Standardized Communication Model for Home Energy Management System

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ABSTRACT As the number of electric vehicles and PhotoVoltaic (PV) panels per household increases, the need for a coordination between these active components becomes more imminent. Home energy management systems (HEMS) have been proposed to increase efficiency, renewable energy capture and reduce costs for the owners. However, renewable energy is intermittent and time dependent. To increase the capture of this source, an integrated control with Electric Vehicle (EVs) is required to store excessive solar energy. Furthermore, coordination with the load profile enables storage for use at a later time or selling the excess energy to the grid. This requires the use of a Home Energy Management System (HEMS) that can coordinate all these components with the grid. Operation of these controllers need to be validated before actual deployment. In this paper, a standardized communication modeling based on IEC 61850 is developed for a HEMS controller. An integrated emulation platform using network simulator and IEC 61850 Intelligent Electronic Devices (IEDs) emulator is set up and the operation of HEMS is demonstrated with proper message exchanges. Such validation is crucial to project’s success before on-site deployment.

INDEX TERMS The Internet of Things, IEC 61850, power system communication, energy management, smart homes.

NOMENCLATURE

ACRONYMS
BLE Bluetooth Low Energy
CID Configured IED Description
EV Electric Vehicle
ETE End to End
HAN Home Area Network
HEMS Home Energy Management System
ICD IED Capability Description
IED Intelligent Electronic Devices
LD Logical Device
LN Logical Node
PV PhotoVoltaic
PLC Power Line Carrier
SCD System Configuration Description
SMD Solar Measurement Device
SoC State of Charge
SV Sampled Value
V2G vehicle-to-grid
WiFi Wireless Fidelity

VARIABLES
\[ \text{cost}_{\text{EV discharge}} \] Cost to discharge EV
\[ \text{cost}_{\text{GRID}} \] Cost of grid power
\[ \text{EV}_{\text{available}} \] Availability of EV
\[ \text{load}_{\text{predicted}} \] Predicted load for time t
\[ \text{purchase}_{\text{GRID}} \] Cost of power sold to grid
\[ \text{PV}_{\text{gen}}_{\text{predicted}} \] Predicted PV generation for time t

IEC 61850 LOGICAL NODES
DBAT Describes battery characteristics
DEEV Describes information of EV
DHEM Describes HEMS controller characteristics
DPVC Models Photovoltaics array controller
DPVM Describes the photovoltaic characteristics of a module
DSCH Describes DER energy and/or ancillary services schedule
LLN0 Contains common information of LD
LPHD Information related to the physical device
LSVS For diagnose and monitoring supervision of sampled value messages
MMXU Describes measurement of currents, voltages, powers and impedances

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I. INTRODUCTION

Number of Electric Vehicles (EVs) and PhotoVoltaiс (PV) panels deployed at houses is on the rise [1]. This is due to benefits of having own PV generation at home and a clean mode of transportation [2]. Despite its widespread use, PV generation is dependent on intermittent solar irradiation. For this reason, PV panels are not dispatchable and not reliable sources of generation [3]. Research shows that proper coordination between PVs and EVs can help increase the renewable energy capture at a household and over a distribution network at large [4].

To address this gap, approaches that can track PVs, EVs, the load and the grid conditions such as prices, has been developed [5]. Home Energy Management System (HEMS) needs to follow the load profile of the house, estimate PV generation profile and coordinate EV’s battery keep the battery charge at an appropriate level [6], [7]. In addition, HEMS is responsible for coordinating power purchase transactions with the grid [8], [9]. So that, excess energy can be sold for a profit and very costly peak-hour purchases from the grid can be avoided with stored energy.

All these capabilities need to be integrated over an information and communication technology infrastructure. A suitable communication infrastructure is required to monitor the current status of the household and to notify new operating conditions from HEMS. In literature, HEMS based on different communication technologies such as Power Line Carrier (PLC) [10], [11], Zigbee [12], [13], Bluetooth Low Energy (BLE) [14], [15], and combination of PLC and Zigbee technologies [7] are presented. Considering the variety of HEMS component manufactures, it is imperative to have standardized communication and information models for smooth and interoperable operation. Most of the studies in literature on HEMS [7], [10]–[15] discuss only the performance of communication technologies and network architectures without going into details of how a reliable communication infrastructure is built for different components. Indispensable components such as standardized communication and common information models are not discussed. For real-life implementations, i.e. turning theory into practice for the welfare of consumers, this knowledge gap needs to be filled.

While the literature is rich with HEMS optimization schemes, not much is done about developing a standardized communication for HEMS. This is absolutely vital to achieve interoperability in smart grids and realize plug and play operation in HEMS. IEC 61850 has emerged as a potential solution for developing a standardized communication for HMES [16], [17]. IEC 61850 is becoming more popular and being adopted around the world as global standard for power system automation and smart grids [18]–[21]. This IEC 61850 object-oriented information modeling approach for power system devices helps to organize data, configure objects and map them on to protocols, so that they are consistent and interoperable [22]. Furthermore, IEC 61850 already has widely accepted and well-defined information models for PV and EV. Considering all these, it is advantageous to develop HEMS according to IEC 61850 for enhanced modeling capability and ease of integration with the rest of the components in the grid.

The IEC 61850 communication design of HEMS systems is needed at several layers. Firstly, necessary information modeling is required. Smart algorithms for optimizing operation in smart grids always require several parameters to be exchanged between components, e.g. EV and HEMS. These parameters need to be formed as a model in information domain while the actual equipment is in power domain. Once the models are ready, the steps of a particular control algorithm need to be mapped on these information models and the variables they have [23]. It is also vital to design message structures and how they will be exchanged to perform some of the steps [24]. It is very trivial to create a flow chart for conceptual design, yet real-life implementation details of the communication infrastructure require more effort.

Senke et al. [17], presented a case study of building energy management system using IEC 61850 information models. In previous work, authors developed IEC 61850 information model of a HEMS for coordinating PV panels, EVs and loads in a house [16]. However, these works present only basic information model as a conceptual design. The implementation and evaluation of these information models with appropriate message exchanges to achieve energy management is missing. To address this knowledge gap, this paper extends the previously developed IEC 61850 information models in [16] and maps them with appropriate message exchanges required for implementing energy management function in HEMS. Furthermore, for analyzing the performance of developed communication model, an integrated network emulation platform using the real-life implementations of IEC 61850 communication models and network simulator is presented in this paper.

Rest of the paper is organized as follows: Section II shows the operation principles of HEMS controller. Section III details the standard communication models that are developed and shows messages exchanges for different situations. The Section IV shows the co-simulation environment with a network emulator where different communication technologies were subjected to performance analysis. Section V draws the conclusions.

II. HEMS OPERATION PRINCIPLES

To address the needs mentioned above, a HEMS is developed. The main aim of such implementation is to coordinate PV generation, vehicle-to-grid (V2G) support, i.e. amount discharged from EV’s battery and the amount of energy purchased from the grid.

XCBR  Models switches with short circuit breaking capability
ZINV  Defines a DER energy and/or ancillary services schedule
FIGURE 1. HEMS Operation Architecture.

As shown in Fig. 1, HEMS is supposed to monitor and control operation of several equipment. Therefore, it needs to have access to various operation parameters as well. These include the solar radiation to predict the PV generation, consumption patterns as well as time of day to predict the house load, State of Charge (SoC) of EV’s battery, EV’s scheduled drives and current electricity price from the grid.

The overall goal of HEMS can be set to different things. For instance, if it was controlled by the grid operator, then it may be set to maximize the grid support. On the other hand, considering ownership, HEMS is more likely to be used to maximize the financial benefit for the house owner. This can be done in such a way that PV capture is maximize, purchase from the grid is minimized and EV is utilized to sell energy with V2G during peak hours. This would enable house owner to minimize his energy bill and maximize his sale to the grid operator.

However, such operation would put more strain on the equipment, e.g. too much charge-discharge operation for the EV battery and may create inconvenience such as inability to drive due to V2G operation. Therefore, alternative approaches can be taken to optimize equipment health, convenience of use and the financial benefit.

HEMS implemented in this paper takes an optimized approach where user preferences are taken into account. That being said, it is important to note that aim of this paper is to develop a communication model for a HEMS in a standard manner. Design of a particular HEMS operation model is beyond its scope. The implemented HEMS follows the algorithm below:

**HEMS Controller Algorithm**

1. Read current load conditions and past load patterns
2. Predict the load for the next time step, \( t \)
3. Obtain measurements for solar radiation and predict PV generation for the next time step \( t \)
4. Set the mode of operation of PV to ‘driven by energy source’ (i.e. generation is constrained by availability of sunlight);
5. Obtain SoC and drive plans for next time step from EV
6. if (\( \text{load}_{\text{predicted}} > \text{PVgen}_{\text{predicted}} \)) \&\& (\( \text{cost}_{\text{GRID}} > \text{cost}_{\text{EVdischarge}} \)) \&\& (\( \text{EV}_{\text{available}} == \text{True} \)) then, discharge EV to support home load
   where \( \text{EV}_{\text{available}} = \text{True} \) if SoC is more than required for next time step and EV is parked in the house
7. if (\( \text{load}_{\text{predicted}} > \text{PVgen}_{\text{predicted}} \)) \&\& (\( \text{cost}_{\text{GRID}} < \text{cost}_{\text{EVdischarge}} \)) \&\& (\( \text{EV}_{\text{available}} == \text{True} \)) \&\& (\( \text{EV}_{\text{available}} == \text{False} \)) then, purchase from the grid;
8. if (\( \text{load}_{\text{predicted}} < \text{PVgen}_{\text{predicted}} \)) \&\& (\( \text{purchase}_{\text{GRID}} > \text{threshold} \)) then, sell excess PV energy to the grid
9. if (\( \text{load}_{\text{predicted}} < \text{PVgen}_{\text{predicted}} \)) \&\& (\( \text{purchase}_{\text{GRID}} < \text{threshold} \)) \&\& (\( \text{EV}_{\text{available}} == \text{True} \)) then, charge EV

As shown, the algorithm takes into account EV’s availability, i.e. driving plans for the EV, to minimize the impact on the owner’s daily life. Different lifestyles can be accommodated into the HEMS with driving and load patterns. This algorithm needs to monitor and control of loads, EVs, solar radiation measurement devices, e.g. pyranometer, and PV inverter. A standardized communication approach is indispensable as there are countless many varieties from different manufacturers. Such approach would enable plug and play capability in HEMS.

**III. HEMS MODELING WITH IEC 61850**

Building blocks of IEC 61850, i.e. Logical Devices (LDs) and Logical Nodes (LNs) are utilized to build communication models of PV, EV, load and HEMS. The interaction with the Utility Grid and the Solar Measurement Device (SMDs) are limited to one-way transmission of electricity price and solar radiation data, respectively. The IEC 61850 based models are shown in Fig. 3.

EV model includes standard LNs utilized to represent physical status and health of the vehicle, e.g. LLN0, LPHD1.
In addition, ZINV1 and DBAT1 LNs are utilized to model and control charging inverter and the battery of the vehicle. DSCH1 LN holds the schedule information of the EV while DEEV1 LN is utilized to implemented necessary charge and discharge controls. LSVS1 LN is required to configure Sampled Value (SV) messages sent from EV. In this implementation, SV messages are used to monitor SoC level of EV during charging and discharging.

Controllable Load contains MMXU1 LN which is responsible for measurement of total real, reactive, apparent power as well as the power factor. XCBR1 LN represents the circuit breaker that links the load to the grid, and it can be used to isolate the load, i.e., load shedding, or reconnect it.

PV model includes LNs pertaining to measurement, MMXU5, circuit breaker, XCBR5, inverter, ZINV1 as well as those that are specific to PV panels such as DPVC1 and DPVM1 that include information related to the PV cell and modules.

Finally, the developed HEMS controller model has a newly proposed LN, DHEM1 that includes all the information related to HEMS functions, such as PV generation, EV’s charge and discharge amount. These data objects and communications are utilized to implement the HEMS algorithm explained above.

When HEMS wants to read current load conditions along with past load patterns these are fetched from the load as follows:

\[
\text{Load.MM Xu} \rightarrow \text{HEMS controller}
\]

The prediction for the next time step \( t \) is performed within HEMS and stored as:

\[
\text{HEMS.DHEM} \rightarrow \text{HEMS controller}
\]

HEMS predicts the PV generation based on the above measurements and this is stored as:

\[
\text{HEMS.DHEM} \rightarrow \text{HEMS controller}
\]

Then, the HEMS sets the mode of operation of PV to ‘driven by energy source’ (i.e., generation is constrained by availability of sunlight):

\[
\text{HEMS} \rightarrow \text{PV plant.DOPM} \rightarrow \text{OpModPM} \rightarrow \text{SPC} = 1
\]

Current SoC is fetched from EV:

\[
\text{EV.DEEV} \rightarrow \text{HEMS.DHEM} \rightarrow \text{SoC} \rightarrow \text{BCR}
\]

The active power required for the next time step, i.e., driving plans, are stored in HEMS:

\[
\text{HEMS.DHEM} \rightarrow \text{HEMS.TotWEvd} \rightarrow \text{BCR}
\]

The comparisons for HEMS algorithm in steps 6 to 9 are performed as below.

For step 6,

\[
\text{If } \left( \text{HEMS.DHEM} \rightarrow \text{HEMS.TotWpr} > \text{HEMS.DHEM} \rightarrow \text{HEMS.TotWPv} \right) \text{ and } \left( \text{HEMS.DHEM} \rightarrow \text{HEMS.SoC} > \text{HEMS.DHEM} \rightarrow \text{HEMS.TotWEvd} \right) \text{ and } (\text{EV.DEEV} \rightarrow \text{EVStat}1 = 0 \text{ or } 9)
\]

then,

\[
\text{HEMS.DHEM} \rightarrow \text{HEMS EVStat} \rightarrow \text{ENS} \rightarrow \text{EV.DEEV} \rightarrow \text{EVStat} \rightarrow \text{ENS} \rightarrow 2 \text{ (enable V2G support)}
\]

While EV is discharging it updates its current SoC level to HEMS controller:

\[
\text{EV.DEEV} \rightarrow \text{HEMS.DHEM} \rightarrow \text{SoC}
\]

For step 7,

\[
\text{If } \left( \text{HEMS.DHEM} \rightarrow \text{HEMS.TotWpr} > \text{HEMS.DHEM} \rightarrow \text{HEMS.TotWPv} \right) \text{ and } (\text{EV.DEEV} \rightarrow \text{EVStat} = 0 \text{ or } 9)
\]

then,

purchase from grid (If EV is not instructed to discharge, power is purchased from the grid automatically)

for Step 8,

\[
\text{If } \left( \text{HEMS.DHEM} \rightarrow \text{HEMS.TotWpr} < \text{HEMS.DHEM} \rightarrow \text{HEMS.TotWPv} \right)
\]

then, sell excess energy to grid

for Step 9,

\[
\text{If } \left( \text{HEMS.DHEM} \rightarrow \text{HEMS.TotWpr} < \text{HEMS.DHEM} \rightarrow \text{HEMS.TotWPv} \right) \text{ and } \left( \text{HEMS.DHEM} \rightarrow \text{HEMS.SoC} < \text{HEMS.DHEM} \rightarrow \text{HEMS.TotWEvd} \right) \text{ and } (\text{EV.DEEV} \rightarrow \text{EVStat}1 = 0 \text{ or } 9)
\]

then,

\[
\text{HEMS.DHEM} \rightarrow \text{HEMS EVStat} \rightarrow \text{ENS} \rightarrow \text{EV.DEEV} \rightarrow \text{EVStat} \rightarrow \text{ENS} \rightarrow 1 \text{ (initiate EV charge operation)}
\]

While EV is charging it updates its current SoC level to HEMS controller:

\[
\text{EV.DEEV} \rightarrow \text{HEMS.DHEM} \rightarrow \text{SoC}
\]

Table 1 summarizes the message flows and type of message used for realizing the HEMS controller algorithm.

IV. LAB TESTS, NETWORK EMULATION AND RESULTS

In this fashion, all the message exchanges, interactions and coordination between HEMS controller and other components are tested in the lab and validated.

As a first step, IED Capability Description (ICD) files for different HEMS components, i.e., HEMS controller, EV, PV etc., are developed using their respective information models shown in Fig. 3 using SCL configuration tools. The ICD files contain the template of capabilities of each IED.
By combining these ICD files, a system level common description file called System Configuration Description (SCD) file for complete HEMS is created using SCL configurator tool. Finally, Configured IED Description (CID) files for each IED (i.e., EV, PV, HEMS controller, load) are developed by stripping down the common SCD file to contain only the information concerned or required to a particular IED. Using these CID files, the communication behavior of any particular IED can be emulated using appropriate IEC 61850 emulation tool.

Figure 4 shows the lab test setup where real-life implementations of communication models are connected over a network emulator. An integrated emulation platform involving a network emulator and IEC 61850 IED emulator is set up. In Fig. 4, the two terminals with IPs 192.168.0.4 and 192.168.0.5 are running the developed CID files using the commercial IEC 61850 emulator software. First one is emulating HEMS controller by running its CID file, while the other one is emulating an EV in the communication world. These terminals are connected to each other via an ethernet cable and a switch. However, the communication inside Home Area Network (HAN) is more likely to be a wireless communication such as Wireless Fidelity (Wi-Fi) or IEEE 802.15.4. In order to solve this issue, network simulator is inserted in between, and wireless network is emulated between these nodes. Network simulator tool is utilized to simulate the HAN. The HAN consists of HEMS, EV, PV nodes connected to a wireless access point as shown.
in Fig. 4. In this paper different Wi-Fi communication technologies, namely IEEE 802.11b, 802.11g, 802.11n and 802.11ac, and IEEE 802.15.4 have been considered for HAN. Wi-Fi technologies have a range of 140-250 mts, which is sufficient for HEMS in a HAN. Whereas the IEEE 802.15.4 technologies have a range of 10-40 mts. Table 2 shows the different parameters of wireless technologies used in simulation.

The terminal emulating HEMS controller (IP: 192.168.0.4) is bind to ‘HEMS node’ in simulation. This is done by
modifying the routing table of terminal (IP: 192.168.0.4) such that all the traffic generated by this terminal is sent to ‘HEMS node’ in simulation via the Network Interface Controller (NIC) card of the terminal hosting the simulation. Similarly, the terminal (IP: 192.168.0.5) emulating EV is bind to ‘EV node’ in the simulation. Hence, when a real message packet is sent by emulated HEMS controller (IP: 192.168.0.4) to emulated EV (IP: 192.168.0.5), it enters the simulation world through ‘HEMS node’ and pass through the Access point and ‘HEMS node’ before reaching the emulated EV (IP: 192.168.0.5). Thus, the packet experiences the network effects such as delays, etc., inside the simulation world before reaching destination. Figure 6 shows EV model’s operating modes which are: not connected ‘0’, i.e. EV is not at home; not available ‘9’, i.e. EV is at home but not available for V2G or charging operation; grid to vehicle ‘1’; and vehicle to grid support ‘2’. These modes are utilized to instruct EV to perform a specific operation. HEMS monitors and keeps record of all equipment. Therefore, status of EV which is normally kept in EV.DEEV $ EVStat has a copy inside HEMS, HEMS.DESE.1$ EVstat.

After obtaining the values of EV SoC and operating mode, as per step 6 and 9 of HEMS controller algorithm, communication message exchanges between different entities, as explained in the previous section, are configured. For running the HEMS algorithm, the HEMS controller requires the information of current SoC and the operating mode/status of EV. HEMS controller obtains this information by sending an MMS read-request message to EV. Figure 5 shows the Wireshark capture of MMS messages exchanged between emulated HEMS controller and emulated EV controller. The HEMS controller reads the values of DOs ‘SoC’ and ‘EVStat’ of EV. These MMS messages exchanged between emulated HEMS controller and EV controller passes through the network simulator before reaching destination.

After setting up the emulation platform, communication message exchanges between different entities, as explained in the previous section, are configured. For running the HEMS algorithm, the HEMS controller requires the information of current SoC and the operating mode/status of EV. HEMS controller obtains this information by sending an MMS read-request message to EV. Figure 5 shows the Wireshark capture of MMS messages exchanged between emulated HEMS controller and emulated EV controller. The HEMS controller reads the values of DOs ‘SoC’ and ‘EVStat’ of EV. These MMS messages exchanged between emulated HEMS controller and EV controller passes through the network simulator before reaching destination.
the HEMS instructs the EV to either initiate discharging operation (i.e., V2G support) or charging operation (i.e., G2V support).

From Fig. 5 it can be observed that the value of SoC obtained from EV is 90 and here it is assumed that SoC is greater than the SoC required for EV’s driving plan for current time step. In this case, HEMS instructs EV to initiate discharging operation. This is realized by sending MMS write-request message to set the value of DO ‘EVstat’ in DEEV LN to 2. Figure 7 shows the Wireshark capture of the MMS message sent from HEMS to EV. In this message, HEMS is instructing EV to set EV.DEEV $ EVStat to 2, which configures EV to V2G mode and it starts discharging to support grid or HEMS. Figure 7 also shows an acknowledgment i.e. MMS write-response message that reports successful “write operation” to HEMS. Similarly, by sending MMS write-request message HEMS can instruct EV to initiate charging operation.

All the messages exchanges in the emulation setup passes through the HAN network in network simulator before reaching destination. Hence, the network emulator is utilized to test performance of different communication technologies in HAN. In this paper, different IEEE 802.11 Wi-Fi technologies and IEEE 802.15.4 are simulated in network simulator. The average End to End (ETE) experienced by MMS messages inside HAN simulation for different Wi-Fi technologies and IEEE 802.15.4 is given in Table 3. It is observed that the choice of wireless technology can significantly affect the performance, may reduce by five-fold. Furthermore, it also noticed that these ETE delays within the acceptable range and any Wi-Fi technology can be deployed for IEC 61850 based HEMS communication. It is also possible to add traffic on the communication network to observe the performance of the packet exchanges.

| Communication Technology | End to End Delays in ms |
|--------------------------|-------------------------|
| IEEE 802.11 ac           | 0.328                   |
| IEEE 802.11 g            | 0.569                   |
| IEEE 802.11 n            | 0.602                   |
| IEEE 802.11 b            | 1.610                   |
| IEEE 802.15.4            | 3.94                    |

The successful demonstration of the message exchanges through the emulation platform involving commercial IEC 61850 testing tools validates the effectiveness of developed IEC 61850 information models and proposed communication design for HEMS.

V. CONCLUSION

Integration of intermittent renewable energy technologies and use of EVs require extensive monitoring and control. With proper EMS controllers, PV capture can be maximized and EV can be used in a more effective way. This can minimize the energy purchased from the grid and maximize the financial benefit for the house owners. Considering the variety of equipment that can be used in a house and the diversity of manufacturers, it is imperative that a standard communication infrastructure be developed. This ensures that HEMS can communicate with different devices in an interoperable way. In this regard, IEC 61850 has emerged as promising communication standard of future smart grids.

In this paper, an IEC 61850-based communication model is developed for a home EMS. The developed communication models are implemented in real time and message exchanges are demonstrated. The results validate the developed models and message mapping. This work provides an insight on developing and validating the IEC 61850 communication models for HEMS before their actual deployment as consumer products. Furthermore, a network emulator is utilized to connect HEMS with EV for testing performance of different Wi-Fi technologies, that are used in HANs. Results show, in low traffic HANs, all Wi-Fi technologies show acceptable performance, although some technologies are significantly faster than others. This needs to be taken into account for EMS with higher number of nodes such as office buildings or industrial estates. As a part of future work, different communication technologies such as PLC and BLE can be integrated with emulation platform for further performance analysis of these technologies.

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