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IEC 61850-Based Communication Modeling of EV Charge-Discharge Management for Maximum PV Generation

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ABSTRACT Photovoltaic (PV) modules are the most common distributed energy resource utilized at household level, owing to the subsidies and payback schemes. Proliferation of residential PV reduces the bills for its owner and supports the grid by local generation when needed. However, since they are located at distribution networks, too much local generation causes over-voltage issues. The traditional solution is to curtail the PV generation when the voltage limit is reached. This limits the benefits of the residential PV systems, makes expected payback period longer, and reduces the amount of captured renewable energy. Alternative approaches that make use of the available storage, such as electric vehicles (EVs), to avoid over-voltage issues in the network and maximize the PV generation, are required. In this paper, a charge–discharge management scheme is shown, where the estimated PV generation as well as the EV location and its state of charge are utilized to calculate the expected PV curtailment due to the over-voltage issues. Based on this information, EV battery is utilized to capture the energy that would, otherwise, be curtailed. This scheme requires the exchange of data and information between different entities, such as irradiation sensors, households, and grid energy management system. Considering the variety of devices included in this communication network, a standardized approach is vital for its successful implementation. Therefore, IEC61850-based communication models are developed for the house energy management system, PV, EV, and grid energy management system. Furthermore, communication message flows have been developed, and their performances have been investigated using different communication technologies.

INDEX TERMS Smartgrid communications, voltage control, active distribution networks, standard information modeling, communication system modeling, distributed energy resource management system (DERMS), PV curtailment mitigation, vehicle to grid (V2G), peak-shifting with EVs.

NOMENCLATURE

SYMBOLS

B	Battery storage capacity of EV.
c	Conversion/weighted coefficients.
$\boldsymbol{\gamma}$	Parameter set of line drop compensator (LDC) method.
$\overline{D}(\cdot), \underline{D}(\cdot)$	Cumulative differences between target and reference voltage.
δ	Threshold for tap control in on-load tap changer (OLTC).
$e(\cdot)$	Function for calculation of electricity.
ε	Dead band for LDC method.
$\boldsymbol{i}$	Complex vector of secondary current of OLTC.
j	Node index in MV distribution system.
$\mathcal{J}$	Node index set in MV distribution system.
l	Line length.
$\mathcal{L}$	Set of appropriate parameter candidates of l.
m	Index of house with house energy management system (HEMS).
$\mathcal{M}$	Index set of houses with HEMSs.
n	Index of house without HEMS.
$\mathcal{N}$	Index set of houses without HEMSs.
$O^{\mathrm{c}}, O^{\mathrm{d}}$	Rated EV output of charging and discharging.
s	Tap position of OLTC.
$\overline{s}, \underline{s}$	Upper and lower limits of tap position of OLTC.

S	SoC of EV.
t	Index of time.
u	Index of time interval.
v	Scalar value of voltage.
$\overline{v}$, $\underline{v}$	Upper and lower limits of appropriate voltage.
$\dot{\boldsymbol{v}}$	Complex vector of secondary voltage of OLTC.
V	Set of appropriate parameter candidates of v^{tar}.
$\boldsymbol{x}$	Vector of power profile.
$\boldsymbol{y}$	Vector of EV state.
$\dot{\boldsymbol{z}}$	Complex vector of unit line impedance between OLTC and reference point.

SUBSCRIPTS AND SUPERSCRIPTS

.c	For calculation of PV curtailment.
.d	For calculation of electricity consumption of scheduled EV drive.
.G	For calculation of grid energy management system (GEMS).
.H	For calculation of HEMS.
.j	At node j.
.m	At house m (with HEMS).
.n	At house n (without HEMS).
.o	For calculation of EV output.
.p	For calculation of purchased electricity.
.PV	For calculation of residential PV output.
.q	Of query.
.r	For calculation of residential electricity consumption.
.ref	At reference point.
.rev	For calculation of reverse power flow.
.sc	Of scheduled driving.
.SoC	For calculation of SoC.
.t	At the time t.
.tar	Of target.
.u	At the time interval u.
.u1, .u2	For calculation of unit.
.ur	Of urgent driving.
.V2H	For calculation of connection sate to EV charger in house.
.$*$	Realized; $\boldsymbol{x}^*$ indicates actual sequence.

I. INTRODUCTION

Tackling global warming requires collective effort of governments around the world [1]. Impacts of global warming are apparent and the discussion is not about raising awareness anymore, but how to mitigate them [2]. To take solid steps towards this goal, governments around the world set specific targets for CO2 reduction and the share of renewable energy-based generation in the overall mix [3], [4]. Additionally, global conflicts made countries more concerned about their energy independence. Countries that heavily rely on imported energy sources are looking at ways to replace these with renewable energy (RE) sources which are ubiquitous [5]. To accelerate this change, incentives such as tax-reductions, feed-in-tariffs or pay-back schemes are implemented across the globe [6], [7].

One of the fastest growing sectors in RE field is PV based generation [8]. There are several reasons behind this fact. PV systems can be deployed virtually anywhere, in contrast to site-specific technologies such as Wind or Geothermal. Furthermore, it is possible to implement PV systems at different scales: as a 100 W solar home system in Tanzania or as a 500-MW solar farm in Morocco [9]. Despite these advantages, PV systems have a very big drawback: they are dependent on time and their peak-generation occurs at noon, which does not correspond to peak-load hours. Too much generation during day time cannot be absorbed by the grid and the generation is limited, i.e. PV curtailment. This results in not getting the best result out of PV investments. An effective way to capture the curtailed energy and transfer it to peak hour use is required [10]. Smart inverters with voltage and frequency support can achieve the former to a certain extent but cannot help with the latter [11].

Transportation has a large share in countries' overall energy consumption which makes it a big contributor of CO_2 emissions [12]. Electric Vehicles (EVs) can play a large role in tackling the above mentioned environmental and energy-related concerns. Electric motor is more efficient than internal combustion engines and can reach high torques at small revolutions [13]. When considered collectively, EV batteries represent a large storage capability with a unique feature: mobility. They can contribute to power system operation at different locations, at different times.

Making use of this potential, it is possible to develop solutions that coordinate the charge-discharge cycles of EVs with generation profiles of local PV systems. Solution developed in [14] uses estimated PV generation and the calculated curtailment information to schedule EV charge and discharge operations. In this fashion, more RE can be captured, curtailment can be reduced and EVs can charge for much less while generating income for their support to grid via Vehicle-to-Grid (V2G).

However, the above-mentioned solution only focuses on the formulation and solution of the optimization problem. Although it is heavily dependent on two-way communication between households and the grid operator, it does not touch on the communication design at all. Furthermore, considering the number of different devices manufactured by a myriad of companies, designing this communication infrastructure in a standard way is vital. Only in this way, can different devices be seamlessly integrated and plug-and-play (PnP) in power systems be achieved.

IEC 61850 is poised to be the de facto communication standard of future power systems. It follows an object-oriented modeling style and allows for standardized devices modeling as well as message exchanged [15]. There is a dynamic research work around extending IEC 61850 for new power system components to achieve complete interoperability: e.g. fault current limiters [16], EVs with V2G operation [17], distributed energy resources [18], smart meters and home energy management systems [19], power system protection schemes [20] and microgrid operation [21].

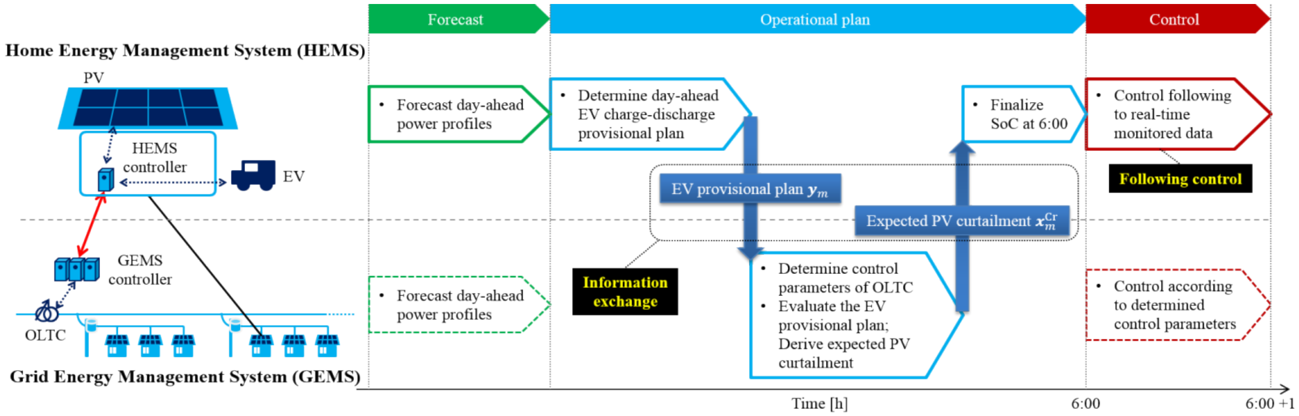


FIGURE 1. Energy coordination scheme outline. Extensive information exchange between HEMs and GEMS; and among HEMS components, is needed.

In this paper, an IEC 61850-based solution is developed for the charge-discharge management of [14]. All components are modeled according to IEC 61850, new logical devices (LDs) and logical nodes (LNs) have been introduced, when required. Furthermore, information exchange that is necessary for the optimization scheme is mapped to IEC 61850 messages with corresponding data object (DOs). Further, the information model and communication framework developed in this paper are demonstrated by generating the required IED capability (ICD) files and then simulating them over a commercial IEC 61850 testing tool Avenue and SCL Runner [22]. Finally, extensive simulation works have been undertaken to test the performance of the system with different communication technologies; especially, wireless networks as they are more likely to be used for systems with EVs.

The rest of the paper is organized as follows: Section II details the utilized EV charging-discharging management scheme. Section III shows the models that are developed for the components of this scheme according to IEC 61850 standard while Section IV shows the developed IEC 61850 based message exchanges for the implementation of that scheme. Section V shows simulations results for evaluating the performance of the communication infrastructure. Finally, Section VI draws the conclusions.

II. EV CHARGING AND DISCHARGING MANAGEMENT FRAMEWORK

The management framework used in this paper has been adapted from [14]. It is important to understand the optimization scheme and what kind of information is exchanged. There are two components: grid EMS (GEMS) has its own controller and coordinates on-load tap changer (OLTC). The other one is the house EMS (HEMS) that manages EV and PV in a house. EMS controllers are capable of changing parameters of their components. HEMS and GEMS exchange information at certain times, yet they operate independently most of the time. HEMS has the goal of maximizing PV generation, reducing electricity bills and meeting charge requirements of EVs. This happens in two ways. First, HEMS makes sure that PV generation is used to cover house's energy consumption, then extra energy is either used to charge the EV or is sold back to the grid. This decision is based on the price of energy from the grid and the revenue that can be generated by selling to it. The important limitation is that the more energy is exported to the grid, more voltage rise is induced on the system which is bound by the grid code. GEMS has the responsibility to make sure grid operates in a safe and stable fashion. For the grid operator, if more generation is coming from household PVs that will decrease the operation costs. For this reason, increase PV output has mutual benefit for grid operator and household owners. Integration of GEMS and HEMS can yield higher benefits in terms of avoiding PV curtailment.

This coordination can be achieved with the components and interactions as shown in Fig. 1, below. It is versatile and can work on a 24-hourly basis for day-ahead optimization, as well as for shorter periods such as hourly optimization. Regardless of the selected optimization period, the optimization approach is the same. Firstly, based on local irradiation measurements residential power generation is estimated while residential consumption is estimated based on the past consumption data. Information exchange is utilized to coordinate operations of HEMS and GEMS. After collecting the local generation and consumption information from all houses in the network, GEMS calculates the power flow to determine locations of over-voltage. GEMS sends this information back to HEMS as a potential curtailment indicator. Based on this information HEMS determines an EV charge-discharge plan to avoid PV curtailment as much as possible and minimize the residential operation cost.

Needless to say, forecasted consumption and generation may differ from the actual values. To address this issue, a *following control* is implemented in HEMS. In operation, the EV charge-discharge plan is corrected according to the mismatch between forecasted and realized values of consumption and generation. In this fashion, electricity purchase is optimized and more revenue is generated from sold energy. Following control requires continuous information exchange among the components of HEMS such as PV inverter, EV battery, and smart meter (SM). Procedures involved are explained below in detail.

A. EV ENERGY PLAN IN HEMS

For the specified optimization period (e.g. 24 hours or 1 hour), HEMS controller determines an EV energy plan. The main motivation is to bring down the daily energy bill. During these calculations, voltage rise in the distribution network is not taken into account. To achieve this, EV charging is scheduled when the electricity is cheap from the grid, or there is excess energy from the PV; and EV discharging is for times when the grid operator purchases electricity at high prices. It is important to keep EV's SOC over a certain minimum level to accommodate unplanned, ad-hoc trips. Let t be the time in a day and $m \in \mathcal{M}$ be the index of house with HEMS where $\mathcal{M}$ be the index set of the houses HEMSs. Also, let $\boldsymbol{x}^{\mathrm{PV}} = \left(x_t^{\mathrm{PV}}; t \in \{1, \ldots, T\}\right)$ and $\boldsymbol{x}^{\mathrm{r}} = (x_t^{\mathrm{r}}; t \in \{1, \ldots, T\})$ be sequences of the forecasted daily PV output and residential electricity consumption; $\boldsymbol{x}^{\mathrm{d}} = (x_t^{\mathrm{d}}; t \in \{1, \ldots, T\})$ be a sequence of the electricity consumption for scheduled EV drive; $\boldsymbol{y}_{m,t} = \left(y_{m,t}^{\mathrm{o}}, y_{m,t}^{\mathrm{SoC}}, y_{m,t}^{\mathrm{V2H}}\right)$ be the set of EV states in a house m at time t where $y_{m,t}^{\mathrm{o}}$ be the EV output to the house, $y_{m,t}^{\mathrm{SoC}}$ be the SoC, and $y_{m,t}^{\mathrm{V2H}} \in \{0, 1\}$ be the connection state to the EV charger in the house; and $\boldsymbol{y}_m = \left\{\boldsymbol{y}_{m,1}, \ldots, \boldsymbol{y}_{m,T}\right\}$ be the daily EV charge-discharge provisional plan. In order to link EV schedule with PV generation and electricity consumption of a house, estimated generation and consumption values are used to solve the following minimization problem $\boldsymbol{x}_m^{\mathrm{H}} = \left\{\boldsymbol{x}_m^{\mathrm{PV}}, \boldsymbol{x}_m^{\mathrm{r}}, \boldsymbol{x}_m^{\mathrm{d}}\right\}$.

$$\begin{aligned} \boldsymbol{y}_m = \underset{\boldsymbol{y}_m}{\arg\min} & \sum_{t=1}^{T} \Big(c_t^{\mathrm{p}} e_{m,t}^{\mathrm{p}} \left(\boldsymbol{y}_{m,t} | \boldsymbol{x}^H, \boldsymbol{y}_{m,t-1}, \ldots, \boldsymbol{y}_{m,0}\right) \\ & - c_t^{\mathrm{PV}} e_{m,t}^{\mathrm{rev}} \left(\boldsymbol{y}_{m,t} | \boldsymbol{x}^H, \boldsymbol{y}_{m,t-1}, \ldots, \boldsymbol{y}_{m,0}\right)\Big), \\ \text{subject to } & -O^{\mathrm{c}} \leq y_{m,t}^{\mathrm{o}} \leq O^{\mathrm{d}}, \\ & y_{m,t}^{\mathrm{o}} = 0 \text{ if } y_{m,t}^{\mathrm{V2H}} = 0, \\ & \underline{S}_{m,t}\left(x_{m,t}^{\mathrm{d}}\right) \leq y_{m,t}^{\mathrm{SoC}} \leq \overline{S}, \end{aligned} \tag{1}$$

where

$$\underline{S}_{m,t}\left(x_{m,t}^{\mathrm{d}}\right) = \begin{cases} \underline{S}^{\mathrm{ur}}, & \text{if } \displaystyle\sum_{t=t+1}^{T} x_{m,t}^{\mathrm{d}} = 0, \\ \underline{S}^{\mathrm{ur}} + \underline{S}^{\mathrm{sc}}, & \text{otherwise.} \end{cases}$$

Here, c_t^{p} and c_t^{PV} are the cost conversion coefficients of the power purchase and selling, respectively; $\boldsymbol{y}_0$ is the initial state; $e_{m,t}^{\mathrm{p}}\left(\boldsymbol{y}_{m,t} | \boldsymbol{x}^{\mathrm{H}}, \boldsymbol{y}_{m,t-1}, \ldots, \boldsymbol{y}_{m,0}\right)$ and $e_{m,t}^{\mathrm{rev}}\left(\boldsymbol{y}_{m,t} | \boldsymbol{x}^{\mathrm{H}}, \boldsymbol{y}_{m,t-1}, \ldots, \boldsymbol{y}_{m,0}\right)$ are the purchased electricity and the reverse power flow from PV, respectively, as a function of $\boldsymbol{y}_{m,t}$ under the previous parameters subset $\left\{\boldsymbol{y}_{m,t-1}, \ldots, \boldsymbol{y}_{m,0}\right\}$ and the power profiles $\boldsymbol{x}^{\mathrm{H}}$; O^{c} and O^{d} are the rated EV output of charging and discharging, respectively; $\overline{S}$ is the upper limit of the SoC; $\underline{S}_{m,t}\left(x_{m,t}^{\mathrm{d}}\right)$ is the lower limit of the SoC as a function of $x_{m,t}^{\mathrm{d}}$; and $\underline{S}^{\mathrm{ur}}$ and $\underline{S}^{\mathrm{sc}}$ are the minimum SoC required for the urgent and scheduled driving, respectively, where the latter one is derived by the time length and electricity consumption for the scheduled driving.

Once this local optimization is done at each household by HEMS, provisional EV plans $\boldsymbol{y} = \left(\boldsymbol{y}_m; m \in \mathcal{M}\right)$ are sent to GEMS along with estimated PV generation and consumption data for the optimization period.

B. CALCULATION OF TAP POSITION BY GEMS

GEMS handles the voltage control phase by dividing it into U time intervals. The voltage control parameter set $\boldsymbol{\gamma}_u; u \in \{1, \ldots, U\}$ is updated in each time interval to appropriately perform the voltage control according to the voltage variation in the time intervals. Let $n \in \mathcal{N}$ be the index of house without HEMS where $\mathcal{N}$ be the index set of the houses without HEMSs. The appropriate voltage control parameter set of the OLTC are determined using the forecasted power profiles and the EV provisional plan $\boldsymbol{x}^{\mathrm{G}} = \left\{\boldsymbol{x}_m^{\mathrm{PV}}, \boldsymbol{x}_m^{\mathrm{r}}, \boldsymbol{y}_m; m \in \mathcal{M}\right\} \cup \left\{\boldsymbol{x}_n^{\mathrm{PV}}, \boldsymbol{x}_n^{\mathrm{r}}; \in \mathcal{N}\right\}$ and the EV provisional plans sent from HEMSs $\boldsymbol{y}$ are evaluated under the voltage constraint. GEMS includes a controller and an OLTC, the tap ratio of which is regulated with line drop compensator method [23] where secondary voltage and current values are tracked to control the taps. Let $\dot{\boldsymbol{i}}_t$ and $\dot{\boldsymbol{v}}_t$ be the secondary current and voltage of the OLTC, respectively. The OLTC estimates a voltage v_t^{ref} at a voltage reference point on the secondary side of the OLTC:

$$v_t^{\mathrm{ref}}(l) = \left|\dot{\boldsymbol{v}}_t - l_u \dot{\boldsymbol{z}} \dot{\boldsymbol{i}}_t\right|, \tag{2}$$

where l_u is the line length between the OLTC and the voltage reference point at time interval u and $\dot{\boldsymbol{z}}$ is the unit line impedance. Then, the OLTC regulates the tap position s_t when the cumulative differences between the target voltage v_u^{tar} and v_t^{ref} with the dead band ε,

$$\overline{D}_t\left(\boldsymbol{\gamma}_u\right) = \max\left\{0, \overline{D}_{t-1} + v_t^{\mathrm{ref}}(l_u) - v_u^{\mathrm{tar}} - \varepsilon\right\}, \tag{3}$$

$$\underline{D}_t\left(\boldsymbol{\gamma}_u\right) = \max\left\{0, \underline{D}_{t-1} + v_u^{\mathrm{tar}} - \varepsilon - v_t^{\mathrm{ref}}(l_u)\right\}, \tag{4}$$

exceed the threshold δ as follows,

$$s_t = \begin{cases} s_{t-1} - 1, & \text{if } \overline{D}_t\left(\boldsymbol{\gamma}_u\right) > \delta \text{ and } s_t \neq \underline{s}, \\ s_{t-1} + 1, & \text{if } \underline{D}_t\left(\boldsymbol{\gamma}_u\right) > \delta \text{ and } s_t \neq \overline{s}, \\ s_{t-1}, & \text{otherwise,} \end{cases} \tag{5}$$

where $\boldsymbol{\gamma}_u = \left\{l_u, v_u^{\mathrm{tar}}\right\}$ is a parameter set of the line drop compensator (LDC) method at the time interval u, $\underline{s}$ and $\overline{s}$ are the lower and upper tap position, respectively. The cumulative differences $\overline{D}_t\left(\boldsymbol{\gamma}_u\right)$ and $\underline{D}_t\left(\boldsymbol{\gamma}_u\right)$ become zero when the tap position is changed.

OLTC automatically controls the voltage if the control parameter set $\boldsymbol{\gamma}_u$ is implemented. GEMS controller determines the appropriate control parameters $\boldsymbol{\gamma}_u^q$ for each time interval u so as to minimize the amount of voltage violation from the appropriate range. Let $v_t^j\left(\boldsymbol{\gamma}_u^q | \boldsymbol{x}^{\mathrm{G}}\right)$ be the voltage at the medium-voltage (MV) node $j \in \mathcal{J}$ under the given parameter set $\boldsymbol{\gamma}_u^q$ where $\mathcal{J}$ is the index set of MV nodes in the DS, $\overline{v}^j$ and $\underline{v}^j$ be the upper and lower limits of the appropriate voltage at the node j, respectively, c_1 and c_2 be the weight coefficients, the appropriate parameters $\boldsymbol{\gamma}_u^q$ can be obtained by solving the following minimization problem using the forecasted power profiles and the EV provisional plan $\boldsymbol{x}^G = \left\{\boldsymbol{x}_m^{\mathrm{PV}}, \boldsymbol{x}_m^{\mathrm{r}}, \boldsymbol{y}_m; m \in \mathcal{M}\right\} \cup \left\{\boldsymbol{x}_n^{\mathrm{PV}}, \boldsymbol{x}_n^{\mathrm{r}}; \in \mathcal{N}\right\}$.

$$\begin{aligned}\boldsymbol{\gamma}_u^q = \arg\min_{\boldsymbol{\gamma}_u^q} &\left\{\sum_{j\in\mathcal{J}}\sum_{t=1}^{\mathrm{T}_u} h_1\left(v_t^j\left(\boldsymbol{\gamma}_u^q|\boldsymbol{x}^{\mathrm{G}}\right); \overline{v}^j, \underline{v}^j\right)\right.\\ &+ c_1\sum_{t=1}^{\mathrm{T}_u}|s_{t-1}-s_t|\\ &\left.+\ c_2\sum_{j\in\mathcal{J}}\sum_{t=1}^{\mathrm{T}_u} h_2\left(v_t^j\left(\boldsymbol{\gamma}_u^q|\boldsymbol{x}^{\mathrm{G}}\right); \overline{v}^j, \underline{v}^j\right)\right\},\end{aligned} \tag{6}$$

where

$$h_1\left(v_t^j; \overline{v}^j, \underline{v}^j\right) = \begin{cases} v_t^j - \overline{v}^j, & \text{if } v_t^j > \overline{v}^j,\\ \underline{v}^j - v_t^j, & \text{if } v_t^j < \underline{v}^j,\\ 0, & \text{if } \underline{v}^j \le v_t^j \le \overline{v}^j,\end{cases}$$

$$h_2\left(v_t^j; \overline{v}^j, \underline{v}^j\right) = v_t^j - \frac{\overline{v}^j + \underline{v}^j}{2}.$$

Objective function above is evaluated by performing the power flow calculation for each parameter set $\boldsymbol{\gamma}_u = \left\{l_u \in \mathcal{L}, v_u^{\mathrm{tar}} \in V\right\}$ where $\mathcal{L}$ and V are the candidate sets. GEMS works out the amount of expected PV curtailment in all houses with HEMSs

$$\boldsymbol{x}_m^{\mathrm{c}} = \boldsymbol{x}_m^{\mathrm{c}}\left(\boldsymbol{\gamma}_u^q\,|\,\boldsymbol{x}^{\mathrm{G}}\right); \quad m \in \mathcal{M}, \tag{7}$$

This piece of information is important for HEMS to revise its provisional plans and avoid PV curtailment as much as possible.

C. IMPLEMENTATION OF EV ENERGY PLAN BY HEMS

Once GEMS gathers all provisional plans from houses and works out PV curtailment schedule due to over voltage in the network, these schedules are sent back to HEMS. Each HEMS amends its plan accordingly. During the operation, HEMS implements following control, i.e. monitors EV charge-discharge output $y_{m,t}^{*o}$, data on actual PV curtailment and load values. Looking at the larger picture, it is ensured that SoC, $y_{m,0}^{\mathrm{SoC}}$, is at a level that there is adequate free capacity to accommodate excess PV, which would, otherwise, be curtailed. Also, it is ensured that EV has sufficient charge for planned driving. This is done as follows:

$$y_{m,0}^{\mathrm{SoC}} = \frac{1}{2}\left\{\left(1 - \frac{\sum_{t=1}^{T} x_{m,t}^{\mathrm{c}}}{B}\right) + \frac{\sum_{t=1}^{T}\left(x_{m,t}^{\mathrm{r}} + x_{m,t}^{\mathrm{d}}\right)}{B}\right\}, \tag{8}$$

where B is EV's battery capacity. Let, $\boldsymbol{x}^{*r} = (x_t^{*r}; t \in \{1, \ldots, T\})$, $\boldsymbol{x}^{*\mathrm{c}} = (x_t^{*c}; t \in \{1, \ldots, T\})$, and $\boldsymbol{y}^{*\mathrm{SoC}} = (y_t^{*\mathrm{SoC}}; t \in \{1, \ldots, T\})$ be real PV curtailment profile, SoC and electricity consumption. During phase of control, HEMS tracks consumption of household $x_t^{*\mathrm{r}}$ and the PV curtailment x_t^{*c} to manage the charge-discharge amount of EV battery, as given below;

$$\begin{aligned}&\text{if } y_{m,t}^{*c} = 0,\\ &y_{m,t}^{*o} = \begin{cases} x_{m,t}^{*\mathrm{r}}, & \text{if } \left(y_{m,t-1}^{*\mathrm{SoC}} - c^{\mathrm{u1}}x_{m,t}^{*\mathrm{r}}\right)\\ & \qquad \ge \underline{S}_{m,t}\left(x_{m,t}^{\mathrm{d}}\right),\\ 0, & \text{if } y_{m,t-1}^{*\mathrm{SoC}} = \underline{S}_{m,t}\left(x_{m,t}^{\mathrm{d}}\right),\\ c^{\mathrm{u2}}\left(y_{m,t-1}^{*\mathrm{SoC}}\right.\\ \left.-\underline{S}_{m,t}\left(x_{m,t}^{\mathrm{d}}\right)\right), & \text{otherwise,}\end{cases}\end{aligned} \tag{9}$$

$$\begin{aligned}&\text{if } x_{m,t}^{*c} \neq 0,\\ &y_{m,t}^{*o} = \begin{cases} -x_{m,t}^{*c}, & \text{if } \left(y_{m,t-1}^{*\mathrm{SoC}} + c^{\mathrm{u1}}x_{m,t}^{*c}\right) \le \overline{S},\\ 0, & \text{if } y_{m,t-1}^{*\mathrm{SoC}} = \overline{S},\\ c^{\mathrm{u2}}\left(y_{m,t-1}^{*\mathrm{SoC}} - \overline{S}\right), & \text{otherwise,}\end{cases}\\ &y_{m,t}^{*\mathrm{SoC}} = y_{m,t-1}^{*\mathrm{SoC}} - y_{m,t}^{*o},\end{aligned} \tag{10}$$

where c^{u1} and c^{u2} are the coefficients to convert Watt to SoC percentage [%] and SoC percentage [%] to Watt. When the system ensures that battery's SoC never falls below its lower limit, $\underline{S}_{m,t}\left(x_{m,t}^{\mathrm{d}}\right)$, so that the driving pattern is not disrupted. Let $\boldsymbol{x}^{*\mathrm{PV}} = (x_t^{*\mathrm{PV}}; t \in \{1, \ldots, T\})$ be series of real PV output. It follows that electricity that is purchased $e_{m,t}^{*\mathrm{p}}$ and power that is sold back $e_{m,t}^{*rev}$ can be expressed as

$$e_{m,t}^{*\mathrm{rev}} = \max\left\{0, \left(x_{m,t}^{*\mathrm{PV}} - x_{m,t}^{*c} - x_{m,t}^{*\mathrm{r}} + y_{m,t}^{*o}\right)\right\}, \tag{11}$$

$$e_{m,t}^{*\mathrm{p}} = x_{m,t}^{*\mathrm{r}} - y_{m,t}^{*o} - \left(x_{m,t}^{*\mathrm{PV}} + x_{m,t}^{*\mathrm{c}}\right). \tag{12}$$

D. POWER FLOW SIMULATIONS FOR EV CHARGE-DISCHARGE COORDINATION SCHEME

To verify the effectiveness of this scheme, extensive numerical simulations have been performed in [14]. The details of the network utilized, utility grid's energy purchase and sale prices as well as EV specifications are given in that paper. For the purpose of the communication solution developed in this paper, results given in Figure 2 are very crucial. Simulation works investigated the direct impact of this coordinated EV energy management scheme with 5 methods:

- Method 1 (F1), where there is no coordination with GEMS and HEMS is trying to optimize the operation locally, without global over-voltage information.
- Method 2 (F2), there is continuous information exchange between HEMS and GEMS, which enables error correction during operation
- Method 3 (F3), the information exchange between HEMS and GEMS only takes place once in a day. Plans are developed as day-ahead and not corrected during operation.
- Method 4 (F4), HEMS and GEMS has continuous information exchange, however, SoC of EV battery is not

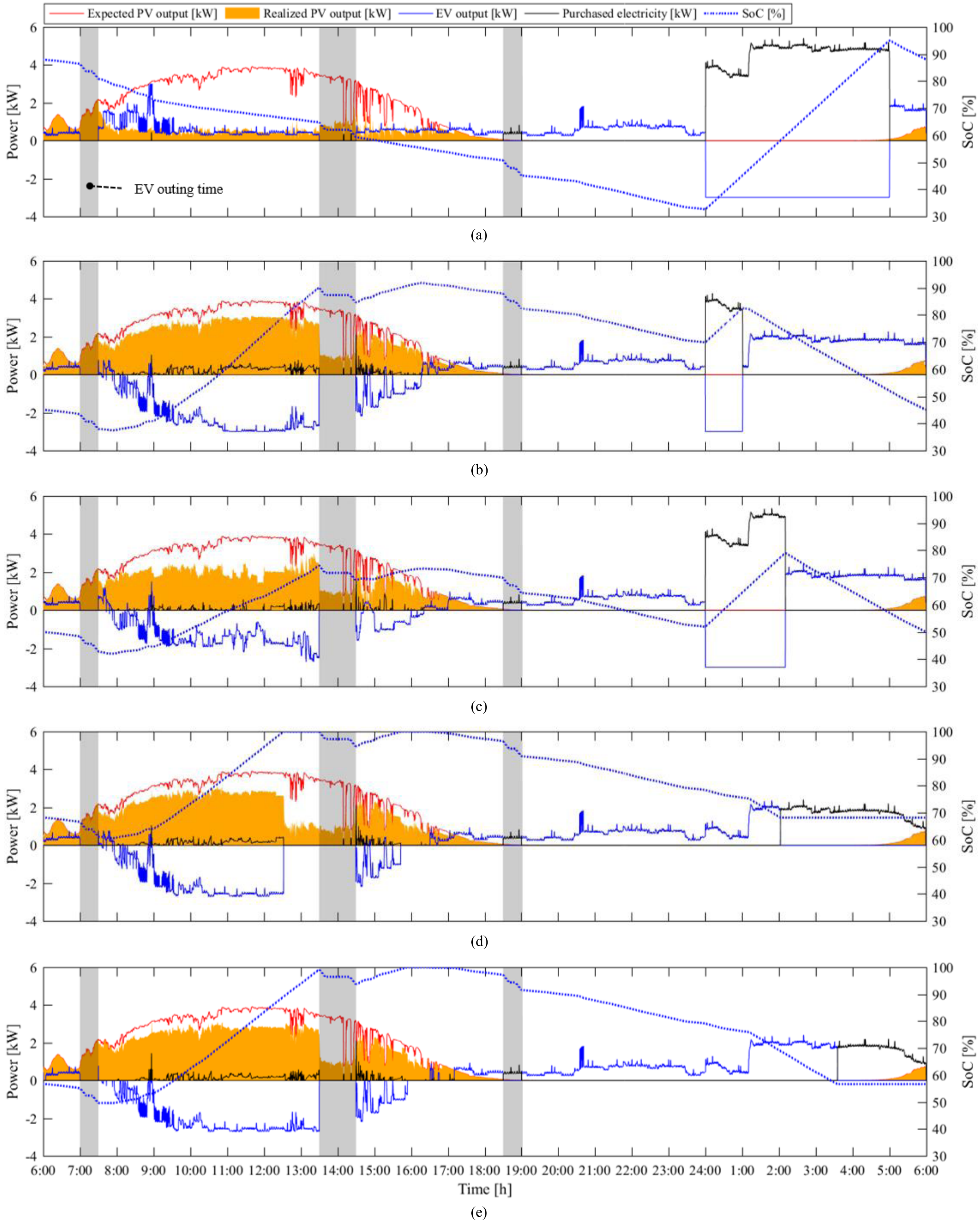


FIGURE 2. Different approaches to implementing PV-EV coordination at HEMS. (a) Method 1 (F1), local optimization by HEMS, no GEMS coordination. (b) Method 2 (F2), corresponds to ideal situation with continuous communication of real time data. (c) Method 3 (F3), Day-ahead operation, information exchange occurs only once in a day. (d) Method 4 (F4), Continuous communication without SoC control. (e) Method 5 (F5), Day-ahead optimization with following control by HEMS.

controlled. Battery may not be in the ideal state at any given time.

- Method 5 (F5), energy plans are created in a day-ahead fashion and HEMS ensures PV-EV coordination during operation. No information exchange between HEMS and GEMS during operation.

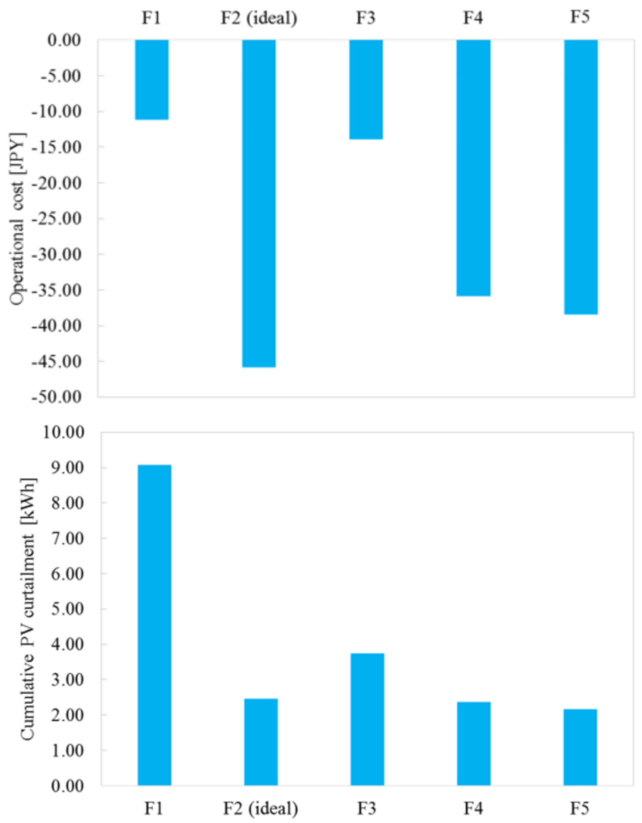


FIGURE 3. Operation cost and PV curtailment per day.

As shown in Figures 2 and 3, the highest benefit is achieved with F2 as it ensures real-time data exchange, while other frameworks rely on 24-hour estimation. The developed optimization scheme is not dependent on any time period and can work with large or small time-steps. Based on these simulation results, it is determined that shorter time steps are much better for the systems performance. Hence, in this paper, hourly optimization is implemented such that the scheme explained in Figure 1 is repeated every hour. In this fashion, the system developed in this paper not only develops a full communication solution but also improves the performance of optimization scheme developed earlier in [14], by enabling more frequent information exchange.

This EV charge and discharge management scheme requires extensive information exchange. Solar radiation measurement should be reported to HEMS from measurement devices, then, EV provisional plan and curtailment plan should be sent back and forth between HEMS and GEMS. During operation GEMS needs constant communication with OLTC while HEMS needs to exchange information with its components to realize following control. Next section details how this communication is made standardized and interoperable by modeling devices and messages according to IEC 61850 standard.

III. IEC 61850 INFORMATION MODELING

IEC 61850 standard presents an object-oriented and interoperable communication for power utility automation. world over as global standard for power system automation. A lot of research on IEC 61850 based automation in different domains of power system has been reported. In past research, different components of power system are modelled with IEC 61850 standard. In this section the information modeling of different actors involved for the proposed charging and discharging management scheme for EVs are presented.

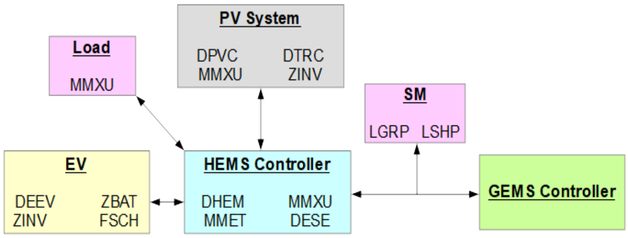


FIGURE 4. IEC 61850 information models of different components.

Figure 4, shows the IEC 61850 information model of different components involved in the proposed EV charging and discharging management scheme. It consists of EV, PV system, HEMS controller, Smart Meter, loads, GEMS controller. The detailed information modeling of different components is discussed below.

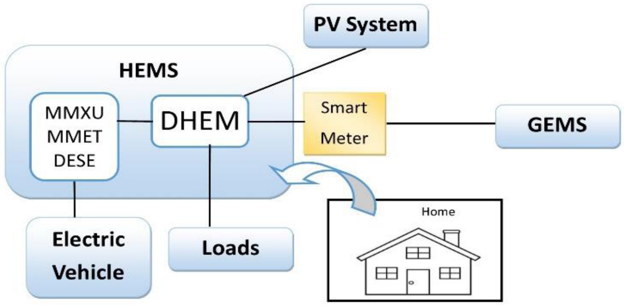


FIGURE 5. IEC 61850 information model of HEMS controller.

A. HEMS CONTROLLER

HEMS is connected to PV system, loads, EV and GEMS. HEMS exchanges messages with GEMS, EV, PV system and loads to coordinate and implement the proposed charging and discharging management scheme. For this, HEMS receives information from EV PV system. After running the local optimization, HEMS exchanges provisional plans with GEMS. When curtailment calculations are received from GEMS, HEMS updates the schedules and keeps talking to PV and EV for following control. For communication with EV, LN DESE, is included in HEMS information model as shown in Fig. 5. A new LN DHEM is defined using the GPAC generic LN model class for enabling communication with GEMS and PV.

DHEM consists of 6 DOs namely '*TotWpr*', '*TotWEvd*', '*TotWEv*', '*SoC*', '*TotWPv*' and '*EVStat*'. DOs '*SoC*' and '*EVStat*' are updated by fetching information from LN DEEV and this information is sent to GEMS as a part of EV provisional plan. HEMS receives the meteorological information from GEMS or DSO to the LN MMET. DOs '*DctInsol*', '*DffInsol*', '*CloudCvr*' and '*EnvTmp*' of the LN MMET are utilized to receive the sensor data related to PV such as direct normal insolation, diffuse insolation, cloud cover and ambient temperature, respectively. Based on this data, HEMS predicts the total active power that will be generated by PV system for the next time step. This information is communicated to GEMS as a part of EV provisional plan through DO '*TotWPv*'. Similarly, from the load profiles logs HEMS predicts the total active power load demand for the next time step and this information is communicated to HEMS through DO '*TotWpr*'. When EV out for a drive, it updates its GPS location and current state of charge via DOs '*Location*' and '*SoC*' to HEMS. Based on the reported location and SoC, HEMS calculates the total amount of power required by EV for the drive for the next time step. This amount, which is the energy discharge from EV battery for the next time step, is communicated to GEMS via DO '*TotWEvd*'. Similarly, if the EV is available and connected to HEMS, HEMS calculates the total active power that EV can discharge in next time step and this information is communicated by DO '*TotWEv*'. Table 1 summarizes the description of all DOs in the DHEM LN of HEMS.

TABLE 1. Description of DHEM logical node.

GPAC Class			
Data Name	**CDC**	**Explanation**	**M/O/C**
LNName		Shall be inherited from logical-node class (see IEC 61850-7-2)	
Measured and Metered Values			
TotWpr	BCR	Total active power consumption by load predicted for next time step	M
TotWEvd	BCR	Total active power consumed for EV drive in next time step	M
TotWEv	BCR	Total active power discharged by EV for next time step	M
SoC	BCR	SoC level of EV received from DEEV LN	M
TotWPv	BCR	Forecasted total active power generated by PV for next time step	M
TotWPvc	BCR	Total active power of PV to be curtailed for next time step	M
Status Information			
EVStat	ENS	Current connection status of EV received from DEEV **Value** – **Explanation** 0 – Not Connected 1 – Grid to vehicle support 2 – Vehicle to grid support 9 – Not Available	M

B. ELECTRIC VEHICLES

The information model of EV with IEC 61850-90-8 LNs is as shown in Fig. 6. The LN DEEV corresponds to Electric Vehicle Communication Controller (EVCC), while LNs ZBAT and ZBTC correspond to battery and its charger, respectively. LN ZINV corresponds to the inverter. LN DEEV, as defined in IEC 61850-90-8, does not contain the DOs required for discharging of EVs, i.e. V2G operation. In previous work [17], LN DEEV was augmented with relevant DOs, as shown in Table 2, to support these functions. In this paper, a new DO '*Location*' is defined which communicates the GPS location coordinates of EV. The DOs of the LN DEEV which are required for the proposed EV charging and discharging management scheme are highlighted in Table 2.

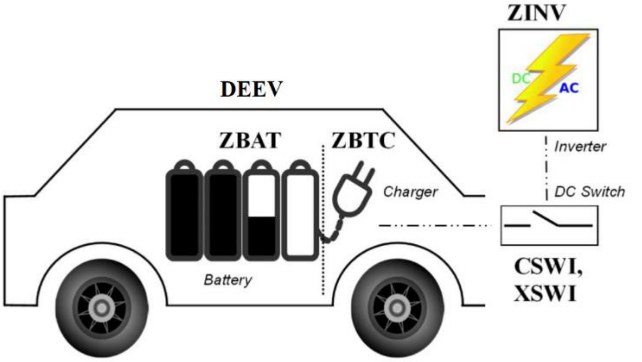


FIGURE 6. Logical node model for EV.

C. PHOTOVOLTAIC (PV) SYSTEM

The PV system consists of primarily four LNs MMXU, ZINV, DPVC and DTRC. LNs DPVC and DRTC correspond to PV array and tracking controllers. MMXU node is responsible for communicating the measurements from the PV system.

D. SMART METER

IEC 61850 information model of smart meter (SM) developed in [19] is adopted in this paper. SM is modelled with primarily two main LNs, namely LGRP and LSHP, for handling the pricing functions. This model is holistic and for the proposed EV charging and discharging management scheme, DOs 'CurrentPrice' of LN LGRP and 'CurrentPrice' of LN LSHP are utilized for fetching the selling and purchasing prices from GEMS.

The load is modelled with two LNs CNLO and MMXU as described in [24]. LN CNLO corresponds to the controllable loads and it contains the required semantics for both direct control and interruptible loads.

IV. IEC 61850 MESSAGE EXCHANGES FOR THE EV CHARGING AND DISCHARGING MANAGEMENT FRAMEWORK

As discussed earlier, HEMS sends the EV provisional plans for all the houses $\boldsymbol{y} = \left(x_m^{PV}, x_m^r, y_m; m \in M\right)$ where $y_m = \{y_m^o, y_m^{SoC}, y_m^{V2H}\}$ to GEMS. Initially, HEMS computes the values of different parameters in $\boldsymbol{y}$.

TABLE 2. Description of DEEV logical node.

DEEV Class			
DO Name	**CDC**	**Explanation**	**M/O**
Description			
EVNam	DPL	EV nameplate value	M
Status Information			
ConnTypSel	ENS	Selected connection type according to 61851-1	O
Beh	ENS	Inherited from: Domain LN	M
EVStat	ENS	Operating Modes of EV **Value** – **Explanation** 0 – Not Connected 1 – Grid to vehicle support 2 – Vehicle to grid support 9 – Not Available	M
Measured and Metered Value			
Soc	MV	State of charge	M
Location	MV	GPS location coordinates of the EV	M
Settings			
EVId	VSG	EVId refers to EVCCID Identifier as per [ISO 15118-2:2014]	M
EMAId	VSG	EMobility Account Identifier as defined in Annex H.1 of [ISO 15118-2:2014]	M
DptTm	TSG	Departure time is used to indicate when the vehicle intends to finish the charging process.	M
EnAmt	ASG	Amount of energy required by the EV until the departure time has been reached or the EV battery's SOC is at 100%.	
DisEnAmt	ASG	Amount of energy to be discharged into the grid by the EV before its departure from the EVSE	M
VMax	ASG	Max. voltage/phase supported by the EV.	M
AMax	ASG	Max. current/phase supported by the EV.	M
AMin	ASG	Min. current/phase supported by the EV.	M
SchdRef	ORG	Reference to the schedule LN instance containing information on the charging profile of the EV.	M
V2GStart	TSG	Vehicle to grid participation time initiation	M
V2GEnd	TSG	Vehicle to grid participation time ceases	M

**DO-Data Object, CDC-Common Data Class*

The x_m^{PV} is the forecasted PV output. HEMS requires the sensor data related to PV such as direct normal insolation, diffuse insolation, cloud cover and ambient temperature for forecasting the PV output power. HEMS receives this sensor data from GEMS or DSO to its LN MMET in DOs '*DctInsol*', '*DffInsol*', '*CloudCvr*' and '*EnvTmp*' respectively.

GEMS / DSO_server → $\mathrm{HEMS_m\_MMET_m}$ \$ DctInsol \$ MV

GEMS / DSO_server → $\mathrm{HEMS_m\_MMET_m}$ \$ DffInsol \$ MV

GEMS/DSO_server → $\mathrm{HEMS_m\_MMET_m}$ \$ CloudCvr \$ MV

GEMS / DSO_server → $\mathrm{HEMS_m\_MMET_m}$ \$ EnvTmp \$ MV

Based on this data HEMS computes the forecasted output x_m^{PV} and communicates it to GEMS through the DO '*TotWPv*' of LN DHEM.

$\mathrm{HEMS_m\_DHEM_m}$ \$ TotWPv \$ BCR → GEMS

x_m^r is the residential electricity consumption by the household for next time step. Based on the consumption log, HEMS estimates active power consumption for next time step and communicates this value to GEMS through DO '*TotWpr*' of the LN DHEM.

$\mathrm{HEMS_m\_DHEM_m}$ \$ TotWPr \$ BCR → GEMS

y_m^o is the estimated electric power supplied by the EV to home. HEMS predicts this and communicates it to GEMS through DO '*TotWEv*' of the LN DHEM.

$\mathrm{HEMS_m\_DHEM_m}$ \$ TotWEv \$ BCR → GEMS

y_m^{SoC} is the value of SoC of the EV. HEMS receives the update on SoC at DO '*SoC*' in LN DHEM from DO '*SoC*' of LN DEEV of the EV. At the beginning of each time step HEMS updates the value of DO '*SoC*' to GEMS.

$\mathrm{EV_m\_DEEV_m}$ \$ SoC \$ MV → $\mathrm{HEMS_m\_DHEM_m}$ \$ SoC \$ BCR → GEMS

y_m^{V2H} represents the connection status of the EV charger to home. The EV updates its connection status to HEMS through DO '*EVStat*' of LN DEEV. HEMS updates the status of EV connection to GEMS along with the EV provisional plan.

$\mathrm{EV_m\_DEEV_m}$ \$ EVStat \$ ENS → $\mathrm{HEMS_m\_DHEM_m}$ \$ EVStat \$ SPS → GEMS

After receiving all these inputs, GEMS calculates the appropriate voltage control parameter setting of the OLTC as described in section II.B. From section II.B as it is assumed in this paper that the tap ratio of OLTC is regulated with line drop compensator method, the GEMS enables the line drop compensation method in OLTC by sending a message to the DO '*LDC*' of LN ATCC.

GEMS → OLTC_ATCC \$ LDC \$ SPG

The OLTC regulates the tap positions according to the secondary voltages as given in (2). The impedance values for calculating the reference secondary voltage are provided by GEMS to the DO '*LDCZ*' of LN ATCC of OLTC as follows

GEMS → OLTC_ATCC \$ LDCZ \$ ASG

As discussed earlier, GEMS calculates the PV curtailment plan, $x_m^c, m \in M$, as per (7), for all the houses on basis of provisional plan. This new PV curtailment plan is sent from GEMS to HEMS which receives at DO '*TotWPvc*' in LN DHEM.

GEMS → $\mathrm{HEMS_m\_DHEM_m}$ \$ TotWPvc \$ BCR

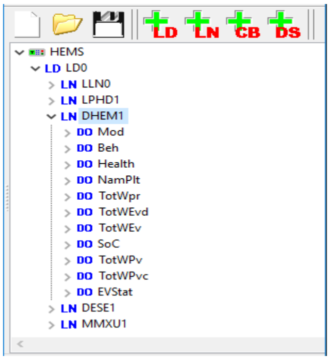
The message exchanges between HEMS and GEMS for implementing the proposed EV charging and discharging management framework are shown in Table 3 with their corresponding ASCI services and PDU types.

A. EXPERIMENTAL VALIDATION IEC 61850 COMMUNICATION MODELING

In order to demonstrate the IEC 61850 information exchanges for EV charging and discharging management framework, IEC 61850 information models for all the components (HEMS, EV, PV system, Load and SM) have been developed using the InfoTech 61850 ICD editor tool [22]. The ICD files for different components were created using the available existing logical node as well as developing the newly defined logical nodes in this paper such as DHEM. The instance of the ICD file developed for HEMS is shown in Fig. 7. The HEMS ICD files contains the existing LNs MMXU,

TABLE 3. IEC 61850 message exchanges EV charging and discharging framework.

Message exchanges for EV charging and discharging management		ACSI Service	Type of PDU / message
Source IED	**Destination IED**		
GEMS	HEMS$_m$→MMET→ *DctInsol, DffInsol, CloudCvr, EnvTmp*	SetDataValues	Write-MMS Request Write-MMS Response
HEMS$_m$→DHEM→ *TotWPv*	GEMS	GetDataValues	Read-MMS Request Read-MMS Response
HEMS$_m$→DHEM→ *TotWPr*	GEMS	GetDataValues	Read-MMS Request Read-MMS Response
HEMS$_m$→DHEM→ *TotWEv*	GEMS	GetDataValues	Read-MMS Request Read-MMS Response
EV$_m$→ DEEV → SoC	HEMS$_m$→DHEM → SoC	SendMSVMessage	SVPDU
HEMS$_m$→DHEM → SoC	GEMS	GetDataValues	Read-MMS Request Read-MMS Response
EV$_m$ →DEEV→EVStat	HEMS$_m$→DHEM → EVStat	SendGOOSEMessage	GoosePDU
HEMS$_m$→DHEM → EVStat	GEMS	GetDataValues	Read-MMS Request Read-MMS Response
GEMS	HEMS$_m$→DHEM →TotWPvc	SetDataValues	Write-MMS Request Write-MMS Response



```
HEMS
  LD LD0
    LN LLN0
    LN LPHD1
    LN DHEM1
      DO Mod
      DO Beh
      DO Health
      DO NamPlt
      DO TotWpr
      DO TotWEvd
      DO TotWEv
      DO SoC
      DO TotWPv
      DO TotWPvc
      DO EVStat
    LN DESE1
    LN MMXU1
```

FIGURE 7. ICD file instance developed for DEMS.

TABLE 4. Parameters of wireless technologies.

Parameters	WiFi 802.11g	WiFi 802.11n
Base Frequency	2.4 GHz	5.0 GHz
Data Rate	54Mbps	65 Mbps
Channel Bandwidth	22 MHz	20/40 MHz
Modulation Type	OFDM	OFDM-MIMO
Maximum Transmission power	0.1 W	0.1 W
FFT size	64	128
No. Sub carriers	52	114
Cyclic prefix duration	0.8 μs	0.8 μs

TABLE 5. ETE delay of message exchanges between HEMS and GEMS.

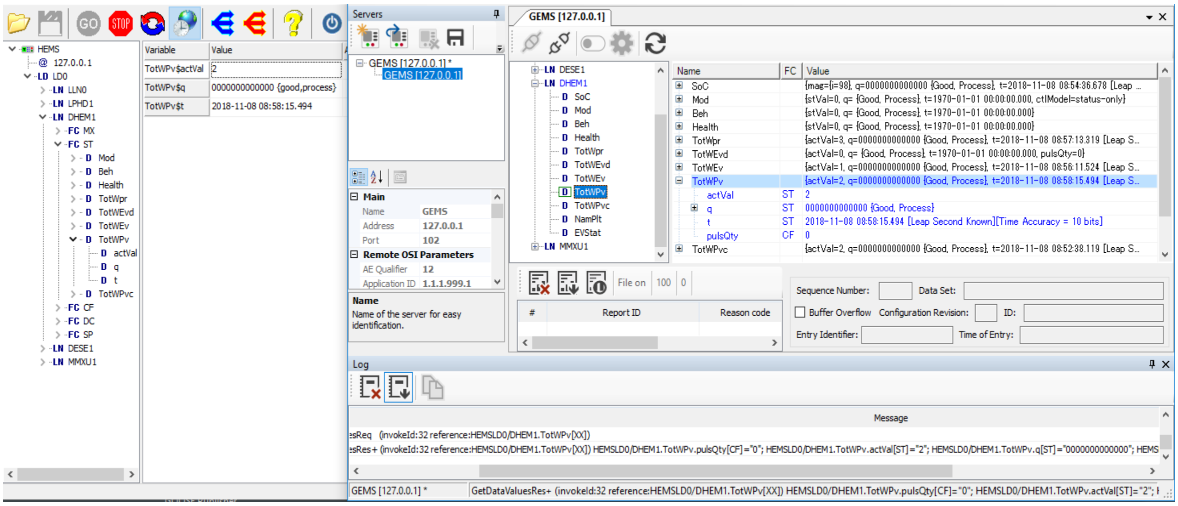
Type of Message → Communication Technologies ↓		Average Delay in milli seconds			
		LAN-10Mbps	LAN-100 Mbps	WiFi-802.11n	WiFi-802.11g
15 HEMS	GEMS → HEMS	1.405	0.197	6.767	5.767
	HEMS → GEMS	2.395	0.259	9.302	6.802
50 HEMS	GEMS → HEMS	2.054	0.284	9.750	6.980
	HEMS → GEMS	2.930	0.361	12.206	8.712

DESE, MMET and the newly developed LN DHEM. The new LN DHEM and its DOs with the appropriate CDCs and attributes, as described in Table 1, were successfully created and included in the ICD file. The successful creation of ICD file with appropriate LN, DO, CDC and attributes are essential for interoperable communication. Similarly, the ICD files for other components was created utilizing the existing appropriate LNs.

The IEC 61850 message exchange between the HEMS and GEMS, shown in Table 3, are implemented by emulating the HEMS and GEMS over Avenue 2.0 and SCL Runner Infotech tools [22] respectively.

The ICD file of HEMS is emulated by the SCL Runner Tool which behaves as HEMS IED. The HEMS IED is accessed by the GEMS running on the Avenue 2.0 tool. Initially, the GEMS IED gets the values of "*TotWPv*", "*TotWPr*", and "*TotWEv*" from the HEMS LN DHEM. These messages are communicated as Read-MMS request/response type. The GEMS simulated in Avenue tool connects to the HEMS and fetches the values of "*TotWPv*", "*TotWPr*", and "*TotWEv*" DOs of LN DEHM in HEMS IED. Figure 8 shows the instance of GEMS fetching the value in DO "TotWPv" of LN DEHM of HEMS. Similarly, Fig. 9 shows the instance of GEMS fetching the status of EV from the DO "EVStat" of the LN DEHM of HEMS.

Similarly, all the message exchanges between GEMS and HEMS listed in Table 3 were performed through the ICD files developed for the proposed information modeling developed in this paper. The successful demonstration of the message exchanges using the commercial testing tools like Avenue and



Variable	Value
TotWPv$actVal	2
TotWPv$q	0000000000000 {good,process}
TotWPv$t	2018-11-08 08:58:15.494

Main
Name GEMS
Address 127.0.0.1
Port 102
Remote OSI Parameters
AE Qualifier 12
Application ID 1.1.1.999.1

Name
Name of the server for easy identification.

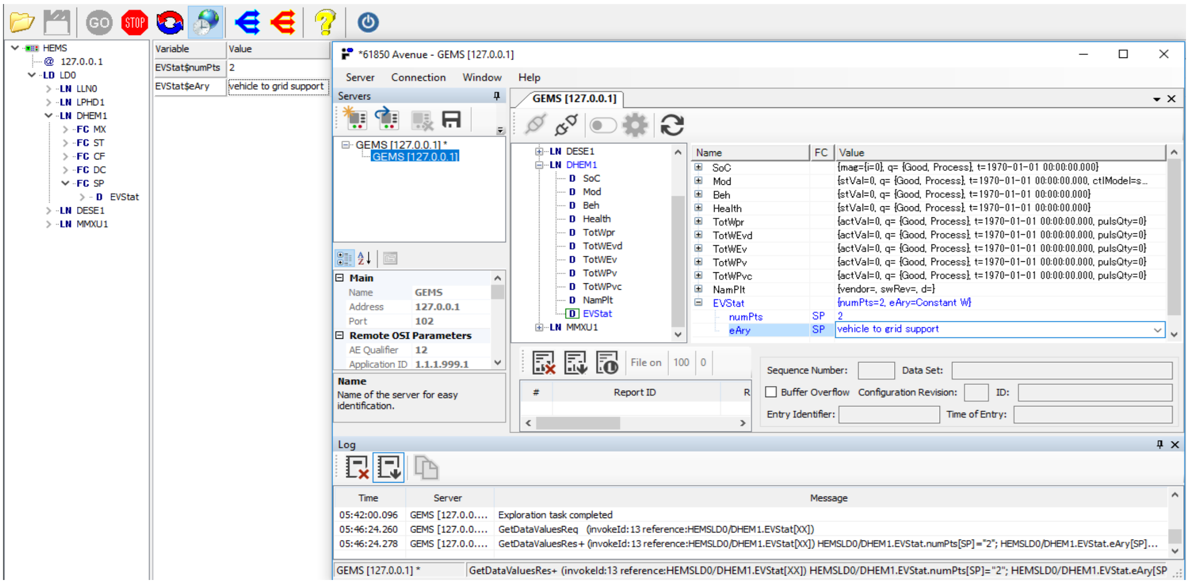
Name	FC	Value
SoC		{mag={i=98}, q=0000000000000 {Good, Process}, t=2018-11-08 08:54:36.678 [Leap ...
Mod		{stVal=0, q= {Good, Process}, t=1970-01-01 00:00:00.000, ctlModel=status-only}
Beh		{stVal=0, q= {Good, Process}, t=1970-01-01 00:00:00.000}
Health		{stVal=0, q= {Good, Process}, t=1970-01-01 00:00:00.000}
TotWpr		{actVal=3, q=0000000000000 {Good, Process}, t=2018-11-08 08:57:13.319 [Leap S...
TotWEvd		{actVal=0, q= {Good, Process}, t=1970-01-01 00:00:00.000, pulsQty=0}
TotWEv		{actVal=1, q=0000000000000 {Good, Process}, t=2018-11-08 08:56:11.524 [Leap S...
TotWPv		{actVal=2, q=0000000000000 {Good, Process}, t=2018-11-08 08:58:15.494 [Leap S...
actVal	ST	2
q	ST	0000000000000 {Good, Process}
t	ST	2018-11-08 08:58:15.494 [Leap Second Known][Time Accuracy = 10 bits]
pulsQty	CF	0
TotWPvc		{actVal=2, q=0000000000000 {Good, Process}, t=2018-11-08 08:52:38.119 [Leap S...

#	Report ID	Reason code

Sequence Number: Data Set:
☐ Buffer Overflow Configuration Revision: ID:
Entry Identifier: Time of Entry:

```
Message
esReq   (invokeId:32 reference:HEMSLD0/DHEM1.TotWPv[XX])
esRes+ (invokeId:32 reference:HEMSLD0/DHEM1.TotWPv[XX]) HEMSLD0/DHEM1.TotWPv.pulsQty[CF]="0"; HEMSLD0/DHEM1.TotWPv.actVal[ST]="2"; HEMSLD0/DHEM1.TotWPv.q[ST]="0000000000000"; HEMS
GEMS [127.0.0.1] *   GetDataValuesRes+ (invokeId:32 reference:HEMSLD0/DHEM1.TotWPv[XX]) HEMSLD0/DHEM1.TotWPv.pulsQty[CF]="0"; HEMSLD0/DHEM1.TotWPv.actVal[ST]="2"; I
```

FIGURE 8. GEMS fetching the TotWPv value from the LN DHEM of HEMS.



Variable	Value
EVStat$numPts	2
EVStat$eAry	vehicle to grid support

Main
Name GEMS
Address 127.0.0.1
Port 102
Remote OSI Parameters
AE Qualifier 12
Application ID 1.1.1.999.1

Name
Name of the server for easy identification.

Name	FC	Value
SoC		{mag={i=0}, q= {Good, Process}, t=1970-01-01 00:00:00.000}
Mod		{stVal=0, q= {Good, Process}, t=1970-01-01 00:00:00.000, ctlModel=s...
Beh		{stVal=0, q= {Good, Process}, t=1970-01-01 00:00:00.000}
Health		{stVal=0, q= {Good, Process}, t=1970-01-01 00:00:00.000}
TotWpr		{actVal=0, q= {Good, Process}, t=1970-01-01 00:00:00.000, pulsQty=0}
TotWEvd		{actVal=0, q= {Good, Process}, t=1970-01-01 00:00:00.000, pulsQty=0}
TotWEv		{actVal=0, q= {Good, Process}, t=1970-01-01 00:00:00.000, pulsQty=0}
TotWPv		{actVal=0, q= {Good, Process}, t=1970-01-01 00:00:00.000, pulsQty=0}
TotWPvc		{actVal=0, q= {Good, Process}, t=1970-01-01 00:00:00.000, pulsQty=0}
NamPlt		{vendor=, swRev=, d=}
EVStat		{numPts=2, eAry=Constant W}
numPts	SP	2
eAry	SP	vehicle to grid support

#	Report ID	R

Sequence Number: Data Set:
☐ Buffer Overflow Configuration Revision: ID:
Entry Identifier: Time of Entry:

```
Time          Server              Message
05:42:00.096  GEMS [127.0.0....   Exploration task completed
05:46:24.260  GEMS [127.0.0....   GetDataValuesReq   (invokeId:13 reference:HEMSLD0/DHEM1.EVStat[XX])
05:46:24.278  GEMS [127.0.0....   GetDataValuesRes+ (invokeId:13 reference:HEMSLD0/DHEM1.EVStat[XX]) HEMSLD0/DHEM1.EVStat.numPts[SP]="2"; HEMSLD0/DHEM1.EVStat.eAry[SP]...
GEMS [127.0.0.1] *   GetDataValuesRes+ (invokeId:13 reference:HEMSLD0/DHEM1.EVStat[XX]) HEMSLD0/DHEM1.EVStat.numPts[SP]="2"; HEMSLD0/DHEM1.EVStat.eAry[SP
```

FIGURE 9. GEMS fetching status of EV i.e. DO EVStat value from the LN DHEM of HEMS.

SCL Runner validates the effectiveness and compatibility of developed information model and communication framework with the IEC 61850 standard.

V. PERFORMANCE EVALUATION OF THE DEVELOPED COMMUNICATION FRAMEWORK

The performance evaluation of the proposed IEC 61850 based framework in terms of End to End (ETE) delay of different messages exchanged between HEMS and GEMS is carried out. Different sizes HEMS and GEMS communication networks are modeled and ETE delays for different messages exchanged for different wired and wireless communication technologies such as Ethernet, WiFi (IEEE 802.11 n/g) using NetSim network simulator tool [25] is carried out.

For NetSim based simulations, it is assumed that GEMS and HEMS clusters are spread over an area of 0.5 km by 0.5 km. In Ethernet based LAN networks the ETE delays are calculated for 10 and 100 Mbps links. Table 4 lists the parameters considered for different WiFi technologies in the simulation. The simulations is carried for 1 day i.e. 24 hrs and message exchanges are set for every one hour as discussed in previous section.

The average ETE delays for message exchanges between HEMS and GEMS for 24 hrs, listed in Table 3, are shown in Table 5. The ETE delays for the wired networks less compared to the wireless technologies as expected. The message exchanges for EV charging and discharging management framework are low the total traffic generated is also low. Hence, this results in lower delays even when the number of homes increases. The increase in number of homes has very little impact on ETE delays. Even the wireless technologies, which inherently have higher delays, show satisfactory performance.

VI. CONCLUSIONS

This paper develops a communication infrastructure for a smart EV charge-discharge algorithm to increase PV generation. The components of this scheme are fully modeled according to IEC 61850 communication standard. Considering the number of different manufacturers and models of EVs, PVs and smart meters, this is very crucial for the successful implementation of such automation schemes. IEC 61850 message exchanges have been developed for all stages of the charging scheme and their performances have been tested with different communication technologies. Simulation results show that the delays are well-within the limitations imposed by IEC 61850 standard and distribution network operation. Even wireless communication networks, which inherently have higher delays, show satisfactory performance. This is a valuable finding, as integration of these different equipment is cumbersome with wired networks and wireless option is always valued.

This work contributes to the main body of knowledge by developing standardized models for smart grid components and implementing a full scheme based on them. This is a solid step towards plug-and-play in power systems. Once this communication solution is implemented, different EVs can be utilized to maximize the output of PV modules by reducing curtailment due to over-voltage. Furthermore, the work in this paper improves the optimization solution developed earlier by implementing more frequent communication.

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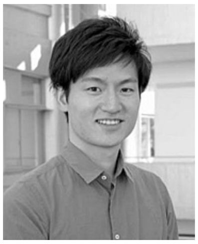

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