scheduling time. AN important part is the communication protocol for the connections between bidirectional charger and EV, and charger with the optimization server. Finally, the obtained decision variables (i.e., charge/discharge commands and amount of power) will be sent to the control box which can be wallbox for AC charger or an off-board DC charger.

## VII. Conclusion

This study developed an optimal EV scheduling model by participating the vehicle in the FCR markets. Two cases of participation to FCR-N and FCR-D were analysed and compared with the case without FCR participation. As the worst-case scenario, it was assumed that the EV can only participate to FCR for 6 hours which was considered between 6 pm and 12 am. The results showed that participating in FCR reduces the scheduling cost by around €10 for a week. On the other hand, the FCR-D case is more profitable than FCR-N.

As an important conclusion, if the FCR participation is not optimized, like what we did in this study, FCR-D can be more beneficial for the EV owner. However, if the service provision is optimized, the EV may earn more money by participating in FCR-N due to activation payment on top of the capacity reimbursement.

## Acknowledgment

The work presented in this paper is financially supported by the following projects: i) V2X-MAS – received funding from Swedish Energy Agency (Project ID 51811-1) and ii) FLEXI-GRID - received funding from the European Community's Horizon 2020 Framework Programme under Grant Agreement No. 864048.

## References

[1] International Energy Agency, "Global EV Outlook 2022," [Online]. Available: https://www.iea.org/data-and-statistics/data-product/global-ev-outlook-2022 , Accessed on: Feb. 2023.

[2] R. Khezri, and A. Mahmoudi, "Optimal energy management strategies for integrating renewable sources and EVs into microgrids," Chapter 9, in Cable Based and Wireless Charging Systems for Electric Vehicles, by R. Singh, et al., IET, UK, 2021, pp. 245–265.

[3] D. Kondor, H. Zhang, R. Tachet, P. Santi and C. Ratti, "Estimating Savings in Parking Demand Using Shared Vehicles for Home–Work Commuting," *IEEE Trans. Intelligent Transportation Systems*, vol. 20, no. 8, pp. 2903-2912, Aug. 2019.

[4] R. Khezri, D. Steen and L. A. Tuan, "Vehicle to Everything (V2X) - A Survey on Standards and Operational Strategies," 2022 *IEEE International Conference on Environment and Electrical Engineering (EEEIC / I&CPS Europe)*, Prague, Czech Republic, 2022, pp. 1-6.

[5] R. Khezri, D. Steen and L. A. Tuan, "A Review on Implementation of Vehicle to Everything (V2X): Benefits, Barriers and Measures," *IEEE PES ISGT Europe 2023*, Novi Sad, Serbia 2022, pp. 1-6.

[6] A. Thingvad, C. Ziras, G. L. Ray, J. Engelhardt, R. R. Mosbæk and M. Marinelli, "Economic Value of Multi-Market Bidding in Nordic Frequency Markets," *International Conference on Renewable Energies and Smart Technologies (REST)*, Tirana, Albania, 2022, pp. 1-5.

[7] A. Khodadadi, L. Herre, P. Shinde, R. Eriksson, L. Söder and M. Amelin, "Nordic Balancing Markets: Overview of Market Rules," 2020 17th *International Conference on the European Energy Market (EEM)*, Stockholm, Sweden, 2020, pp. 1-6.

[8] D. Steen, M. Persson, and A. T. Le, "Smart charging of EVS under different grid tariff structures," *In CIRED Porto Workshop* 2022: E-mobility and power distribution systems (Vol. 2022, pp. 1089-1093). IET, June 2022.

[9] R. Khezri, P. Razmi, A. Mahmoudi, A. Bidram and M. H. Khooban, "Machine Learning-Based Sizing of a Renewable-Battery System for Grid-Connected Homes With Fast-Charging Electric Vehicle," *IEEE Trans. Sustainable Energy*, vol. 14, no. 2, pp. 837-848, April 2023.

[10] H. Turker and S. Bacha, "Optimal Minimization of Plug-In Electric Vehicle Charging Cost with Vehicle-to-Home and Vehicle-to-Grid Concepts," *IEEE Trans. Vehicular Technology*, vol. 67, no. 11, pp. 10281-10292, Nov. 2018.

[11] M. Ebrahimi, M. Rastegar, M. Mohammadi, A. Palomino and M. Parvania, "Stochastic Charging Optimization of V2G-Capable PEVs: A Comprehensive Model for Battery Aging and Customer Service Quality," *IEEE Trans. Transp. Electrif.*, vol. 6, no. 3, pp. 1026-1034, Sept. 2020.

[12] SVENSKA KRAFTNÄT, Frekvenshållningsreserv normaldrift (FCR-N), [Online]. Available: FCR-N | Svenska kraftnät (svk.se)

[13] SVENSKA KRAFTNÄT, Frekvenshållningsreserv störning uppreglering (FCR-D up), [Online]. Available: https://www.svk.se/aktorsportalen/bidra-med-reserver/om-olika-reserver/fcr-d-upp/

[14] J. Wang et al., "Degradation of lithium-ion batteries employing graphite negatives and nickel–cobalt–manganese oxide+ spinel manganese oxide positives: Part 1, Aging mechanisms and life estimation," *J. Power Sources,* vol. 269, pp. 937–948, Dec. 2014.

[15] R. Khezri, A. Mahmoudi and M. Haque, "Impact of Optimal Sizing of Wind Turbine and Battery Energy Storage for a Grid-Connected Household With/Without an Electric Vehicle," *IEEE Trans. Industrial Informatics*, vol. 18, no. 9, pp. 5838-5848, Sept. 2022.

[16] Nord Pool. Accessed: Nov. 20, 2022. [Online]. Available: https://www.nordpoolgroup.com/

[17] W. E. Hart, C. Laird, J.-P. Watson, and D. L. Woodruff, Pyomo—Optimization Modeling in Python, vol. 67, 2nd ed. New York, NY, USA: Springer, 2017.

[18] Gurobi Optimization, LLC, "Gurobi optimizer reference manual," 2018. [Online]. Available: http://www.gurobi.com