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INTEGRATION OF ELECTRIC VEHICLES INTO SMART GRIDS WITH OPTIMAL DECENTRALIZED CHARGING CONTROL

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ABSTRACT

Shifting charging load to off-peak periods is often referred to as valley-filling. This paper studies decentralized methods for solving the valley-filling problem within a DR Aggregator portfolio. It first develops a decentralized utility maximization algorithm based on dynamic pricing and real-time welfare maximization to demonstrate that when using dynamic pricing, the use of concave utility functions is non-relevant. Besides, it shows that the optimal control architecture designed by decentralization can advantageously be adapted to the concept of charging flexibility, leading to simulation results showing significant Peak-Valley Difference reduction with minimal charging cost, without jeopardizing the final State of Charge. The proposed procedure requires no communication between vehicles, and ensures full charging to the level required by the user. It offers a minimal amount of centralized computation that does not suffer from curse of dimensionality as no vehicle specific information is required at the central level.

1 INTRODUCTION

Plug-in Electric Vehicles (PEVs) and Hybrids (PHEVs) have been widely recognized as an essential part of a more sustainable mobility and smarter urbanism. However, it has been shown that uncontrolled charging together with a high penetration rate might not only be harmful for the distribution network, but also represents a major threat for energy security. Indeed, because of the time-correlation between intense charging demand and the existing peak load, charging a large number of PEVs/PHEVs can introduce a significant additional load at an inappropriate time, and hence hazardously exceed the existing power grid capacities. Without considerable investments in grid assets reinforcement, this could lead to unacceptable voltage and frequency domain, phase unbalance or even energy shortage [1]. Moreover, on a larger scale, supplying such an increased peak demand might represent an additional cost or exceed the production capacities, for example 30% of PHEV penetration in the US market would account for a charging load around 140GW, representing 18% of US summer peak load [2]. Hopefully, the rise of ICT for grid application ("Smart Grids" technologies) such as advanced metering or grid monitoring and control infrastructures have brought new opportunities for grid management. Efficient integration of Electric Vehicles in the energy system has been the subject of many recent studies and it has been proved that a smarter charging can not only save irrelevant grid investment but also provide ancillary services. Indeed, first research efforts have been put in bidirectional interactions (Vehicle to Grid, V2G) [3], as EV batteries represent a very suitable source for regulation service such as peak shaving, spinning reserve, voltage and frequency regulation etc. V2G interactions have been subject to remarkable standardization efforts in Europe, leading in particular to ISO/IEC 15118 standard. However, V2G transactions, besides requiring advanced bidirectional power converters, seem to substantially affect the battery lifetime, mainly because of an increased charging/discharging cycle frequency, with prolonged and deeper discharging [4]. On the other hand, it has been proved that good performances in terms of flexibilities and grid capacity optimization can be reached with unilateral charging control, shifting the charging load to off-peak periods, when more network capacity is available [5]. This is commonly referred to as 'valley filling'. Within this load leveling approach, Centralized control strategies have first been investigated, but faced a curse of dimensions with exploding numbers of control variables when applied to realistic fleets. In this context, specific research directions received increasing interest: methods for vehicle clustering were suggested [6], various decentralized optimization have been studied [7]–[9], and finally distributed control within multi agent systems (MAS) were investigated [10]. Soon the need for an entity to coordinate the operations in between electric vehicles (EV) and with other actors of the energy market such as the Transmission and Distribution System Operators (TSO/DSO) has emerged. Considering the existence of EV aggregators even enabled the concept of virtual power plants (VPP), which could cluster and control all the electric vehicles under its responsibility as a single load or source, distributed over a given area [6]. In decentralized architectures, a control signal need to be broadcasted, hence, following advances in Demand Response (DR) management, price incentives and dynamic pricing have been widely used [2]. Following these considerations, welfare maximization methods using concave utility function developed [7], [11]–[13]. Finally, studies have shown that EV charging, when controlled dynamically, brings a partially flexible load that can palliate the intermittency of Renewable Energy Sources (RES), as summarized in [4].

In this paper, we aim to address valley-filling for a DR Aggregator portfolio with welfare maximization and distributed optimal charging control. We first define in part II an architecture for the power-system, a PEV fleet usage model, a user utility function and a pricing model. In part III we formulate the decentralized welfare maximization algorithm before studying its convergence and stating a solvability condition for the valley-filling problem. We then bring modifications to the model and define the new decentralized optimization, before assessing the final performances in part IV.

2 SYSTEM MODEL

2.1 Power system architecture

We consider a Demand Response Aggregator (DR Aggregator) that manages a retail market portfolio composed of conventional load (residential and small industrials) and a set of Electric Vehicles Charging Stations, as described in Figure 1.

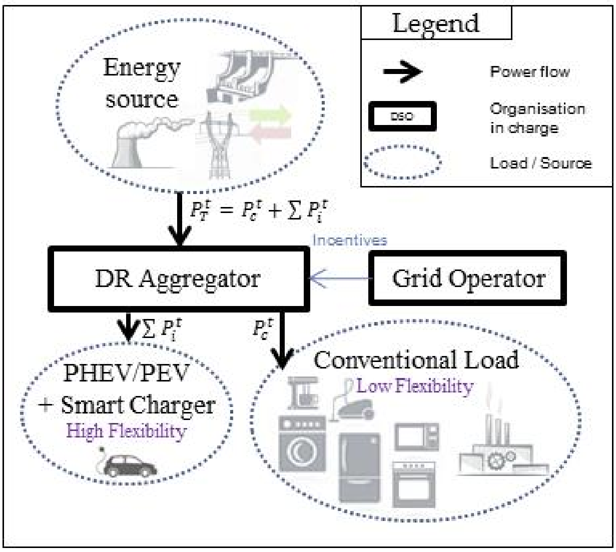

Figure 1: *Simplified Power system architecture.*

The time of operations is discretized into time slots $t \in \mathcal{T}$ of equal length Δt. The architecture we model comprises:

- An energy source that can be either a couple of generators owned by the Aggregator, an Energy Provider Utility, or energy traded on the wholesale market (eventually through a third party pooling company), or a combination of the three.

- A Demand Response (DR) Aggregator whose portfolio consists in: a) A set of conventional load made of subscribers such as Small and Medium Enterprises (SMEs) and residential customers. For each day d, the total load profile of the conventional subscriptions is denoted by the set $\{p_c^t\}_{t\in\mathcal{T}}$. We assume that the DR Aggregator portfolio benefits from smart meters infrastructure and a sufficient communication infrastructure so that the conventional load profile $\{p_c^t\}_{t\in\mathcal{T}}$ can be accurately estimated in "real time", i.e. on an intraday basis with a time resolution Δt b) A set of N PHEV & PEVs. Each EV $i \in \mathcal{N}$ goes along with a charging station that integrates an EV Charging Controller (EVCC) as part of the EV Supply Equipment (EVSE), which aims at controlling the real-time charging rate. We assume the charging power to be unidirectional and consider only Grid to Vehicles (G2V) power flows. For each day d, the total load profile of the Portfolio's electric vehicle fleet is denoted by the set $\{p_{ev}^t\}_{t\in\mathcal{T}}$, while the total load profile of all subscription (conventional and EV load) is denoted by the set $\{p_T^t\}_{t\in\mathcal{T}}$. As for the conventional load, we assume that the DR Aggregator have sufficient information to track the total EV consumption on an intraday basis, with time resolution Δt.We also assume that upon arrival each EV user inform the smart charger of its departure time t_d and expected final state of charge SoC_i^{ex}.
- A Grid operator that can be a TSO or a DSO depending on the type of Portfolio managed. The Grid operator encourages the DR Aggregator to co-operate in the reduction of the Peak-Valley Difference (PVD) by providing, monetary incentives I_d calculated proportionally to the reduction of PVD for each day d:

  $$I_d = \lambda_d \cdot [PVD_C - PVD_T]^+ \quad (1)$$

  where λ_d is the incentive factor (in €cts/kW), PVD_C is the original Peak-Valley Difference, i.e. that of the conventional load profile $\{p_c^t\}_{t\in\mathcal{T}}$, and PVD_T is the ultimate PVD, i.e. that of the total load profile $\{p_T^t\}_{t\in\mathcal{T}}$. The notation $[\cdot]^+$ denote the projection on $\mathbb{R}^+$

Because we focus on the flexibility of EV charging and the efficiency of a charging management in reducing charging costs while compensating for conventional load fluctuations, we will not deal with demand side management for the conventional load.

Note that the physical consistence and geographical location of the DR Aggregator's portfolio considered here is voluntarily not defined for universality. Concretely, such portfolio can be located within a distribution network, laying downstream a primary substation, or a more complex location such as suggested in the web-of-cells concept [14]. A strictly commercial portfolio, such as the Equilibrium Responsible Entity in France, can also be envisaged.

2.2 PEV fleet model

Based upon statistical studies regarding private vehicles' weekdays commutes [15]-[17] we model the probability density functions for the arrival time, departure time and distance travelled per day as follows:

$$f_a(x) = \begin{cases} \frac{1}{\sqrt{2\pi}\cdot\sigma_a} exp\left(-\frac{(x+24-\mu_a)^2}{2\sigma_a^2}\right) & 0 < x \le \mu_a - 12 \\ \frac{1}{\sqrt{2\pi}\cdot\sigma_a} exp\left(-\frac{(x-\mu_s)^2}{2\sigma_a^2}\right) & \mu_a - 12 < x \le 24 \end{cases} \quad (2)$$

with $\mu_a = 17.47$ and $\sigma_a = 3.41$ the arrival time's expectation and standard deviation.

$$f_d(x) = \begin{cases} \frac{1}{\sqrt{2\pi}\cdot\sigma_d} exp\left(-\frac{(x-\mu_d)^2}{2\sigma_d^2}\right) & 0 < x \le \mu_d + 12 \\ \frac{1}{\sqrt{2\pi}\cdot\sigma_d} exp\left(-\frac{(x-24-\mu_d)^2}{2\sigma_d^2}\right) & \mu_d + 12 < x \le 24 \end{cases} \quad (3)$$

with $\mu_d = 8.92$ and $\sigma_d = 3.24$ the departure time's expectation and standard deviation.

$$f_m(x) = \frac{1}{\sqrt{2\pi}\cdot\sigma_m\cdot x} \exp\left(-\frac{(lnx-\mu_m)^2}{2\sigma_m^2}\right) \quad (4)$$

with $\mu_m = 2.98$ miles and $\sigma_m = 1.14$ the expectation and standard deviation of the distance travelled per day.

Assuming that every vehicle leaves the charging station at time $t_d$with a State of Charge $SoC_i^{t_d}$, we express the initial State of Charge $SoC_i^{t_a}$ of vehicle i upon arrival at time t_a as follows:

$$SoC_i^{t_a} = SoC_i^{t_d} - d_i \cdot \frac{E^{100km}}{100\cdot q_i} \quad (5)$$

where $d_i = 1.60934 \cdot m_i$ is the distance travelled during the daily commute of vehicle i in kilometers, m_i being the travelled distance in miles, obtained stochastically in accordance with distribution (4); $E^{100km} = 20kWh/100km$ is the average energy consumption per 100km observed on a sample of commercial PEVs [18]; q_i is the total battery capacity available on vehicle i (in kWh).

2.3 EV User Satisfaction and Utility function

2.3.1 *Concept of satisfaction applied to EV charging*

In order to further control the charging behavior of each user in response to real-time prices and control signal, we define their utility function, a concept originated from microeconomics [19] that has been applied to power consumption [13], ,[20],

[21] and to EV charging management [5], [22]-[24]. The concept of utility can be seen equivalently as the user's benefit of charging, i.e. its level of satisfaction as a function of the battery State of Charge. Although utility function has been modeled as a function of the cost of charging [2], utility is not necessarily linked to the monetary returns [24]. Moreover, utility and monetary scales might differ from each other [25]. Hence, we assume that for each user i, the utility function $U(\cdot)$ is independent from the electricity price and from the cost of charging.

Property 1: Utility functions for power consumption and EV charging are positive, continuous, non-decreasing and concave functions of the State of Charge [13], [23], that is:

$$\begin{cases} U(SoC) \geq 0 \\ \dfrac{\partial U(SoC)}{\partial SoC} \geq 0 \\ \dfrac{\partial^2 U(SoC)}{\partial SoC^2} \leq 0 \end{cases} \tag{6}$$

with $SoC = SoC^{t_d} - SoC^{t_a}$ the total State of Charge acquired throughout charging. In particular, concavity expresses the fact that satisfaction gets gradually saturated as the state of charge increases.

Property 2: For each EV_i, an empty battery brings neither satisfaction nor dissatisfaction to $user_i$:

$$U(0) = 0 \tag{7}$$

Note that (7) rejects from our modelization non-Lyapunov functions such as logarithm-alike utility functions: $U(x) = \omega\left(SoC^{\beta} - 1\right)/\beta$, $\beta < 1$ (giving the log function for $\beta = 0$), whom have benefited from recent popularity in the internet congestion control [26], [27] or in its extension to the PHEV/PEV demand management [28].

2.3.2 *Expression of the Utility function*

Among the wide class of functions eligible to (6) and (7), positive logarithm functions of the form $U(x) = \omega * log(1 + x)$ as used in [11], [29] are eligible solutions. However, quadratic utility functions have recently proven good accuracy and simplicity in transcribing the behavior of power consumers [5], [13], [20], [21], [30], [31]. With very slight dissonances, all these publications modelize satisfaction of a user i as a function of the overall state of charge acquired SoC. We model the utility of a user i given his battery State of Charge SoC_i as follows:

$$U_i(SoC_i) = K_u \cdot \omega_i \cdot Q_i \cdot \left(SoC_i - \frac{\alpha}{2} \cdot SoC_i^2\right) \tag{8}$$

Where K_u is a uniform scaling factor[1], $\alpha \in [0,1]$ is a uniform shape factor and ω_i is a user specific parameter that can be seen as the typical willingness to pay, a concept emerged from the congestion pricing in communication networks [26]; Q_i is the declared battery capacity defined as:

$$Q_i = q_i \cdot SoC_i^{ex} \tag{9}$$

with q_i the total battery capacity available on vehicle i and SoC_i^{ex} the expected state of charge declared by user i upon arrival.

2.3.3 *Expression of the Marginal Utility*

For real-time charging control, we might need to evaluate the marginal utility for a given SoC. Hence, we want to modelize how much additional satisfaction ΔU an elevation ΔSoC of the energy stocked will bring to the user, given that the battery is already charged with a ratio SoC_i^t. It is easy to verify from (8) that the marginal utility at a time slot t for user i given its current State of Charge SoC_i^t, can be expressed as:

$$\begin{aligned} \Delta U_{i|SoC_i^t}(\Delta SoC_i) &= U\left(SoC_i^t + \Delta SoC_i\right) - U\left(SoC_i^t\right) \\ &= K_u \cdot \omega_i \cdot Q_i \left(\left(1 - \alpha \cdot SoC_i^t\right) \cdot \Delta SoC_i - \frac{\alpha}{2} \cdot \Delta SoC_i^2\right) \end{aligned} \tag{10}$$

Note that this expression corresponds to the 2nd order Taylor series of U at a point $SoC_i^t \geq 0$. For commodity, we define the amount of energy $P_i^t = \Delta t \cdot p_i^t$ that corresponds to the charging of a vehicle i with a power p_i^t (in kW), constant during the whole time slot t. For brevity we assume the battery charging process to be linear, thus the incremental State of Charge gained during time slot t can be written as:

$$\Delta SoC_i = \frac{P_i^t}{Q_i} \tag{11}$$

We finally define the Real-Time Willingness to Pay, also referred to as *Price Trigger* [7], [9], [32], [33] as the non-weighted derivative of the marginal utility function with respect to the current charging ratio C_i^t :

$$w_i^t = \frac{1}{K_u \cdot \omega_i \cdot Q_i} \cdot \frac{dU_i\left(SoC_i^t\right)}{dSoC_i^t} = 1 - \alpha \cdot SoC_i^t \tag{12}$$

Thereby, we get the following expression of the marginal utility given its real-time price trigger w_i^t:

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[1] As mentioned in [5], [19], [24] the utility has no unit and its scale often differs from the monetary scale. Thus, as we need to compare this utility with price signals, a scaling factor is required. Further assumptions will determine how to fix this constant.

$$\Delta U_{i_{|w_i^t}}(P_i^t) = K_u \cdot \omega_i \cdot Q_i \left(w_i^t \cdot \frac{P_i^t}{Q_i} \cdot - \frac{\alpha}{2} \cdot \left(\frac{P_i^t}{Q_i} \cdot \right)^2 \right) \quad (13)$$

Where Q_i is the declared battery capacity of vehicle i, and Δt is the length of time slots. Fig. 2 shows a sample of this marginal utility function for different values of the price trigger w_i^t.

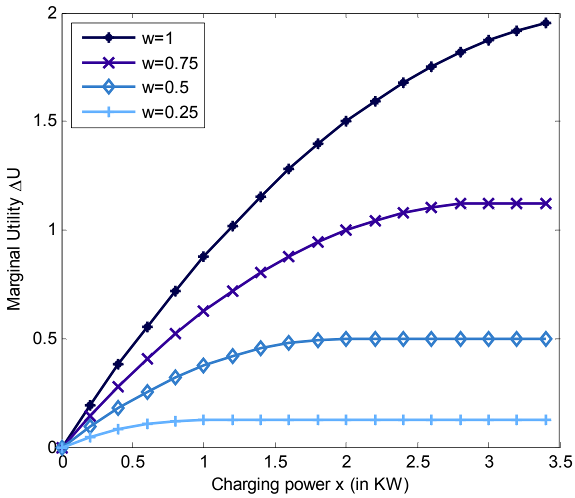

Figure 2: *Sample of Utility functions for different trigger w (α=0.25).*

2.4 Electricity Retailing Cost and pricing policy for Smart Charging

For each time slot t, we attempt to model the real-time cost $C_{|P_c^t}(L_{ev}^t)$ of providing an amount L_{ev}^t of energy to the EV fleet, given the conventional load P_c^t. In order to be able to formulate the optimization problem, we use an approximate model for the cost of electricity (even though we will later use the wholesale market price as a cost reference).

2.4.1 *Electricity Retailing Cost approximation*

We intend to adopt a model for the cost of retailing electricity that would depend on a limited number of local parameters and encompass both procurement and delivery cost. To do so, we consider congestion pricing, a concept emerged from the Internet traffic control [34] that has been used in demand side management [28], [35], [36] for its consistency with the quadratic behavior of the procurement and delivery costs, and with the notion of subscribed power. Thus, we assume that the cost incurred by the DR Aggregator is composed of a constant component and an increasing, strictly convex, quadratic function of the total power retailed L:

$$C(L) = c + a \cdot \left(\frac{L}{P_l}\right)^2 \\ with\ a = \rho \cdot (1+\tau) \cdot P_l \tag{14}$$

where ρ is a marginal price that can be based on Futures Exchange market es[2],.τ is the estimated delivery marginal cost rate, c is a flat fee constant, and P_l is the power limit that might depend on the subscribed power regarding procurement and delivery. Note that this power limit can also represent the local grid capacity if the DR Aggregator has the exclusivity on the network, as in [29].

2.4.2 *Marginal Electricity retailing Cost*

Under the architecture described in 2.1, the power withdrawn corresponds to the sum of the conventional load and the EV load. Hence, writing down the power series of C from (14), it is easy to verify that the locational marginal price for the EV load L_{ev}^t, given a conventional load P_c^t can be expressed as follows:

$$\begin{aligned} C_{|P_c^t}(L_{ev}^t) &= C(L_{ev}^t + P_c^t) - C(P_c^t) \\ &= \frac{a}{P_l^2}\left(2 \cdot P_c^t \cdot L_{ev}^t + {L_{ev}^t}^2\right) \end{aligned} \tag{15}$$

3 DECENTRALIZED OPTIMIZATION PROBLEM

We now formulate the optimization problem based upon the architecture and models already described. We then propose a decentralized solution before studying its convergence and suggesting modifications to the utility function model.

3.1 Optimization Problem

We formulate our optimization problem based on a dual objective: on a 'real-time' basis (intraday) we aim at maximizing the system welfare while respecting the energy resource constraint, and on a 'day-to-day' basis, we aim at maximizing the incentives revenue while satisfying the user SoC requests.

3.1.1 *Intraday Welfare Maximization problem*

On an individual point of view, for each time slot t, each smart charger determines its charging power P_i^t in order to maximize the individual welfare W of its user:

$$\underset{0 \le P_i^t \le P_i^{\max}}{\textbf{maximize}}\ W(P_i^t) = \Delta U_i(P_i^t) - r^t \cdot P_i^t \tag{16}$$

where r^t is the energy price (in €cts/kWh) at time slot t.

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[2] As is the avoided cost used for Renewable Energies compensations in the context of Feed-in Tariffs (FiT) policies[43]

While on the system point of view, we need to maximize for each time slot t the difference between the sums of the additional utility functions $\Delta U_i\left(P_i^t\right)$ and the additional cost $C_{|P_c^t}(L_{ev}^t)$ of providing the generation capacity L_{ev}^t (that powers the charging). Note that the coherence between the generation capacity and the real-time demand is then to be imposed as a constraint.

Hence, for each time slot t, we formulate the efficiently optimal charging and pricing strategy as the solution to the following problem:

$$\begin{gathered}\underset{0\leq P_i^t\leq P_i^{max},L_{min}\leq L_{ev}^t\leq L_{max}}{\textbf{maximize}} \sum_{i\in\mathcal{N}} \Delta U_i\left(P_i^t\right) - C_{|P_c^t}(L_{ev}^t) \\ \textbf{such that} \sum_{i\in\mathcal{N}} P_i^t \leq L_{ev}^t\end{gathered} \tag{17}$$

Problem (17) is convex and can be solved in a distributed way by using the Lagrange Relaxation [37], defining the Lagragian as:

$$\mathcal{L}\left(P_i^t, L_{ev}^t, \lambda^t\right) = \sum_{i\in\mathcal{N}} \Delta U_i\left(P_i^t\right) - C_{|P_c^t}(L_{ev}^t) - \lambda^t\left(\sum_{i\in\mathcal{N}} P_i^t - L_{ev}^t\right) \tag{18}$$

where λ^t is the Lagrange multiplier for time slot t.

By grouping the terms depending on whether they are to be summed up for all EVs i we obtain the following dual optimization problem, equivalent to the maximization of the Lagrangian:

$$\underset{\lambda^t>0}{\textbf{minimize}}\left(\mathcal{V}(\lambda^t) + \mathcal{A}(\lambda^t)\right) \tag{19}$$

$$\mathcal{V}(\lambda^t) = \underset{0\leq P_i^t\leq P_i^{max}}{\textbf{maximize}} \sum_{i\in\mathcal{N}} \Delta U_i\left(P_i^t\right) - \lambda^t \cdot \sum_{i\in\mathcal{N}} P_i^t \tag{a}$$

$$\mathcal{A}(\lambda^t) = \underset{L_{min}\leq L_{ev}^t\leq L_{max}}{\textbf{maximize}} \lambda^t \cdot L_{ev}^t - C_{|P_c^t}(L_{ev}^t) \tag{b}$$

It has been shown in [13] that *strong duality* holds between *centralized problem* (17) and *dual problem* (19), i.e. the solution ${\lambda^t}^*$ of dual problem (19) can be found, and the local solutions ${P_i^t}^*$ and ${L_{ev}^t}^*$ to respectively the *distributed charging problem* (19)(a) and the *optimal energy capacity problem* (19)(b) exist, and match the solution of (17).

Concretely, (19)(a) is solved by the joint action of all the smart chargers, while (19)(b) is solved centrally, on the DR Aggregator side. The aggregator also updates the Lagrange multiplier ${\lambda^t}^*$, which in practice can be interpreted as the energy marginal price, by solving dual problem (19).

3.1.2 *Day-to-day incentives maximization problem*

Complementarily to the Intraday Welfare Maximization problem, the day-to-day incentives maximization problem aims to maximize the incentives revenue (by valley-filling) while satisfying the user SoC requests:

$$\begin{gathered}\underset{param}{\boldsymbol{maximize}}\, I_d = \lambda_d \cdot [PVD_C - PVD_T]^+ \\ \textbf{such that}\, SoC_i^d \geq SoC_i^{ex}\ \forall\, i \in \mathcal{N}\end{gathered} \tag{20}$$

where λ_d is the incentive factor (in €cts/kW), PVD_C is the original Peak-Valley Difference, i.e. that of the conventional load profile $\{p_c^t\}_{t\in\mathcal{T}}$, and PVD_T is the ultimate PVD, i.e. that of the total load profile $\{p_T^t\}_{t\in\mathcal{T}}$. The notation $[\cdot]^+$ denote the projection on $\mathbb{R}^+$. Finally SoC_i^d is the state of charge of vehicle i at time of departure d, and SoC_i^{ex} is the expected state of charge declared by user i at time of arrival.

3.2 Distributed algorithm for charging control

We now propose a solution for the decentralized intraday optimization problem, before studying its convergence and stating a solvability condition regarding the day-to-day optimization problem.

3.2.1 *DR Aggregator side: Optimal Energy capacity and pricing control*

Dual problem (19) is solved using the gradient projection method:

$$\begin{gathered}\lambda^{t+1} = \left[\lambda^t - \gamma \cdot \frac{\partial}{\partial \lambda^t}\big(\mathcal{V}(\lambda^t) + \mathcal{A}(\lambda^t)\big)\right]^+ \\ \lambda^{t+1} = \left[\lambda^t + \gamma\left(\sum_{i\in\mathcal{N}} P_i^{t^*}(\lambda^t) - {L_{ev}^t}^*(\lambda^t)\right)\right]^+\end{gathered} \tag{21}$$

where γ is the step size, $P_i^{t^*}(\lambda^t)$ and ${L_{ev}^t}^*(\lambda^t)$ are the local solutions to respectively problems (19)(a) and (19)(b). The notation $[\cdot]^+$ denotes the projection on $\mathbb{R}_+$.

With the marginal cost function $C_{|P_c^t}(L_{ev}^t)$ defined in (15), problem (19)(b) admits a unique solution ${L_{ev}^t}^*$ that can be interpreted as the speculated EV aggregate load value that the DR Aggregator would require in order to maximize its profits, given the level of non-flexible conventional load P_c^t:

$$\frac{\partial}{\partial L_{ev}^t}\Big(\lambda^t \cdot L_{ev}^t - C_{|P_c^t}(L_{ev}^t)\Big) = 0$$

$$\Leftrightarrow {L_{ev}^t}^* = \frac{\lambda^t \cdot P_l^2}{2a} - P_c^t \tag{22}$$

Writing down the Z-transform of equations (21) and (22) we can draw the Discrete-time Bloc Diagram of the price regulation loop in Fig. 3. The DR Aggregator receives the charging load from smart chargers, updates the total EV load P_{ev}^{t}. According to the information he has regarding the conventional load P_{c}^{t}, he determines its optimal capacity ${L_{ev}^{t}}^{*}$, i.e. the desired EV load, before comparing it to the actual EV load and updating the price through the discrete time integrator.

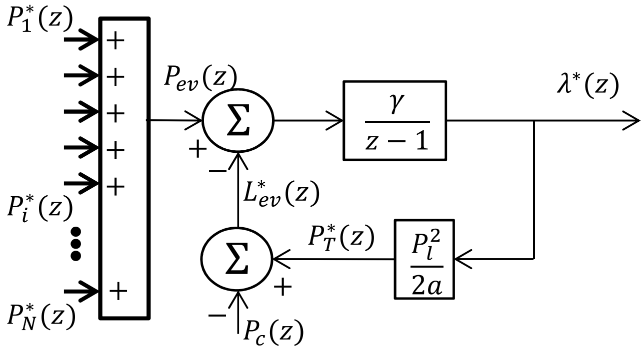

Figure 3: *Block Diagram of the Price Regulation loop executed by the DR Aggregator.*

3.2.2 *Smart charger side: Optimal Charging control*

Each smart charger receives the price from the Aggregator and solves its part of the *distributed optimal charging problem* (19)(a).With the marginal utility function defined in (13), this problem admits a unique solution:

$$\frac{\partial}{\partial P_i^t}\left(\Delta U_i\left(P_i^t\right) - \lambda^t \cdot P_i^t\right) = 0$$

$$\Leftrightarrow {P_i^t}^* = \frac{Q_i}{\alpha} \cdot \left[w_i^t - \frac{\lambda^t}{K_u \cdot \omega_i}\right]^+ \quad (23)$$

We understand from (23) the sense of *Price-Triggered Charging Control* where the price λ^t is weighted and compared to the trigger w_i^t to determine the charging ratio, which is null if the price is above the trigger value.

Using the Z-transform of equations (12) and (23), we can draw the Discrete-time Bloc Diagram of the Price-Triggered charging control.

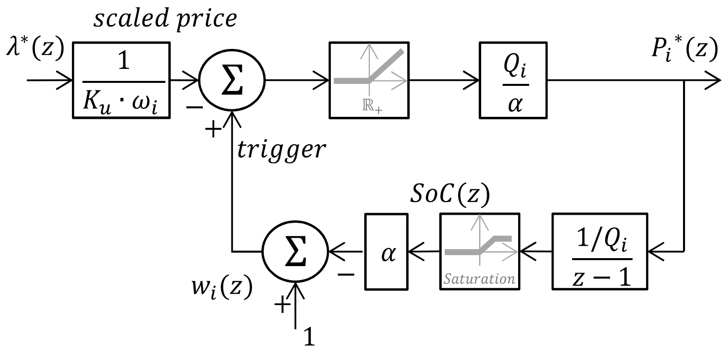

Figure 4: *Block Diagram of the Distributed Optimal Charging Control executed by each smart charger.*

3.2.3 ***Solving the intraday optimization problem***

To sum, an illustration of the distributed approach to solve the decentralized optimization problem (19) is proposed in Fig. 5.

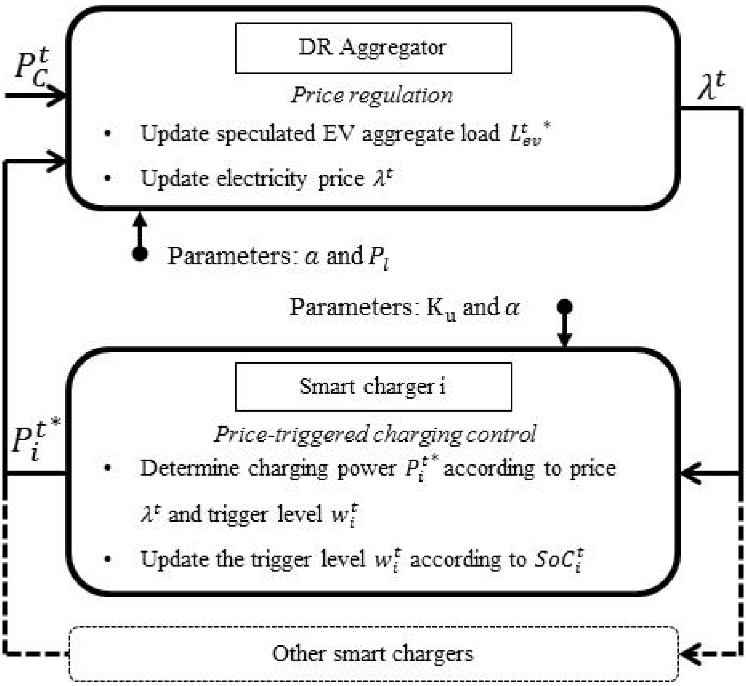

Figure 5: *Decentralized optimization architecture.*

3.3 Convergence & limits of the model

We now examine the steady state condition of the algorithm before stating a solvability condition for the day-to-day optimization problem.

3.3.1 *Steady-state criteria*

We assume here a limit case where the charging demand is sufficient to possibly fill entirely the base load valley, leading to a total load possibly constant in time. We then study the conditions for the steadiness of the price regulation algorithm, that is, we aim at determining the conditions for the price signal to be constant in time[3]:

$$\lambda^t = \lambda \; \forall \; t \in \mathcal{T} \tag{24}$$

where λ is the constant price at equilibrium. According to (21), condition (24) is fulfilled when the speculated EV load ${L_{ev}^t}^*$ equals the actual charging load ${P_{ev}^t}^*$:

$$\sum_{i \in \mathcal{N}} {P_i^t}^* = {L_{ev}^t}^* \tag{25}$$

With the expressions of both terms given respectively in (23) and (22) we can write down (25) as:

$$\begin{aligned} \sum_{i \in \mathcal{N}} \left(\frac{Q_i \cdot w_i^t}{\alpha} \right) - \sum_{i \in \mathcal{N}} \frac{Q_i^2 \cdot \lambda}{K_u \cdot \omega_i \cdot \alpha} &= \frac{\lambda \cdot P_l^2}{2a} - P_c^t \\ \Leftrightarrow \; P_c^t + \sum_{i \in \mathcal{N}} \frac{Q_i \cdot w_i^t}{\alpha} &= \lambda \left(\frac{P_l^2}{2a} + \frac{\sum_{i \in \mathcal{N}} Q_i^2}{K_u \cdot \omega_i \cdot \alpha} \right) \\ &= constant \; \forall t \end{aligned} \tag{26}$$

where the right hand side is constant in time, while P_c^t and w_i^t are the only two quantities that may vary at each time slot.

This allows us to formulate the following property:

Property 3: The closed loop system illustrated in Fig. 5 and composed of the price regulation bloc and the price-triggered charging controllers can reach a steady state in terms of price $\{\lambda^t\}_{t \in \mathcal{T}}$ and total load $\{P_T^t\}_{t \in \mathcal{T}}$ for a varying perturbation $\{P_c^t\}_{t \in \mathcal{T}}$ only if:

$$\frac{\partial P_c^t}{\partial t} + \frac{1}{\alpha} \cdot \sum_{i \in \mathcal{N}} Q_i \frac{\partial w_i^t}{\partial t} = 0 \; \forall \; t \in \mathcal{T} \tag{27}$$

That is, the sum of all triggers $\left\{\sum_{i \in \mathcal{N}} w_i^t\right\}_{t \in \mathcal{T}}$ has to follow opposite variations to the ones of the conventional load profile $\{P_c^t\}_{t \in \mathcal{T}}$.

[3] Note that according to Fig. 3, if the price signal is constant, then the total load is also constant.

3.3.2 *Limits of the initial model*

Based on the steady state criteria stated in **Property 4**, we suggest modifications to the primary model.

3.3.2.1 Utility maximization

We saw that **Property 4** involves a cumulative trigger level $\left\{\sum_{i\in\mathcal{N}} w_i^t\right\}_{t\in\mathcal{T}}$ to be alternatively decreasing or increasing as $\{P_c^t\}_{t\in\mathcal{T}}$ varies. However the concave utility function we defined in (8) leads to a trigger level defined as a strictly decreasing function of the state of charge: $w_i^t = 1 - \alpha \cdot SoC_i^t$, and therefore a non-increasing function of the charging time[4].

More generally, we saw in 2.3.3 that the marginal utility can be approximated by its second order Taylor series (see equation 10) and therefore the price trigger w_i^t is proportional to the first derivative of the utility function $\frac{dU_i(SoC_i^t)}{dSoC_i^t}$ (equation (12)). Hence, **Property 4** holds consequences regarding the utility function, as it implies the first derivative to be alternatively increasing or decreasing as the base load $\{P_c^t\}_{t\in\mathcal{T}}$ varies. But then this contradicts **Property 1** that imposes utility functions for EV charging to be concave.

Hence, we suggest to use a dynamic definition for the utility of charging, using the concept of charging flexibility, a.k.a. urgency of charging, as recommended in [5], [28], [29], [38].

3.3.2.2 Limits of the cost-function model:

Besides being perhaps too simplistic to model the real cost dynamics, the cost function we defined in (2.1) might be inefficient in solving the dual problem that demand side management and load shifting usually addresses. Indeed, as in [39] we can identify a dual demand side management problem made of: a) The limited energy resources issue, which concerns the large scale real-time demand profile (e.g. the aggregate national power demand) and b) The local network congestion problem, which concerns the aggregate load profile on the local scale (e.g. the load at a primary substation). Such local congestion problem can be of concern for DR Aggregators that have representative network locations. In such cases, load shifting and valley filling addressed at the aggregator level might help alleviating local congestion

As these two components might be decoupled[5], we suggest the use of a unique large-scale dynamic pricing, indexed on the wholesale market prices, to address

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[4] Indeed the State of Charge is non-decreasing in time since we only consider Grid to Vehicle (G2V) energy transfers.
[5] Note that Locational Marginal Pricing (LMP) is a way to address this dual problem but might not be in accordance with the public service remit of transport and distribution service operators (TSO & DSO) and of some regulated energy providers, which ensures to every consumers the same price for electricity and access to the network, no matter their location [44].

problem a); and the use of Local Congestion Management to address problem b). In the following, we will consider that from the DR Aggregator point of view, local congestion management corresponds to solving the valley-filling problem for its portfolio, even if this could be challenged for highly geographically dispatched portfolios.

3.4 Revised optimal charging control

The architecture of the charging control deduced from the decentralization formulation of welfare maximization problem (17) still holds as the optimal solution to the intraday optimization problem. The price triggered charging control defined in equation (23), recalled below, is still valid:

$$P_i^{t*} = \frac{Q_i}{\alpha} \cdot \left[w_i^t - \frac{\lambda^t}{K_u \cdot \omega_i} \right]^+ \tag{28}$$

However, a regulation of the trigger level w_i^t is required to comply with **Property 4**, in order to fulfill the solvability condition of the day-to-day problem (20). To do so, we will consider charging flexibility (a.k.a. urgency to charge), a concept widely used by M.D. Galus [5], [24] and other authors [7], [28], [29], [38] for real-time welfare maximization and congestion management.

3.4.1 *Novel regulation strategy for the trigger level*

We define the charging flexibility level as follows

$$\phi_i^t = \left[\tau_i^t - \tau_i^{min} \right]^+ \tag{29}$$

where τ_i^t is the Remaining Charging Time, i.e. the remaining time before departure; and τ_i^{min} is the minimum charging time of vehicle i at each time slot t defined as follows:

$$\tau_i^{min} = \frac{Q_i}{p_i^{max}} \cdot (1 - SoC_i^t) \tag{30}$$

with SoC_i^t its current State of Charge, p_i^{max} the maximum charging power of charging station i, and Q_i the declared battery capacity. Charging Flexibility ϕ_i^t can be interpreted as the urgency level of charging, i.e. the degree of acceptable charging rescheduling

Property 4: The trigger level w_i^t; a.k.a. the real-time willingness to pay should be a decreasing, concave function of the flexibility level [29] while by definition w_i^t should be no less than 0 and no more than 1

$$\begin{cases} 0 \leq w_i^t(\phi_i^t) \leq 1 \\ \dfrac{\partial w_i^t(\phi_i^t)}{\partial \phi_i^t} \leq 0 \\ \dfrac{\partial^2 w_i^t(\phi_i^t)}{\partial {\phi_i^t}^2} \geq 0 \end{cases} \tag{31}$$

Property 5: Regarding charging fulfillment (constraint of problem (20)), no charging load to be rescheduled when the charging urgency is at maximum [5], i.e. Smart Chargers should always be able to charge at maximum rate p_i^{max}, when there is no charging flexibility.

In particular, this implies that the trigger level should be maximum when $\phi_i^t = 0$

$$w_i^t(0) = 1 \tag{32}$$

We choose a linear trigger level function defined as follows, and illustrated in Fig. 6:

$$w_i^t = \left[1 - \delta^t \cdot \phi_i^t\right]^+ \tag{33}$$

where δ^t is the trigger slope, a scalar value regulated by the EV Aggregator by Congestion Management (proportional to the congestion level)

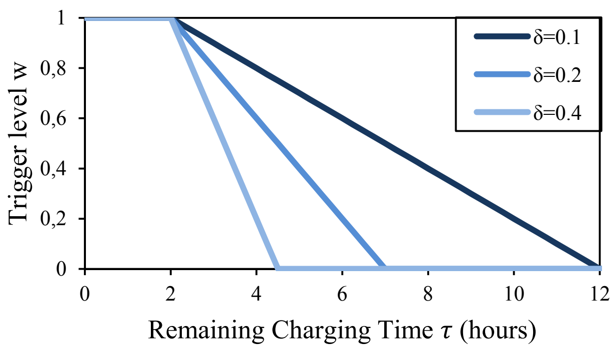

Figure 6: *Sample of trigger level profile for τ_i^{min}=2h and different δ^t.*

Additionally, **Property 5** implies that the price-utility factor K_u should be big enough to allow charging at maximum power p_i^{max}, even when the price is at maximum level λ^{max} and when trigger level is at maximum. Hence:

$$K_u = \frac{\lambda^{max}}{1 - \max\limits_{i \in \mathcal{N}} \dfrac{p_i^{max}}{Qi}} \tag{34}$$

3.4.2 *Real-time pricing strategy*

As recommended in 3.3.2.2, the limited energy resource problem (TSO level, problem a)) and the local network congestion problem (DSO level, problem b)) should be considered separately. The network congestion problem is addressed by DR Aggregator load regulation (shifting and valley filling) while Real Time Prices should exclusively reflect the procurement cost to reflect constraints imposed by the limited energy resource problem. Hence, we use wholesale market prices for the real-time price λ^t.

3.4.3 *Solving the Day-to-day problem*

We saw with **Property 5** that a regulation of the trigger w_i^t is required. Hence, we aim at regulating w_i^t in order to reach a steady-state regarding the total load $\{P_T^t\}_{t\in\mathcal{T}}$. Indeed, it has been proved repeatedly [2], [7]-[9] that the optimal solution of the valley-filling problem (20), is reached for an optimal load leveling which allows a 'flat' total load profile in the 'valley' period for the original load. so that a local steady-state level P_T^* is the minimal value of the total load for day d:

$$\forall t \in T: P_T^t = P_{ev}^t + P_c^t = \begin{cases} P_T^* & P_c^t < P_T^*, P_{ev}^t > 0 \\ P_c^t & P_c^t > P_T^*, P_{ev}^t = 0 \end{cases} \tag{35}$$

For illustrative purposes, Fig. 7 shows an example of optimal solution to the day-to-day problem (20) obtained by the authors of [8] by centralized optimization.

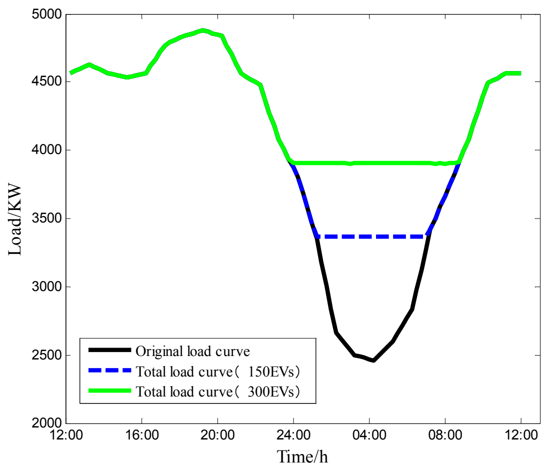

Figure 7: *(Excerpt from [8]) Illustration of the optimal total load steady-state level.*

For each day d, P_T^* can be defined as the total load steady level such that the energy used to fill the Original load valley up to a plateau P_T^* is equal to the sum of the energies required by every EVs during the day:

$$P_T^* \text{ such that } \sum_{t\in\mathcal{T}} \Delta t \cdot [P_T^* - P_C^t]^+ = \mathrm{E_{ev}} = \sum_{i\in\mathcal{N}} q_i \cdot (SoC_i^{ex} - SoC_i^{t_a}) \quad (36)$$

3.4.4 *Regulating the trigger level* $\boldsymbol{w_i^t}$

Supposing the optimal load plateau P_T^* predictable, and assuming that the total power consumed by the whole EV Aggregator portfolio can be known in 'real time', we design a control strategy for the aggregate EV charging load that aims at complying with the day-to-day optimality condition (35). To do so, we implement a trigger control with the Lagrange projection method, where the common trigger slope δ^t is regulated according to the total load deviation from the plateau $\mathrm{P_T^*}$ as follows:

$$\delta^{t+1} = \delta^t + \gamma_\delta (P_{ev}^t + P_c^t - P_T^*) \quad (37)$$

We recall that the trigger level of EV i $w_i^t = \left[1 - \delta^t \cdot \phi_i^t\right]^+$ depends on the individual charging flexibility ϕ_i^t but also on the slope δ^t, which is common for the whole local fleet. Hence, the EV aggregator, by regulating δ^t, can raise or depreciate the trigger level w_i^t of EVs with nonzero flexibility. Thus, the aggregate EV charging load P_{ev}^t can be regulated to comply with the optimal strategy (35) by adjusting the real-time individual charging power $P_i^{t^*}$ (see equation (23)), as illustrated in Fig. 8.

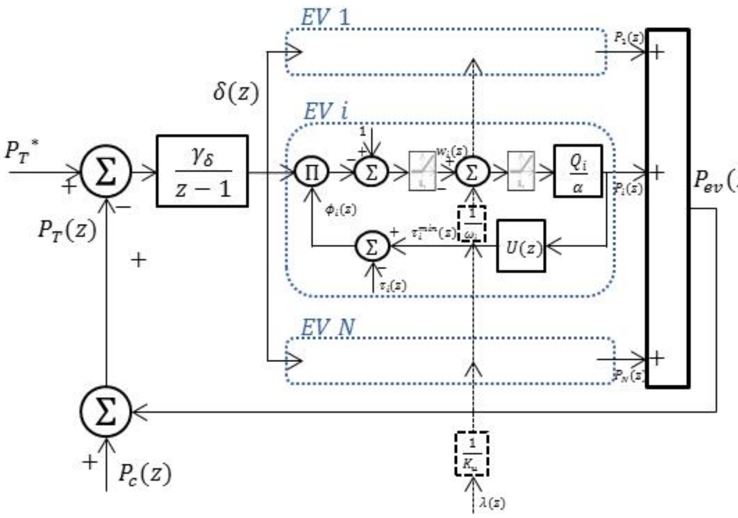

Figure 8: *Block diagram of the optimal trigger control.*

with $U(z)$ the Z-transform of the minimum charging time defined by equations (29) and (11):

$$U(z) = \frac{\tau_i^{min}(z)}{P_i(z)} = -\frac{1/p_i^{max}}{z-1} \tag{38}$$

In practice the dynamic performances of the slope update can be improved without losing stability by increasing dynamically the gain γ_δ of the Lagrange projection block. To do so, we consider the dynamics of perturbations such as the price nal λ^t or the number of EVs currently plugged-in n^t and its first derivative

$$\gamma_\delta^t = g_0 + g_n \cdot n^t + \frac{g_d}{n^t} \cdot \frac{\Delta n^t}{\Delta t} + g_\lambda \cdot \frac{\Delta \lambda^t}{\Delta t} \tag{39}$$

4 SIMULATION RESULTS

4.1 Model features

4.1.1 *Context & Portfolio Features*

We assume the DR Aggregator portfolio to correspond to a West-European suburban area of 5,000 inhabitants, and approximately 2,500 dwellings[6]. In practice, we use a downscaled version of the load observed in Pairs area, France for the conventional load [40].

We set the time slot length Δt to 15 minutes, in order to be coherent with both the one-hour-long time step of the continuous intraday electricity market [41] and the 10 minutes to one hour long time step of the smart meters [42].

We use the Epex Spot continuous intraday market index for the wholesale market price λ^t. The price indexes for each day and each country are available online at [41]. To be coherent with the choice of Paris area for the representative conventional load we use the French price index, taking data of the same day for both load and prices.

4.1.2 *PEV Fleet features*

We consider a fleet of N PEVs,each of them going along with its smart charger of maximal charging power p_i^{max} equal to either 3.3 kW for 50% of the fleet or 7kW for the remaining 50%. This corresponds to single phase 240V plugs with respectively 16A or 32A maximum current, taking into account a charging efficiency around 90%. For simplification, we assume that every PEV leaves its charging station with a State of Charge $SoC_i^{t_d} = 0.8$ prior to its daily commute. We also assume that the whole PEV fleet is equipped with uniform battery capacity $q = 30kWh$

[6] According to [45], European countries had an average of 475 Dwellings per 1,000 inhabitants rate in 2010

4.1.3 *Simulation values*

K_u is defined according to (34) and we set $\alpha = 1$, $g_0 = 1.10^{-4}$, $g_d = 5.10^{-7}$ and $g_\lambda = 4.10^{-7}$

4.2 Results

We run the simulation with two types of typical base load obtained by downscaling the total load of Paris area during working days in winter and spring (February 03rd-04th and June 16th-17th 2014) [40]. We choose the theoretical optimal value for P_T^* defined in (35), i.e. $P_T^* = 4435.07\ kW$ for February 03rd-04th and $P_T^* = 2971.41\ kW$ for June 16th-17th.

Results are presented respectively in Fig. 9 - Table 1 and Fig. 10 - Table 2.

The total load curves obtained without charging control are provided in Fig. 9 and Fig. 10 for reference in order to illustrate the load shifting phenomenon.

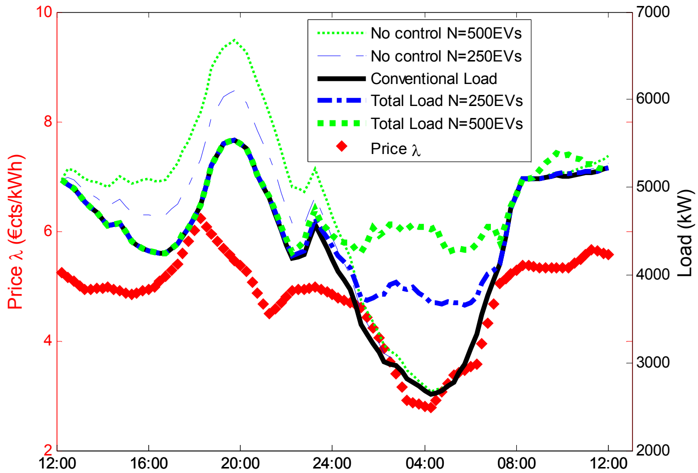

Figure 9: *Simulation results February 03rd & 04th 2014.*

Table 1: *Simulation results February 03rd & 04th 2014*

	N=250 EVs	*N=500 EVs*
Reduction in PVD	$\frac{[D_{PV_c}-D_{PV_T}]^+}{D_{PV_c}} = 55.55\%$	$\frac{[D_{PV_c}-D_{PV_T}]^+}{D_{PV_c}} = 34.96\%$
PDV deviation from optimal	$\frac{(D_{PV_T}-D^*_{PV_T})}{D^*_{PV_T}} = 10.48\%$	$\frac{(D_{PV_T}-D^*_{PV_T})}{D^*_{PV_T}} = 16.34\%$
Average relative Final SoC	$< \frac{SoC_i^{td}}{SoC_i^{ex}} >= 100\%$	$< \frac{SoC_i^{td}}{SoC_i^{ex}} >= 100\%$

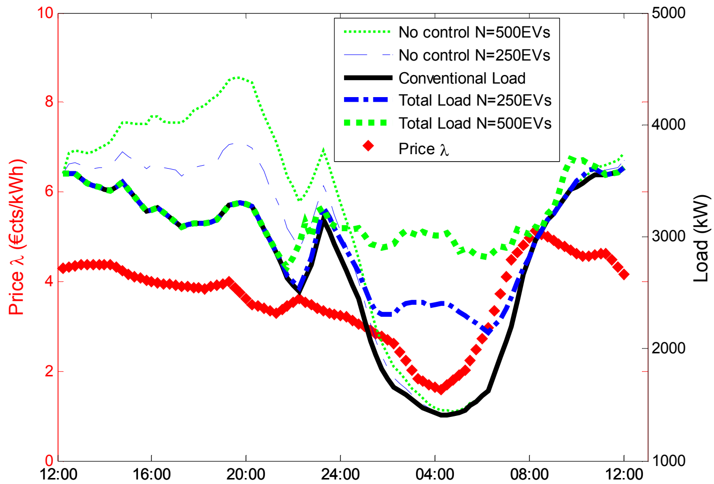

Figure 10: *Simulation results June 16th & 17th 2014.*

Table 2: *Simulation results June 16th & 17th 2014*

	N=250 EVs	*N=500 EVs*
Reduction in PVD	$\frac{[D_{PV_C}-D_{PV_T}]^+}{D_{PV_C}} = 56.08\%$	$\frac{[D_{PV_C}-D_{PV_T}]^+}{D_{PV_C}} = 33.62\%$
PDV deviation from optimal	$\frac{(D_{PV_T}-D^*_{PV_T})}{D^*_{PV_T}} = 20.67\%$	$\frac{(D_{PV_T}-D^*_{PV_T})}{D^*_{PV_T}} = 50.64\%$
Average relative Final SoC	$< \frac{SoC_i^{td}}{SoC_i^{ex}} >= 100\%$	$< \frac{SoC_i^{td}}{SoC_i^{ex}} >= 100\%$

We observe that for both cases the final state of Charge reaches the expected level for 100% of the fleet, this being due to the strategy defined in **Property 5**.

However, the inertia introduced by the integrating bloc of the Lagrange projection method defined in (37) introduces undesired local minima around 22:00, while the poor correlation between market prices profile and local load profile might lead to additional deviation from the optimal solution.

Finally, these sources of deviation from optimal solution lead to incomplete charging of a part of fleet at the time when both prices and conventional load rise up (around 8:00), causing an undesired local maximum around 10:00, when they have no flexibility anymore (see **Property 5**).

4.3 Predicting the optimal steady state level P_T^*

The prediction of the optimal steady state level P_T^* mainly depends on the kind of information that is made available to the EV Aggregator in advance and in real-time. Using the total load profile, it is possible to calculate P_T^* *a posteriori* and so a reinforcement learning algorithm (such as a neural network with backward propagation) to predict the value of P_T^* a day ahead is conceivable.

However, it is important to note that there is a strong correlation between the median $\widetilde{P_T}$ of the total load profile $\{P_T^t\}_{(t\in\mathcal{T})}$ and the optimal steady state level P_T^*: Fig. 11 shows the difference between those two values for different number N of EVs charging, and for a representative sample of total load profiles.

All EVs are assumed to charge from $SoC_i^{t_a} = 0.2$ to $SoC_i^{ex} = 0.8$. The load profiles are obtained by downscaling the total demand of Paris area [40] for a sample of 7 days that are chosen to be representative of each day of the week and of the 6 first months of the year.

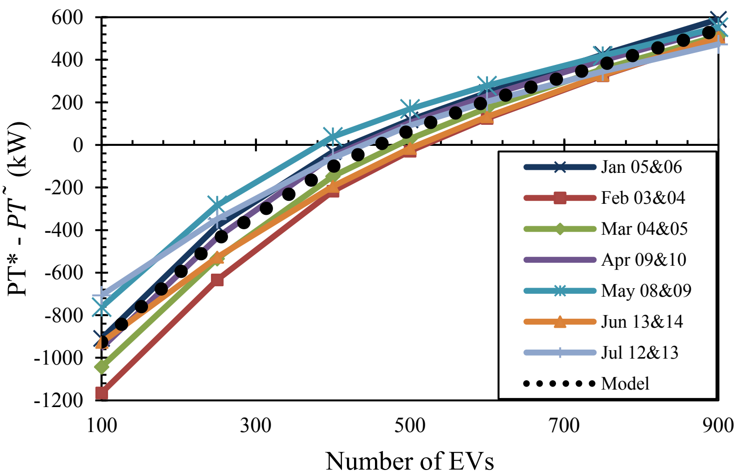

Figure 11: *Relation between P_T^*, $P_T^\sim$ and N for a representative week.*

Hence, we observe that the optimal steady state value P_T^* can be predicted in a first approximation from the expected median value $\widetilde{P_T}$ with a 3rd order polynomial Model. For the area and load profiles we consider, this polynomial is expressed as follows:

$$P_T^*(N) = \widetilde{P_T} - 1343.69 + 4.63 \cdot N - 4.59.10^{-3} \cdot N^2 + 1.97.10^{-6} \cdot N^3 \quad (39)$$

Where $\widetilde{P_T}$ is the base-load median value, and N is the total number of EVs registered in the local network for day d.

Note that such model could be adapted every day with the conventional load profile known *a posteriori*.

5 CONCLUSION

In Spite of the proved irrelevance of utility maximization used with dynamic pricing, the control architecture obtained by decentralization turn out to be advantageously adaptable to the concept of charging flexibility. The price trigger can indeed be regulated within an optimal charging control strategy that ensures all vehicles to reach the state of charge requested by the user, while giving the priority to charge to vehicles with less flexibility. This enables the aggregator to blindly regulate the trigger level without any specific information for each vehicle. However, the main challenge that remains consists in predicting the optimal steady state level P_T^*. We saw that a correlation exists between this steady state level, the conventional load median and the number of PEVs charging but the next step could be to implement a cognitive algorithm to predict more accurately this value. Moreover, such a dynamic charging control could be suitable to coordinate EV-charging with Decentralized Energy Resources (DER) production. In future developments, the regulation of the trigger value could advantageously incorporate real-time local DER production by subtracting it to the total load level, but this would require to be able to predict the overall DER daily production in order to take it into account in the steady state level prediction.

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COMPREHENSIVE INFRASTRUCTURE FOR ELECTRIC VEHICLE CHARGING INTEROPERABILITY AND GRID COMPLIANCE TESTING

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Keywords: electric mobility, smart grid, interoperability, test architecture, laboratory validation, charging infrastructure.

ABSTRACT

Functional and electrical interoperability is a key requirement for the successful implementation of charging infrastructure for electric vehicles. European research projects such as COTEVOS and PlanGridEV deal with upcoming challenges of electric mobility and testing of charging infrastructure. This paper discusses a test architecture as an essential tool in testing the interoperability, conformance and functionality for multiple actors and services in the e-mobility and Smart Grid environment developed in the context of these projects. The main requirements are discussed as well as architectural considerations that resulted in the implemented solution. An application use case demonstrates the functionality of key features of the test system.

1 INTRODUCTION

It is expected that electric mobility will be a key element in future transport systems. Although a 100 % shift from propulsion concepts based on fossil energy sources to concepts utilizing electric energy produced by renewable sources cannot be expected, e-mobility will have a massively increasing share in the global transportation system. Current predictions for growth rates of electric vehicles (EV) and plug-in hybrid EV (PHEV) have a broad range. Wietschel et al. [1], for example, predict more than 50 % of new registered cars in 2020 will be PHEVs with at least 50 % electric ratio. This would result in roughly 1.3 million PHEVs of which ~300,000 would be fully electric in Germany alone. E-mobility should not be expected to be the one and only new transportation technology but it will be an alternative that can be used in an eco-friendly way.

Beside IEC (with IEC TC69 and SC23H) and ISO, which operate on a global level, CEN and CENELEC are active in EV related standardisation within Europe. After the European Commission issued the standardisation mandate M/468 [2] for fostering interoperability in the field of EV and EVSE, several standardisation groups have been founded and activities initiated. CEN/CENELEC, for example, set up the joint CEN/CENELEC "Focus Group on European Electro-Mobility - standardisation for road vehicles and associated infrastructure". In response to the M/468 mandate this group published the "Report for Standardization for road vehicles and associated infrastructure" [4]. Besides general recommendations and standards concerning EV related interoperability, also information concerning EV charging modes, connection systems, communication approaches, regulatory concerns, and smart charging are included considering a wide range of already available standards and quasi-standards. As stated in the latest EU DIRECTIVE 2014/94/EU [3], despite the high standardisation efforts of recent years, interoperability is only partially fulfilled and not yet sufficiently complete. Due to this fact, this contribution presents a comprehensive infrastructure for EV charging interoperability and grid compliance testing.

In order to raise the attractiveness of e-mobility, different incentives can be utilised. These can have a very broad range from special traffic rules to reduced tax rates [5]. A very common example of a special traffic rule for EVs would be to allow them in cities to use bus or car pool lanes or even to enable free parking where conventionally driven cars would have to pay parking fees. These types of incentives have a natural limitation. The bus lane will be equally crowded and the benefit practically gone with the rising number of EVs. A similar behaviour can be expected from tax incentives as every country relies on the income from taxes such that tax rate reductions for EVs will only work to a certain penetration of EVs. In the Scandinavian countries, which were among the very first to support e-mobility, such limiting effects for incentives can already be observed.

In order to maintain the interest in EVs and PHEVs new sustainable incentives need to be generated. The current paradigm shift in the field of electric power grids with the implementation of smart grid technologies is the opportunity that e-mobility can generate those incentives [6]. Concepts like *Adaptive Charging, Smart*

Charging, *Vehicle to Grid* and *Grid to Vehicle* are currently under discussion. There is no doubt that those features represent huge possible benefits for all, the user of the EV, the distribution system operator (DSO) or the energy retailer. However, the infrastructure required for such applications is currently not yet in place and thus requires immediate attention.

European research projects such as COTEVOS [7] and PlanGridEV [8] deal with these upcoming challenges. The PlanGridEV project adopts a European approach involving DSOs as well as Original Equipment Manufacturers (OEMs) to develop new distribution network planning rules and operational principles. This approach accounts for the need to adopt a multi-stakeholder perspective to satisfy customer expectations and to ensure a safe and efficient network operation integrating EVs. The aim of the FP7 project COTEVOS is to establish the optimal structure and capacities to test conformance, interoperability and performance of all systems comprising the infrastructure for the charge of EVs. Projects like these can be expected to help generating incentives for e-mobility that are sustainable regardless of the penetration of EVs. The test architecture presented in this contribution aims to be an essential tool in testing the interoperability, conformance and functionality for multiple actors and services in the e-mobility and Smart Grid environment.

2 MOTIVATION

Charging schemes for EVs and PHEVs have a very wide range of technical functionalities and underlying business cases. In the same way the complexity of such functionalities and business cases varies massively. A very simple case might be charging at a public charging station, where the EV user wants to charge e.g. while he is shopping in a mall. This simple example already requires extensive information exchange and interoperability features.

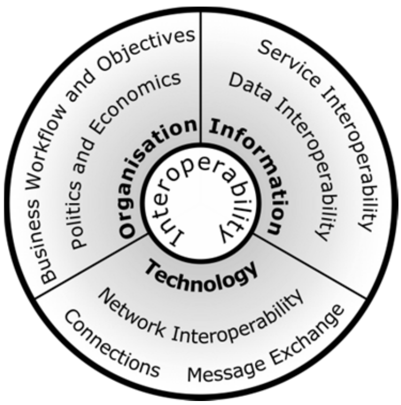

Figure 1: *Different levels for Interoperability in Smart Grids (cf. [9]).*

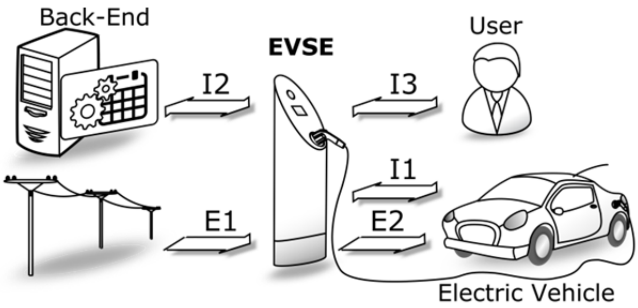

Figure 2: *Interfaces of a charging station [10].*

First of all, mechanical interoperability must be provided as the plug of the charging station needs to fit into the EV's socket. Secondly, the electric grid connected to the electric vehicle supply equipment (EVSE) needs to be capable of providing the required amount of energy at the necessary power rate. And last but not least, the energy that was consumed by the EV has to be paid. More complex use cases as e.g. smart charging even further increase the complexity mainly by adding required communication layers. Figure 1 illustrates the different levels for interoperability in smart power grids in general. For the simple example of an EV user who wants to make use of a managed charging service, needs his EV to be fully charged within the next 10 hours and has a certain costs limit, the amount of interoperability required is immense. In addition to the previous example, issues such as charge scheduling, market price observation, vehicle to grid services and many more are required. Figure 2 depicts the energy and communication interfaces that need to be addressed for this case.

A future mobility system will be strongly interlinked with the energy system, both grid and market. EV owners will have different options how to interact with grid operators and energy retailers. The resulting technical system will require a new dimension of testing both in the power and communication interface domain. A comprehensive testing infrastructure for EV charging systems typically consisting of a charging station (EVSE) and the electric vehicle (EV) is required.

3 REQUIREMENTS & CONCEPT

Fostering interoperability among relevant components of the electric mobility ecosystem is of interest for the following stakeholders, which have been identified in previously conducted research ([10], [14]) and are in agreement with actual international work (cf. [15]):

- EV owners
- EV manufacturers
- EVSE manufacturer
- EVSE operator
- DSOs

The following two groups of test cases have to be covered in order to evaluate interoperability and give recommendations for its improvement:

- Single component (EV, EVSE) evaluation/component tests in the lab
- Compound and large-scale interaction tests of the component

While the first group of test cases focuses on the evaluation of interfaces (on physical, electrical, and informational level), the latter one focuses on the complex interaction of relevant components and actors.

From these test case groups, the following requirements for a lab-based EV charging system test infrastructure can be derived.

- Comprehensive power grid emulation: In order to mimic the behaviour of the power grid and relevant grid states, a power grid emulator together with a power amplifier is necessary to emulate a real three phase power grid in the laboratory.
- EV/battery emulation: In order to be able to properly test EVSE in a component test, a freely configurable EV/battery emulator must be available. This is necessary because it cannot be guaranteed that an appropriate EV is available at any time. Also, different battery types, with an arbitrary State of Charge (SoC) can easily be emulated.
- EVSE emulation: For the opposite case which is the testing of EVs, the EVSE has to be emulated in both, the information and the electrical domain.
- Flexible information exchange: If only the EV or the EVSE is tested, the emulated counterpart must be capable of exchanging necessary information with the device under test (DuT).
- Availability of uniform lab communication and control entity: For the generation of test cases, the automatic conduction of tests and for data persistence a common lab communication and control entity is necessary.
- HIL integration in large scale simulation: In order to conduct compound- and large-scale interaction tests, simulation of power system and charging systems is necessary. Furthermore the real-world component(s) have to be integrated into these simulations.

Figure 3 shows a generic concept for the lab-based EV charging system test set-up, which is aligned to the previously identified requirements.

Depending on the test set-up, either single component tests (DuT1, DuT2), compound component tests (DuT1+2), or large scale component tests with simulated components can be conducted.

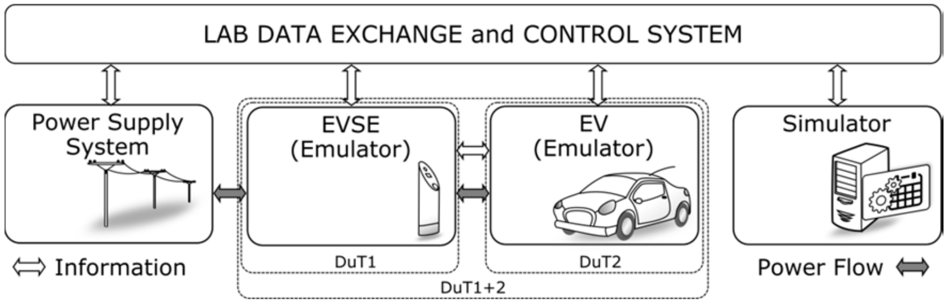

Figure 3: *Concept for the lab-based EV charging system test set-up.*

Power flow is established between the power grid emulator, the EVSE or its emulated component, and the EV or its respective emulation. Two-way information exchange is necessary. The first communication path is the one between the EVSE and the EV, which is also available in the field. The second set of information paths is necessary in order to control the lab components (e.g. amplifiers, power sinks) to ensure proper component emulation. This second information part is required for data exchange and system controls in the lab.

4 IMPLEMENTATION

After describing the concept, this section shows a first implementation of a hardware-based test system for the e-mobility charging infrastructure. As a first stage of implementation the system focuses to the electric domain and all components directly depending to it. The test system allows the full control of the charging process and enables the possibility for different operation modes described later.

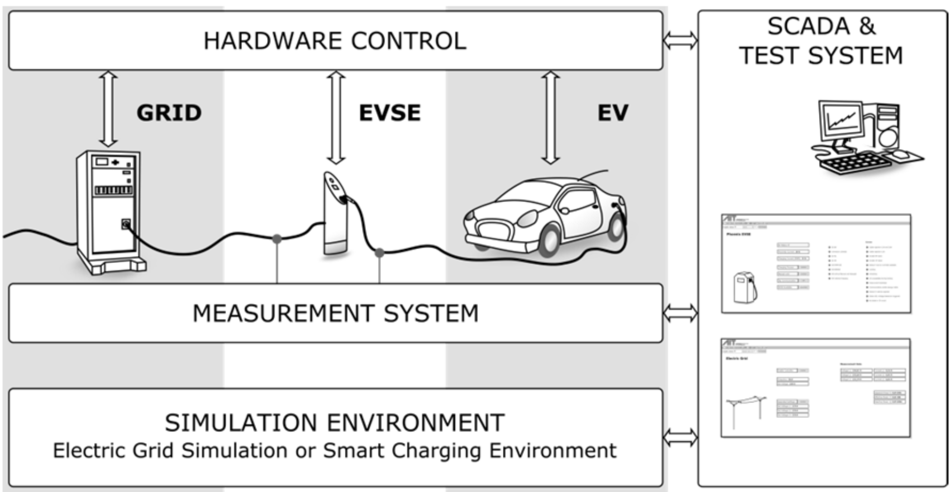

Figure 4: *Schema of the implemented EV Test System.*

Figure 4 illustrates the schema of the implemented test and research stand for EV in the AIT SmartEST laboratory. In the first implementation state the system allows the control of the relevant parameters of the EV charging process including the possibility to set the maximum possible charging current as also the possibility to influence the voltage levels of the electric grid.

The shown test stand is constructed for a maximum electric power of the charging process up to 25 kVA. Therefore at the current status all EV and EVSE that are connected via mode 1 to 3 according IEC 61851-1 [11] can be utilized as a DuT. The electric part of the EV charging infrastructure is divided into three domains, the electric grid, the EV charging equipment (EVSE) and the EV. These domains are also present in the implemented test system.

4.1 Components of the EV/EVSE's test system implementation

Components of EV's charging infrastructure represented in the test setup will be described subsequently. Aside of these there are also additional components for control and observation of hardware.

- ***Electric Grid and Electric Grid Emulator***

  The test system can be directly supplied by the electric distribution grid. In this operation mode it is not possible to influence any characteristic of the electric supply. Otherwise to solve this control restriction in the system it is possible to supply the EVSE and EV from a 4-quadrant-power amplifier up to 25 kVA. This grid emulation enables the freedom to change the electric characteristic of the supply and it allows emulating different scenarios that occur in an electric distribution grid. A simple example of such an emulation scenario would be the voltage level adjustment of each separate phase of the electric grid.

- ***Controlled EVSE***

  The first implementation uses a commercially available EVSE with IEC 61851-1 Mode 3 support. Most available electric vehicles can be charged with the system currently implemented. The charging station is controlled by a PC-based control system. This solution enables full control of the test system, such as enabling and disabling the charging process or adjusting maximum possible charging current.

- ***EV***

  The electric vehicle is used in the first configuration of the test system as the DuT. Therefore the interoperability and the electric conformance of the EV can be tested with this configuration.

- ***Control and Test System***

  All described components are controlled by a Supervisory Control and Data Acquisition (SCADA) system, which is based on the open-source project ScadaBR [13]. This system works for safety reasons as a single point of control and shows all relevant parameters of the controlled hardware units. In Figure 4 the screenshot of the control view for the connected EVSE is shown as an example. This view allows e.g. the adjustment of the charging current and shows the state and possible errors of the charging controller.

Additionally a test system with automatic test execution [10] is also implemented into the control system. This allows the execution of scripted test cases with automatic generation of reports. This feature is used for future interoperability and conformance testing of the EV charging infrastructure.

- ***Measurement System***

  For the analysis of the electric characteristics during a charging process of an EV a measurement system is included in the test system. All electric voltages and currents within the system are recorded in configurable resolution.

- ***Simulation Components***

  The EV test system is connected to a simulation system [14]. This allows simple hardware-in-the-loop simulations. As example the electric power of the charging process is measured at the EVSE. This value is transmitted to an electric grid simulation with a corresponding load of this EVSE. On the access point of this electric load the line voltage is calculated in the simulation and the result is sent back to the grid emulator. This emulator sets the voltage on the electric line of the connected hardware. The configuration with a connected simulator allows future extensions of the EV test system for testing and researching smart charging algorithm on real hardware devices.

Figure 5: *Screenshot of the control system page for the EVSE.*

4.2 Operation modes

With the set-up as described above different test scenarios can be executed. The following three operation modes give an example of the capabilities provided.

A future extension of these is currently planned and scheduled and is discussed in the following section of this contribution.

1. ***Measurements and Charge Cycle Analysis***
   The simplest application for the EV test stand is the recording of electric parameters for a whole charging cycle of an electric vehicle. New information about the EV's charging characteristics can be extracted from these measurement data and therefore the models for EV charging simulations can be improved.

2. ***Conformance Testing***
   The test stand can also be used for a test execution scenario, which has already been shortly described in the section before. With scripted test cases, like unit tests in the software development, the execution will be automated and the test results are generated immediately as passed or failed.

3. ***Hardware-In-the-Loop-Simulation***
   With the integration of simulation components within the test stand a simple hardware-in-the-loop simulation is possible. Especially the integration of an electric grid simulator can be used to reproduce the characteristics of an electric distribution grid within the laboratory environment. The simulation components can also be used testing the effects of smart charging algorithm with the interaction of real-world EVSEs and EVs.

5 DISCUSSION

The biggest drawback of the current implementation of the test architecture for EV/EVSE interoperability and compliance testing at the given time is the limitation to AC based charging (namely Mode 1, 2 and 3 according to IEC 61851-1). This was a limitation of choice for the first implementation due to the fact that at the current time the market share of DC products is roughly 10 % of the EVSE market share. If this changes in foreseeable future the required adjustments to the test infrastructure need to be applied.

At the current stage of development only the IEC 61851 is implemented. Looking at the current EV and EVSE market there is still a lack of ISO 15118 [12] applications. It cannot be expected that OEMs fully implement the ISO 15118 if they cannot attach a valid business case. Right now the implementation of the ISO 15118 into the test stand environment would take about two months of development time. This is a reasonable short time period such that it can be implemented in time if applied examples occur.

The complexity of the test stand with six components that need to interact with each other is the mayor drawback of the system. Due to the fact that one of the goals of this test infrastructure is to test interoperability and conformance not only with the electric grid itself but also with multiple actors out of the e-mobility and smart grid environment the given complexity might be acceptable. Still it will be one future side goal to reduce the complexity of the test system.

Based on the equipment utilized the current power limitation is 30 kVA. This would not be enough to supply two EVSE and EV at the same time. Connecting multiple EV as real hardware might become a very interesting use case in the near future. The control of the power amplification is implemented via a separate hardware board that translates given signal parameters into an analogue output signal. Every power amplification unit that has an analogue channel available in order to control the power output can be controlled via the utilized hardware. One will then have to reprogram the output signal amplitude according to the amplification unit used.

6 APPLICATION EXAMPLE

The following application example demonstrates key capabilities of the test system. Therefore a simple rule-based charge current modulator is implemented within the EV test system. The communication between the EV and the controllable EVSE is based on the IEC 61851 standard. The system configuration allows the control of the IEC 61851 charging constraints. More specifically, the charging current is controlled and the time behaviour is monitored according to the standard. The utilized equipment for this application example is shown in Table 1.

The local charge current modulator can easily be implemented in an EVSE. The modulator measures the voltage at the EVSE connection point and controls the charging current of the connected vehicle using low level communication according to IEC 61851. Figure 5 shows the measurement results of an experiment demonstrating the key capabilities of the implemented EV test stand.

For a nominal voltage of the connection point of 230 V a predefined charging current of 16 A is used to charge the EV. If the measured voltage drops under a defined level (Fig 6, 1) the EVSE controller detects this and reduces the charging current (Fig. 6, 2) after a threshold time. In the experiment, the grid voltage can be determined by the test stand and is arbitrarily reduced from 230 V to 215 V independently of the charge current. After a successful return of the voltage to the normal grid conditions (Fig. 6, 3) the EVSE sets the charging current to the previous value of 16 A (Fig. 6, 4). The same procedure will be used, if the voltage at the charging spot rises (Fig. 6, 5). It can be observed how the controller increases the used charging current of the vehicle (Fig. 6, 6).

Table 1: *Main components used in the application example*

Electric Vehicle	Renault ZOE ZEN
Charging Station	Phoenix Contact EV Charge Controller
Charging Cable	Type IEC 62196-2 32 A
Grid Emulation	30 kVA 4-quadrant linear power amplifier

The application example provided in this contribution does not aim to present a novel algorithm or smart charging control methodology. The voltage threshold was chosen for demonstration purposes only and with no respect to any standard or regulation. The application example was designed such that the key features of the test stand can be demonstrated clearly. Complex and novel smart charging algorithms and control methodologies can be implemented in the environment of the test stand such that future use-cases can be evaluated.

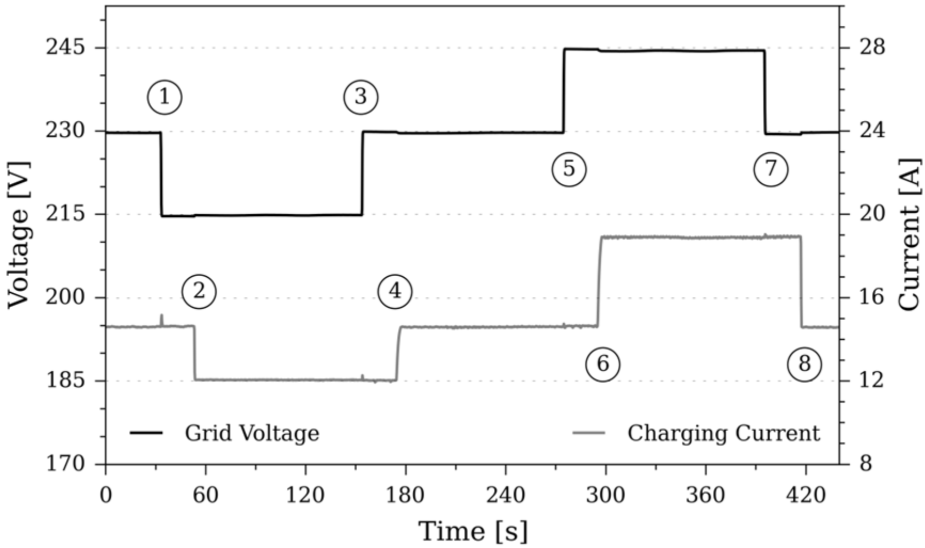

Figure 6: *Measurements of the simple Smart Charging Algorithm.*

7 OUTLOOK

Future work will focus on the implementation and validation of the three major hardware components identified: the grid, the EVSE and the EV. In addition to the currently available hardware, all components will be implemented to support simulation and emulation. The grid itself is already available as simulation, emulation and real hardware due to the SmartEST Laboratory facilities.

Using real EVSE/EV in the test set-up reduces the ability to quickly run multiple test cases. Emulating these components increases the flexibility and accuracy of the test system.

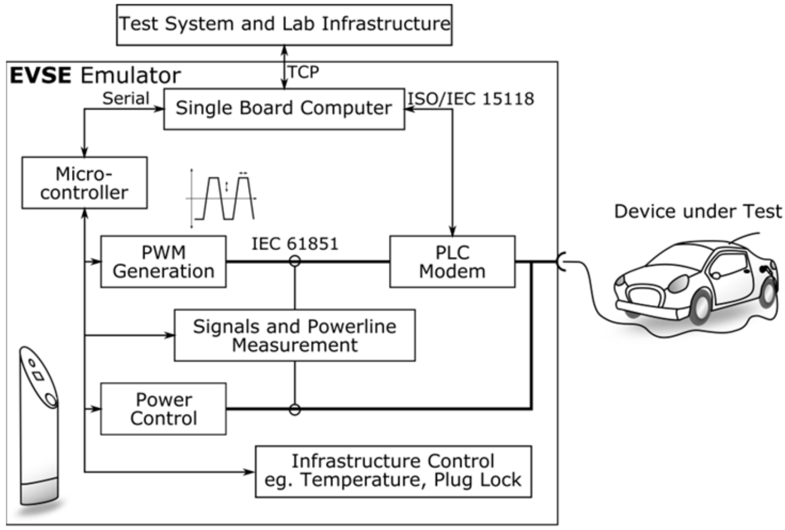

Figure 7: *Concept of the EVSE-emulator.*

Figure 7 shows the main components of the EVSE emulator. The interface to the test system is a TCP-connection to a single board computer. This computer controls a microcontroller and a PLC-interface, which provides communication according to ISO/IEC 15118. The Microcontroller communicates with the EV according to IEC 61851 via a PWM-signal. This signal can be distorted in order to test the systems sensitivity to decreasing signal quality. The infrastructure control handles additional EVSE peripherals like the plug lock motor, ventilation of the charging station and temperature monitoring.

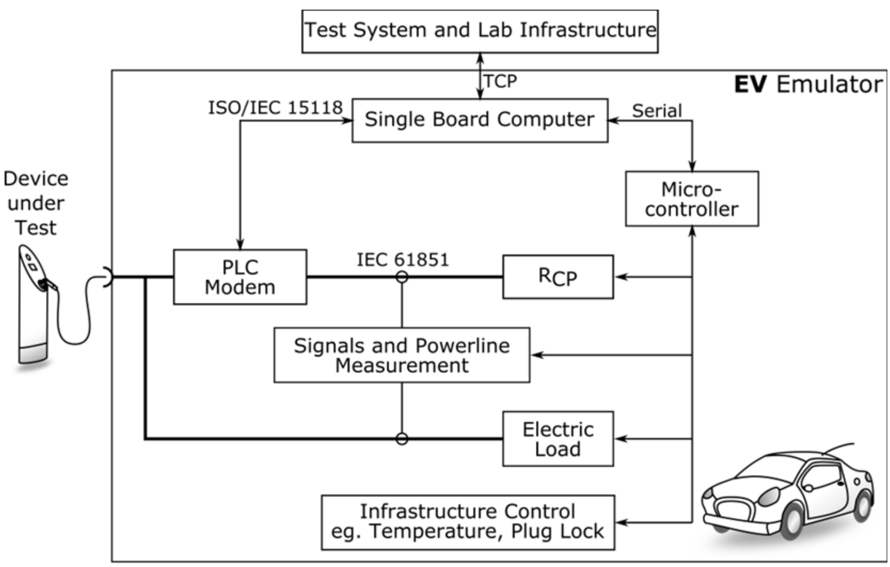

Figure 8: *Concept of the EV-emulator.*

Figure 8 shows the components of the EV emulator, which uses the same basic components like the EVSE emulator: a single board computer to communicate with the test system and the microcontroller, a PLC-interface, and an infrastructure control unit. Additionally, the microcontroller communicates with the EVSE by manipulating the EVSE-provided PWM signal (R_{CP}). The electric load is used to emulate the power sink of the EV and will include a battery model in the future.

8 CONCLUSION

The test infrastructure discussed in this paper provides a comprehensive environment for EV and PHEV charging interoperability and grid compliance testing. The rise of e-mobility as future major player in the transportation system and the challenges and opportunities that open up for smart grid-e-mobility interactions require such a profound testing infrastructure.

The ability to integrate large scale simulations and real actors of the e-mobility and smart grid environment into the laboratory set-up gives the opportunity to evaluate different functions and services and their real consequences for both the grid and the EV. The emulation of the electric grid enables to test the behaviour of the EV during grid failures as well as different grid conditions. As an example a smart charging use-case was reported that clearly demonstrates the functionalities of the test environment.

The test infrastructure described enables to evaluate and investigate the true interactions between the EV/EVSE and the grid. This Investigation will be possible for all operation conditions and modes of the EV/EVSE and the grid utilizing the different functions and services that are expected to interlink the smart grid and the e-mobility.

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INTEROPERABILITY ANALYSIS OF ELECTRICAL NETWORKS WITH ELECTRIC VEHICLE CHARGING DEVICES AND DISTRIBUTED ENERGY RESOURCES

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Keywords: electric vehicle charging, EV charging load profiles, distribution networks, smart EV charging, smart grid management, storage control, power system stability.

ABSTRACT

This article presents a fast and computationally efficient approach for interoperability analysis of distribution networks with electrical vehicle (EV) charging devices and distributed energy resources (DER). A set of non-constrained typical load profiles of EV charging modes according IEC61851 is studied. Based on the time varying electrical parameters of the EV charging, loads and local distributed generation in each network node the dynamic variation of the grid parameters is obtained. A software realization and a representative test case of 24h time domain analysis of distribution network with EV and DER is presented. The main problematic grid issues arising due to the EV charging are distinguished. As a possible solution a monitoring and control system is presented to improve the interaction between power system and EV charging units. IEC61850 standard is used for data transfer between the local and global monitoring systems. The approach is widely applicable for various network studies considering EV and DER control algorithms testing, grid stability analysis, smart charging and grid power management et al.

1 INTRODUCTION

The electric vehicle (EV) charging devices promise to be one of the most significant challenges for the contemporary microgrids and distribution networks [1, 2, 3, 4]. The European Commission urges the member states to increase their EV share and charging stations infrastructure [5]. EV chargers represent significant loads for the low voltage distribution networks due to the ability of these devices to influence substantially the network parameters [1]. Considering the fact that the electrical networks are already built and the upgrades are difficult, time consuming and expensive new charging control and energy management strategies have to be found in order to allow adequate penetration of the electrical vehicle charging devices into the network. At the same time the presence of bidirectional EV storage has a very good potential to offer novel power balancing and grid support services, by providing dispatchable load or generation [1, 6, 7].

These trends will gradually change the philosophy and the operation concepts of the distribution networks. Since the distribution networks are not originally intended for such kind of operation a special attention and analysis of both network parameters, charging and grid feeding processes has to be performed in order to guarantee proper interoperability of these devices with the network. Although some interoperability testing standards like IEC 61851, ISO-IEC 15118 and IEC 62196 are already present the interaction between the grid infrastructure and the EV is still a critical factor [2, 5].

Unlike the most industrial systems the electrical power system exhibits complex inherent with multi dimensionally coupled physical parameters in each of its various nodes, all of them together depending on the features of each individual element. The smart grid functionality is strongly dependent on the interaction between power system and information system which requires interdisciplinary knowledge and expertise. Before entering in the real world the newly defined smart charging and power management solutions have to be tested not only separately in a limited laboratory environment but also the global performance and interaction within a multi node power system also has to be tested. Since the physical power system testing experiments are not feasible a computer based power system analysis techniques are used [8, 9].

The main purpose of this article is to present an approach for interoperability analysis of distribution networks with electric mobility charging devices using long-term quasi-dynamic simulation analysis.

2 METHODOLOGY

Different power system analysis techniques are currently available. The classical power flow analysis offers very fast and accurate computation of the network state parameters even for multi node power system. However, it is limited to only one operational state and since the EV charging process proceeds in a specific manner over the time this simple approach cannot give a deep in-sight.

On the other side, the conventional time domain simulations using differential equations are complicated and very time consuming for multi node power systems especially when analyses of slow dynamic processes with duration from tens of hours to days have to be performed.

In this work, a “quasi-dynamic” simulation using modified nonlinear algebraic equations is applied for slow dynamics time domain analysis [1] of the EV charging devices operation in the network. Its applicability has been already proved and well accepted for long- term analysis of networks with distributed energy resources [10]. The approach uses a concept of division of the variables in “fast” and “slow”, with very different time constants, under the assumption that fast transients settling time is shorter than the time step used for the slow variables simulation.

Focusing on the slow variables, the evolution of the grid parameters over the time is simulated as a sequence of steady state snapshots. For each snapshot, a static grid model is used for studying the power system behavior in response to slow variation of loads, generations and other input settings. The “quasi-dynamic” type of simulations is characterized by time constants of tens of seconds to hours. Since the processes and the variables are very slow, the typical simulation time steps are within the same range.

The “quasi-dynamic" analysis is best suited for time domain simulations with duration from several minutes to several weeks [10]. These types of simulations are useful for interoperability analysis between the EV charging devices and the other network players and components. Moreover it is also useful for analyses of the power system behavior due to slow variations, studies on power and energy management, active and reactive power balancing, demand side management, voltage control strategies, determination of the proximity to operating limits, power system stability etc. The main variables of interest for the quasi-dynamic analysis of the electrical power system are the node and branch variables: voltage magnitude, voltage phase, active and reactive power. The state of each node in each individual snapshot is given by the state equations:

$$P_k = \sum_{m \in k} V_k V_m (G_{km} \cos\theta_{km} + B_{km} \sin\theta_{km}) \quad (1)$$

$$Q_k = \sum_{m \in k} V_k V_m (G_{km} \sin\theta_{km} - B_{km} \cos\theta_{km}) \quad (2)$$

Where P_k is the active power at node (bus) *k*; Q_k - Reactive power at node k; V_k - Voltage magnitude at node k; V_m - Voltage magnitude at node m,

$\dot{Y}_{km} = G_{km} + jB_{km}$ - Element *k, m* from the bus admittance matrix;

θ_k - Voltage angle at node k; θ_m - Voltage angle at node m, and $\theta_{km} = \theta_k - \theta_m$.

A more detailed mathematical and algorithmic description of this method is given in [1].

3 COMPONENTS MODELING

If none network constrains are present each individual EV charging device in each network node can be modeled using its active and reactive load profile over the time. When EV storage interaction is studied, each device is represented via active and reactive power node vectors over the time. In case of smart grid power flow control the charging devices node variables can be set as dependent on the network parameters at the point of common coupling. If bidirectional EV charger-inverters are present the active and reactive power consumption and generation is defined.

Inherently the EV charging load profile is similar with any battery charging load profile. However some typical properties need to be noted. The most EV batteries possess high capacity and low internal resistance. The initial battery charging current during the "bulk" charging phase can be significantly higher than the one in the conventional storage batteries. However the charging power in this phase is most commonly limited from the charging infrastructure which finally results in constant power charge. IEC61851 defines 4 standard charging modes [11] (fig. 1)

Output Mode	Specific connector for EV	Type of charge	Maximum current	Protections	Special features
Mode 1	No	Slow in AC	16 A per phase (3.7 kW - 11 kW)	The installation requires earth leakage and circuit breaker protection	EV connection to the AC network using standard power connections
Mode 2	No	Slow in AC	32 A per phase (3.7 kW - 22 kW)	The installation requires earth leakage and circuit breaker protection	Special cable with intermediate electronic device with pilot control function and protections
Mode 3	Yes	Slow or semi-quick Single-phase or three-phase	In accordance with the connector used	Included in the special infrastructure for EV	EV connection to the AC power supply using a specific device (SAVE)
Mode 4	Yes	In DC	In accordance with the charger	Installed in the infrastructure	EV connection using a fixed external charger

Figure 1: *Charging modes according IEC 61851.*

After the bulk phase is completed an "absorption" phase with constant voltage is applied. During this phase the charging power decreases until the charging process is terminated.

The charging profile depends also on the initial state of charge (SOCi) and the battery state of health (SOH). [12, 13].

In order to estimate the impact of the electrical vehicles on the grid an analysis of the charging parameters of the currently best-sold EV's is made. A set of typical charging load profiles is extracted and presented. The load profiles are constrained and dependent from the charger maximum power, battery initial state of charge (SOC), battery capacity, battery maximum acceptable current, battery resistance, battery temperature. The load profiles are derived from real life charging process records and manufacturers information. Several typical charging modes as defined in IEC 62196 and IEC 61851 are considered.

Fig. 2 presents load profiles of 3,6kW Mode 1 and a 6,6kW Mode 2 charging process of EV with 16 kWh batteries, starting from 15% initial state of charge (SOC).

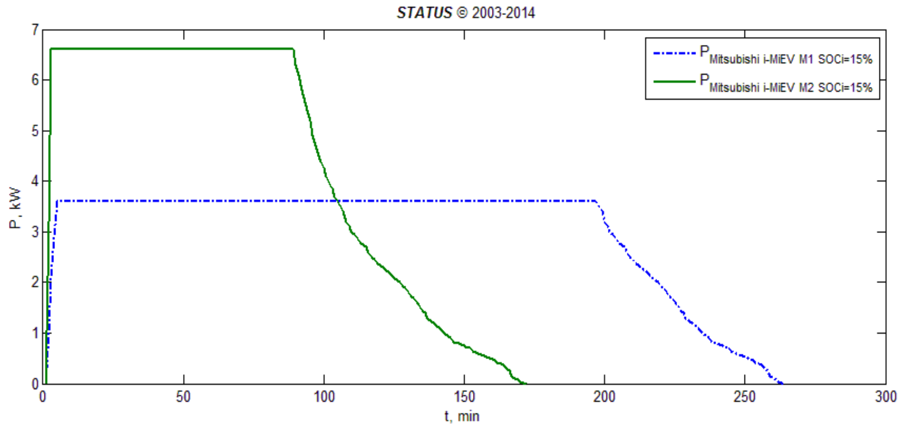

Figure 2: *Load profiles of 3,6kW Mode 1 and a 6,6kW Mode 2 charging.*

Fig. 3 presents load profiles of 3,6kW Mode 1, 6,6kW Mode 2, 22kW Mode 3 and fast DC charging Mode 4 of EV with 24 kWh batteries, starting from 40% initial state of charge (SOC).

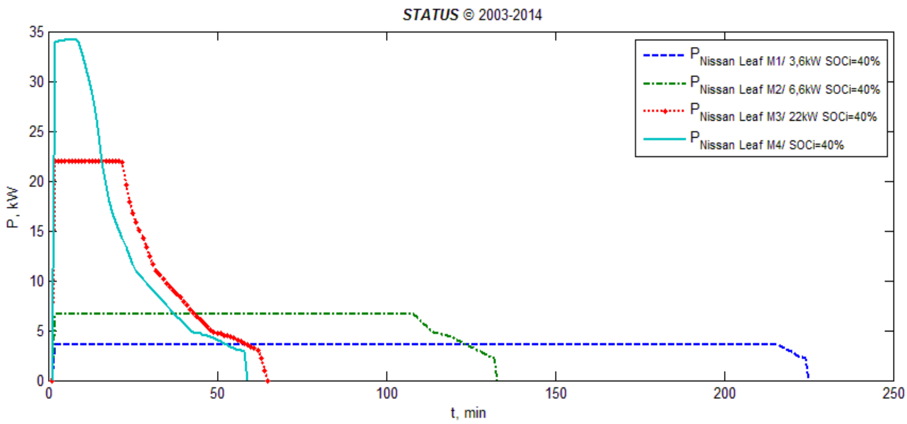

Figure 3: *Load profiles of 3,6kW Mode 1; 6,6kW Mode 2; 22kW Mode 3 and fast charging Mode 4.*

Fig. 4 presents load profiles of fast charging Mode 4 of EV with 60 kWh and 85 kWh batteries, starting from 10% initial state of charge (SOC).

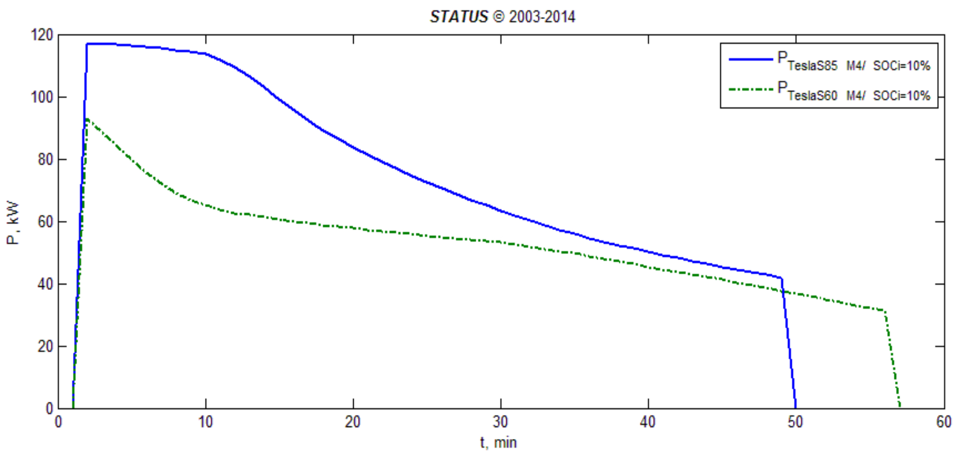

Figure 4: *Load profiles of Mode 4 fast charging of EV with 60 kWh and 85 kWh batteries.*

The loads and the distributed generators are similarly represented.

4 TEST CASE

A representative simulation test case of existing 0,4 kV, 21 bus distribution network of a village near Sofia, Bulgaria is presented (Fig. 5) [14,15].

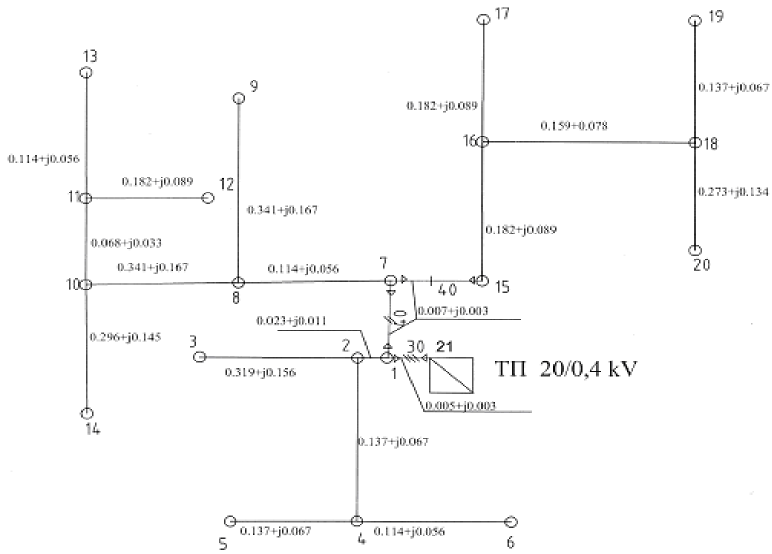

Figure 5: *One-line scheme of the tested system.*

The network (Fig. 5) has uniformly distributed, symmetric, predominantly active load. The minimal and the maximal domestic loads without EV charging are Pmin=33,2 kW and Pmax=110,8 kW respectively. Two inverter tied photovoltaic generators are interconnected at bus 10 and at bus 18. The photovoltaic generator

G1 with nominal power PG1=30 kW is connected at bus 10. The photovoltaic generator G2 with nominal power PG2=50 kW is connected at bus 18.

A presence of 10 electrical vehicles totaling 7% of the vehicles in the village is assumed. The average daily run per vehicle is 64 km achieved using 13,2 kWh. A probabilistic distribution of the EV charger placement, starting moment of the charging and the initial SOC is applied similarly to the purpose in [3 and 4]. It is supposed that the most EV users will start the charging after returning home after work which occurs most probably at 18:30h.

The case study represents a quasi-dynamic simulation over a typical 24 h period. The simulation time stamp is 1 minute. Based on the network data and the load, generation and charging profile data for each individual node the system parameters over the time are computed. In order to obtain specific and clear results the interaction of the protection devices is prohibited.

The following scenarios are considered:

1) *Scenario 1* Base case scenario of network operation without EV charging. The load is supplied from the transformer station and local PV generation;

2) *Scenario 2* Multiple EV applying charging Modes 1, 2, 3 and 4;

3) *Scenario 3* Multiple EV applying charging Mode 1 and 2.

Table 1 presents the EV charging load profile data in scenario 2 and 3 giving the load profile pattern, initial moment of charging start t_i, min and the charging device interconnection node *Bus №*.

***Table 1:** EV charging load profile description*

	Scenario 2		*Scenario 3*	
Bus №	t_i, min	***Charging device load pattern***	t_i, min	***Charging device load pattern***
12	1144	Mitsubishi i-Mi, Mode1, SOCi=15% 3,6kW	1144	Mitsubishi i-Mi, Mode1, SOCi=15% 3,6kW
14	1112	Mitsubishi i-Mi, Mode2, SOCi=15% 6,6kW	1112	Mitsubishi i-Mi, Mode2, SOCi=15% 6,6kW
13	1045	Mitsubishi i-Mi, Mode1, SOCi=15% 3,6kW	1045	Mitsubishi i-Mi, Mode1, SOCi=15% 3,6kW
17	821	Mitsubishi i-Mi, Mode2, SOCi=15% 6,6kW	821	Mitsubishi i-Mi, Mode2, SOCi=15% 6,6kW
4	1087	Nissan Leaf Mode1, SOCi=40%, 3,6 kW	1087	Nissan Leaf Mode1, SOCi=40%, 3,6 kW
20	1020	Nissan Leaf Mode2, SOCi=40%, 6,6 kW	1020	Nissan Leaf Mode2, SOCi=40%, 6,6 kW
18	1121	Nissan Leaf Mode3, SOCi=40%, 22 kW	1121	Nissan Leaf Mode3, SOCi=40%, 22 kW
10	230	Nissan Leaf Mode4, SOCi=40%, fast charge	230	Nissan Leaf Mode4, SOCi=40%, fast charge
16	972	Tesla S 60, SOCi=10%, Mode fast charge	972	Mitsubishi i-Mi, Mode2, SOCi=15% 6,6kW
8	1097	Tesla S 85, SOCi=10%, Mode fast charge	1097	Mitsubishi i-Mi, Mode2, SOCi=15% 6,6kW

Fig. 6 presents the aggregated domestic load, PV generation and EV load.

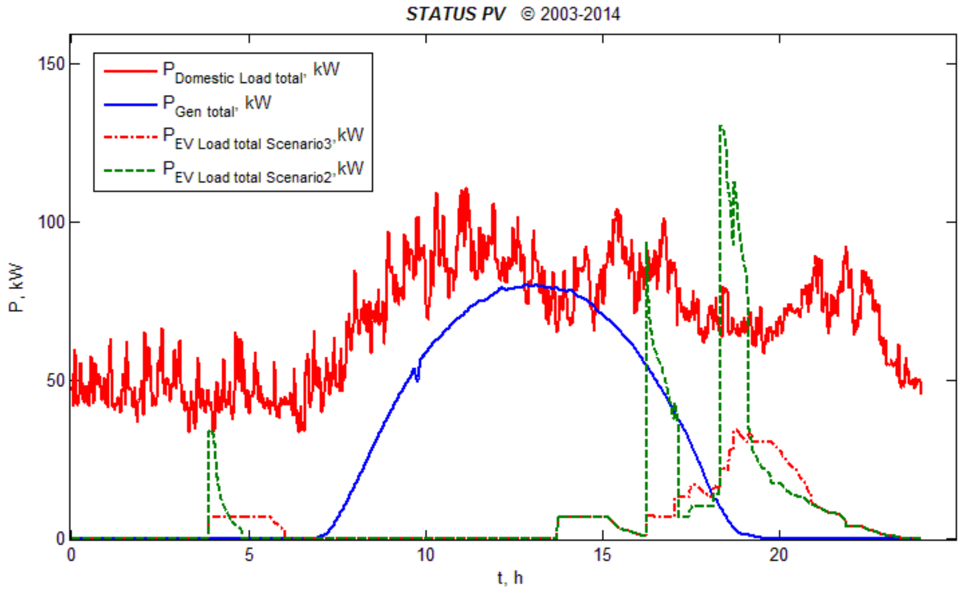

Figure 6: *Aggregated load and PV generation profile without EV charging.*

5 SIMULATIONS RESULTS

The following results for the test case simulation scenarios are obtained:

1) *Scenario 1* Fig. 7 presents the voltage variation in each bus over the time when EV charging is not present. The active power injection of the PV generators causes significant voltage rise during the midday generation maximum. With transformer tap setting of V=1.00 p.u. the maximum voltage reaches 428 V and the voltage variation band is 72V correspondingly (Fig. 7). Due to the presence of distributed generation close to the load the electrical distance between the sources and the consumers remains small which finally results in admissible power and energy losses (Fig. 10). The energy losses in this case are 42,25 kWh.

2) *Scenario 2* Fig. 8 presents the voltage variation in each bus over the time when Mode 1, Mode 2, Mode 3 and Mode 4 EV charging is applied. The EV charging devices cause significant and unacceptable voltage deviations and power line overloading- especially during the Mode 4 fast charging processes (Fig. 4). The maximum voltage remains 428 V and the minimum voltage value reaches 310 V. The voltage variation band is 118V. The line overloading during the fast charging modes results in significantly increased power and energy losses in this scenario (Fig. 8). The energy losses in this case reach the remarkable value of 71,92 kWh.

3) *Scenario 3* The EV charging devices cause significant voltage deviations also when Mode 1 and Mode 2 charging is applied. Fig. 9 presents the voltage variation in each bus over the time. The maximum voltage remains 428 V and the minimum voltage value reaches 335 V. The voltage variation band is 93V. The energy losses

in this case are 56,90 kWh. Although the system state is not admissible it has to be however noticed that it is still less critical than in Scenario 2.

Table 2 summarizes the results obtained for each scenario.

Table 2: *Simulation results summary*

Scenario	*Umin,V*	*Umax,V*	*ΔU,V*	*ΔE,kWh*
1) Operation without EV charging	356	428	72	42,3
2) Mode 1,2,3 and 4 EV charging	310	428	118	71,92
3) Mode 1 and Mode 2 EV charging	335	428	93	56,90

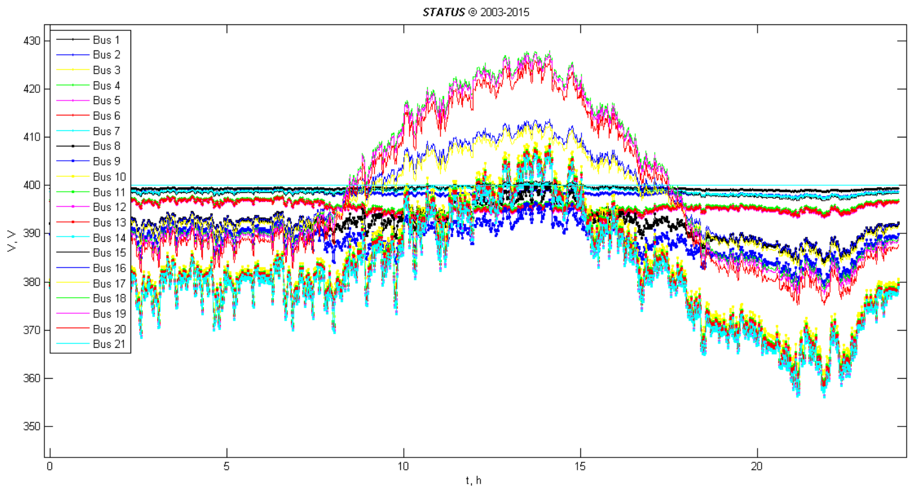

Figure 7: *Voltage profile evolution without EV charging (Scenario 1).*

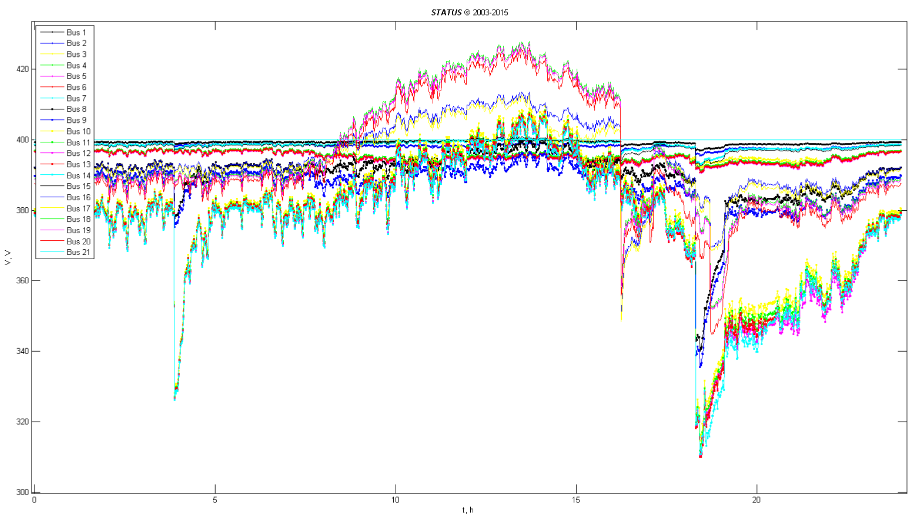

Figure 8: *Voltage profile evolution with Mode 1, 2, 3 and 4 EV charging (Scenario 2).*

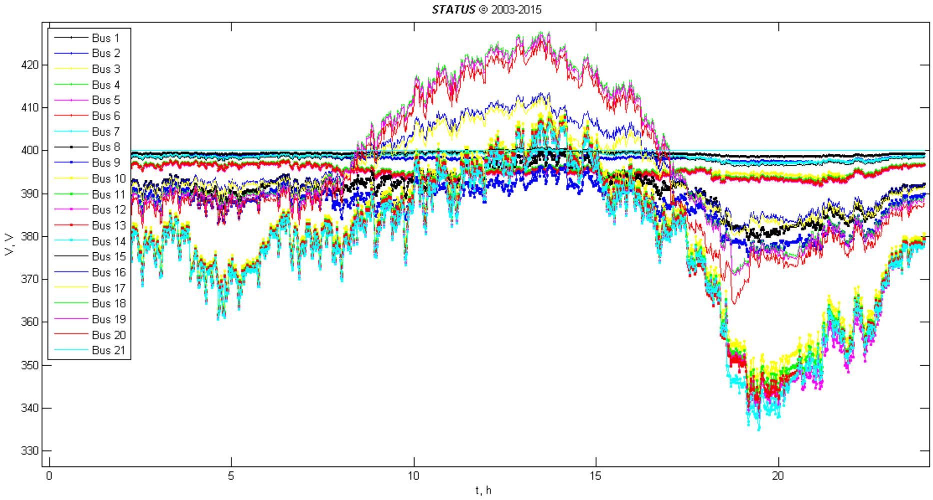

***Figure 9:** Voltage profile evolution with Mode 1 and Mode 2 EV charging (Scenario 3).*

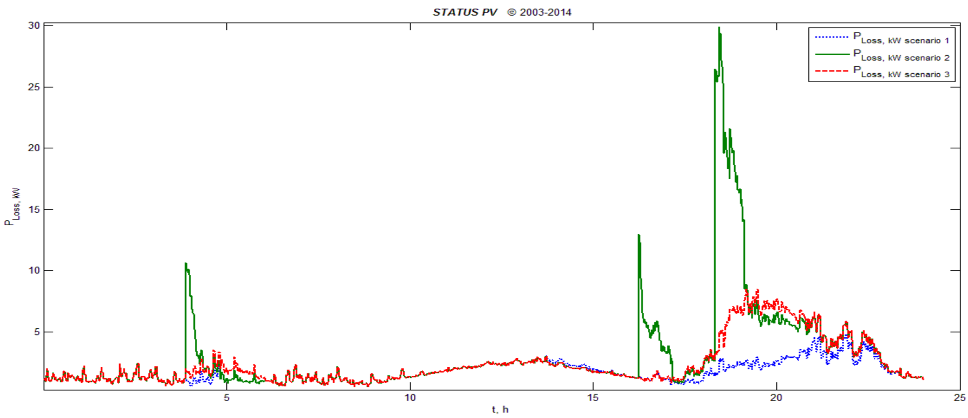

***Figure 10:** Aggregated power losses evolution during Scenario 1, 2 and 3.*

6 SYSTEM FOR EV CHARGING MONITORING AND CONTROL

In both scenarios with EV charging and especially in Scenario 2, high energy consumption peaks are present. Depending on market conditions an energy consumption schedule could be active. In this case the power peaks and the network congestions are limited. To solve the problems presented a control system with measurement of the technical parameters and calculation of optimal charging regimes could be implemented. A SCADA ensures measurement of the consumed active and reactive power, energy, current, frequency, battery charge voltage and current (Fig. 11 and Fig. 12).

The control system allows limitation of the consumed power depending on the current technical situation and market conditions. Two main modes of charging are available:

- The fast charging mode
- The economy charging mode

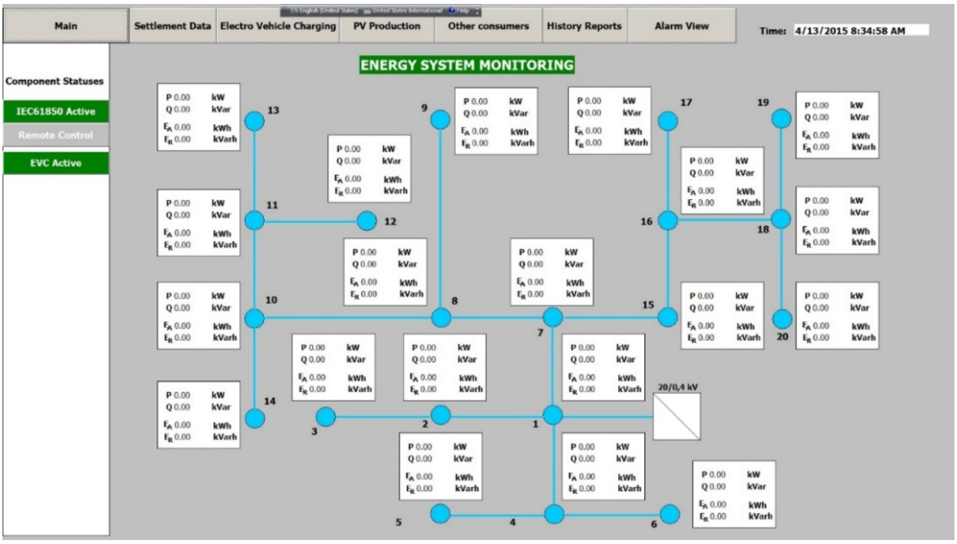

Figure 11: Main screen of SCADA for the tested system.

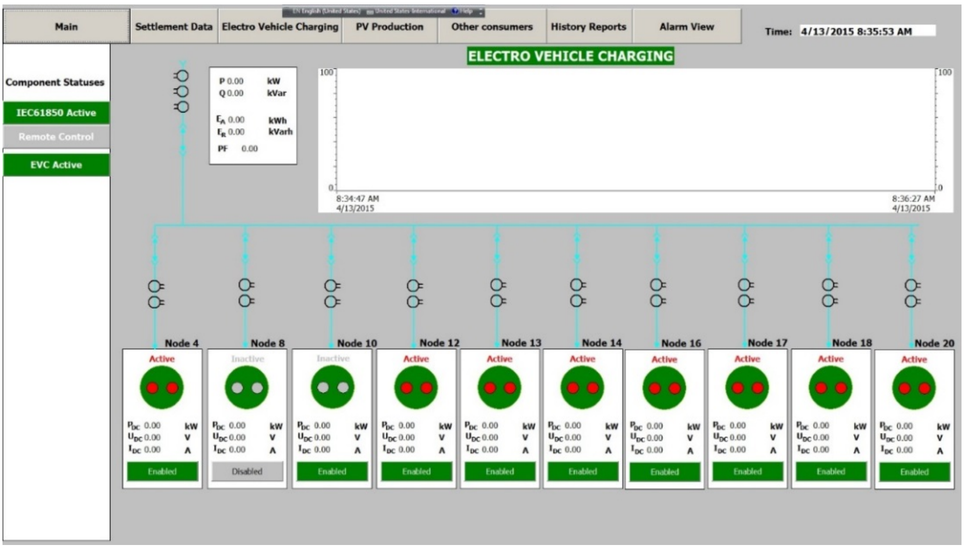

Figure 12: EV charging monitoring and control of the tested system.

In fast charging mode the limitations are only in power derivative which clears the rapid power changes in the system (Scenario 2). In economy charging mode the system calculates the available power as a difference between the scheduled set point for power consumption in the system and the total real consumed power of the system. In this case optimization algorithm [16, 17] distributes the power between the active battery chargers based on the optimality criteria:

$$F(x) = \beta\left|\left(\sum_{i=1}^{n} P_i\right) - P_A\right| \rightarrow min \qquad (3)$$

where:

β is the difference between the scheduled price of electricity and the price on the electricity free market.

P_i - is the available power of the i-th EV;

P_A - is the total available power for EVs charging.

The power and its derivative constrains are given by:

$$\beta = \begin{cases} \beta_1 \; if \; (\sum_{i=1}^{n} P_i) - P_A > 0 \\ \beta_2 \; if \; (\sum_{i=1}^{n} P_i) - P_A \leq 0 \end{cases}$$

$$P_i^{min} \leq P_i \leq P_i^{max}$$

$$\Delta P_i^{min} \leq \frac{\Delta P_i}{\Delta T} \leq \Delta P_i^{max} \quad (4)$$

where:

P_i^{min}, P_i^{max} - minimum and maximum power requirements for charging;

$\frac{\Delta P_i}{\Delta T}$ – limitation of the gradient for charging of the i-th vehicles.

Selecting the charging mode influence on the minimal power required (P_i^{min}) for charging.

For data exchanging with external technical and market systems IEC61850 Server is implemented (Fig. 13). The standard communication protocol used (IEC61850) guarantee the interoperability of the control system with other similar or larger energy systems.

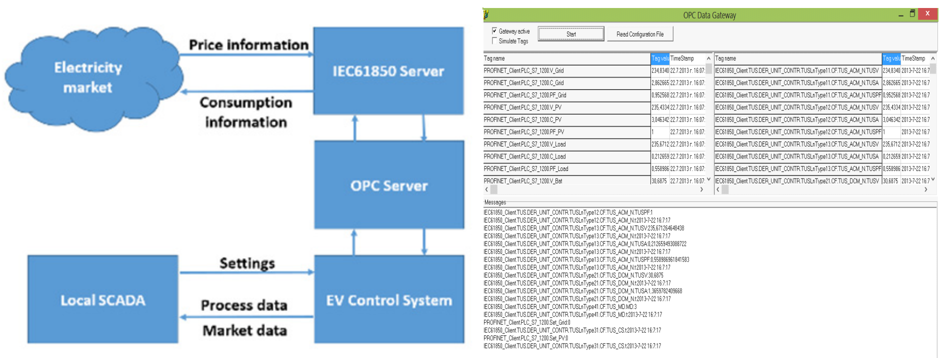

Figure 13: *Information exchange system.*

The market and settlement data are available in Local SCADA system (Fig. 14).

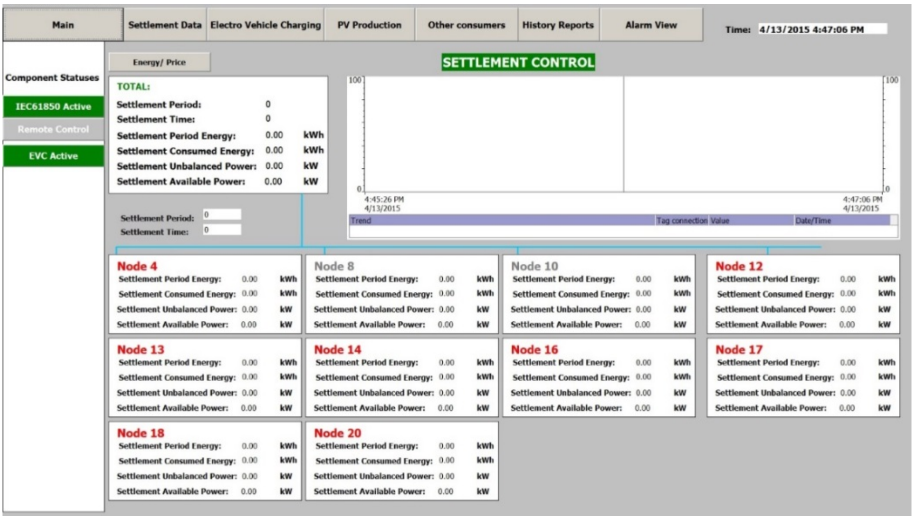

Figure 14: *Settlement Control.*

The implementation of the proposed optimized load control strategy, influencing the peak EV charging loads is demonstrated by considering a test case of application of the EV charging control systems for Scenario 2 with limitation of EV loads at level 30 kW and 20 kW. Fig. 15 presents the original and the optimized charging load. The impact of the control system on the distribution system voltage profile is shown on Fig 16 and Fig 17. With the implementation of the control system the power peaks and the voltage drops are significantly lowered. The voltage of the system during the peak load for some of the nodes of Scenario 2 is 310 V. The implementation of the power limitation control system reduces the power peaks and keeps the voltage levels for the same nodes at 340 V which improves the stability and the quality of the electricity in the distributions system. As a result of the power limitations the time of EV charging is extended. In this example the power is limited at a constant value. It can be also related to the desired load schedule of all loads (domestic and EV). The market prices β are ignored but they also can be implemented in the model which is a subject to the future development of the control system.

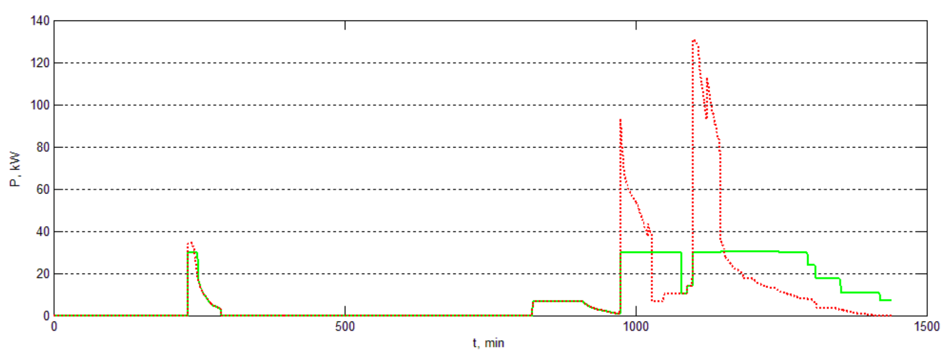

Figure 15: *EV charging power with and without control system at EVC Pmax=30kW.*

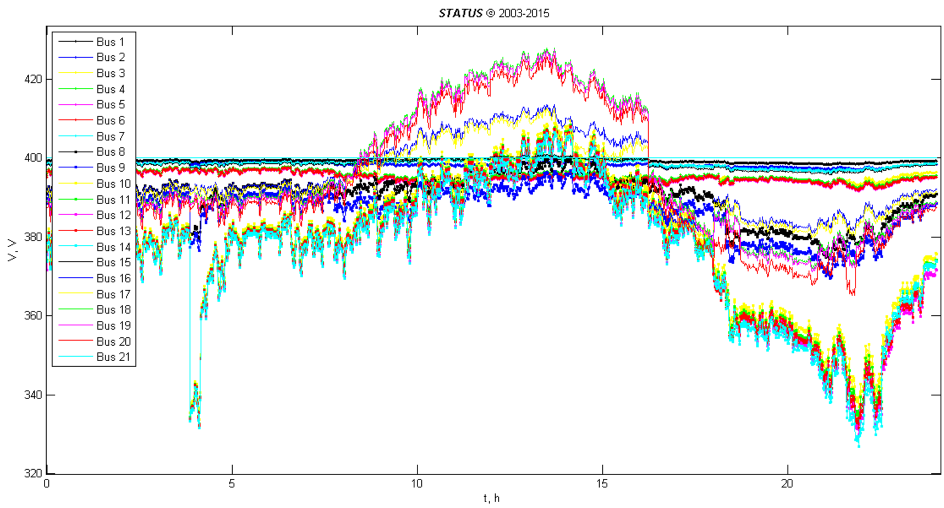

Figure 16: *EV charging power with a control system and EVC power limit P=30 kW.*

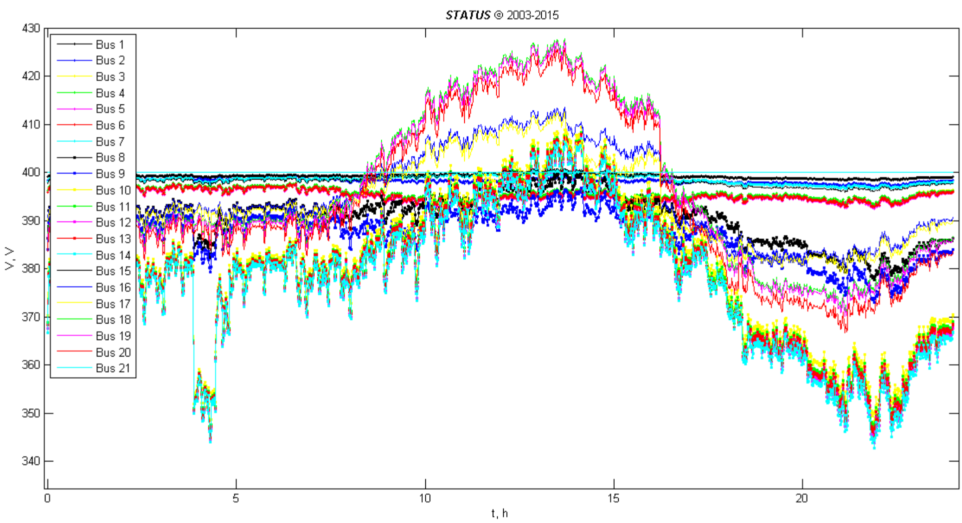

Figure 17: *EV charging power with a control system and EVC power limit P=20 kW.*

7 CONCLUSIONS

A promising and computationally efficient approach for interoperability analysis of distribution networks with EV charging devices and DER is presented. The dynamic simulations test cases confirm that the EV charging represents a significant challenge for the distribution networks, which imposes detailed study. Due to its high computational efficiency the approach is capable and very well suited to represent the multi node network slow dynamics behavior which is vital for the interoperability analysis in long term power hardware in the loop tests and also for the majority of the power system studies like control algorithms testing, EV and DER hosting capacity evaluation, EV charging interoperability testing, grid stability analysis and smart grid power management testing. New properly selected smart grid control concepts have to be defined and analyzed in order to allow stable and reliable network operation with EV charging.

A system for EV charging monitoring and control can be used to improve the power management control and stability of power grids with distributed energy resources. The simulations show good impact on electricity system when the control algorithm is implemented.

8 ACKNOWLEDGEMENT

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LOTTERY-BASED SCHEDULER MODEL FOR ELECTRIC VEHICLE CHARGING IN THE SMART GRID

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Keywords: electric vehicle charging; lottery scheduling; smart grid.

ABSTRACT

Renewable energy sources and electric vehicles (EVs) are gaining more popularity but they may lead to various problems in a grid when there is no implementation of smart strategies. Blackouts, peaks and voltage sags are among possible future grid problems. Long charging times of EV batteries make this problem even worse. Converting current grids to smart grids by using advanced technological equipment and artificial intelligence will also solve these types of problems. The charging problem is very similar to the process-scheduling problem of modern operating systems. This paper presents a lottery-based scheduler model for EV charging. It has been shown by simulation results that the proposed model achieves better average waiting time than other scheduler models. The proposed model can also reduce peak loads by determining the maximum allocation amount.

1 INTRODUCTION

Electric vehicles (EVs) are becoming more popular because of several factors such as technological advances, rising oil prices and low carbon emission policies. Car manufacturers are in a tight competition so that every year they are releasing new and better EV models. Beneficiaries of this competition are not only the consumers but the environment as well. EVs are already accepted as the key mechanism to lower the carbon emission, and this mechanism is expected to help U.K. a %20 decline and to U.S. a %30 decline in emissions [1].

However, this new technology comes with several challenges. One challenge is the problem of installed car batteries. For smartphones, a lot of portable charging technologies exist to overcome battery capacity problems. Similar to smartphone owners, EV owners also need to charge their batteries frequently. Unfortunately, traditional grids are not ready to handle heavy loads that may have been produced by the EV charging processes. A typical EV charging demand is at least 3 times higher than a typical home's total daily usage demand [1]-[3]. High loads may cause blackouts, peaks and voltage sags in the traditional grid; and all of these problems should be avoided.

In order to deal with the peak load problem either we need grids that supply more energy or we need car batteries that consume less energy and have greater capacities. Increasing a grid's energy supply is costly and it is not environmental friendly. Further, it may be a short-term solution if we consider rapidly growing numbers of EVs. Developing a better car battery is another research area and it is not a very easy task to quickly achieve. A feasible way to deal with this problem is developing smarter mechanisms, which will be used to schedule battery-charging demands. Actually, smarter mechanisms should be developed and implemented to convert current grids to smart grids.

In this paper, a scheduler model is proposed for EV charging in the smart grid. The remaining paper is organized as follows. Section 2 summarizes the related work. Proposed scheduler model and other scheduler models are described in Section 3. And then Section 4 discusses the simulation results. Finally, the conclusion is given in Section 5.

2 RELATED WORK

There are a number of papers in the literature that proposed solutions to the EV charging problem. One of these papers used genetic algorithms to solve the electric vehicle-charging problem [4]. In this study, performance measurement data implied that this genetic algorithms based methodology didn't perform much better than a random scheduling method. Another study applied linear programming to calculate and investigate costs of EV charging process [5].

A couple of studies investigated the problem by applying multi-agent system concepts [6-7]. Vandael et al. [6] proposed multi-agent scheduling strategies and they discussed the superiority of their strategies by comparing them with each other. A similar approach [7] introduced multi-agent systems with evolutionary optimization algorithms. In this study, a multi-agent system was developed to response dynamic conditions. The weakness of this study was specified as the computation time; even in the study population size had to be reduced for collecting simulation results.

There are also other contributions in the literature about finding ideal geographical locations to place EV charging stations [8-9]. In one study, coordinated clustering algorithms were used to determine the placement of charging stations in an urban environment [8]. Another study used particle swarm optimization method to decide positions of EV charging stations [9].

Vasirani and Ossowski also proposed a lottery-based allocation policy for EV charging [10]. Although this study is relevant to our model it did not provide a detailed model; and our study benefits from lottery-based scheduling strategy in a different way than this work. Furthermore, the proposed model also focuses on peak load reduction by limiting total allocation amount.

3 SCHEDULING MODELS

In this section, three scheduler models are presented for the charging problem. These models first formulate the problem to be studied as a resource allocation problem. Then a suitable heuristic is used to solve that allocation problem.

3.1 EV Charging Problem

EV charging problem can be described as finding a scheduler model, which distributes the resources in a way that it minimizes the average waiting time of EVs.

There are hourly discrete time slots in the model. For every time slot, a portion of grid's capacity is allocated for EV charging. The amount of this portion is determined according to grid's supply capacity. Since we do not want to allocate a grid's all capacity for EV charging; allocating a small portion of its available capacity for charging is a better approach. This allocation can be either static or dynamic. When the allocation is dynamic, it may also benefit from the real-time pricing data by being a part of a demand response model.

There are some assumptions for the problem. First, all EV batteries are assumed to be charged at the same rate. Second, all EV batteries are assumed to have the same capacity. These assumptions only simplify the construction of the simulation environment and they do not affect the outcome of the study.

EV charging problem can be described as finding a scheduler model, which distributes the resources in a way that it minimizes the average waiting time of EVs.

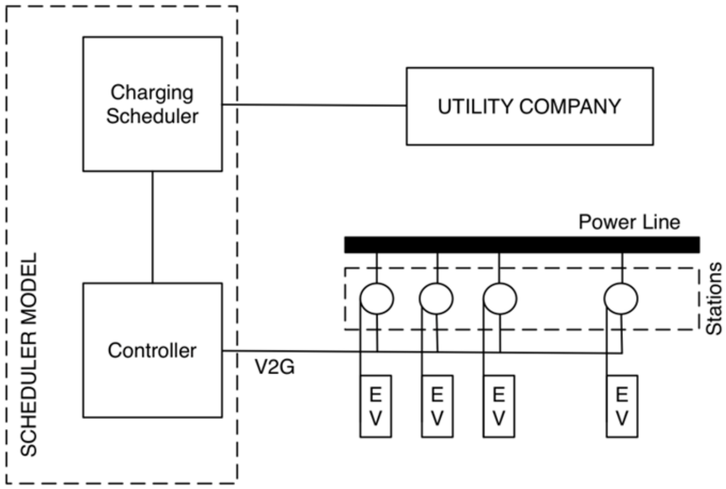

Figure 1: *Proposed scheduler model.*

3.2 The Proposed Lottery-based Scheduler Model

EV charging problem is very similar to the process-scheduling problem of modern operating systems so that it is possible to apply process-scheduling algorithms to the problem. Lottery scheduling is a randomized mechanism where lottery tickets are used to allocate available resources [11]. Clients get resources when they win the lottery. Chance of clients is fair and this chance is proportional to the number of tickets that clients hold.

Lottery scheduling can be generalized and then applied to other type of scientific problems. This methodology efficiently manages shared resources, and it also works fairly when the number of clients or tickets dynamically changes. We decide to adopt this methodology to develop a charging scheduler model.

We propose a scheduler model based on the lottery scheduling methodology. The proposed scheduler communicates with the utility company and EVs waiting at the charging stations. Then, it randomly selects winning lottery tickets to distribute available resources.

In Fig. 1, the proposed scheduler model is presented. In this model, charging scheduler receives grid constraints from the utility company. Grid constraints are used to determine the maximum allocation amount. A demand response model can be used here to dynamically supply these constraints. The controller uses a communication method to receive data from EVs, which are waiting at stations. Charging scheduler uses a lottery-based control strategy to select winning EVs, which will immediately receive resources.

In the scheduling scenario, an EV driver makes a reservation as a charging request. A standard communication mechanism can be used to perform this purpose. After receiving a charging request, the scheduler prepares and distributes lottery tickets.

Each EV receives its lottery tickets. These tickets are uniform and each winning ticket gives chance of one hour charging. A ticket becomes active when it is being selected in the lottery. For a complete charge of an EV, it should use all of its lottery tickets.

An EV sends a terminate message to the scheduler when it finishes the charging process or when it leaves the station before using all of its tickets. In the model, there isn't any starvation problem because an EV with tickets will eventually win the lottery. However, winning lottery isn't enough for satisfactory charging process. Total waiting time is important for every EV, and this amount should be minimized.

Let V = {1, 2, … , m} denotes the set of all EVs in the system and S = {1, 2, … , n} denotes the set of charging stations. A subset of V defines the set of EVs at charging stations so this subset has maximum n elements.

Total number of hours to complete a full charge is denoted with k; so that every new EV receives k tickets in the beginning. Allocating a grid's all capacity to EV charging is not desirable and it may cause peaks. Thus only some of the charging stations are active at a time. This limitation determines the maximum number of winning tickets.

3.3 GA-based Scheduler

A scheduler model based on genetic algorithm (GA) is implemented to test the proposed model. As it is described in Section 1, there are several studies in the literature that applied genetic algorithm to the EV charging problem. In our implementation, each chromosome represents situation of charging stations for a time slot. In this chromosome, the number of genes is equal to the number of charging stations; an active station is represented with value of 1 and inactive station is represented with value of 0.There are hourly discrete time slots in the model. For every time slot, a portion of grid's capacity is allocated for EV charging.

A two-dimensional allocation table produces a candidate solution to the problem. A candidate solution is evaluated according to the fitness function. In our scheduler model, average waiting time is used as fitness value. In GA model, set of candidate solutions create a population. Iterations with genetic operators are expected to evolve the population and to create better generations, where there are candidate solutions with better fitness values.

3.4 Random Scheduler

Random scheduler model is created to test efficiency of smarter scheduling models. In random scheduler model, decision mechanism has no intelligence. In each round active stations are determined randomly. If an EV is waiting at the activated station, charging process will start.

4 SIMULATION RESULTS

Simulations have been conducted to evaluate our proposed model. In the first simulation environment there are 200 EVs, which are randomly distributed to the charging stations. To simulate the lottery-based model, every EV started charging process with 4 tickets. In simulations, average waiting time is calculated by dividing total queuing time by total number of vehicles.

In Fig. 2, the proposed lottery-based model is compared with other models according to the average waiting time. The proposed model performs much better than the random scheduler and GA-based scheduler. In addition to this, average waiting time drops rapidly in the proposed model when the number of available stations is increased. In all models an increase in resources decreases average waiting time, but this performance increase is much better in the proposed scheduler.

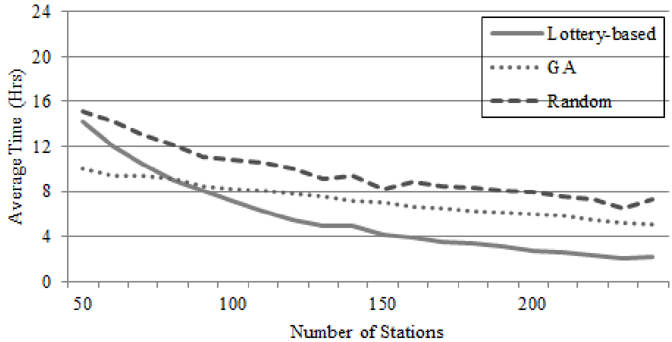

Figure 2: *Impact of number of stations.*

In the second simulation environment, average waiting time is analysed when the number of stations is constant and the number of EVs is increasing. In Fig. 3, it is observed that the proposed scheduler model performs better than the other scheduler models. The performance margin is bigger when there are either more resources or fewer EVs.

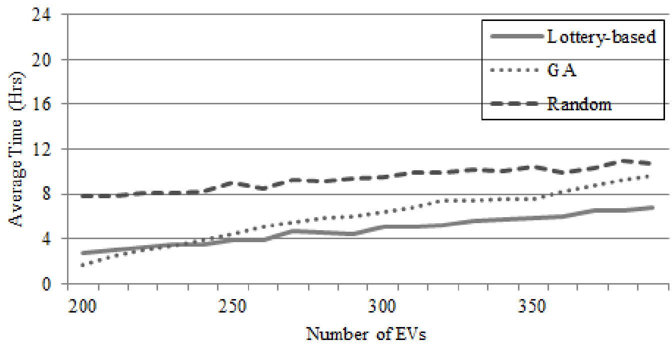

Figure 3: *Impact of number of Electric Vehicles.*

5 CONCLUSIONS

A lot of research has been carried out about EV charging because integrating high number of EVs into grids may lead to problems. In this paper, we present a lottery-based scheduler model for EV charging. EV charging problem is very similar to the process-scheduling problem in operating systems. Hence, lottery-scheduling methodology was selected and used to construct an EV scheduler model. The simulation results show that the proposed model achieves a better performance than other scheduler models.

In the future, we plan to extend our study by comparing the proposed scheduler model to the models based on different heuristics.

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AN EV MANAGEMENT SYSTEM EXPLOITING THE CHARGING ELASTICITY OF EV USERS

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Keywords: Electric Vehicles, Load Management, Smart Charging.

ABSTRACT

Besides the economical and environmental benefits introduced by electric vehicles (EVs), the mass roll-out of EVs can significantly modify the demand profile of distribution networks. This may provoke several network operational issues, such as voltage excursions and grid equipment overloading depending on the grid characteristics. In order to avoid such issues, it is necessary to implement EV smart charging management. This paper aims to introduce a centralized management scheme aiming to meet the energy charging requirements of EV users without violating network technical constraints. The proposed energy management algorithm exploits the elasticity offered by EV users, i.e. the non-commuting period is longer than the requested time for a full charging, in order to shift the EV charging demand from hours with network operational issues to subsequent ones. The proposed EV charging management defines the set-points of each EV considering EV users' charging requirements, the duration of plug-in period and the network operational capacity defined by the system operator.

1 INTRODUCTION

The intense interest in developing and deploying electric vehicles (EV) and plug-in hybrid electric vehicles (PHEV) technology is depicted by the ambitious national targets being announced around the world for the increase of EV/PHEV sales. The review in [1] is indicative reporting an annual production of over 100 million vehicles by 2050. However, it is expected that the mass roll-out of EV/PHEV [2] will significantly modify the load profile of power systems [3] and it will affect the way distribution networks are operated [4]-[7].More specifically, the integration of EV into distribution networks under the *"plug-n-play"* concept (*"dumb charging"*) can provoke feeder voltage excursions (mainly in rural distribution networks) and equipment overloads (mainly in urban networks). Under such circumstances, the additional EV charging demand will necessitate reinforcement of the existing grid infrastructures, according to the foreseeable EV penetration scenario, aiming to ensure the secure and stable grid operation. By exploiting the demand elasticity offered by EV during non-commuting periods, such premature grid investments can be postponed or deferred.

Therefore, there will be need for developing and implementing EV charging coordination mechanisms which aims to fulfil EV charging energy needs respecting, simultaneously, the grid operational constraints. There are several EV demand management schemes introduced in the literature applying different coordination strategies, such as energy cost minimization, peak shaving, frequency and voltage support, reactive power compensation, harmonic and reactive power compensation etc. [8]. Various approaches can be implemented for EV coordination, such as auction or Lagrangian Relaxation based optimization, "max-weight" policy, Nash certainty equivalence and mean-filed games, non-dominated sort genetic algorithms, droop-based control, resistance emulation methods, etc [9]-[29].

The aim of this paper is to introduce an EV management system which enables the coordination of the charging of an EV fleet considering EV users' energy needs and the grid constraints dictated by the system operator. The maximum additional charging demand that can be served by the existing network infrastructures is defined by the system operator for each time interval (ex. 1 hour or 15minutes). The requested charging demand of the EV fleet under study must not exceed this maximum allowable power. Unless there is violation of that maximum value, the EVs are charged at their maximum charging rate. Otherwise, the excess load must be shifted to subsequent time intervals. The proposed EV management system aims to efficiently allocate the excess load within the next time intervals respecting the mobility needs (i.e. battery state-of-charge) and constraints (i.e. arrival and departure time) of EV users as well as the additional demand capacity of the network. The proposed energy management system exploits the demand flexibility offered by EV users, when the required charging duration for full battery charging is shorter than the available parking period, such that all EVs are fully charged at the departure time. In extreme cases, such when the grid is highly stressed during a period and the network capacity is not adequate to completely serve the charging energy requirement of the EV fleet, a percentage of the EV batteries remains uncharged. This percentage is decided by the EV management system introduced in this paper based on some criteria: the elasticity offered by the EVs, the battery's state-of-charge (SOC) and the time remained parked without being charged.

In Section 2, the operation of the proposed management system is explained. The efficiency of the proposed EV management system is assessed by examining a Medium to Low Voltage (MV/LV) transformer serving commercial non-EV loads and a charging infrastructure network. The simulation parameters and the scenarios under study are presented in Section 3. The results are presented and analyzed in Section 4, while conclusions are drawn in Section 5.

2 EV CHARGING MANAGEMENT SYSTEM

The scope of this section is to present the proposed EV charging management system. The operation of the proposed EV management system is illustrated by the flowchart in Figure 1.

Initially, a grid analysis is necessary to be performed considering the non-EV demand so as to define the maximum allowable charging demand (P_{av}) in each time interval. Unless this maximum value is violated, all EVs are charged at the maximum charging rate defined by the nominal power of the charging station and the EV battery's operational constraints. In case that the aggregated EV charging demand cannot be completely served during a time interval, due to network operational constraints, part of the charging demand should be shifted to subsequent time intervals avoiding network congestion issues. The number of EVs that must remain idle during the problematic time interval is defined by the proposed EV management system based on the following criteria:

1. Maximum charging demand that can be served by the existing network infrastructure.
2. Duration of the non-commuting period
3. The battery energy consumption of the EVs before plugging-into the grid
4. The number of time intervals an EV forced to remain idle while plugged-in in order to avoid grid operational issues.

More specifically, during a time interval, the plugged-in EVs are classified into two categories: the first one (A1) comprises the EVs that were connected into the grid in a former time interval, while the second one (A2) comprises the EVs that have just arrived in a charging station. The number of EVs that can be charged in the current timeslot is defined in respect to the P_{av}. In case that the charging demand of plugged-in EV (both categories A1 and A2) does not provoke any network issue, they are charged with the maximum charging power rate defined by the charging infrastructure. Otherwise, the plugged-in electric vehicles are discriminated into two groups: those which offer charging elasticity and those do not.

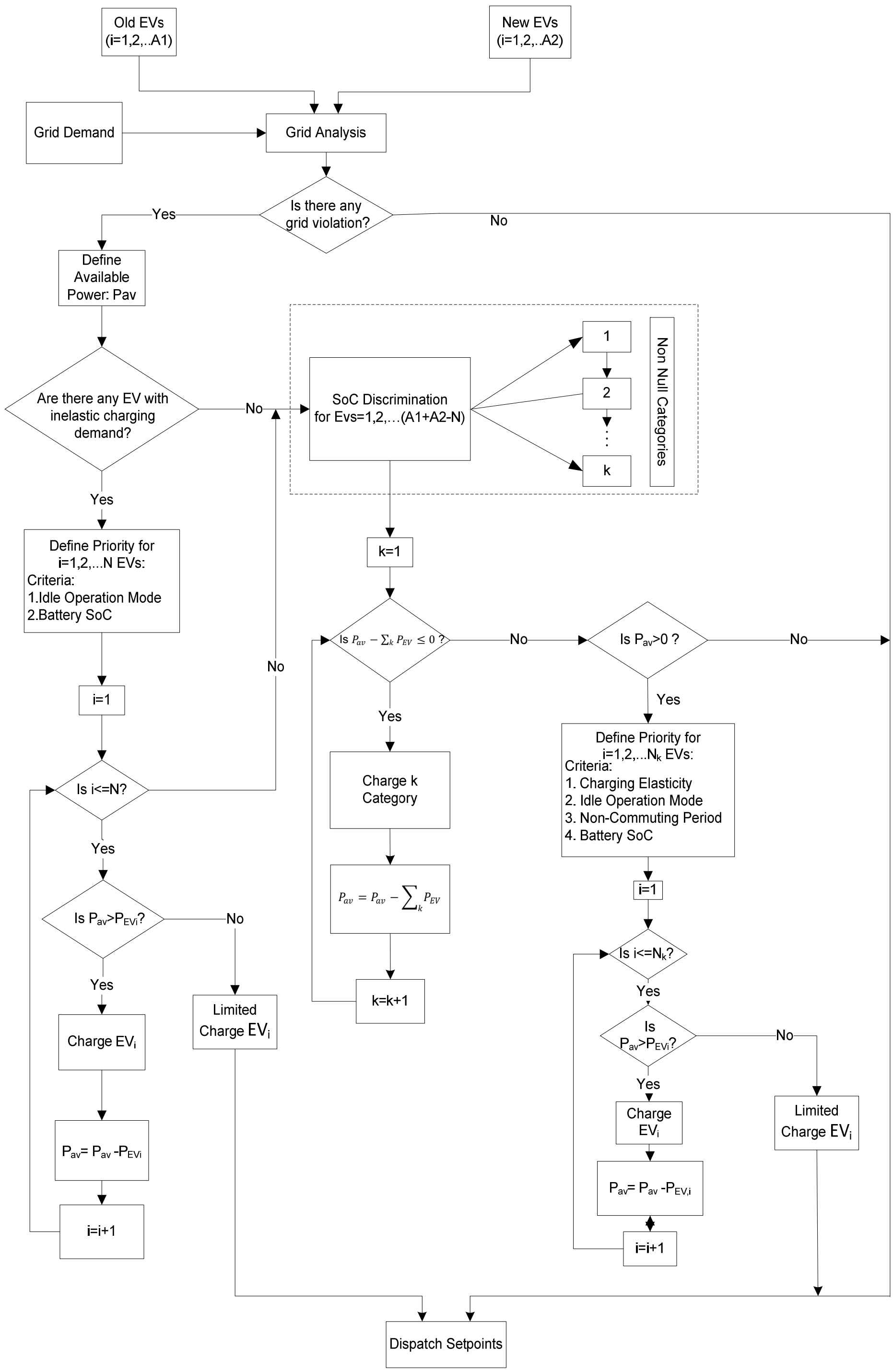

Figure 1: *Flowchart of the Management System's Operation.*

The Elasticity (E) offered by each EV is defined as:

$$E = \left(T_{departure} - T\right) - \left(T_{full}\right) \quad (1)$$

where $T_{departure}$ is the departure time of the vehicle, T is the time interval examined and T_{full} defines the number of the requested charging time intervals for full battery charging. The parameter T_{full} is calculated taking into account the energy E_{full} required by the EV to get fully charged, which is calculated as

$$E_{full} = (1 - SOC) * C \quad (2)$$

where C is the battery capacity of the EV defined in kWh. Therefore, the amount of time for a vehicle to get fully charged can be calculated by the following formula:

$$T_{full} = \frac{E_{full}}{P} \quad (3)$$

where P is the nominal power of the charging infrastructure.

EVs without elasticity are prioritized compared to the ones offering elasticity. The EVs with inelastic demand (N) are placed in a priority list considering the following criteria: the number of time intervals an EV remained idle during non-commuting period and the battery's SOC. The EV with the largest number of idle operational mode and the lowest SOC presents the highest priority.

Assuming that the EVs with inelastic demand are charged, the respective available power (P'_{av}) for the EVs offering elasticity is defined by the following formula:

$$P'_{av} = P_{av} - \sum_{i=1}^{N} P_{EV,i} \quad (4)$$

where $P_{EV,i}$ is the power to charge the i^{th} EV with inelastic charging demand. As far as the EVs offering elasticity are concerned, they are discriminated into k categories according to their battery's SOC. In this paper, four categories are assumed as they are tabularized in Table 1, considering that the lower the battery SOC is, the higher is the charging priority. The first category is the High priority (H) one which comprises EVs with very low battery charging level, i.e. lower than 30% of the battery capacity. The EVs which battery is highly charged, i.e. the battery SOC is above 90%, are categorized in the low priority category (L). The rest EVs belong to the Average Priority (A) category. This category is further divided into two subcategories: the High-Average (HA) one, EVs with SOC between 30-70% belong here, and the Low-Average (LA) one which comprises EVs with SOC between 70-90 %.

Table 1: *SOC Discrimination*

SOC	***Priority***
0% - 30%	High Priority (H)
30% - 70%	High-Average Priority (HA)
70% - 90%	Low-Average Priority (LA)
90% - 100%	Low Priority (L)

For each one of these categories, the available power from the grid (P'_{av}) is compared to the charging demand of the examined EV category. If the power demand of a certain category exceeds the available grid power, then a percentage of the EVs belonging to this category will not charge. Moreover, in this case, the EVs with lowest priority (if there are) will not be charged as well. The EVs which are not charged are defined in respect to the abovementioned criteria:

1. *Charging Elasticity:* A list of plugged-in EVs according to their charging elasticity is created in descending order. A top-down approach is adopted for curtailing the excess EV demand during the problematic time interval.
2. *Idle Operational mode:* the number of time intervals an uncharged, plugged-in EV did not charge.
3. *Non-commuting period*: the number of time-intervals a vehicle has remained connected to the grid
4. *Battery SOC:* the charging level of the EV battery expressed as percentage of the battery capacity

At the end of the process the management system outputs the charging power for each station, which either is equal to the nominal power of the station (or a fraction of this power) or it is equal to zero, in case the available power is not enough to charge the whole EV fleet.

3. STUDY CASE

A Medium to Low Voltage (MV/LV) transformer with nominal power 1250kVA supplying commercial load is considered. The commercial load supplied by the transformer presents a peak of approximately 1.1MW at 18:00 and quite a high demand during the morning and middle day hours, as illustrated in Figure 2.

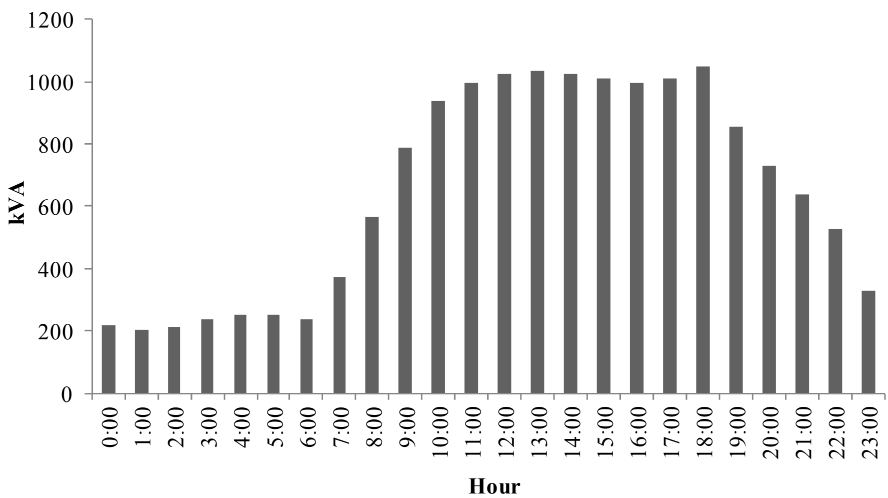

Figure 2: *Commercial load curve for the examined transformer.*

The network demand comprising the commercial non-EV demand ($P_{load,t}$) and the load from the charging infrastructure network must not exceed the nominal power of the transformer (P_{nom}=1250kVA). Therefore, the available transformer capacity for serving the additional EV charging demand ($P_{av,t}$) equals to:

$$P_{av,t} = P_{nom} - P_{load,t} \tag{5}$$

It is assumed that the charging network infrastructure comprises charging stations with nominal power of 7.2 kW and efficiency of 90 %. The battery's SOC, when EV plugs-in, is randomly defined (uniform distribution) between 20 % and 40 %. The battery capacity of each vehicle is considered equal to 24kWh. Furthermore, it is assumed that a total number of *180 charging sessions* occur during the examined period (24 hours). The percentage of charging sessions occurring each hour of the day is illustrated in Figure 3 ([10]). The probability of a charging session to occur during the time period from 9:00 to 16:00 is the highest one.

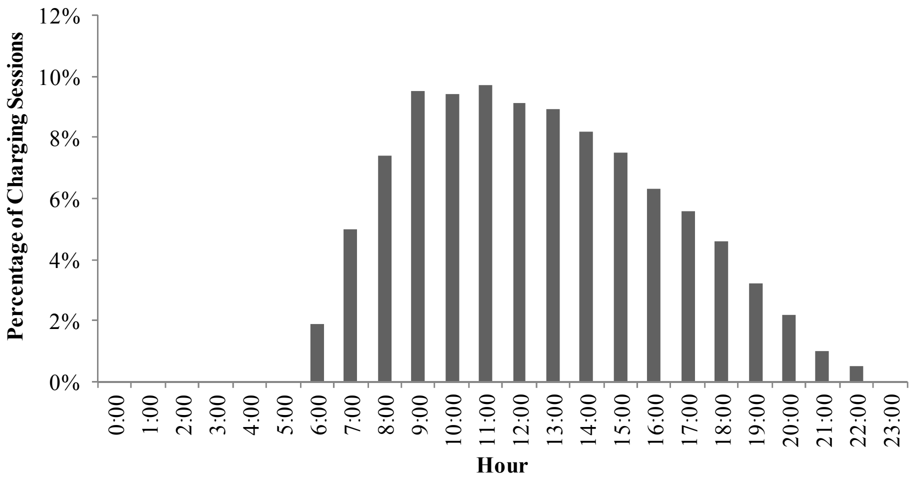

Figure 3: *Charging sessions per hour [30].*

Three scenarios are examined for evaluating the operation of the proposed EV management system:

- Scenario A: *All EVs offers charging elasticity.* In this scenario the parking period is considered to be longer than the time requested for complete battery charging. The departure time for each EV is defined considering a normal distribution with mean value equal to four hours and a standard deviation of one and a half hour.
- Scenario B: *No EV offers elasticity.* In this scenario, the EV users are not willing to offer charging elasticity. The parking time equals to the time required for a complete battery charging.
- Scenario C: *Sensitivity analysis considering charging elasticity.* In order to examine the impact of the charging elasticity to the battery SOC at the departure time, a number of simulations are executed considering different

percentage of EV users offering elasticity (from 10% to 90%). The Monte Carlo method is applied in order to define the range of the output battery SOC for each elasticity percentage.

Each one of the aforementioned scenarios is compared to the uncontrolled charging case considering EVs start charging as soon as they plug-in irrespectively of the technical constraints of the grid. The Scenarios under study are summarized in Table 2.

Table 2: *Description of the Scenarios under study*

Scenarios	*Charg-ing Sessions*	*Departure Time*		*% EV Users offer-ing demand elas-ticity*	*Initial SOC*
		Mean Value (hour)	*Standard Deviation (hour)*		
Scenario A	180	4	1.5	0%	20% - 40%
Scenario B	180	Equal to a full charging period		100%	20% - 40%
Scenario C	180	4	1.5	10% - 90%	20% - 40%

4. RESULTS

The EV demand in the case of Scenario A is illustrated in Figure 4. The continuous dashed line indicates the hourly loading limits of the transformer under study. During early morning hours, the EV charging demand as well as the transformer loading is low. Consequently, all the requested charging sessions during this period are fully served. However, after 10:40, the transformer is highly stressed and the EV charging demand is high enough.

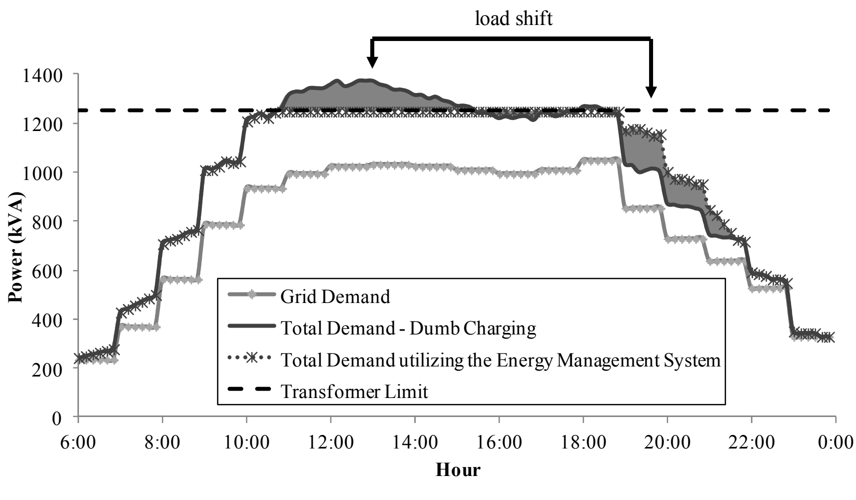

Figure 4: *Total Demand of the examined transformer for the case of Scenario A.*

Since the transformer cannot completely fulfil the charging requirements of all EVs, the implementation of an energy management system is required so as to shift the excess EV demand to subsequent time intervals in order to avoid transformer's overloading. The shaded areas in Figure 4 indicate the charging demand shift. Consequently, during such problematic timeslots, part of the occupied charging stations will interrupt the charging of the EV battery based on the criteria defined in Section 2. The number of operating charging stations compared to the occupied ones is illustrated in Figure 5.

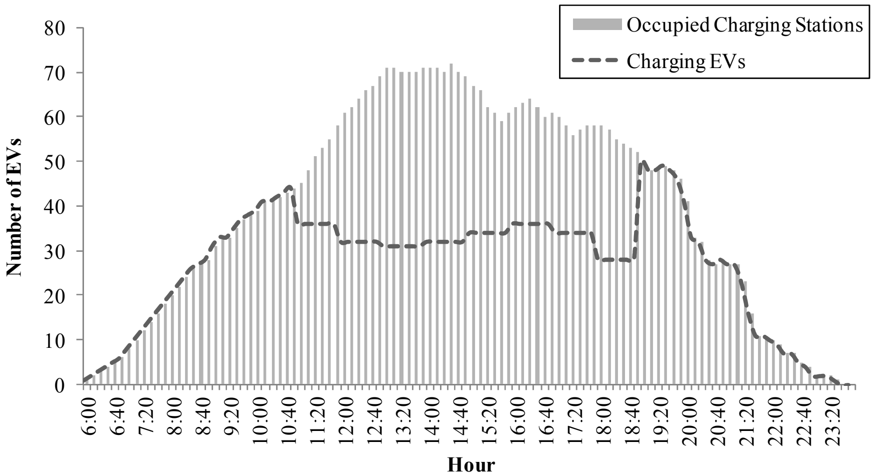

Figure 5: *Occupied charging stations and charging EVs in Scenario A.*

In Scenario B, the EVs do not offer any elasticity, thus, there is no capability of shifting the charging demand. In this case, part of the additional EV load must be curtailed in order to maintain the stable operation of the network. The EV demand derived by the energy management system is illustrated in Figure 6.

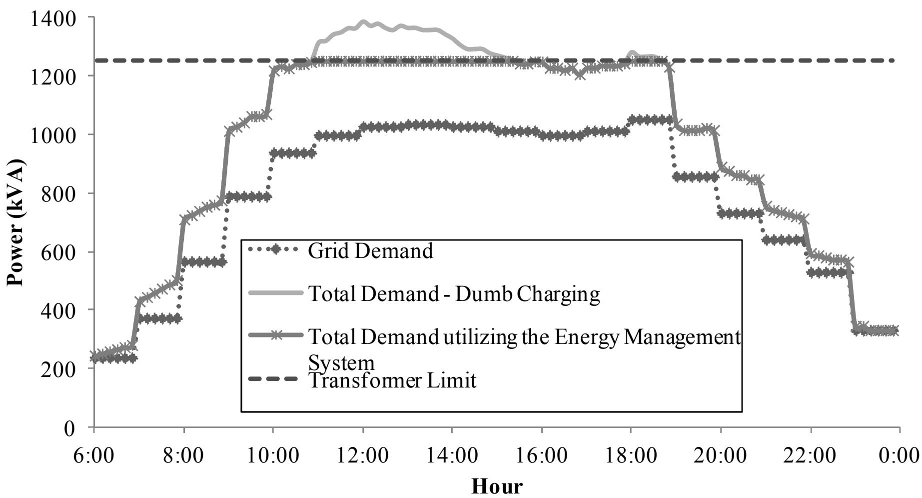

Figure 6: *Total Demand of the examined transformer for the case of Scenario B.*

The number of operating charging stations compared to the number of occupied ones during each time interval is illustrated in Figure 7.

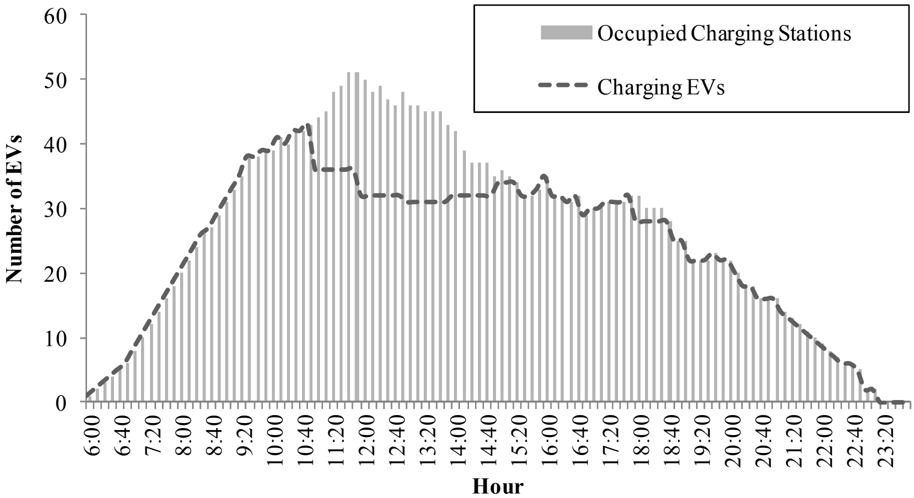

Figure 7: *Occupied charging stations and charging EVs in Scenario B.*

In Scenario B, the lack of elasticity results in 64% of the examined charging sessions being uncompleted. Due to the stochastic nature of EV behaviour, the Monte Carlo method is applied in order to examine the battery SOC of the vehicles leaving the stations without being fully charged. The departure battery SOC of these EVs depends on the mobility constraints and needs of the whole EV fleet plugged-in during the examined period. Figure 8 illustrates the range of the battery SOC of the EVs as departing from the charging station. As the number of plugged-in EVs increases during the peak hours when the network infrastructure is highly stressed, the lack of charging elasticity results in lower departure SOC.

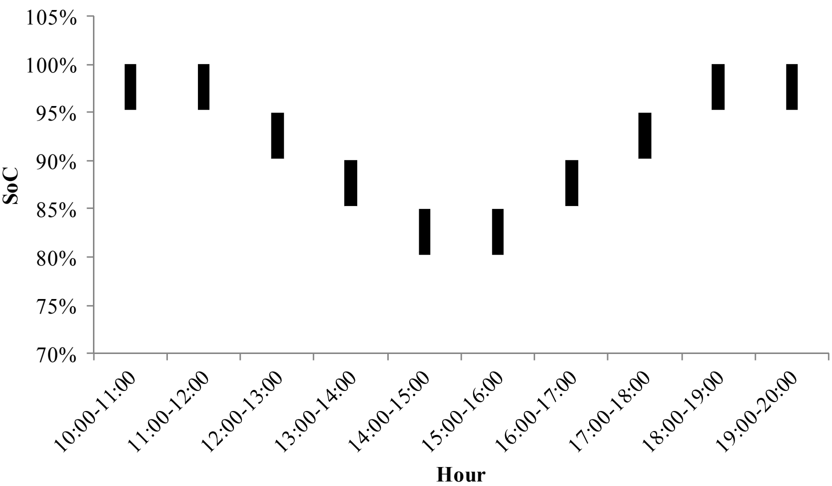

Figure 8: *Battery SOC of the majority of EVs leaving the stations not fully charged.*

It is derived that the uncharged EVs with the lowest battery SOC (80 - 85 %) depart between 14:00 and 16:00. The results in Figure 8 proves that, under highly stressed network conditions, the proposed charging management system distribute fairly the available charging power among the uncharged EVs maintaining a balanced departure SOC for the batteries.

In Scenario C, different percentages regarding the charging elasticity offered by the EV users are examined. The number of EVs departing from the station without being completely charged as percentage of the total plugged-in EVs is illustrated in Figure 9. The number of the uncharged EVs reduces as the number of EVs offering elasticity increases as well.

Figure 10 illustrates the departure battery SOC of the non-fully charged vehicles in respect to the number of EVs offering elasticity. As the percentage of EVs offering elasticity decreases, the uncharged EVs presents lower departure battery SOC. This is expected since the performance of any charging management approach is highly dependent on the EV charging elasticity. For high percentages of elasticity, the proposed charging management system coordinates EV charging such as almost all EVs are fully charged.

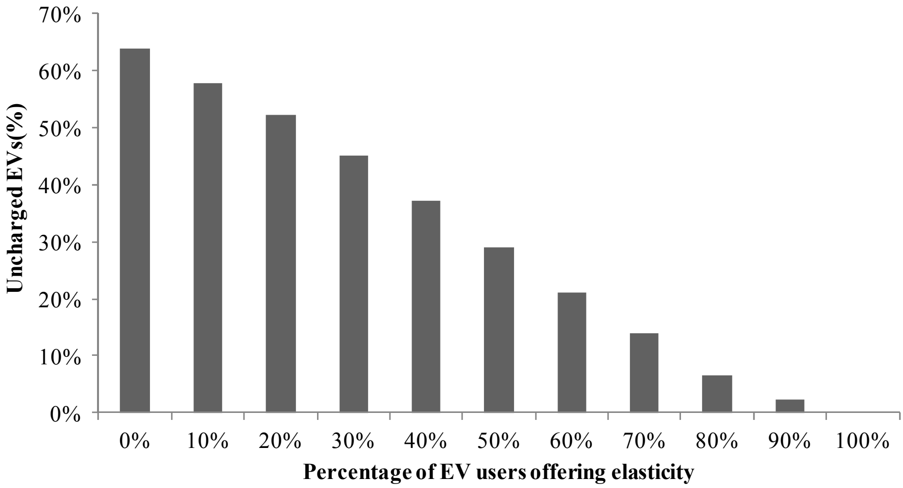

Figure 9: *Percentage of EVs leaving the stations not fully charged according to the elasticity offered.*

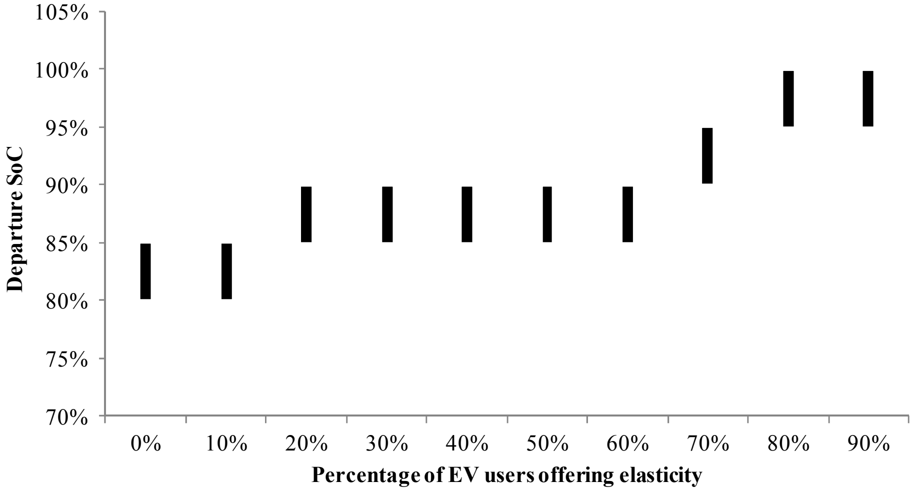

Figure 10: *SOC of the majority of EVs leaving the stations not fully charged, regarding Scenario C.*

5. CONCLUSIONS

The Energy Management System proposed in this paper can effectively allocate the available grid power among the charging stations. In case that all EVs offers charging flexibility, the proposed management scheme fully exploits this demand elasticity allowing for the complete battery charging of EVs without provoking any grid operational issue. In the worst case scenario, when EVs do not offer charging elasticity, EVs departure without being completely charged and the lowest departure battery SOC is observed during the system peak load. Even in this case, the management system aims to fairly balance the departure SOC of the EVs during the high consuming hours by maintaining an average departure SOC. The elasticity offered by the EV users affects directly the performance of the proposed EV management system.

The proposed management scheme has been implemented in a MV/LV transformer but it can also be adopted for wider applications related to the operation of distribution networks aiming to avoid congestion and voltage excursions issues.

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ISO/IEC 15118 HW/SW IMPLEMENTATION AND THE WAY IT IS INTEGRATED IN THE E-MOBILITY SYSTEM

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ABSTRACT

The e-Mobility system is composed by many actors, from the Electric Vehicle (EV) to the Distribution System Operator (DSO), who need to interact through the exchange of information. As in any incipient system, there is a lack of standards affecting, for example, the way the information should be transmitted among different parties and the specification of functional performance, which defines the tasks that each actor must cover. At the same time, more than one standard is available to carry out certain functionalities and both manufactures and developers have to choose the solution that fits best their requirements. On the other hand, there is still not a wide experience on the implementation of certain protocols on real systems due to a limited market development. This article provides implementation guidelines for EV and EVSE manufacturers, as well as for other e-Mobility actors, to take advantage of the ISO/IEC 15118 protocol features, in order to help improve the EV integration within smart electrical grids. To achieve this objective, both IEC 61851-1 and ISO/IEC 15118 standards for EV charging were implemented using an integrated infrastructure. This infrastructure was developed and validated for both EV and EVSE (EV Supply Equipment) in the framework of EU FP7 COTEVOS research project.

1 INTRODUCTION

1.1 History

The IEC 61851-1 [1] standard, covering aspects related to the EVSE (Electric Vehicle Supply Equipment) and the EV (Electric road Vehicle), defines the communication protocol between both systems. It describes four different charging modes, although only modes 2, 3 and 4 include communication between the EV and the EVSE by means of a dedicated cable called Control Pilot (CP). This standard is widely adopted nowadays because it just needs two cheap circuit boards, one inside each system, and a simple protocol.

According to the procedure defined in the standard, the EVSE sends through the CP a PWM (Pulse Width Modulation) signal that the EV must read. The duty cycle of the signal sets the maximum current to be drawn by the vehicle during the charge; the higher the duty cycle (between a valid range of values), the faster the EV charge is allowed. The concept of this standard is simple, but it allows charging the EVs in a controlled way, which is a first step towards the smart charging. However, this standard is mainly focused on security, ensuring that the charge limits are kept.

At the IEC 61851 definition time, the charging limit was designed to avoid exceeding the EVSE and supply cable capacities. This approach ensured that the EV could not be charged in unsafe scenarios. However, if the Charging Service Operator (CSO) wanted to make use of the smart charging, such as sending a charging schedule, an ad-hoc implementation had to be developed and installed in the EVSE. This meant that, in a first step, manufacturers had to create a communication protocol, define a data model and integrate it with the PWM signal generator to provide that service to their customers. Moreover, because of CSOs would demand solutions suiting their own service portfolio, the manufactures of Charging Stations had to implement additional software and integrate it with the protocol in order to fit each customer's needs, resulting in proprietary implementations not interoperable between them.

1.2 ISO/IEC 15118 irruption

As previously mentioned, IEC 61851 defines a low level communication protocol between EV-EVSE for power management focused on safety. ISO/IEC 15118 [2] [3] [4] was conceived to cover the current and mid-time future scenarios for smart charging, taking into account the new roles, actors, functionalities, etc. This standard only covers the part where the EV is present. In fact, it defines the communication between the EV and the 'EV infrastructure'. This is the first key to understand this standard: some messages produced by the EV are consumed by the EVSE, whereas other messages are addressed to the CSO, the EMSP, the DSO or other third parties.

Another important aspect is that the EV has to manage, validate and register every event, information, configuration and any other problem produced in the whole charging process. This forces the EV to face more complex use cases, data models and protocols than the IEC 61851 standard.

The ISO/IEC 15118 standard is divided in eight parts:

- Part 1 - General information and use cases definition (released 2013-04-16). A general overview to understand the scope of the standard, it includes the use cases demanded by the actors, charging processes, payment and load levelling.
- Part 2 - Network and application protocol requirements (released 2014-03-31). It describes the OSI 3 to 7 layers, which includes the data model, IP network and transport protocol.
- Part 3 Physical and data link layer requirements (released 2015-05-26). It describes the OSI 1 and 2 layers.
- Part 4 and 5. Conformance tests for parts 2 and 3 respectively (under development).
- Part 6, 7 and 8. Wireless communication (under development).

The 1, 2 and 3 parts define the use cases, data models and protocols between the EV and the EV infrastructure through the EVSE. It includes the way the communication is established and performed (part 2 and 3), the messages involved with the 'EV infrastructure' (part 2, Annex C - Schema definition), including smart charging, authentication, etc., and the complete charging process (part 1 and 2).

1.3 Linking EV charging with other actors

Although some functions, such as power limitation, user identification, etc. are covered and defined in the ISO/IEC 15118 standard, the way of obtaining this information from third parties, or secondary actors, is out of the scope of the standard. This means that the data model in part 2 defines how the power limitation is finally received by the EV, but the standard does not specify the actor who produces it (the DSO, EMSP, CSO…).

In the smart grid environment, EV specific protocols coexist with other communication standards adopted between actors. When some information has to be finally sent to the EV, a mapping has to be done from the origin data/protocol to the target:

- When using IEC 61851, the mapping has to be done at the EVSE; converting high level messages into electric signalling. Notice that only power limitation and charge schedule can be mapped to this protocol.
- When using ISO/IEC 15118, its XML data model can be used for mapping. Moreover, according to the network described in part 2, the EVSE can route the messages from the producer to the consumer without any change. This means that, should no other protocol or mapping be defined with other actors, the same ISO/IEC 15118 message could be dispatched to the final destination without any changes.

Manufactures have slowly started to implement the ISO/IEC 15118 because it provides additional functionality. Other protocols, for example OCPP, designed by the Open Charge Alliance [5] for EVSE - CSO communication, have adopted some parts of the ISO/IEC 15118 data model for seamless integration.

2 LABORATORY IMPLEMENTATION

The implementation detailed in this article was performed to prove the concept of the described EV-EVSE charging standards and the way this infrastructure can be integrated with other actors within the e-Mobility system. The system consists of two platforms, for EV and EVSE, as well as the necessary hardware and software for integrating them with other e-Mobility actors.

Basically, each platform is divided into four modules. The IEC 61851 module covers the conventional EV charging. The ISO/IEC 15118 module also covers the EV charging, but adding advanced services described in this standard. As this module uses some parts of the previous one, an integration package was also developed. The e-Mobility module covers the added value services, e.g. smart charging, user authentication, etc. It includes the necessary interfaces to be integrated into a real scenario.

A fourth module was developed in order to trace all actions, events, messages, states and measured values within the whole charging process. Moreover, a testing package was also developed in order to perform conformance tests. Therefore, this module also allows replacing a platform (e.g. the EV) by a real EV from any manufacturer in order to see if it complies with the standards specification.

2.1 Hardware

There are two platforms, the EV and the EVSE, fully capable of performing charging processes according to both IEC 61851 and ISO/IEC 15118. In other words, both platforms are able to behave as real EVs and EVSEs. At this stage of the implementation, only AC charging is developed.

2.1.1 *Hardware selection for EV*

This emulated EV has most of the components of a real one (see next figure): a battery, a charger/inverter (with V2G capabilities), a plug, and the required computational infrastructure to install the software and firmware to control all these components.

Notice that in the figure some components such as power sources, switches, etc. are not depicted for image clarity. This infrastructure should be powerful enough to adopt the previously described standards.

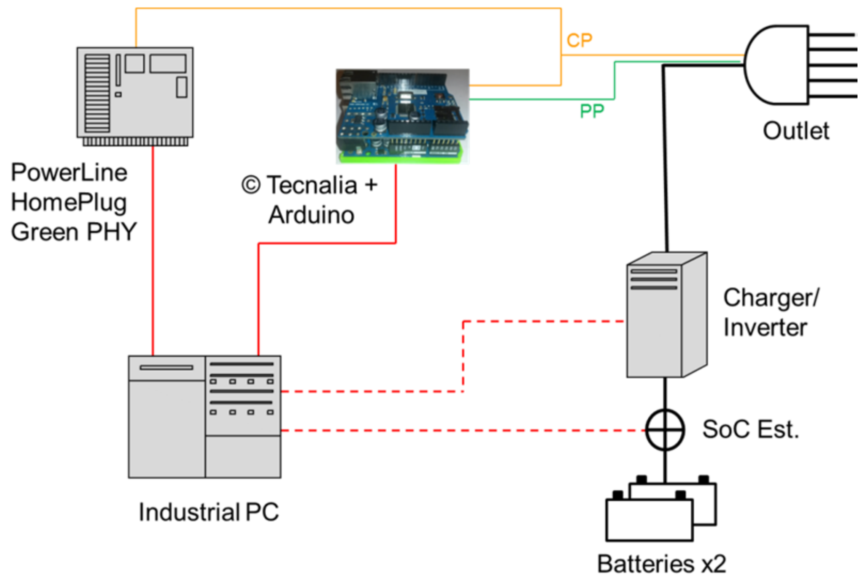

Figure 1: *Components diagram for the EV implementation.*

The description of the components is provided below:

- *Battery*. Two PbO_2 batteries are used to prove the concept.
- *Charger/Inverter*. This device charges the batteries, allowing charging at different rates. The inverter is used for V2G purposes.
- *State of charge (SoC) estimator*. In order to charge the batteries in an efficient way, their state of charge must be known in advance.
- *Tecnalia© + Arduino board [6]*. A Tecnalia designed board was mounted onto the Arduino platform, in order to manage and monitor the Control Pilot (CP) and the Proximity Pilot (PP) according to the IEC 61851 specification for the EV.
- *Powerline HomePlug Green PHY module*. This device uses the CP to send and receive information according to the HomePlug specification, defined in ISO/IEC 15118. It acts as a communication bridge between Ethernet and PLC (Power Line Communication).
- *Industrial PC*. This device contains all the software, firmware and drivers to control the described components. It also contains developed software which complies with the IEC 61851 and ISO/IEC 15118 specifications to charge the EV.

2.1.2 *Hardware selection for EVSE*

The emulated EVSE has the same main components of a real charging pole (see Figure 2): a plug for connecting the EV to the supply cable, a main relay connected to the electric grid, a Tecnalia© + Arduino board to control the CP and the PP and a powerline analyser for measuring the delivered energy. It also has the computational infrastructure to control the described components, where the corresponding standards will also be implemented.

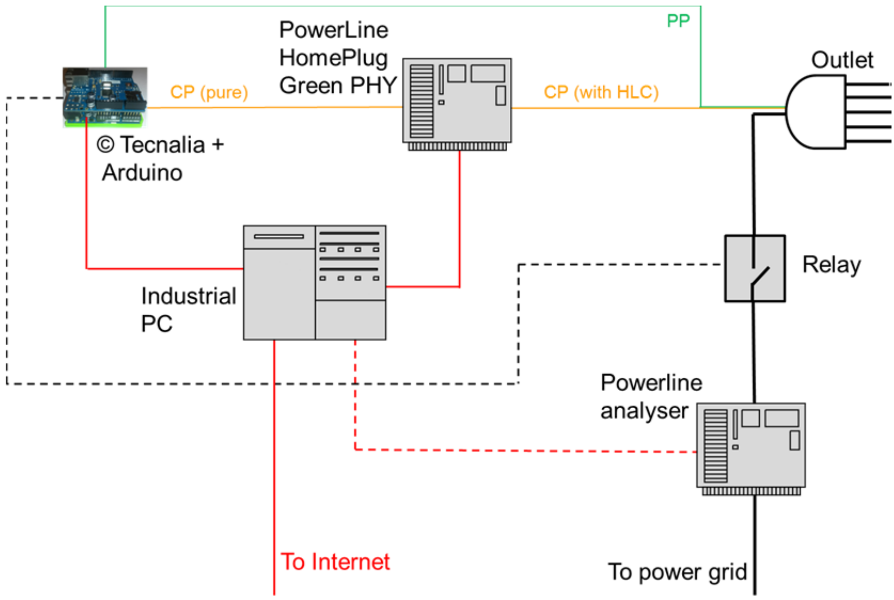

Figure 2: *Components diagram for the EVSE implementation.*

The components are described below:

- *Powerline analyser*. This device is monitoring the delivered energy to the EV, the voltage and the current.
- *Relay*. This remotely controlled relay allows (or denies) charging the EV according to standardized orders.
- *Tecnalia© + Arduino board*. This board developed by Tecnalia is similar to that of the EV, but adapted for the EVSE functionality, as defined in the IEC 61851 specification.
- *Powerline HomePlug Green PHY module*. This is the same component of the EV side, adding EVSE features for EV discovery and communication setup.
- *Industrial PC*. This device contains all the software, firmware and drivers to control the described components. It also contains own developed software, which complies with the IEC 61851 and ISO/IEC 15118 specifications, to charge the EV and to send/receive messages to other e-Mobility actors.

2.2 Software

Figures 1 and 2 show the selected hardware developed for a complete EV and EVSE emulation, complying with both IEC 61851 and ISO/IEC 15118 specifications. This hardware contains the necessary software and firmware to control the components inside both systems in accordance with the standards. All this software is installed in the industrial PC and in the Tecnalia© + Arduino board.

All software is scalable, there are some common components that are shared by both EV and EVSE, such as XML/EXI transformation, sockets implementation, message configuration, etc. This implementation uses several external libraries for messaging, message transformation, communication protocols and certificate utilities. As this implementation is designed for testing EVs and EVSEs, it is necessary to force unexpected situations in both specifications. Therefore, we need to control completely the messages, the state machine, communication and transformations, modifying the execution as desired to check the performance. We have reached to the conclusion that the best way to fulfil this is programming from scratch, not using other EV specific software.

2.2.1 *EV modules*

The modules developed for a complete EV implementation for both standards are divided into three groups:

- *IEC 61851 modules*. This is a complete implementation of the standard. The state machine and events are deployed in the industrial PC, whereas the variable measures and commands are deployed in the Tecnalia board.
- *ISO/IEC 15118 modules*. This is also an implementation of the standard, completely deployed in the industrial PC.
- *Devices modules*. This is a set of applications, drivers and firmware used to control the SoC estimator and the charger/inverter installed in the EV hardware system.

A complete software specification can be seen in Figure 3, which shows the deployment diagram. In order to easily adopt new functionalities that future versions of the standards can demand, all the developed software was designed taking into account the system scalability, developing the functionalities in separate modules to ensure component interoperability.

This diagram shows the software developed by TECNALIA to emulate an EV that can be charged by both protocols. All the standard specifications are implemented in the industrial PC. The Tecnalia© + Arduino board contains only basic functions for reading CP and PP values and performing basic actions.

The Tecnalia© + Arduino EV node has two components. The first one is an interface and its implementation for any incoming commands or requests, for instance measured information. The second, the monitoring and control module, is continuously reading the CP and PP values that will be returned when required by the first component. The latter also executes actions or commands that modify the Tecnalia© + Arduino board.

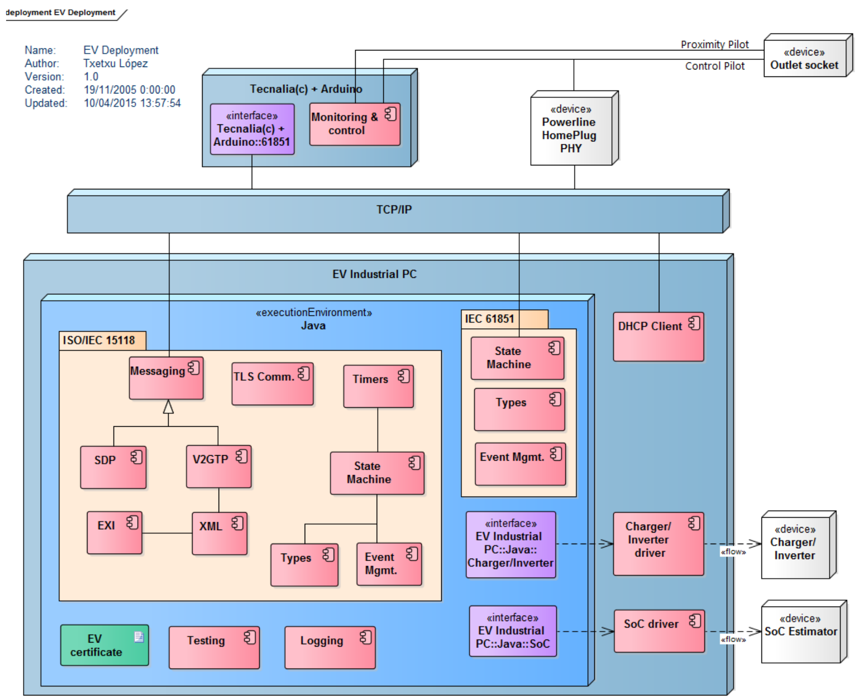

Figure 3: *EV deployment diagram.*

The industrial PC has two drivers to access to the charger/inverter and the SoC estimator, providing the corresponding interface for Java based applications. These drivers read the information when required by the invoking application and send commands (start charging, limit charge to 10A...) to the charger.

The module which implements the IEC 61851 standard is an event-driven state machine. The Event Management module is constantly asking to Tecnalia© + Arduino board for some voltage values and the received PWM signal. These measurements are mapped to a specific state according to the standard. Every time that the state changes between two consecutive readings, an event is automatically launched. The events are associated to some actions (start charging, reduce power demand, stop charging, etc.) that have to be executed sending a command to the charger or to the Tecnalia© + Arduino board (the EV is ready to charge).

In contrast, as the ISO/IEC 15118 is more complex, the implemented module has more packages, protocols, data model, messages and states. The specification defines the way the EV and the EVSE establish the communication. This is done by means of the powerline HomePlug PHY. This device implements the part 3 of the specification, which contains the rules for establishing the EV-EVSE connection by means of PLC. Moreover, it is a PLC bridge, which can be connected to a computer in order to send/receive messages from an Ethernet network to a PLC line.

In addition, a DHCP client was also installed in the EV side for discovering its IP address. Once this process has finished, both EV and EVSE are connected in the same communication network and they are ready to perform a charging session.

At this stage, the application wakes up the state machine, which is implemented as a state machine driven by received messages. The ISO/IEC 15118 package depicted in the Figure 3 contains the state machine, all the messages, events, types, error handling, transformations, encryption, certificate handling, etc. specified in the standard.

When the state machine module is launched, the message interaction begins following the order stablished by the standard. This module checks if the received message is the one it was expecting within a specified time. Depending on the message and the timing, the state machine moves to a specific state. The EV will perform an action according to the received information and the current state. The 15118 implementation was developed from scratch, using external libraries for those technologies not related specifically to V2G, such as XML messages, EXI, certificate handling, etc. This way, we can check up to what extent existing V2G libraries, such as OpenV2G, are interoperable with other implementations.

Once the charging process is completed, the communication can finish, stopping the state machine, releasing timers and disconnecting the communication network.

2.2.2 *EVSE modules*

Similarly to the EV, the EVSE implementation has several components grouped into three modules: the IEC 61851, the ISO/IEC 15118 and the devices group, which are adapted for the EVSE functionality. The deployment diagram can be seen in the next Figure 4, whose components were also designed to allow scalability.

The described infrastructure is able to charge any EV connected to the outlet socket by means of both protocols. It also collects valuable information for third parties in the e-Mobility system. Some depicted components are replicated from the EV deployment diagram, since the same types, communication protocols and data conversion are used by both EV and EVSE. However, other components share the same name, but the implementation is diverse.

The IEC 61851 is performed in two components. The Tecnalia© + Arduino board module processes the voltages measured in the Control and Proximity Pilot and sends them to the IEC 61851 package installed in the industrial PC. This board also executes the commands received from the industrial PC and performs the corresponding actions, such as the PWM signal modification; open/close the power delivery relay, etc.

The ISO/IEC 15118 module processes all the messages received from the EV and checks if the message was received on time and if it is the message expected by the state machine. In case any of these premises is not fulfilled or any other error occurs, the exception sequence specified by the standard must be followed to finish the charge process. If no error arises, the response message is configured and sent back to the EV. The powerline HomePlug Green PHY modulates the communication messages in the Control Pilot for message transmission. This device has enabled a SLAC server, so that any EV can identify the EVSE it is connected to.

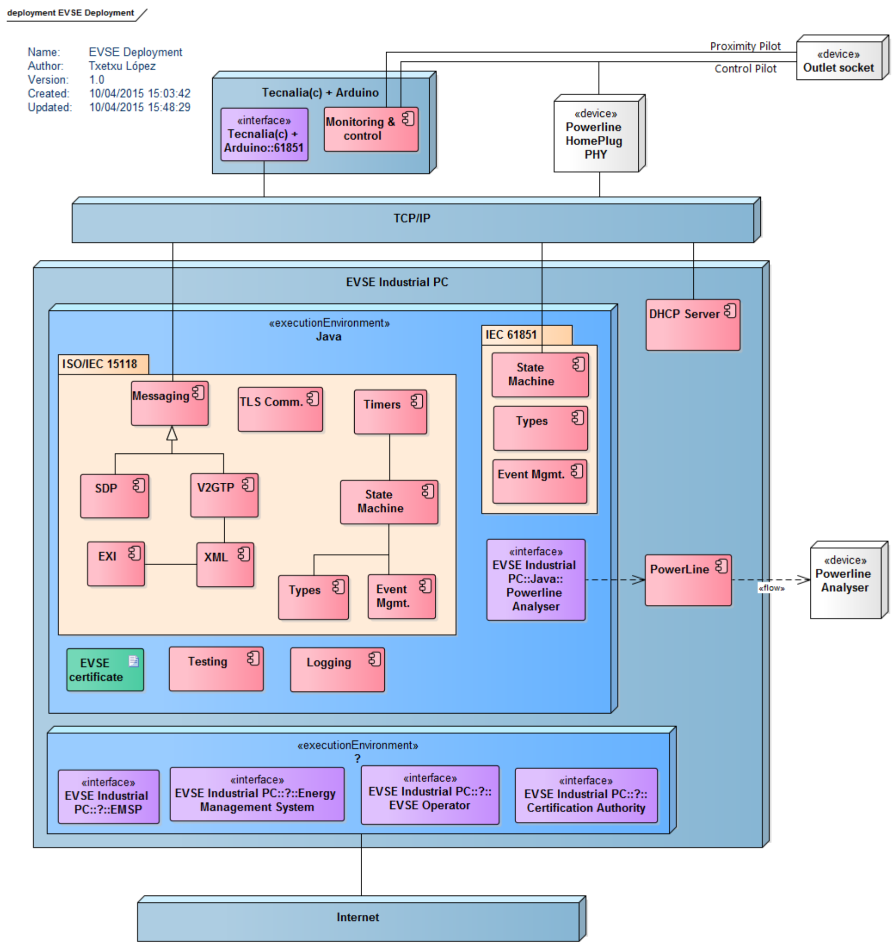

Figure 4: *EVSE deployment diagram.*

The DHCP server is used as a standalone application to provide valid network addresses to any connected EV, so that both EV and EVSE belong to the same network domain and, therefore, can communicate.

Ad-hoc software was developed to retrieve any data from the powerline analyser. This information is used to know the charging rate and to control the power and current which are being delivered to the EV. Moreover, this device also provides the total energy consumed.

2.2.3 *IEC 61851 with ISO/IEC 15118 charge integration*

According to the ISO/IEC 15118 specification, the EV charging is performed using High Level Communication (HLC). However, the charging process can be done in accordance to two modes defined in the 'start of charging process' use case:

- *A1 Use Case. Begin of charging process with forced HLC*. The EVSE must send a constant 5% duty cycle. This value is reserved for HLC in the IEC 61851 standard. Once the EV receives this 5% value, the charge will be driven by the high level messages. Whenever the HLC is lost, the charging process is aborted.

- *A2 Use Case. Begin of charging process with concurrent IEC 61851-1 and HLC*. The EV charge starts the charge following the IEC 61851 protocol. However, the HLC can be started at any time. At this moment, if both EV and EVSE have HLC enabled, they configure the network and establish the HLC. Once this negotiation is successfully finished, the charge will be driven by the HLC messages. However, if this communication cannot be established, or if it is lost during the charging process, the charge will be driven by the duty cycle, following the IEC 61851 standard.

As a result, an EVSE which complies with the ISO/IEC 15118 standard can be configured to work in any of these two modes. If the A1 use case is selected, only EVs with HLC enabled will be able to charge. If the A2 use case is selected, any EV can be charged at the EVSE, with HLC priority.

As shown in the EV and EVSE deployment diagrams, two separate modules for EV charging have been designed, one per standard. Although these modules are independent, they can be configured to fulfil the ISO/IEC 15118 A1 and A2 use cases, as well as the IEC 61851 charge. This is achieved through parameter configuration in the testing module.

3 E-MOBILITY ACTORS INTEGRATION

The charging process is not restricted only to the EV and the EVSE. Several e-Mobility actors are actually involved in this process and they need to share information among them, for example: the charging information data that must be sent to the Charging Service Operator, the user/EV authentication that must be validated by a Certificate Authority, the charging authorization by the EMSP, the charging profile in case of power limitation, user preferences, etc.

In some cases it is direct 1:1 communication, where the information is generated in one actor and consumed by the actor which is directly connected to it. The session establishment between EV and EVSE is an example of this, where both devices are collaborating to configure a logical connection. However, there are other cases that, in spite of being 1:1 communication, they are not physically or logically connected. A router or bridging functionality is needed in order to send the messages through intermediate actors to the final consumer. The most significant example is the authorization process, when the user identification has to be sent towards the EMSP through the Charging Service Operator, EVSE, etc.

There are some scenarios which demand 1:N communication. It implies that the information produced in one point must be collected and consumed by multiple endpoints and even actors. In case of an electric network contingence, the DSO could launch power limitation signals to the Charging Service Operators with EVSEs installed in the affected area. Once the signal is received, each Charging Service Operator must ensure that the connected EVs or EVSEs receive the order to reduce its energy demand.

At the bottom of the Figure 4, there is an execution environment aimed to integrate the developed platform with other e-Mobility actors through wide area networks. This environment is designed to allow standard and non-standard communication with external actors. Since actors demand different protocols, separate environments must be developed as well.

OCPP versions 1.2 and 1.5 have been developed so far. Therefore, the EVSE can communicate with any CSO implementing one of these protocol versions. However, as the system has been designed for scalability, other versions and protocols can be easily deployed.

3.1 Integrating ISO/IEC 15118 with e-Mobility actors

In the ISO/IEC 15118 standard, the EV manages the communication, sending messages to the ‘charging infrastructure’. The standard specifies the sort of messages that might be processed by third actors, such as the EV certificate management, the authorization and the charge parameters before the supply begins. Moreover, there are other messages that can also be demanded by those actors, such as the ones referred to added value services, billing and the charging progress.

From the point of view of the standard, this integration is out of its scope, but still the charging station must provide some functionality to give access to remote actors such as bridging, routing and message composition, as well as performing any necessary data transformation.

The EV can only receive the messages defined in the standard, therefore, the EVSE is responsible for adapting the incoming messages to the communication needs of the actor which will consume the data. Similarly, any message received from the remote actors should be mapped to the defined messages so they can be understood by the EV. These processes can imply to store some data temporally.

In the ISO/IEC 15118, the charging process is always driven and controlled by the EV. Once the EV-EVSE communication is established and the EV is allowed to charge, a negotiation is performed before the charging process. This negotiation is aimed to configure the optimal charging schedule according to the EV charger, the cable capacity, the EV user preferences, the EVSE and any power limitation set by the DSO. When this schedule is accepted by the EV and all the involved actors, the charge begins and the EV manages the charging according to the accepted conditions. In case the conditions change in the middle of the charging process, a renegotiation must be performed.

The implementation allows performing a real charge scenario. Therefore, the two ways of identification for EV charging were implemented in both sides:

- Identification by Plug and Charge (PnC). The EV contains internally a certificate with its identification. At the beginning of the charge, the authorization process is executed. The EV reads the certificate and sends it to the EVSE. After checking if the certificate is valid, the EVSE must allow or reject the charge. To do so, the EV identification contained in the EV certificate is sent to the CSO via the OCPP authorization message.

- Identification by External Means Identification (EIM). In this case, users identify themselves at the charging pole introducing a key in the EVSE, and the EV must wait for the authorization. Therefore, the key is sent through the OCPP authorization message to the CSO, which will respond allowing or rejecting the charge, which is finally notified to the EV.

3.2 Integrating IEC 61851 with e-Mobility actors

The IEC 61851 standard only manages the charge process. It assumes that any information has already been processed before, including the user authorization. In fact, it is a controlled charge by a PWM signal generated at the EVSE that the EV must execute. The only means that the EVSE has to know if the EV is connected or not is just measuring the voltage in the Control Pilot wire. In other words, the EV does not send or receive any complex message, but PWM and voltage measurements. The integration with third actors is 100% executed by the EVSE.

Nowadays, most EVSEs are compatible with IEC 61851 standard and they implement OCPP messages for upstream connection with the CSO. These EVSEs have identification means which allow users to identify themselves using a RFID or credit card and a connection for charge authorization, power limitation, billing, etc.

This approach can also be deployed in the execution environment depicted in the Figure 4. This EVSE-Charging Service Operator communication is completely managed by the EVSE. When a power limitation message is received by the EVSE, this information is transformed into a PWM signal: the only message that the IEC 61851 compatible EV can understand.

As a result, in a normal IEC 61851 charge with OCPP, the complete charging process is constantly monitored by the Tecnalia© + Arduino boards, where all commands are received from the IEC 61851 modules installed in the industrial PCs. This means that the user must identify himself at the charging pole (with a RFID card, a pin code, etc.). The identification must be sent to the Charging Service Operator (or checked against the white list stored at the EVSE), which decides whether the charge is allowed or rejected. Once the process ends and the user wants to leave, the information related to billing must be also communicated, including delivered energy, time elapsed, etc.

4 CONFORMANCE TESTING

4.1 Local testing

The developed hardware and software was designed to work as real devices. The EV platform can be charged at any charging station whose charging protocol is IEC 61851 or ISO/IEC 15118 and the EVSE platform can charge any EV with IEC 61851 or ISO/IEC 15118 charging enabled. Moreover, in both systems a testing and a log module were added to trace all the information produced in the whole process.

The log module just writes all the parameters and values at any stage of the charging process. It includes the state of the charge process (according to the state machine implementation specified by the IEC 61851-1 standard), the state transitions, the PWM value, frequency and voltages. When an ISO/IEC 15118 charge is in progress, the XML messages are also stored, as well as the states that belong to this standard. Once the charge has finished, the information can be analysed to see whether it complies with the specification or not.

The testing module goes one step beyond, providing the means for performing conformance test in an automatic way. For this purpose, this module reads a testing procedure file, which specifies the charge that has to be performed. This file contains a sort of actions to be executed within the charging process. The actions may include demanding more power than defined by the PWM signal, suddenly connect or disconnect EV availability, provide more power than the cable can support, modify the duty cycle to invalid values, modify the signal frequency to the limit of the specification and even violating it, etc.

This file gathers all these actions per time unit. The information is defined from the beginning of the charging and actions can take place any time: 5 minutes after the start of charging, modify the frequency, 6 minutes later modify the duty cycle, etc. Therefore, the test can be predefined once and the testing can be carried out afterwards automatically, without the presence of any person in the testing process. As all the information is stored by the log module, the testing results are obtained by analysing the recorded data. This log information is also valuable for the EV or EVSE manufacturer too to identify what part of their implementation did not meet the specifications.

4.2 Collaborative inter-laboratory testing

For charging testing purposes, the Device under Test (DuT) must be present in the laboratory. This way, the platform can check the DuT and test its behaviour when charging. Moreover, the highest added value that this platform offers is that it is able to integrate other laboratories to perform the tests. Because the EV and EVSE are beginning to be integrated with e-Mobility actors, a laboratory should also offer testing services for their integration.

The communication between all actors includes several standards, as well as open and private protocols. Some of them are advanced and even are available nowadays, whereas others are still under definition. For example, OCPP is worldwide deployed with the versions 1.2 and 1.5. However, other protocols can also be adopted in the short and mid-terms. As a result, a testing laboratory should offer e-Mobility integration tests to the manufacturers.

A manufacturer may want to test if its EVSE complies with the charging specification in accordance to the IEC 61851-1 standard and if it is able to access to the Charging Service Operator system using the OCPP v1.5. Other manufacturer may demand OCPP, but version 2.0. A third manufacturer may decide to test a smart grid protocol for integrating EV charge in DSOs' operational procedures. It is probably difficult for a laboratory to have all modules and protocols implemented but, however, the offer of a comprehensive set of services for e-Mobility can be achieved through the collaboration between parties. To solve this, an inter-laboratory structure is proposed within COTEVOS project, where the testing capabilities of several laboratories are shared through internet communications.

Based on this approach, the real world (CSO, EMSP, etc.) can also be tested using this platform. If the manufacturer wants to know if its EVSE will be able to communicate with the control system of the customer who will purchase it, the platform is also able to provide this service, accessing directly to the customer's real implementation through wide area network gateways.

5 CONCLUSIONS

The platform described in this article defines two different and independent devices. The first one is an EV implementation with most of the functionalities of a real EV, including batteries and charger/inverter. The second is an EVSE implementation, also with the functionalities of real EVSEs such as the power grid connection, meter, relays, etc. Both devices are controlled by software which implements the IEC 61851 and the ISO/IEC 15118 standards. Moreover, testing capabilities were implemented in the platform to offer manufacturers detailed information on their products features according to their specifications. The platform is designed not only to prove the concept for charging with both standards, but also to integrate new systems in present and mid-time future e-Mobility scenarios with real equipment and actors. This article also provides a guideline for the EV and EVSE standards implementation, the components needed to comply with the specifications, as well as the different functionality modules defined by these standards.

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A MODEL-BASED ANALYSIS METHOD FOR EVALUATING THE GRID IMPACT OF EV AND HIGH HARMONIC CONTENT SOURCES

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Keywords: FFT; Harmonic Measurement; Inductive Charger impact; LV-grid; Power Quality Measurement.

ABSTRACT

The impact on the distribution grid when Electric Vehicles are connected is an important technical question in the development of new smart grids. This paper looks in detail at the predictive capability of a model, calculating harmonic voltage and current levels, in the situation where an electric vehicle is being charged by an inductive charging plate which acts as a substantial source of harmonic distortion. The method described in this paper models distortion at the LV side of the distribution grid by reconstructing the HV harmonic distortion levels seen at a typical LV substation. Additional LV connected harmonic-rich current sources can then be added, allowing a quantitative analysis of the impact of such sources on the distribution grid in terms of measurable harmonics magnitude and phase angle with respect to the fundamental.

1 INTRODUCTION

The adoption of electric vehicles (EVs) for decarbonisation of transport is gathering pace. Manufacturers of EVs as well as charging equipment are proposing new technology while standardisation efforts across the supply chain are being undertaken. The integration of electric vehicle supply equipment (EVSE) into the electricity network has several aspects such as increased load on the system, power quality concerns, business models for ownership of infrastructure, secure monetary transactions for electrical energy used in vehicle charging and participation in demand-side response, all in the back-drop of future smarter grids. The EVs utilise power-electronic hardware to interface with the grid. As such, the assessment of consequences for power quality on the network becomes important. The current drawn by EVs connected to the grid has harmonics, which distort the voltage waveform at the point of common coupling (PCC) and beyond. The distortion of the voltage depends is normally more important when the fault level at the PCC is low [1]. In order to provide a measure of the distortion in current and voltage caused by the harmonics, indices such as the total harmonic distortion (THD). Guidance on THD limits is provided in the relevant standards and engineering recommendations such as ER G5/4-1 [2], which prescribes the planning level at different voltages (for the United Kingdom) for example a maximum of 4% at 11 kV and 5% at 400 V [1]. Limits for harmonic currents emission by equipment connected to public low-voltage system is set out in BS EN 61000-3-2 [3], BS EN 61000-3-12 [4] and ER G5/4-1.

Under Stage 2 of ER G5/4-1, an assessment of background harmonic voltage may be required before the low-voltage (LV) non-linear load, which falls outside the Stage 1 assessment due to its higher power rating or harmonic current emissions, is allowed to be connected. A measurement period of at least 7 days is advised and voltage assessment is to be made at low voltage. Harmonics up to and including the 50^{th} are required to be used for calculation of THD. Mitigation measures are necessary where the predicted 5th harmonic and voltage THD values fall outside limits as defined in Table 1 below from [2].

Table 1: *Planning Levels for Harmonic Voltages in 400V Systems*

Odd harmonics (Non-multiples of 3)		***Odd harmonics (Multiples of 3)***		***Even harmonics***	
Order 'h'	***Harmonic Voltage (%)***	***Order 'h'***	***Harmonic Voltage (%)***	***Order 'h'***	***Harmonic Voltage (%)***
5	4.0	3	4.0	2	1.6
7	3.0	9	1.2	4	1.0
11	3.0	15	0.3	6	0.5
13	2.5	21	0.2	8	0.4
17	1.6			10	0.4

Table 2: *Maximum Permissible Harmonic Current Emissions in Amperes RMS for Aggregate Loads and Equipment Rated > 16A per phase*

Harmonic Order, h	Emission current, I_h	Harmonic Order, h	Emission current, I_h
2	28.9	13	27.8
3	48.1	14	2.1
4	9.0	15	1.4
5	28.9	16	1.8
6	3.0	17	13.6
7	41.2	18	0.8
8	7.2	19	9.1
9	9.6	20	1.4
10	5.8	21	0.7
11	39.4	22	1.3
12	1.2	23	7.5

For this piece of work, it is assumed that the LV wireless fast charger has a per-phase current greater than 16 A with harmonic currents larger than those specified in Table 2 from [2] and therefore will need an assessment of background distortion.

This paper extends the simulation based analysis method of benchmarking existing harmonics, discussed in [1], at a point in the network which can be other than the PCC.

Several studies found in literature have addressed the impact of power-electronic interfaced equipment on LV networks. Amongst them, [5, 6, 7, 8] can be referred to.

2 NETWORK DETAILS AND MEASUREMENT OF EXISTING DISTORTION

The network topology used for the implementation of the model-based analysis method is shown in Figure 1 below, which is based on a part of the distribution network in central Glasgow. The modelled network consists of an 11 kV and an LV network with fault levels of 250 MVA and 25 MVA, respectively.

The LV network is composed of four feeders fed by the distribution substation (S/S) F. One of the four feeders supply the inductive wireless charger, while the other three feeders supply a mix of load which is largely residential and commercial.

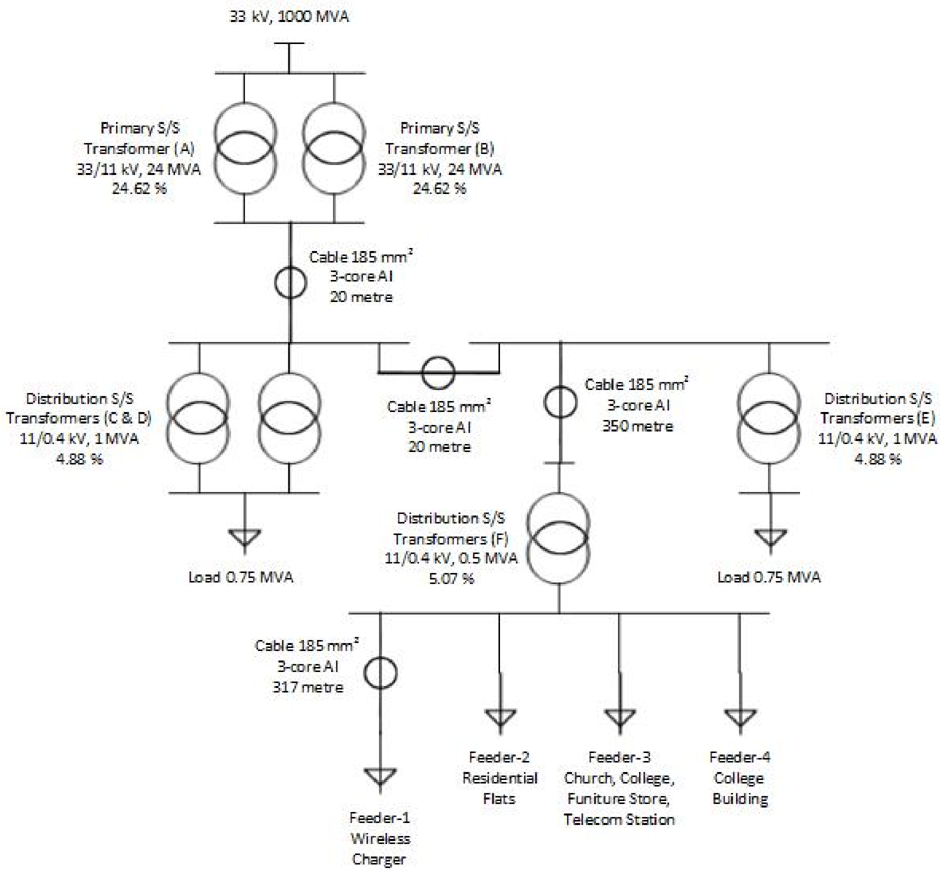

Figure 1: *Network schematic used in simulation model.*

The electrical data for the transformers is provided in Table 3 while Table 4 lists cable parameters.

Table 3: *Network transformer details*

Transformer Type Identifier	***Voltage [kV]***	***Power [MVA]***	***Impedance [%]***
Primary A, B	33/11	12/24	24.62
Distribution C, D, E	11/0.4	1	4.88
Distribution F	11/0.4	0.5	5.07

Table 4: *Characteristics of the 3-core Aluminium cable modelled in simulation*

Cross-section [mm²]	***Resistance [Ω/km]***	***Inductance [H/km]***	***Capacitance [F/km]***
185	2.11×10^{-1}	3.30×10^{-4}	3.60×10^{-7}

3 METHOD

The network shown in Figure 1 is modelled in SIMULINK using standard transformer blocks and 3-phase PI sections to simulate conductor lengths between the transformers and measurement point. When the properties of the physical network have been adequately represented, the next stage is to attempt to recreate a real physical measurement taken at point X with an Outram Power Quality Analyser [9]. This is done by simulating the model with a HV supply at fundamental frequency and additional sources of voltage harmonics and current harmonics, which can be tuned to match the observed distortion at the measurement point.

The method by which the distortion can be retrospectively added to the model has been described in a previous publication [1]. This involves calculating the magnitude and phase shift induced by the network components, in a harmonic source voltage and current, where these parameters are known.

The difference between the harmonic source and what is seen at the measurement point is a complex quantity representing the magnitude and phase difference. Therefore, the ratio between the source values and the measurement point values for each harmonics considered in this study can be defined as a set of complex coefficients, which transform the harmonic source values to the measurement point values, and vice versa. In short, the method aims to use the SIMULINK model to first establish these coefficients in the most effective manner possible and then use them on a measured waveform in order to create the harmonic voltage and current sources necessary to reconstruct the measurement.

The benefit of using this approach is that another harmonic source can be added at any point in the network and by the principle of wave superposition, its effect can be accurately modelled at the measurement points in the SIMULINK model.

3.1 SIMULINK

Standard SIMULINK/SimPowerSystems blocks are used to model the distribution system in Figure 1 with its step-down transformers. On the LV side of S/S F there is a measurement point X, implemented using standard signal measurement blocks, where the feeder currents are summed together. Since in reality the measurement of harmonic data is done at bus-bar level in this system, therefore the feeder power levels have been summed.

3.2 Complex amplitude transfer coefficients

The modification made here to the method previously proposed in [1] for calculating the complex transfer coefficients is to automate the process using fast Fourier transform (FFT) analysis. Harmonic frequency components of a waveform are a complex quantity with a magnitude and phase. Therefore, the ratio of the measured harmonic signal to the harmonic input source at the same frequency, defines the transfer coefficient, which is the same complex quantity described in [1].

$$I_{Dh} = a_{iih} I_{Sh} + a_{ivh} V_{Sh} \tag{1}$$

$$V_{Dh} = a_{vih} I_{Sh} + a_{vvh} V_{Sh} \tag{2}$$

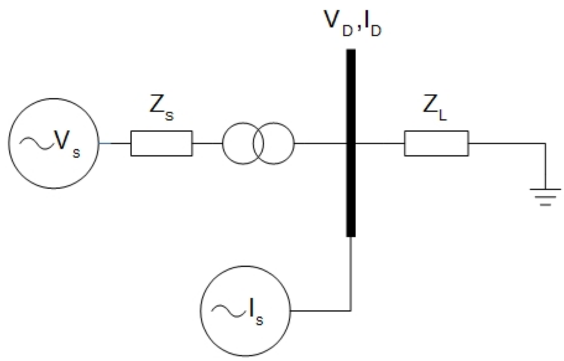

Figure 2: Definition of the voltage and current quantities in the network.

This is defined in equations (1) and (2), where the subscript D indicates a measured quantity, h denotes a particular harmonic frequency, S corresponds to a harmonic source, a is a complex transfer coefficient with its subscript indicating that it represents the relationship between corresponding measured quantity (first letter) and source quantity (second letter). For example, a_{iih} is a complex number representing the ratio between the measured current and source current at a particular harmonic frequency h. One can also see from equations (1) and (2) that there is an interdependence between voltage and current measurements and their harmonic sources.

3.3 Coefficient Determination

Since the measurement point voltage and current are dependent on the harmonic voltage and current sources V_s and I_s, the simplest method to determine coefficients is to perform two simulations. Firstly with $V_s = 0$, this simulation allows the calculation of a_{iih} and a_{vih} from equations (1) and (2) directly. Then with $I_s = 0$, the same calculation returns a_{vvh} and a_{ivh}.

A separate FFT analysis of the harmonic source and measurement point waveforms created by the SIMULINK model, allows the ratio of the FFT complex-valued output arrays created by the FFT MATLAB function to be used for calculating the coefficient values over the entire frequency range of the FFT array.

Therefore, at harmonic frequency h and with $V_s = 0$, the coefficient a_{iih} can be calculated as:

$$a_{iih} = FFT\ (i_{Dh})/FFT(i_{Sh}) \tag{3}$$

4 RESULTS

To demonstrate the method, the simulation model was run using a set of harmonics with equal magnitudes to allow the calculation of the coefficients. Following this, the coefficients are used on the measured data to calculate the harmonic voltage and current sources that would be needed to reproduce this measurement in the model. Then an extra 3-phase harmonic source is introduced at the LV side of the model, imitating the effect of an inductive charger used for wireless charging of electric vehicles in this case.

Figure 3 below shows the measured voltage waveform for one phase at the measurement point, and the modelled waveform is also shown for comparison.

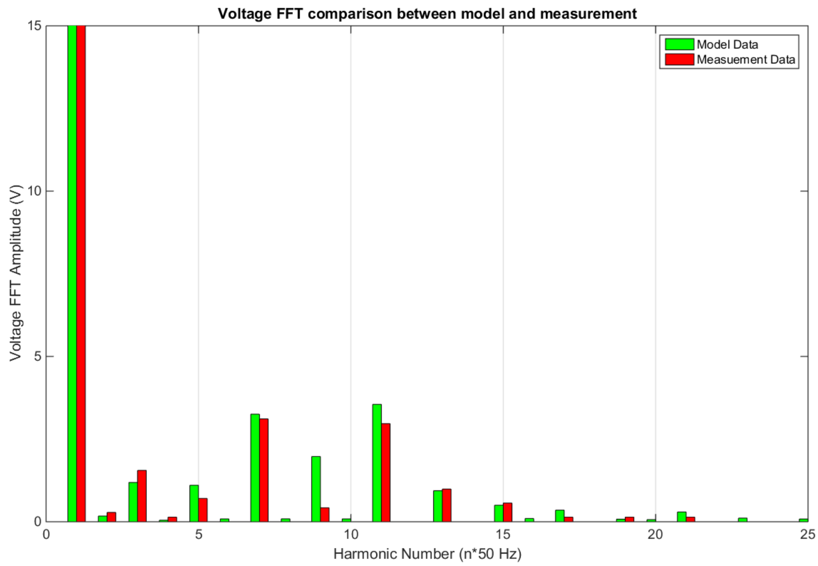

Figure 3: *Comparison of the measured and reconstructed voltage at the measurement point. The triplen harmonics of 9 and 21 show a significant disagreement from measurement, and investigation of this will be part of further investigations in the future.*

Figure 4 shows the harmonic voltage source waveform which was created using the process described in Section 3. This waveform is superimposed on the 33kV fundamental sine wave to generate the high-voltage input which recreates the conditions at the measurement point.

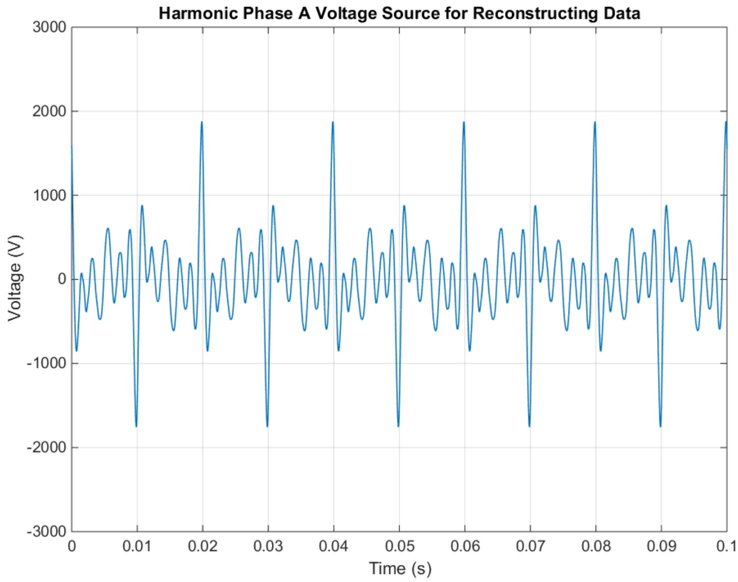

Figure 4: *Harmonic Voltage source used to recreate the measured LV quantities.*

Figure 5 shows the harmonic components of the real current measurement and the modelled values.

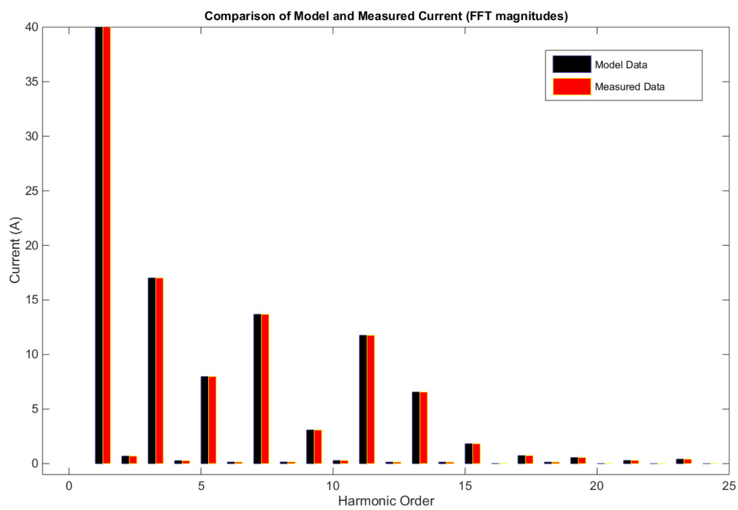

Figure 5: *A comparison of the harmonic current components measured by the Outram Power Quality Analyser and recreated by the model at the measurement point.*

The important result here is the comparison in Table 5 showing the comparison in LV voltage THD value between the measured values and the reconstructed values. The error between measurement and model here is~0.2%.

Table 5: *Results comparing measured harmonic parameters and the model results on phase A*

	LV Voltage THD	***LV Current THD***
Measurement Data	1.39%	8.0%
Modelled Data	1.56%	8.4%
Difference	0.17%	0.4%
Modelled Data with Inductive Charger	5.30%	20.4%
Difference between modelled data and model including inductive charger	3.74%	12.0%

After injecting the distorted waveform associated with the inductive charger into the model, Table 5 also shows the observed increase in voltage and current THD at the model measurement point.

It can be seen that the inductive charger causes a large increase in the LV Voltage THD as observed at the measurement point. The modelled increase in THD of the LV voltage supply actually exceeds the specified limits of the G5/4-1 recommendations here, and since the agreement between model and measurement is fairly good, it is possible to identify the main source of this extra distortion.

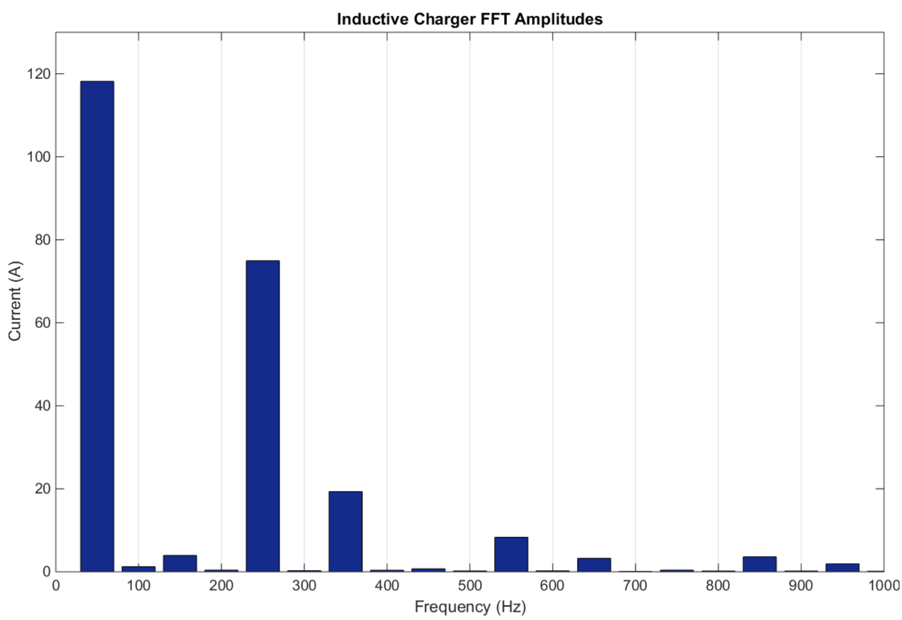

Figure 6: *FFT analysis of the Inductive Charger harmonic current components which are injected into the model.*

Figure 6 shows the inductive charger harmonic components, where the 5th harmonic component of the current has been deliberately set at a very high level in order to establish the limit in this network configuration where the guideline THD limit would be exceeded. The total THD of the current signal injected by the Inductive Charger which exceeds the G5/4-1 limits is modelled here to be in excess of 66%.

5 CONCLUSION

This paper demonstrates the potential of an extension to the method described in [1] for approaching a synthetic reconstruction of harmonic sources present in a power network, which allows the use of modelling software like SIMULINK to calculate the impact on the network from adding other sources of harmonic distortion.

A method has been demonstrated which builds upon previous work to automate the creation of a table of coefficients which allows the recreation of distorted voltage and current from real network data.

The results section shows an agreement of 10 % for the voltage reconstruction and 5% for the current reconstruction between the model and the measured data. This is the platform for adding in other sources of distortion in the model and gaining predictive power for the network conditions occurring when a source of distortion such as an inductive charger for EVs is connected to the distribution system.

This method is aimed at analysing the grid compliance and network effect of the expected surge in distributed generation and electric vehicles in the future development of smart grids.

6 FUTURE WORK

It has been observed that the attenuation of the triple harmonics (h=3, 9, 15…) which is expected in a delta-star transformer, is not properly represented in this SIMULINK model. This does not significantly affect the calculation of THD shown in Table 5, however this issue will be investigated in detail in future applications of this model. Extending the scope of the case study for different network configurations and a variety of transformer will also be a priority in future model applications.

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LABORATORY INFRASTRUCTURE FOR TESTING INTEROPERABILITY WITHIN E-MOBILITY ACTORS – LABORATORY OF DISTRIBUTED GENERATION (LGR)

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Keywords: electrical vehicle, vehicle-to-grid (V2G), charging station, IEC 61850, vehicle-to-X (V2X), electrical vehicle supply equipment (EVSE).

ABSTRACT

For a last decade Electrical Vehicles (EVs) became common like never before, giving opportunity for new market development. It is observed all over the world. Wide and rapid development caused that many manufacturers of EV and related equipment, intending to participate the e-mobility markets should develop individual technical solutions. In a result, EV users travelling abroad face the interoperability issues in EV charging process, billings or charging station reservation. To solve that problem within the European Union, the EC established several calls for research consortiums that will provide procedures for testing e-mobility related standards. The COTEVOS (Developing Capacities for Electric Vehicle Interoperability Assessment) is the one of the project dealing with detecting and covering interoperability gaps in e-mobility standards. The paper presents the laboratory infrastructure for testing interoperability issues in e-mobility, that is developed at the Institute of Electrical Power Engineering of the Lodz University of Technology (TUL) - the partner in the COTEVOS consortium.

1 INTRODUCTION - TUL'S INFRASTRUCTURE

One of the main COTEVOS' goals is to make progress in interoperability assessment at higher levels of communications between EV/EVSE and a Smart Grid. For this purpose, within COTEVOS, the V2G test cases should be developed and tests must be performed. In order to make tests of V2G services possible, it is necessary to initially:

- implement the Smart Grid architecture (including network metering and control)
- develop the EV/EVSE equipment with V2G functionality (mainly in the field of hardware and communication)

Since, V2G architecture is meant to be the integral part of Smart Grid, it should not be introduced without it. Additionally, the presented concept of system should be coherent with both: the general COTEVOS architecture and communication scheme and with the existing Smart Grid solutions. Other words, it is assumed that the V2G architecture must be adopted to the existing Smart Grid infrastructure, not conversely.

The depicted V2G laboratory architecture in TUL was designed on the basis of this approach and is currently under development.

The framework describing a Smart Grids, with implemented V2G services, are presented in Figure 1.

One should note that a joint consideration of many MV and LV areas, in case of many additional actors such as EVs, DGs, controllable loads etc., would introduce serious modelling problems. Thus, it is believed that a Distribution System Operator (DSO) should control a LV network operation by additional controllers. Such separation is necessary to properly conduct optimization and other management activities. In certain cases, for example in LV network with just EVSE connected (such as big charging station/parking), the DSO controller and EVSE Operator would not differ from technical point of view.

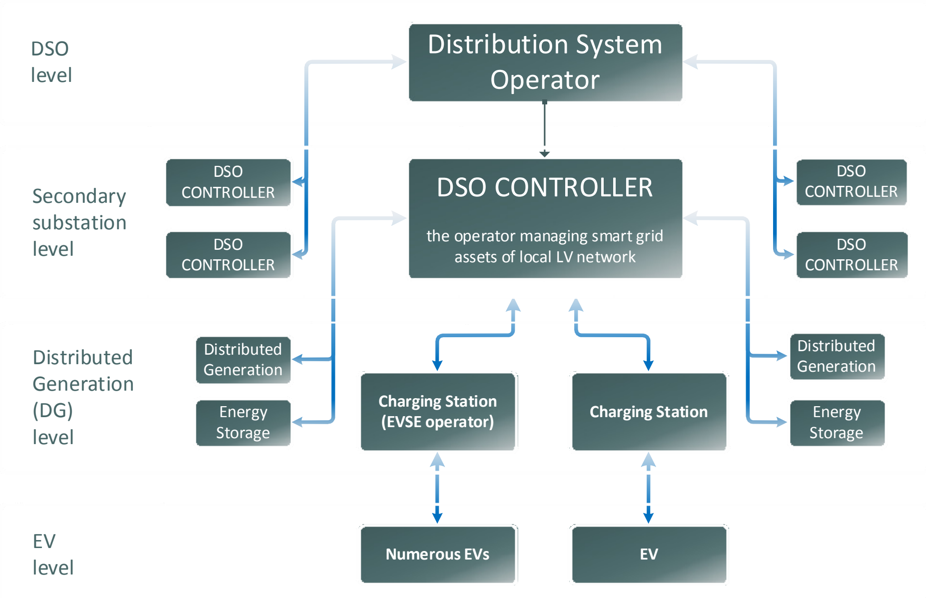

Figure 1: *General concept of Smart Grid control structure.*

In Smart Grid accommodated in power system environment (including legal aspects), any operator of Smart Grid actually must be a network operator and should be subject to the Distribution System Operator. In the concept presented, the DSO controller serves as an operator of a Smart Grid, which is understood as a LV network area supplied by a single MV/LV substation. Such DSO controller can represent a legal entity or be a DSO's server or a controller. It would perform autonomously, controlling tasks according to defined criteria. In the DSO network it is conceivable that several DSO controllers can operate. The single controller would collect information from all DER units and EVSEs connected to its network. The DSO controller, taking into account metering data from: a grid, the DER units and the external signals from DSO, should be able to arrange operation of its network and send control signals to the actors.

The detailed communication layout, describing V2G concept is presented in Figure 2. Two types of EVSE infrastructures are assumed:

- single EVSE with V2G ability
- EVSE cluster – numerous EVSEs with V2G ability. The EVSE cluster may also be seen as the controller of many single EVSEs located in a single place, e.g. in car park next to shopping mall.

In the first type of EVSE implementation, all information required for V2G provision is transmitted from EV by EVSE to DSO controller. In the second case, EVSE-Operator manages numerous dependent EVSEs and then DSO controller receives only aggregated information, e.g. aggregated available power in defined network node.

Since a V2G is a kind of power system ancillary services, related communication should be coherent with a communication already existing in an electrical power networks. One of communication protocols that are strongly developed and used in a distribution systems is IEC 61850.

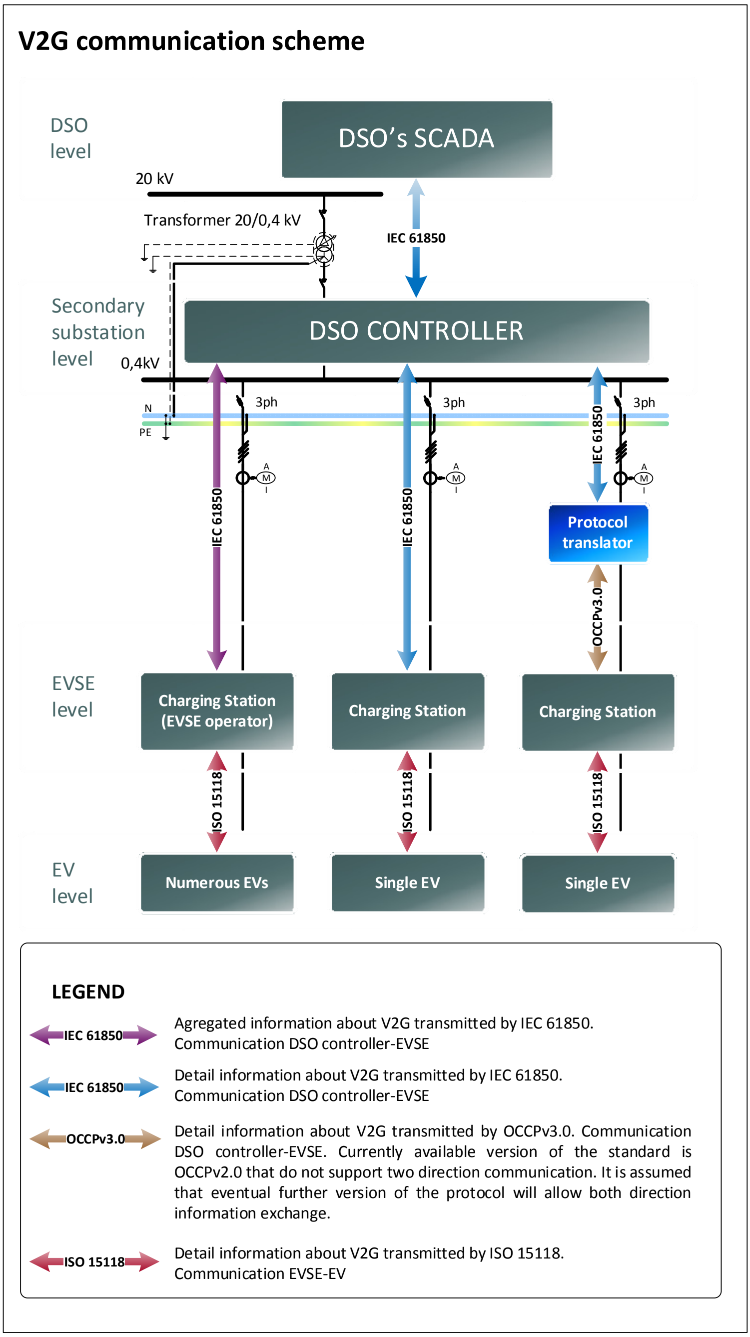

Figure 2: *Layout of communication links between entities according to a general concept presented in Figure 1.*

This standard allows for double-side communication and is being adopted to the needs of V2G services. Therefore, it is reasonable that the communication between a DSO controller and an EVSE/EVSE-O will be established within IEC 61850. The standard IEC 61850 is designed in a very generally way, thus the spectrum of application is very wide [17]. The standard is made for the communication within substations, i.e. the communication with devices for protection control and metering. IEC 61850 does not define a communication stack with relation to the OSI layer model. It is utilizing TCP/IP as its basic transmission protocol and supporting both the Manufacturing Messaging Specification (MMS) and the File Transfer Protocol (FTP) for classic client/server communication. Two peer-to-peer services for real time communication are also described.

In some cases, an EVSE with V2G ability would utilize some other double-side communication standard, such as OCPP (at present existing ver. 2.0 allows only for smart charging). Then "protocol translator" would be required to adjust communication from EVSE/EVSE-O to DSO controller backend.

For communication between an EVSE and an EV, the IEC 15118 standard is assumed, as the most promising standard in this field.

2 V2G LABORATORY ARCHITECTURE

The main objective of the TUL V2G infrastructure is to test IEC 61850 communication at various levels:

- DSO - DSO controller,
- DSO controller - Single EV/EVSE,
- DSO controller - EVSE-O. This communication is needed when the charging controller of the EVSE operator performs the EVSEs management. The DSO controller is provided only with aggregated information from charging controller (no detail information about EV is necessary).

The communication layout together with the main equipment needed for V2G tests are presented in Figure 3.

The SCADA (DSO) and the DSO Controller installed in TUL are based on commercial SCADA PRINS system, provided by BTC AG. Communication in this system is based on IEC 60870-5-104 which is a popular transmission protocol between grid control systems and substations. This standard enables the communication between control stations and substations via common TCP/IP networks using connection oriented, protected data transfer [17]. For the purpose of V2G test, the existing SCADA was upgraded to support the IEC 61850.

Nevertheless, the IEC 60870-5-104 is utilized in EV/EVSE emulators for communication (in technical channel) between software emulated EV/EVSE and real devices such as programmable PLC controllers.

The utilized real devices consists of:

- the universal telecontrol module utilized as IEC 61850 servers - Bilfinger Mauell ME4012PA-N,
- programmable logic controller – used for management of real power inverter and emulate the EV - SAE Gate,
- energy storage power converter - ABB PCS100 and DTSTATCOM,
- signal emulator - custom computer application,

Real model of MV and LV networks with DER (PV, gas microturbine, loads, etc) and Real Time Digital Simulator with power amplifier used in Smart Grid model. Although, in the presented TUL infrastructure, the IEC 60870-5-104 is used for communication between EV and EVSE, it is possible to replace it in future with IEC 15118.

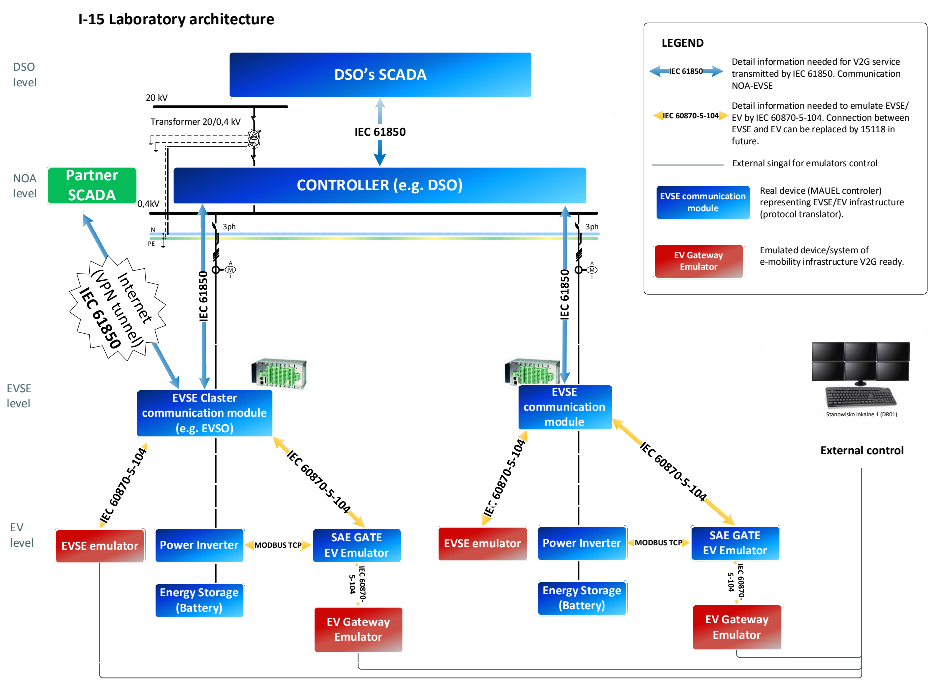

Figure 3: V2G Laboratory architecture developed by TUL.

To enable communication (needed for V2G services), that complies with IEC 61850 standard, it was necessary to emulate EVSE and EV utilizing the logical nodes, Figure 4. The physical device is modelled by IED device (Intelligent Electronic Device), which includes one or more Logical Device (LD). LD model represents information about the resources of the host itself including real equipment connected and the common communication aspects applicable to a number of Logical Nodes (LN). LN model includes set of signals which represents detailed measurements, statuses etc. The description of the e-mobility logical devices and nodes can be found in the draft of IEC 61850-90-8 "Object Models for Electrical Transportation".

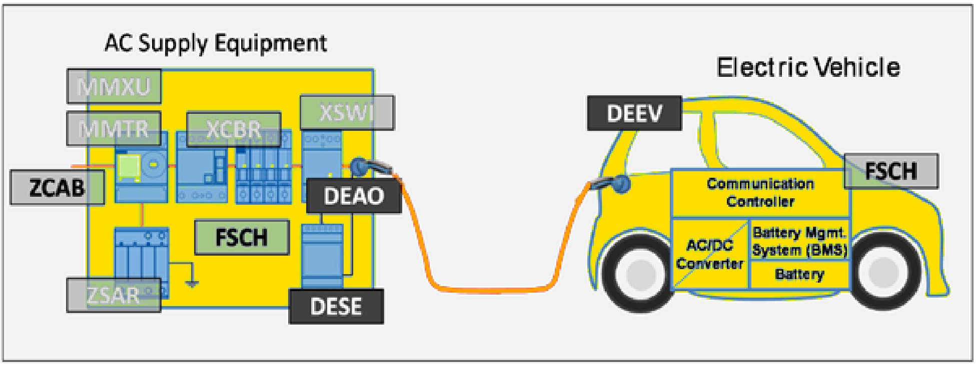

Figure 4: *Logical Nodes overview of AC supply equipment and the EV.*

2.1 IEC 61851 testing infrastructure for EV-EVSE charging operations

Besides testing capabilities in the scope of IEC 61850, TUL can perform number of interoperability tests involving real life and market accessible devices, such as: ABB Terra 51 [13] charging station and Mitsubishi i-Miev [14] electric vehicle. The available equipment can be utilized for the examination of communication between an electric vehicles and a charging stations, performed by IEC 61851. However some tests, referring to IEC 15118 or OCCP, are possible. Additionally, presented equipment can be used for the assessment of electric power quality parameters (e.g. to monitor the charging station's influence on the supplying grid during the charging and the idle stages). For the purpose of preserving "real life" conditions, during EV charging, this equipment is not modified nor customized. It should be taken into account, especially that for example the Mitsubishi I-Miev has no factory provided IEC 155118 capabilities, for example, this vehicle can be used to evaluate the responses of IEC 15118 devices "trying" to communicate with it.

For the measurements and analysis of electrical characteristics of charging processes the FLUKE 1760 (manufactured by Fluke Corporation) [15] will be utilized. This instrument enables the assessment of supplying voltage indices according to criteria defined in European standard EN 50160 [4]. The Fluke 1760 can be connected to Terra charging station feeder or to the regular socket feeder (used to measure the slow charging processes). Some of the technical parameters of charging station and the electric vehicle are as follows:

Some of the technical parameters of charging station and the electric vehicle are as follows:

- The ABB Terra 52 is a dual outlet (AC/DC) 50 kW fast charging station. Available network connection: 10/100 Base-T Ethernet (OCPP), GSM/GPRS/3G/CDMA/EVDO. It is compatible with electric vehicles compliant to: CHadeMO protocol - for DC charging and the EN61851-1 standard - for AC charging (type 2, mode 3 charging). The Terra 52 rated input power is 55 kVA (simultaneously changes up to 77 kVA). The DC output maximum power is 50 kW, voltage range from 50 to 500 VDC, and maximum current is 120 ADC. The AC output allows for charging with maximum power up to 22 kW, voltage range is 400 VAC +/-10% and maximum current up to 30 AAC.

- The Mitsubishi i-Miev parameters are as follows:
  - Propulsion System: Battery Electric Vehicle,
  - Onboard, one phase 3.5 kW charger
  - Inlet compliant to CHadeMO and EN 61851-1
  - Battery type: Lithium Ion,
  - Nominal System Voltage: 330 V
  - Rated Pack Energy: 16 kWh
  - Fast charging characteristics: 30 min, 330 VDC, 150 ADC (up to 80 %),

3 COTEVOS REFERENCE ARCHITECTURE MAPPING

TUL's infrastructure focuses on the real power flow. Hence, EV, EVSE and electricity network are implemented in a test system. Tandem of EV and EVSE is treated jointly and represented by emulator with real advanced power converter and battery storage. Electricity network can be modelled in various ways from real, physical model to computed digital model. Complete test bed can be controlled by SCADA system. Additionally, connection of EV and EVSE can be analysed within real, market available solutions.

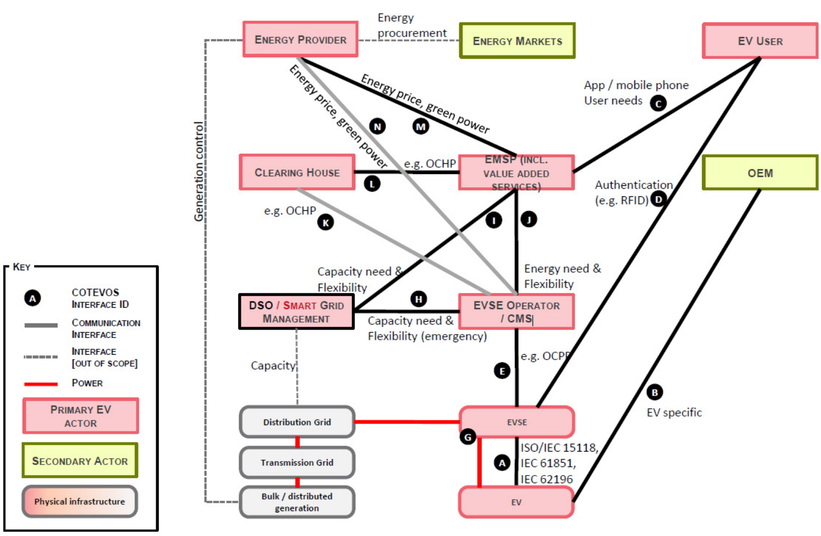

Figure 5: *COTEVOS Reference Architecture.*

The mapping of TUL's infrastructure with COTEVOS reference architecture is depicted in Figure 5. Laboratory implementation covers interface H, E, A, G. Interfaces H and E are implemented with IEC 61850. Interface A is covered with protocol IEC 61851. Interface G indicates a real power flow and in TUL's implementation it includes emulators of EV+EVSE and electricity network model.

4 OTHER RESEARCH FACILITIES

The e-mobility is one of the several fields of research that is developed at the Institute of Electrical Power Engineering. The laboratory is generally focused on Distributed Generation, which besides of e-mobility includes also Renewable Energy Sources (RES), Fuel Cells, Energy Storages etc. The LGR is equipped with:

- Two wind turbines 5,5kWe each,
- Static photovoltaic system – consisting of 37 cells, with a cumulative power of 6 kWp, divided into separated phases
- Tracking photovoltaic system - consisting of 3 panels by 15 modules each. Each panel is mounted on the trucking system including mast equipped with hydraulic actuators, allowing for the panels rotation in both horizontal and vertical directions. By the system, panels are always set with the optimal angle towards the sun rays, supporting fully effective use of the sun energy. The tracking systems with total nominal power of 9kWp operates with 3 kWp per phase.
- PULSTAR hydrogen system with Ballard fuel cells - constructed based on two NexaGen type fuel cells delivered by the Ballard, with proton exchange membrane (PEM). The PULSTAR controller, controls all of the appliances which are included into the system. Nominal capacity in grid mode is up to 2 kW.
- Capstone C30 gas microturbine – CHP power unit (combined heat and power) with the nominal power is 30 kWe (electrical) and 60 kWth (thermal). Microturbine is adjusted to continuous operation in parallel mode with the network (Grid Connected Mode) or to support separate network (Stand Alone Mode). The turbine can be operated at a power given in the range of 0 to 30 kW, controlled remotely by using Remote Capstone Monitoring System or via the control panel located on the turbine. Programming of operation schedules is available.
- Real-Time Digital Simulator (RTDS) – the devices for: simulation of the various network operation in real time, modelling of the power electronic systems (m.in. HVDC, SVC, TCSC), developing of the fully configurable sub-network (including VSC, transformers, lines, cables, breakers, filters, etc,) simulation of transitional states in the power system, Hardware-in-the-loop simulation, modelling of the extended circuits and control systems

used in the PV, STATCOM, HVDC, examination of protective relays works together with multi-function generator's Netwave Emtest.

- Power inverters - nominal power of 10kVA, controlled appropriately by three independent current reference signal allows for the simulation of the following working patterns: load or asymmetrical, non-linear generator with parameters given, active filter, energy storage
- Real load model – including: 4 squirrel cage engines with the cumulative power 3,5 kW, loaded with the DC power generators, controlled by the excitation current, 3 coils with the controllable reactance value and apparent power controlled by the autotransformer, three-phase, half wave rectifier with a power controllable in the range 0-30 kW by autotransformers
- Physical network model - able for connecting the isolated network with double transformers rated at 70 kVA each and 12 branches with controllable lines impedance and resistance. The network is equipped with the short circuit simulator and measurement infrastructure, separately from SCADA system, allowing for analysis of total harmonic distortions (THD) in the network.
- Weather Station - Davis Weatherlink – providing following measurements: inside and outside temperature, solar radiation, wind velocity, air pressure, humidity.
- Generator EmTest NetWave - multifunctional, programmable 3-phase AC/DC power source with recovery system and additional measurement system. The nominal power is 60 kVA. In the LGR, generator operates connected with real-time simulator RTDS. The system dedicated for measurements and researches includes: build-in arbitrary generator, electronic AC/DC source, energy recovery system.
- Dynamic Energy Storage (DES) Vycon Flywheel - The energy storage with high speed Vycon flywheel, which is installed in the LGR allow for conversion and accumulation of electrical energy in a form of kinetic energy. Basic characteristic of the Vycon flywheel: power: 350 kW, velocity of full charge state: 36 0 000 rpm, efficiency: above 99 %. The DES is connected to the power system through Socomec UPS system (160kVA). The system is designed for supplying in short time power outages (up to 7s). In case of longer outages, energy is taken from chemical batteries (both storages are connected to the same UPS system).

All of the appliances above listed, are connected to the internal grid and to the SCADA system (Figure 6).

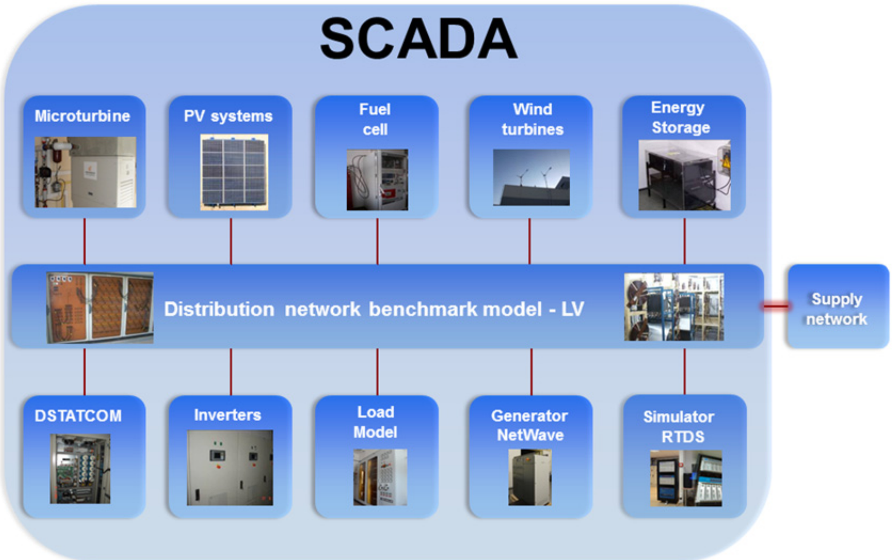

Figure 6: *Research facilities of the LGR.*

Due to that wide variety of available distribution systems and equipment makes the LGR the unique laboratory for complex testing for grid integration of smart grids, EV, renewables, energy storages systems, etc.

5 CONCLUSIONS

The rapid development of EVs and EVSE gives new opportunities for grid integration. However high level of innovation causes interoperability gaps that should be covered. The COTEVOS project deals with identification of interoperability gaps and propose testing procedures for standards where gaps were identified. The TUL is one of the project partners and deals with V2X services.

The Laboratory infrastructure that was developed within the project, allow for testing entire communication chain, from EV, through EVSE, EVSEO, NAO to the DSO. The infrastructure is able for testing several communication protocols (e.g. IEC 61850, IEC 60870-5-104), between different actors covering all of the communication stages. The SCADA system that is the main part of the system integrates set of real devices and software emulators that pose models of different configuration of charging infrastructure. The LGR is also equipped with various generation, storage and load systems allowing for wide variety tests and grid configurations, making the laboratory a complex infrastructure for e-mobility tests.

6 ACKNOWLEDGEMENT

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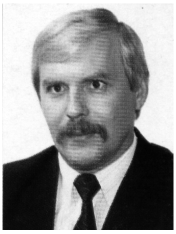

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TECHNOLOGY &SCIENCE

PLANGRIDEV APPROACH FOR REPRESENTING ELECTRIC VEHICLES IN DISTRIBUTION GRID PLANNING – PROOF OF CONCEPT

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Keywords: distributed energy resources; distribution grids; electric vehicles; grid planning.

ABSTRACT

European Energy Systems are facing a range of challenges. Besides climate and energy efficiency targets and increasing urbanization, the massive introduction of distributed energy resources (e.g. wind turbines or photovoltaic systems) and a rising market-penetration of electric vehicles are challenging for electricity networks as well as for current grid planning rules and methods. Two different methods of representing electric vehicles in load flow simulations are compared within a use-case in low voltage network. A statistical state-of-the-art method, using average static charging profiles, and a novel method developed within the European project PlanGridEV are tested and analysed. The results show significant deviations of effects to the power grid depending on which method is applied, which confirms the need for realistic and accurate methods for simulations and grid planning.

1 INTRODUCTION

European Energy Systems are facing a range of challenges. Besides climate and energy efficiency targets and increasing urbanization, the massive introduction of distributed energy resources (e.g. wind turbines or photovoltaic systems) and a rising market-penetration of electric vehicles are challenging for electricity networks as well as for current grid planning rules and methods.

The overall objectives of the European project PlanGridEV [1] are therefore to develop new network planning tools and methods for distribution system operators (DSOs) for an optimized large-scale roll-out of electro mobility in Europe whilst at the same time maximizing the potential of integration of distributed energy resources (DERs).

Early distribution planning tools and methodologies followed a deterministic process, since the existing computational power and availability was limited. In time, parts of the process were automated, but the main rationale remained unchanged. Recently, increasing levels of Distributed Generation (DG) plus the expected rollout of Electric Vehicles (EVs) have been introducing uncertainties at generation as well as consumption side. The worst case scenario that should be evaluated is no longer necessarily peak load, as off-peak conditions could violate quality of supply indicators and for instance cause voltage and reactive power problems in presence of DG. At the same time, there is a greater concern in developing long term plans with the prospect of achieving better overall solutions.

In the course of work of PlanGridEV, eleven existing grid planning tools were analysed in respect to their main tasks (operation simulation and investment decisions) and additional functionalities [2] [3]. Besides the tools used at European DSOs (e.g. DPLAN [4], NEPLAN [5], PSS@SINCAL [6] or PowerFactory [7]), also software mainly used in the research and academic environment was taken into account. The results of the state of the art analysis [3] show that none of the analysed tools provide new functionalities for modelling new components and entities in the grid such as renewable energy resources (RES) (wind turbines, PV systems), EVs or controllable storage systems. Additionally to the state of the art analysis of existing tools, methods for addressing new functionalities were investigated and evaluated in respect to the requirements of grid planning as defined in PlanGridEV [2]. Methods regarding the statistical behaviour of EVs in respect to grid planning requirements the analysis [8] shows that none of the 12 investigated methods addresses all requirements. Especially network constraints are addressed only by three methods as is bidirectional charging. Whilst for aggregated charging areas (usable for simulations in medium voltage (MV) grids) a number of suitable methods are existing, methods for simulations in low voltage (LV) networks are rare. The generation of appropriate behaviour patterns of individual vehicles in limited geographical areas and especially in data poor areas is not sufficiently solved. The PlanGridEV approach to address this problem combines statistical models and an agent-based method which allows fast generations of individual profiles (according to area type and charging infrastructure) in data rich as well as for data poor areas [9].

2 METHODS

This work compares two different methods (Statistical method vs. agent based method) for the simulation of EVs in distribution grids. Figure 1 illustrates the simulation and analysis process. The network data (e.g. topology, electrical characteristics and parameters) and grid user data have been combined with PV production profiles and EV load profiles as input for simulations. These simulations have been performed with DIgSILENT PowerFactory [7] and resulted in information about transformer loading, feeder loading, network voltages and losses. The simulation results have further been processed with Matlab [10]. The following key performance indicators (KPI's) were investigated:

- Ratio between minimum and maximum electricity demand
- Percentage utilization of electricity grid elements
- Voltage quality performance of electricity grids
- Level of losses in transmission and distribution networks

The first two KPIs apply to the transformer and feeder loading. Together with the voltage quality assessment, the investigation of the transformer and feeder loading result in the hosting capacity of a network and the identification of the limiting factor for this hosting capacity.

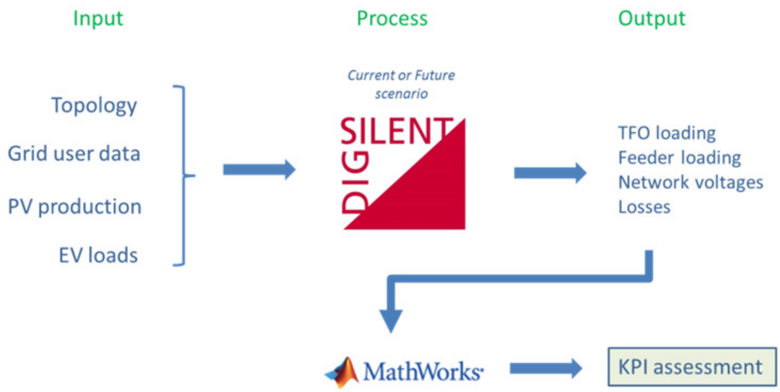

Figure 1: *Simulation process overview.*

Regarding the behaviour of vehicles (in this case electric vehicles) two different approaches were investigated:

- Statistical models - Modelling the behaviour of vehicles (in these case EVs) based only on the temporal component of the appearance of the vehicles on a specific aggregation level.
- Agent-based models - Consideration of the whole traffic system of an area, which means keeping track of individual vehicles within a specific period of time.

In literature, for statistical methods, mainly Markov [11], [12] and Semi-Markov chains are used for forecasting the behaviour of EVs. One drawback of stochastic modelling in this way is that it is mainly suitable for a large number of vehicles. [12] shows that forecast accuracy is decreasing with shrinking numbers of vehicles and therefore not unrestrictedly suitable for a small number of EVs in a small grid branch of an LV distribution grid, whilst MV grids can be covered sufficiently by such methods. Different approaches exist for agent-based electric vehicle simulation. Whilst the approach using MATSim [13] (or similar transport simulation tools) in combination with EVSim in [14], [15], [16] allows controlling the charging process without interfering with the day plan of the agents, the method in [17] takes re-planning (rerouting) of the agents day plan due to the charging process into account (e.g. delay of departure to provide more time for fully charging the car). Disadvantages of such traffic simulations are their need for specific local data (street network and agent data plans) and extensive setup-time and computational performance.

2.1 State-of-the-art method for representing EVs

The first part of this work aims for a simulation of the use-case representing the charging activities of EVs with a state-of-the-art method, as used during the Projects EmporA and EmporA2 [18]. Figure 2 shows the average charging profile of an EV for a week in summer and winter. Since this profile derives from aggregated statistical data, its accuracy decreases with the number of EVs in the grid.

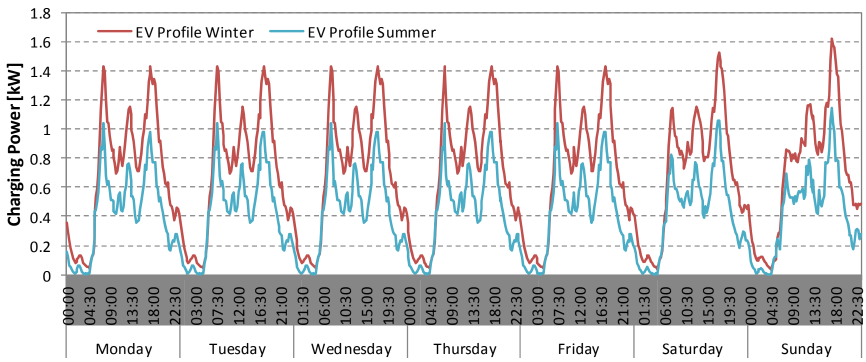

Figure 2: Charging profiles of the state-of-the-art method. The profiles reflect an aggregated charging behaviour and its accuracy decreases with the number of EVs simulated.

2.2 PlanGridEV approach method for representing EVs

A detailed description of the PlanGridEV method was published in [9] and [19]. The following section provides a brief overview of the main functions of the method. Three steps are used for this method (population-, travel chain- and event generation).

Based on the number of the local EV population and statistical information of the ratio of in-, intra- and out-commuters an inbound EV population is defined (in-commuters). Since this method aims at being applicable across the different European countries it is important to depend on as little data as possible for staying functional in data rich as well as data poor areas. Whilst information regarding the network (grid data) and charging infrastructure are essential, the usage of local mobility data is optional and default values are provided.

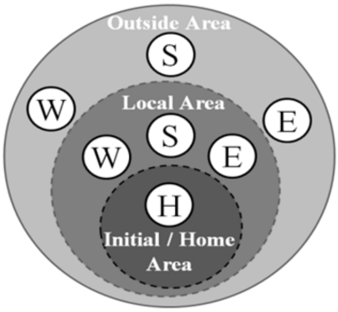

Figure 3: *Overview of possible interconnections of charging locations for creating travel chains (starting at the initial state, vehicles can approach either local or outside destinations, or alternate amongst both).*

Markov Chains [20] including state transitions matrices (individually for rural and urban areas as well as for local and inbound population) are used for creating individual travel chains for every agent (EV). An example of such a matrix is shown in Table 1. Table 1 shows the structure of the transition matrix used for this use case. It includes the initial state, and different local and outside destinations (W=work, S=shop, E=else, H=home, I=initial). Each transition from an individual state to another has its own calculated probability.

Table 1: *Transition matrix (eight states) for the generation of individual travel chains (including local [L] and outside [O] destinations)*

		State 1 $I_{L/O}$	*State 2* W_L	*State 3* S_L	*State 4* E_L	*State 5* W_O	*State 6* S_O	*State 7* E_O	*State 8* $H_{L/O}$
State 1	$\mathbf{I_{L/O}}$	p_{ii}	p_{iwl}	p_{isl}	p_{iel}	p_{iwo}	p_{iso}	p_{ieo}	p_{ih}
State 2	$\mathbf{W_L}$	p_{wli}	p_{wlwl}	p_{wlsl}	p_{wlel}	p_{wlwo}	p_{wlso}	p_{wleo}	p_{wlh}
State 3	$\mathbf{S_L}$	p_{sli}	p_{slwl}	p_{slsl}	p_{slel}	p_{slwo}	p_{slso}	p_{sleo}	p_{slh}
State 4	$\mathbf{E_L}$	p_{eli}	p_{elwl}	p_{elsl}	p_{elel}	p_{elwo}	p_{elso}	p_{eleo}	p_{elh}
State 5	$\mathbf{W_O}$	p_{woil}	p_{wowl}	p_{wosl}	p_{woel}	p_{wowo}	p_{woso}	p_{woeo}	p_{woh}
State 6	$\mathbf{S_O}$	p_{soi}	p_{sowl}	p_{sosl}	p_{soel}	p_{sowo}	p_{soso}	p_{soeo}	p_{soh}
State 7	$\mathbf{E_O}$	p_{eoi}	p_{eowl}	p_{eosl}	p_{eoel}	p_{eowo}	p_{eoso}	p_{eoeo}	p_{eoh}
State 8	$\mathbf{H_{L/O}}$	p_{hli}	p_{hwl}	p_{hsl}	p_{hel}	p_{hwo}	p_{hso}	p_{heo}	p_{hh}

Figure 4 shows the aggregated charging activities of profiles of individual EVs generated with the PlanGridEV method [9].

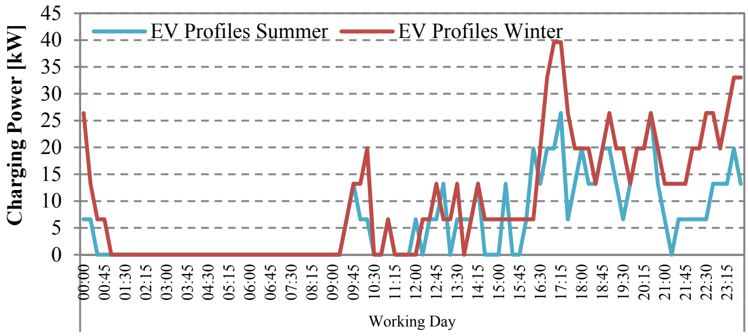

Figure 4: *Aggregated individual charging profiles for the LV grid use-case.*

3 USE CASE DESCRIPTION

For the proof of concept, a rural LV network was chosen as a use case for the simulations with the state-of-the-art and PlanGridEV (PGEV) method. Figure 5 shows the topology of the LV network and Table 2 shows the characteristics of the chosen network.

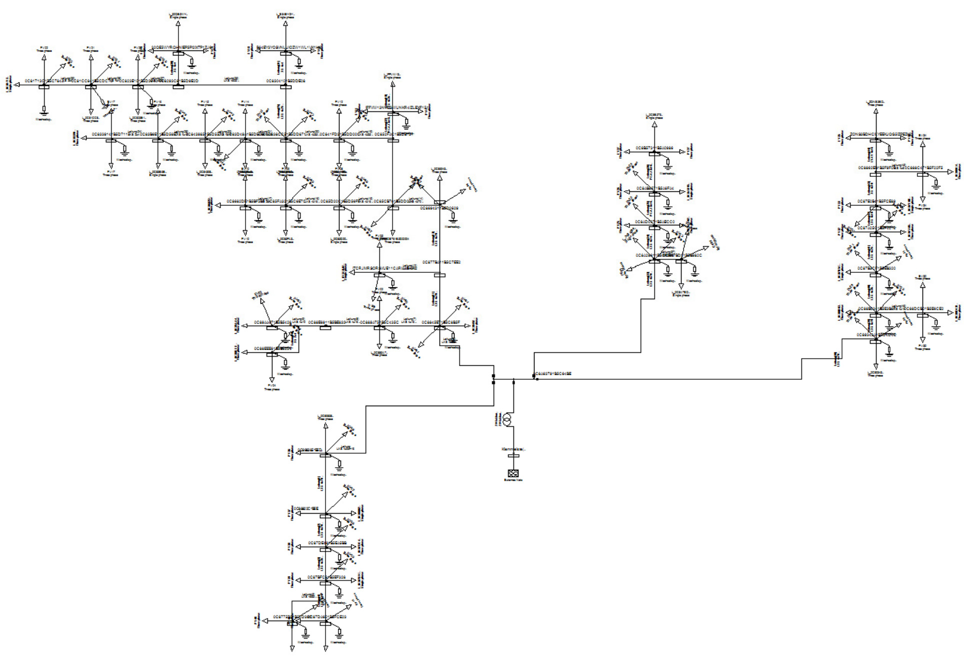

Figure 5: *Network Topology of a rural low voltage.*

Table 2: *Low voltage network characteristics*

Grid Characteristics	
Type	rural
Topology	radial
TFO size	250 kVA
Nr. of feeders	4
Cable/overhead	overhead
Feeder type	various, from Cu16 to Cu95
Avg. Feeder length	437
Nr. of customers	41

For the state of the art method different simulation scenarios have been defined to assess the hosting capacity of different networks:

- ASIS (as-it-is): in this simulation scenario, the current loading of the network is investigated.
- PV scenario: the hosting capacity of the network is assessed by increasing the installed capacity of PV on the network until congestion occurs.
- PV+EV scenario: starting with the installed PV capacity from the PV simulation, EV is connected to the grid until network congestion occurs.
- Extra PV scenario: the potential extra PV capacity which could be connected due to the presence of EV is investigated.

For the PGEV method only two scenarios were simulated based on the previous results of the state-of-the-art simulations. Only two scenarios were simulated for the chosen rural low voltage network, which are PV+EV and Extra PV scenarios considering the same assumptions made for the state of the art method. As input for the simulations, following data have been used:

- Load profiles for each customer based on yearly energy consumption and type of customer (e.g. private, industrial…)
- Measured PV profiles covering 7 days for a critical summer week and a critical winter week.
- Synthetic EV profiles generated from statistical input data (e.g. driven distance) and vehicle specifications (once as average static profile and as individual agent plans)

The simulations have been performed under following assumptions:

- The allowed voltage at the LV customers is +/-10% of the nominal voltage.

- No information about the loading of the TFO in the ASIS situation was available. Therefore, the generated load profiles have been scaled to match following TFO loading:
  - A maximum transformer loading of 50% in the summer and 60% in the winter has been proposed for LV networks in Northern Europe.
  - A maximum transformer loading of 60% in the summer and 50% in the winter has been proposed for LV networks in Southern Europe.
- EVs have a 3-phase connection with symmetrical loading and the following characteristics:
  - Energy consumption 0,2 kWh/km (summer)
  - Energy consumption 0,4 kWh/km (winter)
  - Max. charging power: 6,6 kW
  - Average energy consumption/day: 10 kWh (in 20°C conditions) was assumed for the state-of-the-art method only
  - EVs can charge outside the grid area (only
- PV have a 3-phase connection with symmetrical loading
  - Individual profiles for summer and winter days
  - Individual system size (kW_{peak}) depends on the local hosting capacity
  - The measured PV profiles were scaled along to the installed PV Power per grid node

4 RESULTS

4.1 State of the art method

The results for the rural network section are summarized in this section, according to the simulated scenarios.

Table 3: *Summary of the hosting capacity assessment for a rural low voltage network (Scenarios: PV+EV & Extra PV) [21]*

State of the art method	*PV+EV*	*Extra PV*
Hosting capacity	82 EV total	74 kW total
TFO loading	10% - 98%	13% - 95%
Max. utilization of lines	33% - 71%	32% - 70%
Node Voltages	0,9 p.u. – 1,05 p.u.	0,9p.u. – 1,1 p.u.
Limiting Factor	under voltage	over voltage
% of voltage band used	66%	65%

Results only from PV+EV and extra PV scenarios are considered in the tables (since the hosting capacity of PVs stays the same), and represent the minimum capacities from both, the summer and winter scenario as Table 3 shows.

As mentioned before, the primary goal of the GAP analysis [21] was to estimate the hosting capacity of various LV and MV networks and identify the limiting factors restricting this hosting capacity. Therefore, multiple scenarios have been defined and investigated (see Use-case description). Table 3 provides a summary of the hosting capacity assessment of a chosen rural low voltage network, including the limiting factors restricting this hosting capacity. Considering the limiting factors to the hosting capacity, the rural network is limited by under- and over voltages. These results suggest that for rural LV networks, a monitoring of the voltage is useful when a high number of PV and/or EV are connected. For each of these limitations, KPIs has been calculated which applies to the current loading scenario:

- The maximum transformer loading of the investigated critical summer and winter weeks.
- The utilization of lines, indicating the maximum line loading in the entire network during the critical summer and winter weeks.
- The percentage of the total available voltage band which is already used.

4.2 PGEV method

The same two scenarios (PV+EV and extra PV) were simulated for the selected rural LV network section but for EV profiles generated with the PGEV method and for two different Max. Charging powers of EV’s (6,6 kW and 11 kW).

The results for the rural network section are summarized in this section, according to the simulated scenarios. Results only from PV+EV and extra PV scenarios are considered in the tables, and represent the minimum capacities from both, the summer and winter scenario according to PGEV methodology as Table 4 and Table 5 show.

Table 4: *Summary of the hosting capacity assessment for a rural low voltage network (Scenarios: PV+EV & Extra PV)*

Scenario 6,6 kW	*PV+EV*	*Extra PV*
Hosting capacity	36EV total	4,1 kW total
Max. TFO loading	10 % - 66 %	10 % - 66 %
Max. utilization of lines	30% - 67%	30% - 67%
Node Voltages	0,98 p.u. – 1,08 p.u.	0,98 p.u. – 1,08 p.u.
Limiting Factor	under voltage	over voltage
% of voltage band used	54 %	55 %

Table 5: *Summary of the hosting capacity assessment for a rural low voltage network (Scenarios: PV+EV & Extra PV)*

Scenario 11 kW	*PV+EV*	*Extra PV*
Hosting capacity	32 EV total	4,1 kW total
Max. TFO loading	10 % - 74 %	10 % - 74%
Max. utilization of lines	9 % - 110 %	9 % - 111 %
Node Voltages	0,97 p.u. – 1,09 p.u.	0,97 p.u. – 1,09 p.u.
Limiting Factor	under voltage and line loading	over voltage and line loading
% of voltage band used	59 %	61 %

A preliminary investigation of the correlation between the values of these KPIs and the hosting capacity of a network has been performed. The rural network uses only between 54 and 66 % of its available voltage band, which is low compared to the other networks, but critical voltages are the limiting factor for the hosting capacity. To investigate these correlations more thoroughly, a higher number of networks would have to be assessed.

Besides KPIs, which consider the current loading of the network, the network losses have been investigated. When PV is connected to LV grids, consumption can be covered by local production. This can reduce overall power flows in the network and reduce losses if local consumption and production coincide. This has been confirmed by simulations for different low voltage networks where losses decreased with 10 % to 36 % in summer. However, at full PV hosting capacity, the local generation can exceed local consumption to such an extent that the losses actually increase. The connection of EV increases the losses. However, the increase differs significantly.

It has also been investigated to what extent the connection of EV results in an increase of the PV hosting capacity (extra PV scenario). The connection of EV generally lowers the voltage and allows for further increase of the connected PV. This is especially the case for the state-of-the-art method, where 56 % extra PV could be connected compared to the PV scenario. For the PGEV method, a significant lower number of 3,1 % of additional PV power could be connected.

For the PGEV method, the limiting factors are the same, but it is clear that the ability to connect EVs and the hosting capacity of PV's following this method decreases significantly compared to the state-of-the-art methodology.

4.3 Comparison of State of the art vs. PGEV method

A comparison has been done between the results of the methods which are represented in Table 6.

Table 6: *Summary of the hosting capacity assessment for a rural low voltage network (Scenarios: PV+EV & Extra PV) (different methods)*

Method	*Hosting capacity PV+EV*	*Hosting capacity Extra PV*
State of the art method	82 EV total	74 kW total
PGEV 6,6 kW	36 EV total	4,1 kW total
PGEV 11 kW	32 EV total	4,1 kW total

5 CONCLUSION

Regarding the charging behaviour of EVs, the comparison of Figure 2 and Figure 4 shows, that profiles, generated with the agent based method differ from the state-of-the-art method significantly. Whilst the average profile indicates a morning and evening charging peak, the PlanGridEV method generates profiles which show mainly activity around the afternoon and evening time. This is caused by taking the network type and customer structure into account. Since in this LV grid, charging infrastructure exists only at households and EVs cannot recharge at working or shopping locations, EVs mainly approach home charging infrastructure at later times. For networks which also include working or commercial locations (e.g. urban area distribution grids), a significant different aggregated charging profile can be expected and therefore will also have different effects to the electricity network.

The results in Table 6 show that the hosting capacity decreases dramatically within about more than 50 % if applying the PGEV methodology. The limiting factors are still under and overvoltage which is typical and an expected results for a rural LV network. This results show how different methods (even if scenario settings stay the same) result in significantly different output, which concludes to the importance of new methodologies for representing EVs (and also DERs) with increased realism and accuracy for simulations and grid planning.

Applying charging only at home may be a reason for this decrease (which is given by the customer structure of the chosen network). Although using combinations of charging abilities at home and working, private and public charging may increase the hosting capacity of the network and network stability and reduces the need for network reinforcement. However, this is only possible if the corresponding facilities are within the network area (e.g. shops, working locations…). The results of this work underline the need for more analysis of different network sections with different topologies and types to verify the effect of other aspects on the hosting capacity, e.g. network topology types of customers and their activities to have a chain of possible factors affecting the electricity grid hosting capacity and its stability on the low voltage level.

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