

## Article

# IEC-61850-Based Communication for Integrated EV Management in Power Systems with Renewable Penetration

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**Abstract:** As the number of EVs increases, their impact on electrical systems will be substantial. Novel management schemes are needed to manage the electrical load they require when charging. Literature is rich with different techniques to manage and control this effect on the grid by controlling and optimizing power flow. Although these solutions heavily rely on communication lines, they mostly treat communication as a black box. It is important to develop communication solutions that can integrate EVs, charging stations (CSs), and the rest of the grid in an interoperable way. A standard approach would be indispensable as there are different EV models manufactured by different companies. The IEC 61850 standard is a strong tool used for developing communication models for different smart grid components. However, it does not have the necessary models for implementing smart EV management schemes that coordinate between EVs and CSs. In this paper, these missing links are addressed through the development of corresponding models and message mapping. A hardware-in-the-loop test is performed to validate the communication models and cross-platform operation. Then, a co-simulation environment is used to perform a combined study of communication and the power system components. The developed communication model helps integrate the EVs to a centralized, coordinated voltage control scheme. These models can be used to run extensive impact studies where different domains of smart grids need to be considered simultaneously. The main contribution of this paper is the development of smartgrid communication solutions for enabling successful information exchanges.

**Keywords:** smartgrid communications; centralized control algorithms; scheduling algorithm; IEC 61850; auxiliary support; Internet of Things; battery storage systems



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## 1. Introduction

The transportation sector produces very high carbon emissions; the use of electric vehicles (EVs) can mitigate this issue. However, power system operators are afraid of large-scale EV migration due to its impact on system operation [1]. Distribution networks are not, traditionally, designed to accommodate the high current required to charge EVs. In addition to that, ad hoc charging of EVs may overload some parts of the network, while others may have excess energy. Coordinating charging stations (CSs) and the EVs using them will minimize these problems. Smart EV management schemes have been developed to address these issues [2,3]. One key component of these schemes is continuous communication between different grid components to control the power flow and EV charging [4]. Developing viable communication technologies is just as important as developing these management solutions [5]. The literature proves that theoretical solutions [6] are not ready for full, practical implementation and that more work is required [7,8].

Communication in these systems must be designed at several levels. Firstly, necessary information modeling is required [9]. Smart algorithms for optimizing operation in smart grids require several parameters to be exchanged between components, e.g., EV and CS [10].

These parameters need to be formed as a model in the information domain, while the actual equipment is in the power domain [11]. Smartgrids have different components owned by various entities [12] and this necessitates a standard message exchange framework that transcends model and manufacturer [13].

IEC 61850 was developed to standardize power system communications [14]. Due to its versatility and object-oriented modeling approach, it received considerable attention from stakeholders. Recently, it was extended to model EVs and some portions of vehicle-to-grid (V2G) operation [15]. Some reported research results included CSs, full V2G, and smart charging control [4,16]. Efforts were made to use these IEC-61850-based building blocks to develop smart charging algorithms to decrease the burden of charging on distribution networks and to help EV owners more conveniently charge their vehicles [10,17]. It was also argued that such solutions may help manage traffic congestion in smart cities. Furthermore, in [18], the authors presented a performance evaluation of the IEC 61850 communication network with smart charging algorithms implemented. Nevertheless, no practical implementation of these algorithms in IEC 61850-based networks was discussed.

Focusing on this need, we developed a smart EV management communication solution according to the IEC 61850 standard for EV-CS communication [19]. Two items were realized toward that end. Firstly, a brand new information model was developed to emulate CSs. Secondly, the IEC 61850-90-8 model was altered to accommodate reverse power flow by the CS. The steps of the EV management scheme were transferred to IEC 61850 messages based on their transmission purpose and nature. Simple measurements were sent with sampled values (SVs) and event-based instructions were sent as generic object-oriented substation events (GOOSEs); other ad hoc information was exchanged with manufacturing messaging specification (MMS).

The main contributions of this paper are in the smartgrid communications domain, which are as follows:

- (1) The holistic solution was fully implemented and lab tests were run to validate models and to verify accurate operation by observing real-message transmission. Different emulators were used to verify cross-platform compatibility of the standardized modeling approach. Interoperable operation was verified by the results, meaning that CSs and EVs can be connected using the developed solution.
- (2) A co-simulation platform that included digital real-time simulators, as well as an optimization software to perform calculations on the fly, were used. In this fashion, the developed communication infrastructure was integrated with a centralized co-ordinated voltage control (CVC) scheme to provide auxiliary voltage support. The results showed that such integration was beneficial for the voltage profile of the power network and the amount of overall captured renewable energy. This case study exemplifies the benefits that can be reaped from this standard modeling. This basic CVC was only utilized as a case study, the novelty and contributions of this work relate to IEC 61850 modeling and HIL testing.

The subsequent sections of this paper are as follows: Section 2 discusses EV integration with CSs and present the models. It also maps messages related to smart EV management to standard IEC 61850 messages. Section 3 depicts the validation test details, whereas Section 4 presents a test case where the developed communication infrastructure is used. Finally, Section 5 presents our conclusions and provides some insights for future work.

## 2. Integration of EVs and CSs

There are many schemes in the literature that employ EVs as mobile storage units. Successful implementation of these novel ideas is reliant on the existence of reliable message exchanges with EVs. CS, being the connection point, is the natural candidate for establishing the link between EVs and smartgrids. It can exchange critical information pertaining to EVs and relay commands from the grid operator or optimization controllers. The market has different brands of EVs, CSs, and smartgrid components. It is imperative that a communication solution that can integrate all of these is selected.

To address this need, the IEC 61850 standard is used as the basis for communication [14]. It is a robust modeling approach that allows seamless integration and development of novel models. Firstly, communication models are developed for EV and CS, as shown in Figure 1. In addition to modeling this hardware, necessary logical nodes (LNs) for EV charge control are added as DEEV and DESE LNs. These hold the parameters necessary for charging information and control, as shown in Tables 1 and 2. For instance, the location of an EV is an important piece of information for smart charging algorithms to use in calculating the time until an EV's arrival. This is denoted by the location data object in DEEV LN. The 4-letter LN names used in Figure 1, as well as Tables 1 and 2, are defined in the IEC 61850 standard. For a detailed explanation, interested readers are referred to IEC 61850 [14,15].

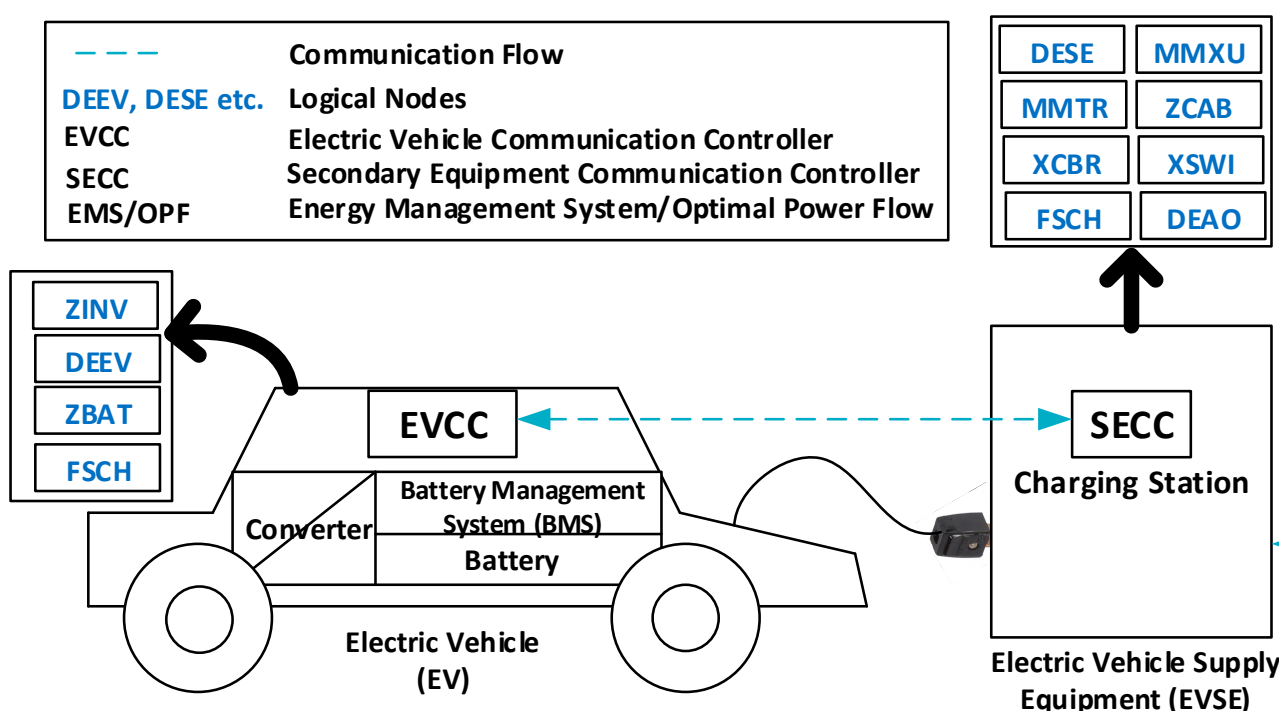


Figure 1. EV and CS information models.

Once the communication models are developed, the next step is to model the communication architecture. This is achieved by studying the considered smart charging algorithm, e.g., [4,19], and extracting the necessary steps for its successful implementation. These actions are shown in Figure 2 with non-bold fonts and include, for example, “Request update of SoC”.

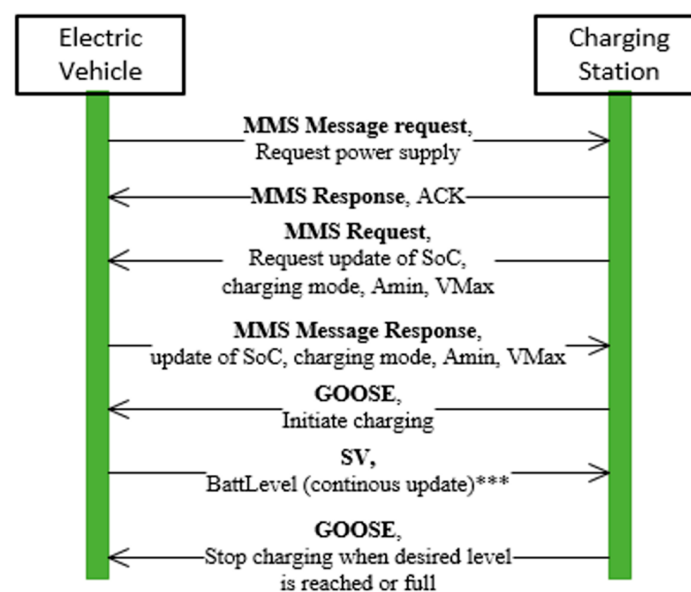
These actions need to be performed following strict message exchange protocols stipulated by the IEC 61850 framework. This means the nature of the message exchange needs to be studied and mapped onto relevant protocols in the IEC 61850. For instance, “Request update of SoC” is an ad hoc action that is triggered when needed. These kind of actions are performed with manufacturing messaging specification (MMS) messages. Messages that are sent to start or stop an action, e.g., “Initiate Charging”, are executed by generic object-oriented substation event (GOOSE) messages. Finally, periodic messages, e.g., continuous measurement values, are sent through sampled value (SV) messages. All these protocols are shown in Figure 2 with the corresponding actions listed below them.

**Table 1.** DEEV logical node.

| Data Name                          | CDC | DEEV<br>Explanation                                                                                | T | M/O/C |
|------------------------------------|-----|----------------------------------------------------------------------------------------------------|---|-------|
| <b>Descriptions</b>                |     |                                                                                                    |   |       |
| EVNam                              | DPL | EV nameplate                                                                                       |   | M     |
| <b>Status Information</b>          |     |                                                                                                    |   |       |
| ConnTypSel                         | SPS | Selected connection type acc. to 61851-1                                                           |   | M     |
| <b>Measured and metered values</b> |     |                                                                                                    |   |       |
| SoC                                | MV  | State of Charge                                                                                    |   | M     |
| Location                           | MV  | GPS location coordinates of the EV                                                                 |   | M     |
| <b>Settings</b>                    |     |                                                                                                    |   |       |
| EVID                               | VSG | In ISO 15118 compliant implementations, EVID refers to EVCCID Identifier as defined in ISO 15118-2 |   | M     |
| DptTm                              | TSG | Departure time after charging                                                                      |   | M     |
| EnAmnt                             | ASG | Charge amount                                                                                      |   | M     |
| Vmax                               | ASG | Max voltage supported by EV                                                                        |   | M     |
| Amax                               | ASG | Max. current per phase supported by EV                                                             |   | M     |
| Amin                               | ASG | Min current per phase supported by EV.                                                             |   | M     |
| SchdRef                            | ORG | Reference to scheduling node that contains charging profile                                        |   | M     |

**Table 2.** DESE logical node.

| Data Name                          | CDC | DESE<br>Explanation                                                                       | T | M/O/C |
|------------------------------------|-----|-------------------------------------------------------------------------------------------|---|-------|
| <b>Descriptions</b>                |     |                                                                                           |   |       |
| EVSENam                            | DPL | EVSE nameplate                                                                            |   | M     |
| <b>Status Information</b>          |     |                                                                                           |   |       |
| EmChrSlo                           | ING | No. of empty charging slots                                                               |   | M     |
| <b>Measured and metered values</b> |     |                                                                                           |   |       |
| ChaPwr                             | MV  | Charging power of the EVSE                                                                |   | M     |
| <b>Settings</b>                    |     |                                                                                           |   |       |
| ChaPwrRtg                          | ASG | Rated max charge power of EVSE                                                            |   | M     |
| ChaPwrLim                          | ASG | Charger's power limit                                                                     |   | M     |
| ConnTypDC                          | SPG | True = DC charging supported                                                              |   | M     |
| ConnTypPhs                         | SPG | True = AC n (n = 1, 2, 3) phase supported<br>Use ConnTypPhs1/2/3 for phase 1/2/3 charging |   | M     |

**Figure 2.** Sequence of message exchanges between EVs and CSs.

The focus of this study was the implementation of this theoretical design in the lab, the integration of different terminals such as EV or CS, and the testing of a successful exchange of desired data objects for different purposes. In addition to this, the test was performed in an integrated simulation environment where power flow simulations were performed simultaneously with communication tests. This helped visualize and confirm the impact of message exchanges on power flow optimization decisions. The integrated test environment, test setup, and results, as well as their interpretations, are given in the next section. Although cybersecurity was beyond the scope of this study, it is an important part of smart grid communications [20] and future work may focus on adding certificate-based authentication or a software-defined security mechanism for the EV–CS connection [21,22].

### 3. Hardware-in-the-Loop Tests for Validation

In order to validate the standardized models and messages developed, a hardware-in-the-loop (HIL) test was performed. The topology is provided in Figure 3. An IEC 61850 emulator was used to model an EV, while a digital real-time simulator (DRTS) was used to model CS (and connection to the grid). The use of DRTS was important for the next set of simulations, where DRTS was integrated with an optimization software to run power system simulations and centralized control algorithms.

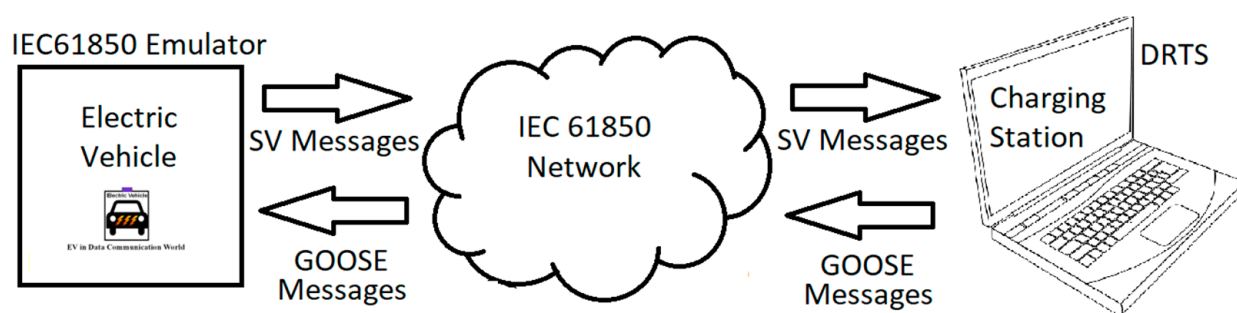


Figure 3. The HIL test set-up for model validation.

This test was important as two different emulators were used on either end, which is a real validation of interoperability of the developed models. Furthermore, such implementation situates the study within real-life limitations. The messages developed in [19] strictly follow IEC 61850 rules. However, in practice, SV messages are deemed too complex to be implemented, and a sub-set was used instead. The light edition (9-2LE) are used in industry to send three-phase voltage and current measurements in addition to neutral values and quality bits. In order to enable HIL implementation with these limitations, the message modeling had to be mapped from IEC 61850 SV to IEC 61850 9-2LE SV messages.

This had a direct impact on the operation and the way the tests were run. For instance, as defined in IEC 61850-9-2, SV messages can be sent at almost any sampling rate. For an EV charging application, appropriate sampling rate might be one per minute. However, IEC 61850-9-2LE allows for only two sampling rates: 80 or 256 samples per cycle. For a 60 Hz system, this corresponds to 4800 and 15,360 messages per second, respectively. This might be meaningful for a protection application, but is too high for EV charging. As the industry progresses more to the generic implementation of SV messages, this rate can be reduced.

Figure 4 shows the message configurations completed for the CS. SoC was received as an SV message from EV and GOOSE messages were sent to start or stop charge/discharge operations. Firstly, phase-A current was used to pass the SoC value. However, as shown in Figure 5, this was a sinusoidal message and an RMS value was required. Unexpectedly, the HIL test showed a variation in RMS values. As the sinusoidal wave (left) shows, there were occasional glitches that distorted the RMS value (right). In this figure, 20% of the SoC is sent, but the received value fluctuates between 18 and 21.5. Since this value is the SoC,

it cannot change this quickly. Making calculations based on such a volatile value would make optimizer results fluctuate as well.

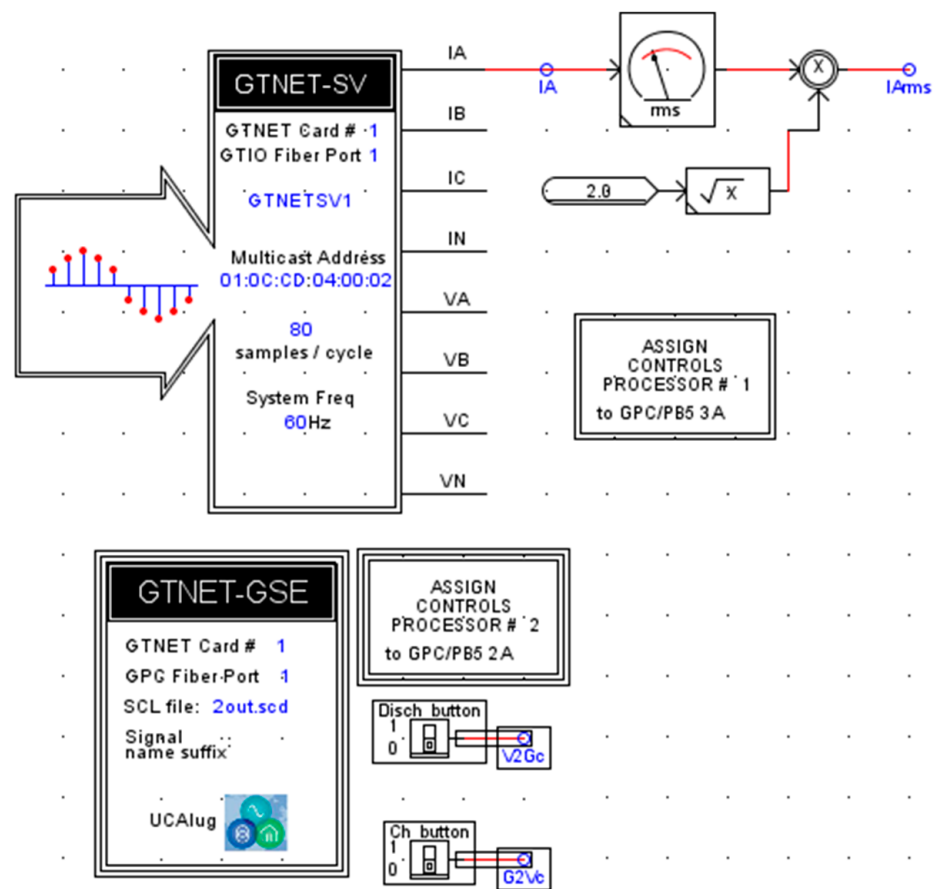


Figure 4. SV and GOOSE message configuration for a charging station.

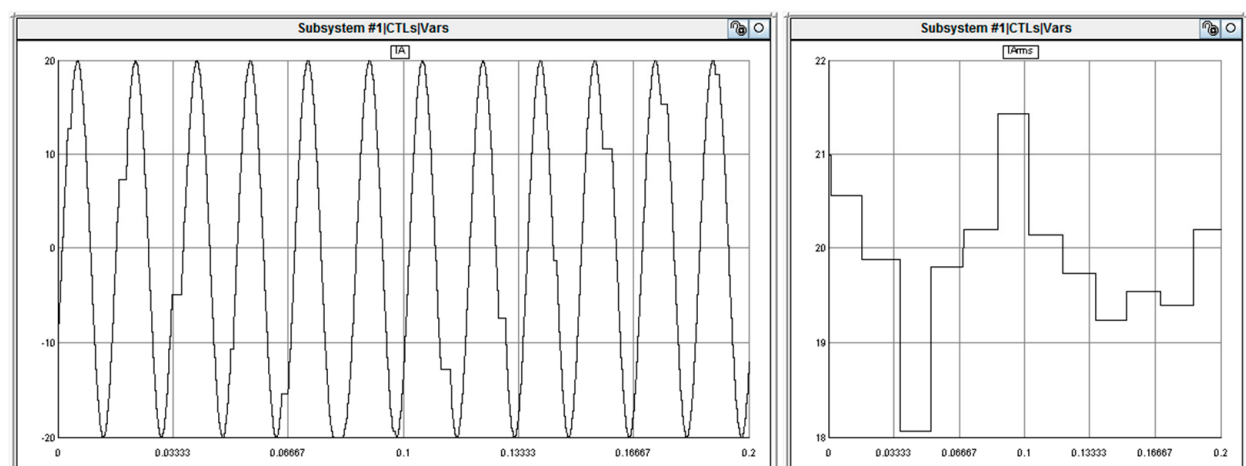


Figure 5. Incoming SV messages (phase-A current).

This was remedied in an innovative way using phase-A current's quality bits (I1). This was a 14 bit value and the first 7 bits were used to represent the percentage of the SoC (0–100%). Furthermore, the next two quality fields were used to send P (I2) and Q (I3) values for the EV charger. Figure 6 shows the EV emulator where an 9-2LE SV was sent for the SoC = 31%, P = 25, and Q = 5.

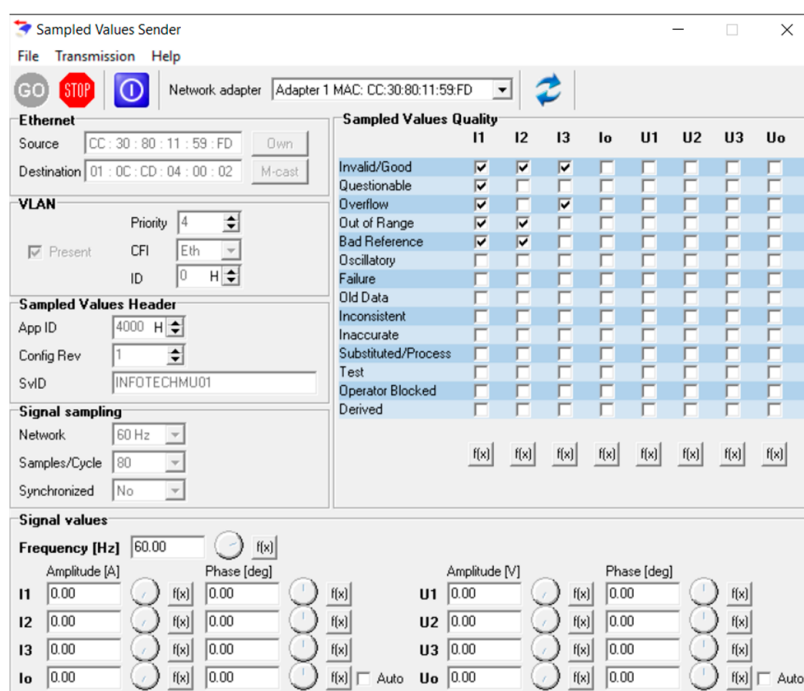


Figure 6. SV message sent from the EV emulator including SoC, P, and Q values.

Figure 7 shows the GOOSE messages received by the EV from CS. It included a command to charge (or discharge) as well as the real and reactive powers required in the process. The ability to set real and reactive power exchange amounts was very valuable for providing auxiliary support.

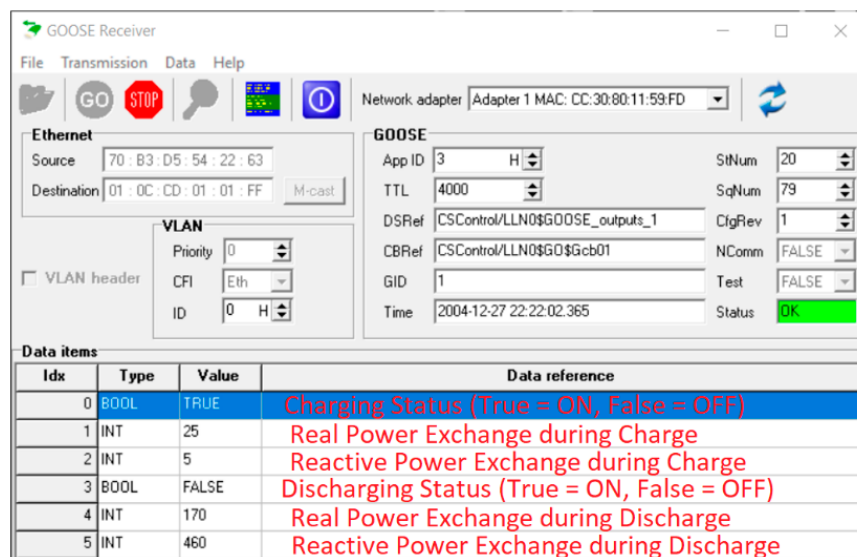
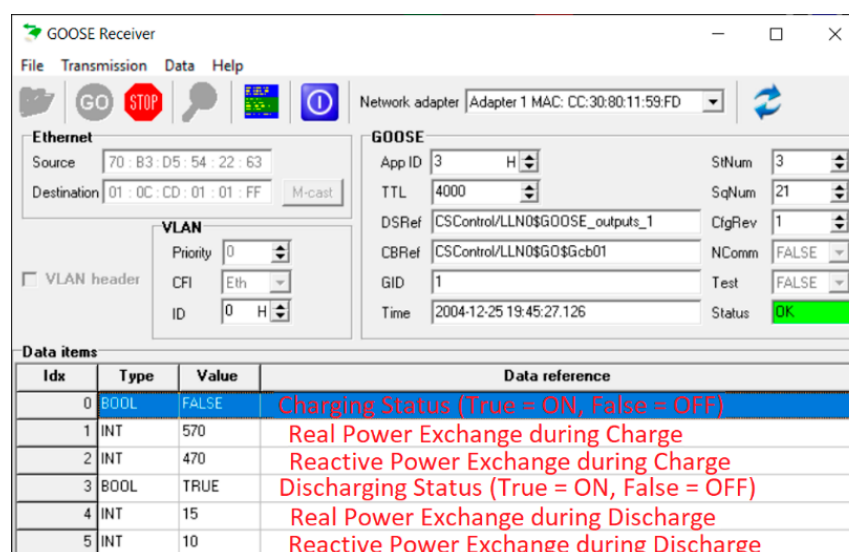


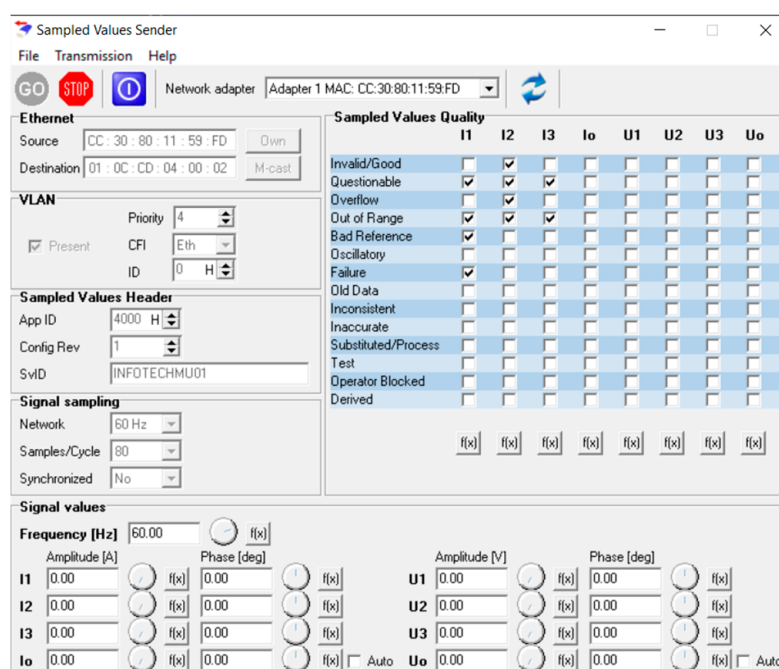
Figure 7. GOOSE message received by the EV, charge command, P = 25, and Q = 5.

Similarly, if a control scheme requires the EV to discharge, i.e., provide grid-support, a GOOSE message that instructs it to discharge is sent as shown in Figure 8. Upon receiving this message, the EV starts discharging (providing grid support) and sends updated SoC (90%), local P (15 kW), and Q (10 kVAR) measurements, as shown in Figure 9.



| Idx | Type | Value | Data reference                              |
|-----|------|-------|---------------------------------------------|
| 0   | BOOL | FALSE | Charging Status (True = ON, False = OFF)    |
| 1   | INT  | 570   | Real Power Exchange during Charge           |
| 2   | INT  | 470   | Reactive Power Exchange during Charge       |
| 3   | BOOL | TRUE  | Discharging Status (True = ON, False = OFF) |
| 4   | INT  | 15    | Real Power Exchange during Discharge        |
| 5   | INT  | 10    | Reactive Power Exchange during Discharge    |

Figure 8. GOOSE message received by the EV, discharge command,  $P = 15$ , and  $Q = 10$ .



| Sampled Values Quality |  | I1 | I2 | I3 | Io | U1 | U2 | U3 | Uo |
|------------------------|--|----|----|----|----|----|----|----|----|
| Invalid/Good           |  |    |    |    |    |    |    |    |    |
| Questionable           |  |    |    |    |    |    |    |    |    |
| Overflow               |  |    |    |    |    |    |    |    |    |
| Out of Range           |  |    |    |    |    |    |    |    |    |
| Bad Reference          |  |    |    |    |    |    |    |    |    |
| Oscillatory            |  |    |    |    |    |    |    |    |    |
| Failure                |  |    |    |    |    |    |    |    |    |
| Old Data               |  |    |    |    |    |    |    |    |    |
| Inconsistent           |  |    |    |    |    |    |    |    |    |
| Inaccurate             |  |    |    |    |    |    |    |    |    |
| Substituted/Process    |  |    |    |    |    |    |    |    |    |
| Test                   |  |    |    |    |    |    |    |    |    |
| Operator Blocked       |  |    |    |    |    |    |    |    |    |
| Derived                |  |    |    |    |    |    |    |    |    |

Figure 9. SV message sent from an EV emulator including the SoC,  $P$ , and  $Q$  values.

The HIL tests showed that the developed IEC 61850 models for EV and CS can operate interoperably while running on different emulators, meaning they can be used by different vendors and manufacturers in real life. Successful message exchanges show that the data were mapped correctly and the desired information was transmitted seamlessly. This means interoperability was achieved with the standardized modeling approach and it removed the communication barrier between the EVs and other grid components. The next section focuses on a case study where this infrastructure was utilized to provide grid support and increase renewable energy penetration levels.

#### 4. Case-Study: Co-Simulation with Centralized CVC for Increased Renewable Energy Penetration

A combined HIL and co-simulation test environment shown in Figure 10 was utilized to integrate an EV (or a fleet of EVs via CS) with the grid. The communication interface

validated in Section 3 was used to exchange messages with the CVC optimizer while power system simulations were run in DRTS.

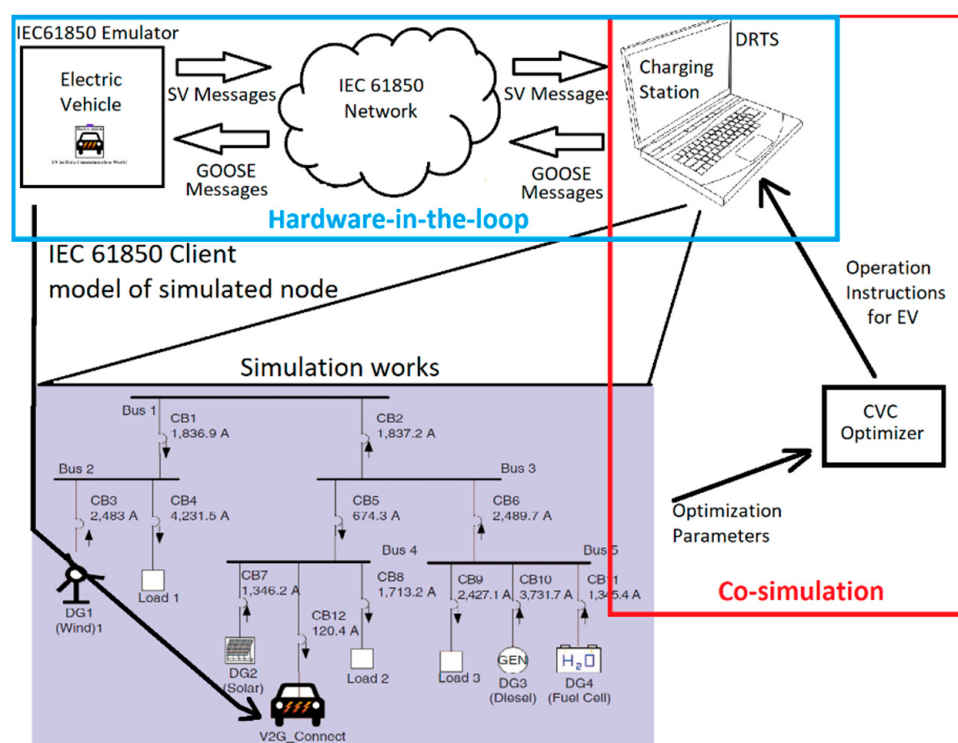


Figure 10. Co-simulation and HIL test set-up for the CVC study.

The tested power system was a microgrid with renewable energy penetration, as shown in Figure 11. In addition to renewable-energy-based generators such as PV and fuel cells, battery storage was deployed to mitigate their impacts such as voltage rise during excess generation. For the purposes of this study, battery storage was replaced with a CS where a fleet of EVs was available. It was also possible to simulate cases where the CS was empty. This was achieved by setting the SoC to 0% with no charging activity.

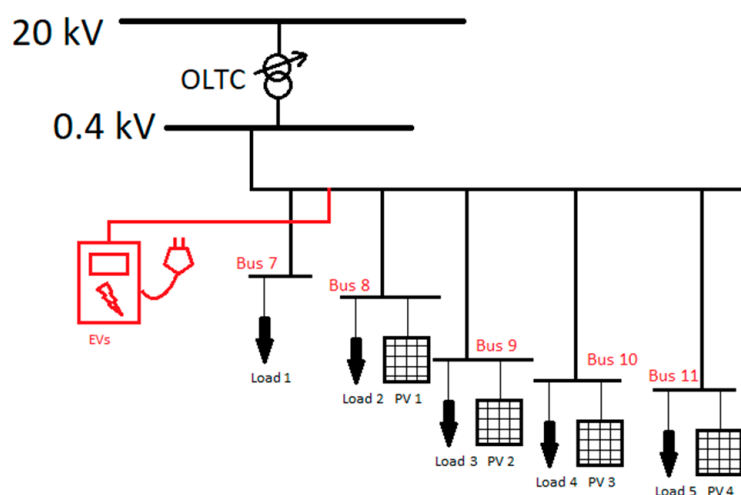


Figure 11. Simulated topology, with buses identified.

The CVC controller monitored the load, the distributed generator status, the SoC, and on-load tap changer (OLTC), as well as the grid parameters, i.e., voltage and frequency [23].

It optimized the charging and discharging cycles of the EVs in the CS to control the voltage deviations in the grid. The objective function minimized the following three items:

- I. OLTC tap change operations;
- II. Voltage fluctuations at load and battery buses;
- III. Line losses.

The CVC operated in real-time to make these decisions. However, the availability of batteries needed to be planned. For this, there were two objectives. Firstly, the EV charging ability was utilized by aligning it with maximum PV generation, hence reducing the voltage rise in the grid. Secondly, the EV's battery charge was utilized at peak-load hours to support the grid and mitigate voltage and frequency drops. The CVC controller, in addition to making real-time decisions, tried to optimize EV battery availability for charging and discharging operations as required.

As EVs are mobile, unlike battery storage systems, they cannot be fully controlled. However, usage patterns and statistical analysis helped to identify a minimum amount of EVs with a minimum amount of SoC available at certain times. At any given time, the cumulative SoC needs to be between 40% and 100%. In other words, EVs do not provide grid support if the SoC is less than 40%.

The network topology was based on the CIGRE's benchmark system for renewable energy integration [24]. As shown in Figure 11, there were five loads and four PV panels. The EV was connected, and could be considered a CS, at the microgrid's main bus. The microgrid transformer had an OLTC system connection of 0.4 kV to the utility grid at 20 kV. The SoC, given in Figure 12, started at 70% and followed charge and discharge instructions given by the CVC. Higher charge and discharge values ( $P$ ) yielded a higher slope in the profile and vice versa. In order to monitor the CVC's performance and the tap changes in OLTC, the voltage fluctuations at the denoted buses and the outputs of PV generators were monitored and plotted as shown in Figures 13–18. As mentioned before, all messages were exchanged through the HIL test with an IE 61850 emulator as explained in Section 3.

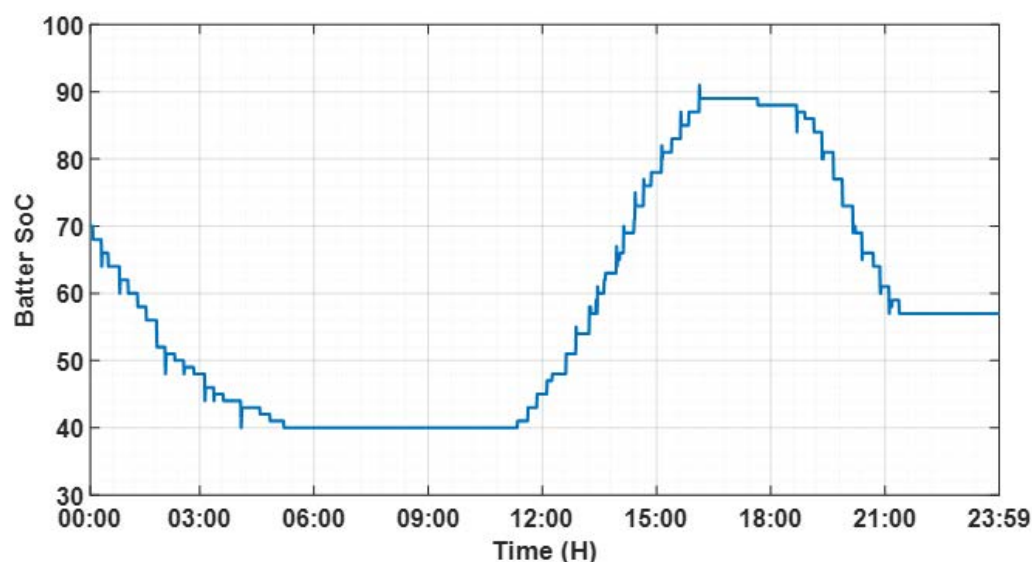


Figure 12. State of Charge.

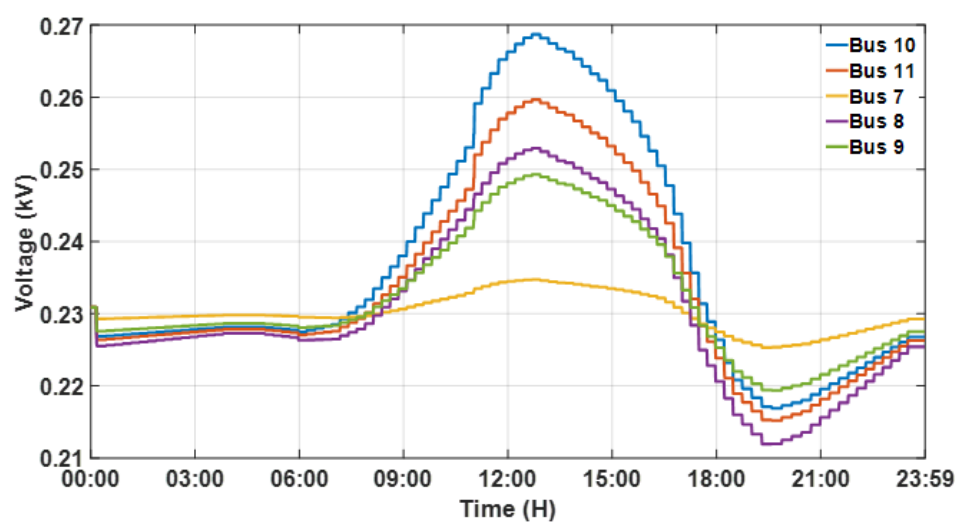


Figure 13. Voltage profiles without CVC.

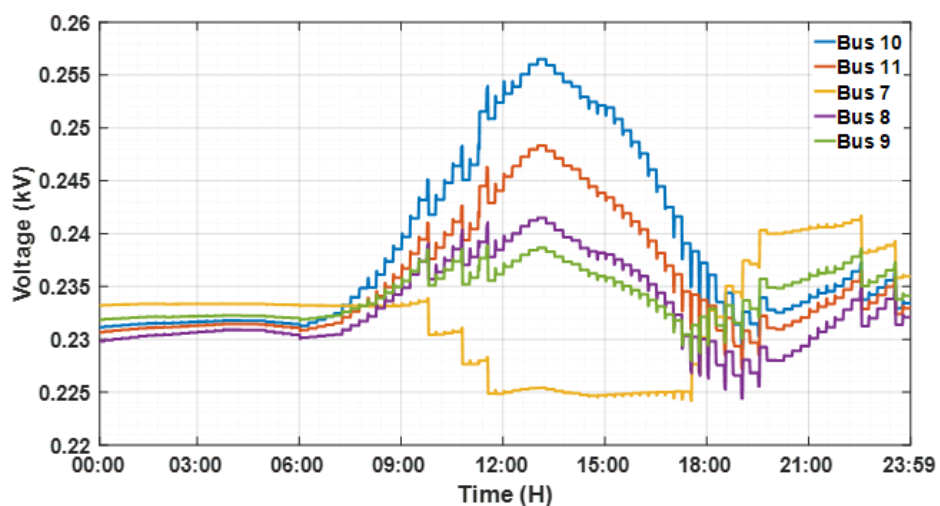


Figure 14. Voltage profiles with CVC.

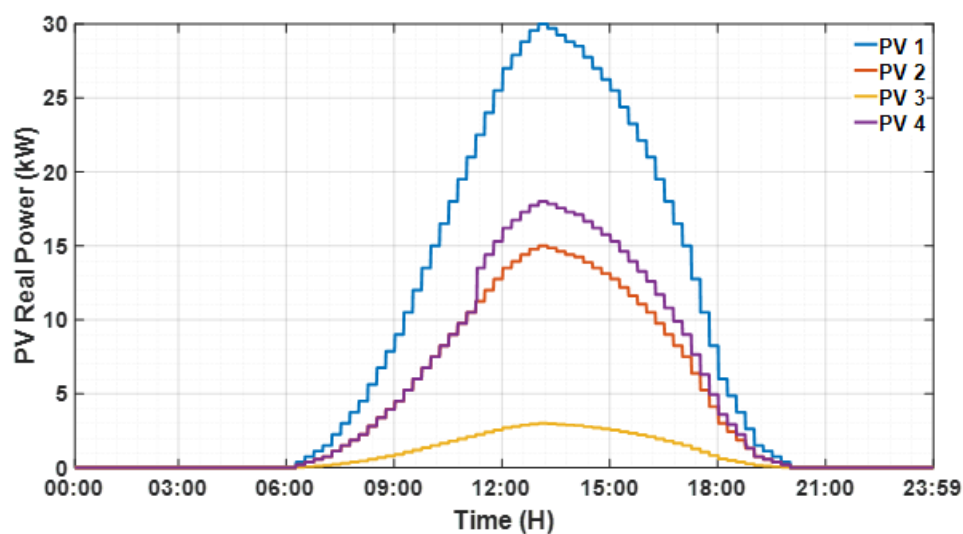


Figure 15. Real power output of PVs.

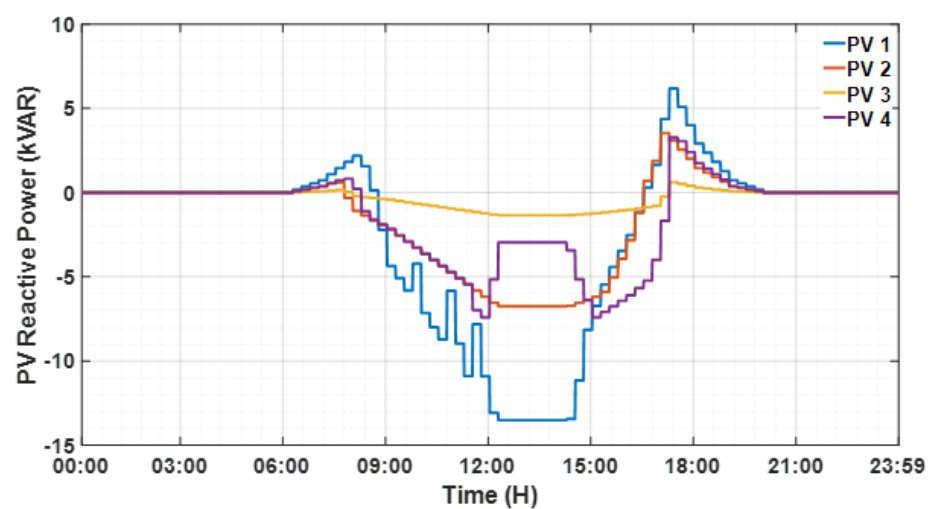


Figure 16. Reactive output of PVs.

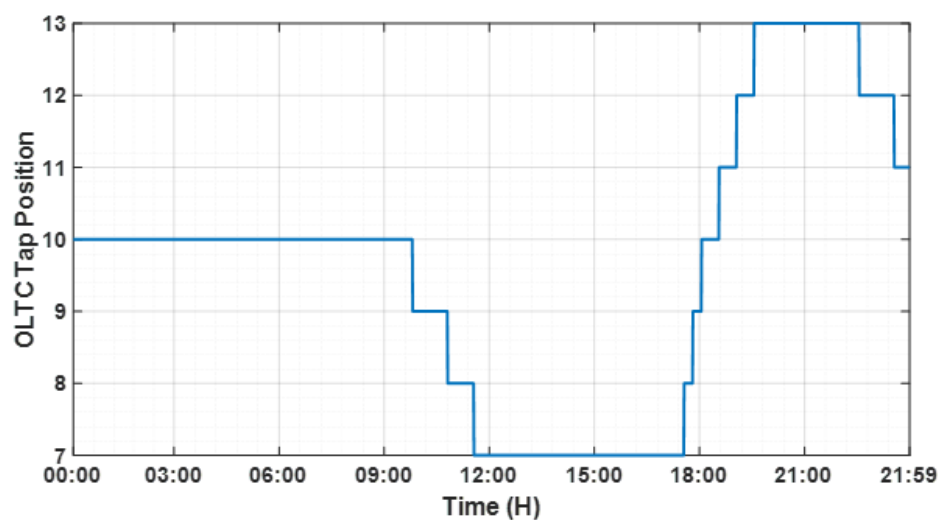


Figure 17. OLTC tap position.

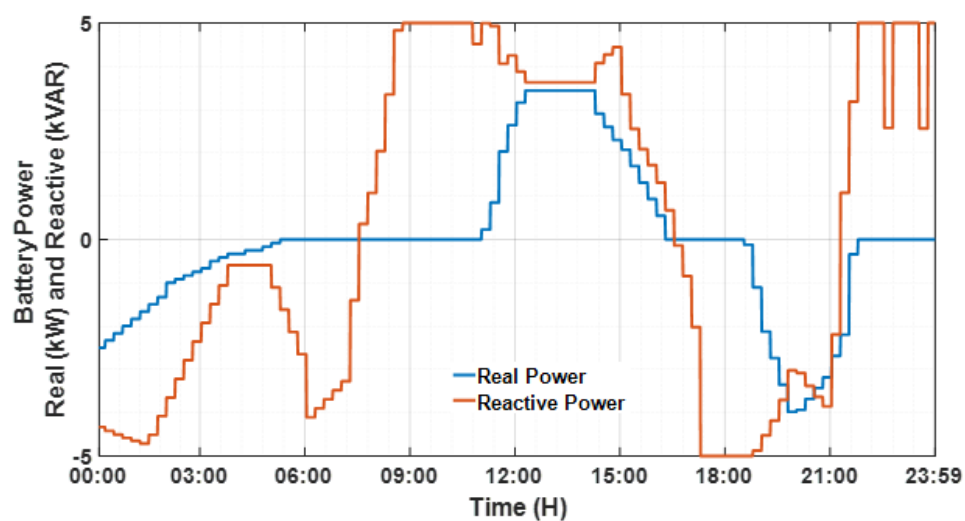


Figure 18. Real and reactive power from EV battery.

A comparison between Figures 13 and 14 shows the benefit of this work. Figure 13 shows clear voltage overshoots during PV peak generation hours and voltage dips during peak load hours. Proper EV management mitigates these issues, as shown in Figure 14, where the voltage at noon does not rise as much. The reduction rate was more than 5%. This means more solar power can be captured by the PV panels and fed into the grid (Figure 15). This is important as it increases the return on investment (ROI) for PV panels and their impact on the environment, and decreases the payback period. As a result, profitability of these generators increases and investors will be more inclined toward funding such projects.

Voltage drop at peak hours is mitigated by providing grid support by discharging the EV batteries. Such grid support lifts the voltage more than 8% at some buses. This addresses the increasing load in distribution networks.

Figure 18 shows the real and reactive power exchanges of EV battery. As expected, power flow occurs on both ways, as is required. It is important to note when the SoC reaches 40% (at around 6:00 a.m.), it stops discharging as this is the lower threshold. The EV battery is kept at this minimum value before peak PV generation hours so that it can be used as extra storage. During peak load hours, the EV battery discharges to support the grid.

The most important contribution of this study is that the EV and its interaction with the utility grid (grid optimizer) was applied with a real communication infrastructure where the messages were exchanged in a standardized way between two physical terminals. Normally, power system simulations assume that such a communication line exists and is operable. For real-life implementations, that assumption needs to be removed. This study addressed this need by developing a real solution that can be used by different EV manufacturers and grid operators. A standardized modeling approach ensures any vehicle can be integrated with any smartgrid seamlessly.

## 5. Conclusions

EVs are a viable option to meet global decarbonization targets, which has increased their popularity. However, EV migration is hindered by different concerns such as the higher cost of EVs and the unknown impacts of large-scale migration to EVs on the current power grid. Distribution networks are the focus as they are not designed for high-volume power exchange with EVs, i.e., both charging and discharging operations. Thorough study of these aspects is indispensable. Large-scale refurbishment of the distribution networks is costly and complex. A better alternative, proposed in the related literature, is coordinating EV power exchange operations with other events in the grid to minimize their impact. There is a universal consensus that such coordination requires constant information exchange between different components, such as grid operators, EVs, and CSs. Despite this, the majority of the related research has focused on coordination schemes and treated communication issues as a black box. The ability to seamlessly connect different equipment, i.e., interoperability, is vital for the applicability of such schemes and implementation details need to be addressed.

In order to fill this gap, standard models were developed for CSs and EVs based on the IEC 61850 standard's common information model. Furthermore, relevant steps of smart coordination algorithms were transferred to different IEC 61850 messages based on their suitability, e.g., SV, GOOSE, and MMS. These theoretical models and communication designs were implemented in the lab with emulators and HIL testing tools. The test results showed that both of the designs are valid and achieve the desired operation.

Since the frameworks were developed according to a popular futuristic standard, the real-time implementation and evaluation of these frameworks enables plug-and-play operation for smart grids. This approach can be used to seamlessly connect EVs and CSs in smartgrids to achieve the IoT concept.

Furthermore, the developed communication infrastructure was tested in a co-simulation environment where the battery's SoC was sent to the centralized controller and relevant

charge and discharge instructions were received. The results showed successful integration of these communication and power system components in a co-simulation environment. In this fashion, more comprehensive tests can be run to investigate full-spectrum impact studies. Instead of treating communication infrastructure as a given, or a black box, researchers can achieve full system implementation where communication and power flow studies run in parallel. Such studies will increase the feasibility of smart EV control algorithms and the EV migration rate in car fleets.

Future work should focus on cybersecurity considerations and the extent of possible attacks on power system operation.

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