Journal of ELECTRICAL ENGINEERING, VOL 73(2022), NO2, 99–107

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PAPERS

Decentralized controlled charging and vehicle-to-grid solution for voltage regulation in low voltage distribution systems

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This paper offers affordable controlled charging and a vehicle-to-grid solution that uses a non-smart power meter. Additional communication infrastructure in the low-voltage distribution network is not needed. Ladder logic control is developed to be easily implemented by any commercial programmable logic controller. The voltage values measured by the power meter and electric vehicle battery state of charge are the decision variables. A validity check based on the Monte Carlo method is conducted to test the effectiveness of the proposed solution. Electric vehicle charging requirements are simulated based on travel surveys. The results demonstrate the effectiveness of the proposed solution. The voltage level is kept within acceptable limits according to the power quality standard EN50160. One may argue that there is a mismatch between the rate of penetration of electric vehicles and the level of smart grid implementation, especially in developing countries with higher rates of wealth inequality. Therefore, the methodology presented in this paper can be seen as an affordable mid-way solution that will help distribution system operators in developing countries prepare for higher penetration levels of EVs.

K e y w o r d s: electric vehicle, controlled charging, vehicle to grid, Monte Carlo, power meter

1 Introduction

1.1 Motivation

In recent years, human civilization has faced an upward trend of air pollution. This problem especially affects urban areas where the number of vehicles with internal combustion engines is significantly high [1]. In contrast to conventional vehicles, electric vehicle (EV) technology is already optimally designed, and there are almost no technological limitations concerning conventional vehicles [2]. To reduce the price gap between EVs and conventional vehicles, many national governments have adopted regulations that stimulate the production and sales of EVs [3]. In addition, the European Union has set criteria for further reduction of greenhouse gas emissions by 40 % by 2030 compared to 1990 [4]. The International Energy Agency (IEA) has predicted that the sales of passenger light-duty EV/plug-in hybrid EVs will reach more than 100 million per year worldwide by 2050 [5].

Uncontrolled charging of EVs will affect the distribution system operation owing to the significant increase in demand and load peaks [6]. The increased demand caused by the uncontrolled charging of EVs leads to several problems in distribution systems, including violation of voltage limits and an increase in network losses. To overcome the problems that arise from uncontrolled charging, researchers have introduced controlled charging (CC) techniques to optimize the charging/discharging process of EVs. These techniques aim to obtain higher EV penetration.

According to [7], coordinated charging/discharging solutions are mainly organized into three categories:

- centralized,
- distributed,
- decentralized.

The first solution is implemented through a central controller that coordinates all the EV charging or discharging processes. Communication between a central controller and all EVs is required for the acquisition of local information. Then, the central controller executes the control algorithm and sends the calculated charging setpoint to each EV under its governance. In this case, significant computational resources are required to process a large amount of collected data [8]. Sharing of sensitive data (arrival and departure times, energy requirements) is required in a centralized solution and should be taken care of [9]. The second solution is the distributed control. This solution requires a local communication network for information exchange. Distributed control provides the opportunity to distribute the computational load among many entities. Thus, distributed control solutions are a scalable alternative for solving the EV coordinated charging problem, and they protect private information such as driving behavior to a certain extent [10]. The third solution is a fully decentralized control strategy, which is based on local information only. This type of control strategy is robust and low-cost to implement in the sense that no communication infrastructure is required.

A smart grid (SG) is an electricity supply network that uses digital communications technology to detect and re-

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https://doi.org/10.2478/jee-2022-0013, Print (till 2015) ISSN 1335-3632, On-line ISSN 1339-309X
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act to local changes in usage. Therefore, to implement any of the coordinated charging solutions, the SG infrastructure is often required. The transition towards SG is an ongoing process that requires continuous investment in the introduction of new technologies, mostly related to information, communication and automatization. This process may advance at different rates depending on the level of socio-economic development of the country and the state of the grid infrastructure. On the other hand, the penetration of EVs may progress at higher rates than SG development (especially in developing countries), thus requiring supporting solutions that are not based on the existence of advanced SG infrastructure. In addition, the policy incentives are mainly focused on the EVs, rather than the required infrastructure, which creates a disparity between the level of development of SGs and EV penetration. The major motivation of this study is to facilitate the integration of EVs without a communication infrastructure. The proposed CC and V2G solutions in this study aim to achieve this only by using the EV charger and household power meter.

1.2 Literature review

As stated above, the changes in the distribution grid operation due to uncontrolled EV charging have been addressed in several different research papers [11], [12]. In recent years, various CC techniques have been investigated. Despite the CC solution used (centralized, decentralized, or distributed), optimization of the charging/discharging process of EVs is mainly based on the following optimizations:

- mathematical: linear, quadratic, dynamic, and mixed-integer linear programming,
- meta-heuristic: genetic algorithm, particle swarm optimization, and evolutionary algorithms,
- heuristic: Artificial neural network and Markov process,

with different optimization goals used to achieve optimized charging/discharging of EVs [7].

To achieve peak load reduction, in [13] the authors used valley filling when the no-EV load had smaller values. This was achieved using a two-stage hierarchical optimization with quadratic programming. The CC in this study was organized as centralized. Centralized CC and peak load reduction were also implemented in [14]. However, the charging optimization was formulated as a Markov decision process. Peak load reduction is one of the objectives of the multi-objective optimization analyzed in [15]. In this study, the CC is also organized as centralized, and the multi-objective optimization is solved using a meta-heuristic approach. In [16] the authors also used peak load reduction as an optimization goal and the CC is organized as centralized. The optimization goal was achieved by implementing a genetic algorithm. Peak load reduction was also used as an optimization goal in [17]. The CC is organized as centralized, and the optimization problem is solved using the swarm optimization method. Papers [18] and [19] are also using peak load reduction as an optimization goal. Contrary to previously analyzed papers, in these two papers, the CC is organized as decentralized. In [18] the optimization goal is achieved by using robust optimization to tackle uncertainties arising from driver behavior. In [19] the optimization goal was achieved using a mixed strategy for a multi-agent system.

All papers reviewed in the previous paragraph used peak load reduction as the optimization goal. The optimization goal of the papers [20] and [21] is to reduce or minimize operational costs from the network operator side, which will finally lead to profit maximization. Even though they have different optimization goals regarding papers reviewed in the previous paragraph, the result is the same: reduction of peak load and higher acceptable EV penetration level. The CC in [20] and [21] was organized as centralized. To solve the optimization problem, the authors in [20] are using mixed-integer linear programming and the authors in [21] linear programming.

1.3 Novelty

Some CC techniques presented in the literature review use peak load reduction as an optimization goal. Others achieved peak load reduction as an outcome of another optimization goal (*ie* operational cost minimization, satisfying network parameters, *etc*). In some of the papers the CC is organized as centralized, and in others, as distributed. Nevertheless, all of them depend on the presence of a SG or communication network. It may be expected that the number of EVs will increase at higher rates than the implementation of SGs, especially in suburban low-voltage distribution systems (LVDS) in developing countries with a higher level of wealth inequality.

Therefore, this paper offers a CC and V2G solution that will help distribution system operators to overcome the undesirable effects of uncontrolled EV charging until the SGs infrastructure is present. The proposed solution is based on technology and devices that are possessed by the owners of EVs (EV charger and power meter. The result is a reduction in the peak load and a higher acceptable EV penetration level. The CC is organized as decentralized, and no communication infrastructure is needed. Thus, the solution can be easily implemented without significant costs. The effectiveness of the solution is validated by a Monte Carlo (MC) model that incorporates the uncertainty arising from drivers behavior.

We propose a solution for CC and V2G, which was designed to help the distribution system operators maintain the system parameters within the allowed limits, without communication infrastructure. This was tested on an LVDS with 18 nodes using a Monte Carlo simulation.

2 Controlled charging and V2G solution

Figure 1 depicts the control diagram for the proposed CC and V2G solution. The proposed solution is based on the use of devices that are already in use in a household with EVs, such as a power meter (PM) and EV charger

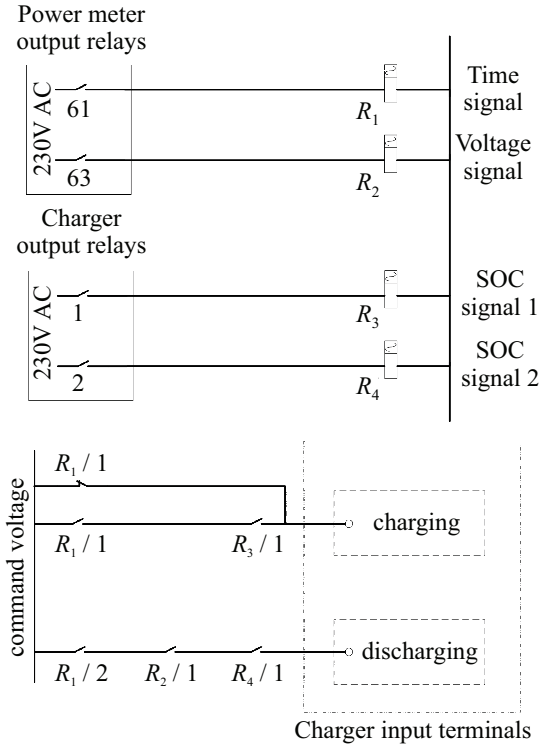


Fig. 1. Control of CC and V2G implementation

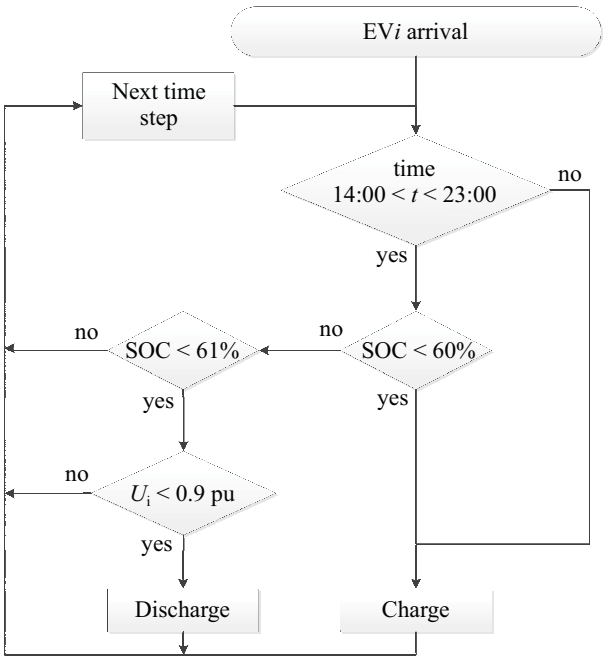


Fig. 2. Flow chart for charging and discharging

(EVC). Four relays are used in the control strategy. Two of them are controlled by the PM as a function of the time of the day and the voltage. The other two are controlled by the EVC as a function of the EV state of charge.

The upper part of the diagram depicts the output normally open (NO) contacts from the PM (61 and 63) and EVC (1 and 2). With activating contacts 61, 63, 1, and 2, relays R1, R2, R3, and R4 are energized. The lower part of the diagram depicts the NO and normally closed (NC) contacts from relays R1, R2, R3, and R4. Relay R1 has two NO contacts (R1/1 and R1/2) and one NC contact (R1/1). Relays R2, R3, and R4 have one NO contact, R2/1, R3/1, and R4/1, respectively. The control logic for EV charging and discharging is presented in Fig. 2.

The solution is developed using data from the MT174 series [22] PM. It is a digital PM with an integrated real-time clock. Contact 61 is programmed to close when the household load peak is expected (*ie* from 14:00 h to 23:00 h). When contact 61 is activated, relay R1 is energized. The PM measures the phase voltages at the connection point. Contact 63 is programmed to close if the phase voltage drops below 0.9 per unit. Then, relay R2 is energized.

To implement the proposed CC and V2G solutions, the state of charge (SOC) of the EV should be known. Because this information is only available from within the vehicle, the EVC should be modified with additional inputs/outputs to be able to signal when a certain SOC is reached and to receive commands for charging and discharging. The authors of [23] provided information on how to upgrade the EV with an additional device that reads the vehicle SOC and emits commands for charging if needed. The EVC has two output NO contacts and two input terminals. Contact 1 from the EVC is programmed to close if the SOC of the EV battery is below 60%. In this case, according to Fig. 1, relay R3 is energized. Contact 2 from the EVC is programmed to close if the SOC of the EV battery is above 61 %. Then, relay R4 is energized. Additionally, charger input terminals are used to send commands to the EVC to start charging or discharging.

Figure 2 depicts a flow chart that summarizes the control of the charging and discharging of an EV based on the proposed solution. According to Figure 1 and Figure 2, if the owner of the EV returns to his house after his final trip for 14:00 h, contact 61 from PM remains open, R1 will be de-energized, and the EV starts charging (NC contact R1/1 remains closed).

If the connection time of an EV is between 14:00 h and 23:00 h, terminal 61 from the PM is closed, and R1 is energized. From here there are two possible outcomes: The first is when the SOC of the EV is below 60 %. In this case, contact 1 from the EVC is closed and R3 is energized. According to Fig. 1, NO contacts R1/1 and R3/1 are closed, and a signal is sent to the EVC to start charging. When SOC reaches 60 %, terminal 1 from the EVC opens, R3 is de-energized, the NO contact R3/1 is open and stops the charging process. The charging process continues after 23:00 h when R1 is de-energized, and the NC contact R1/1 returned to its nominal position. Fig. 3 depicts an example when the EV is connected for charging at 13:00 with a battery charge of 30 %.

The second possible outcome is when the battery SOC is above 61 % before arrival. In this case, terminal 2 from the EVC is closed and R4 is energized. Now, the

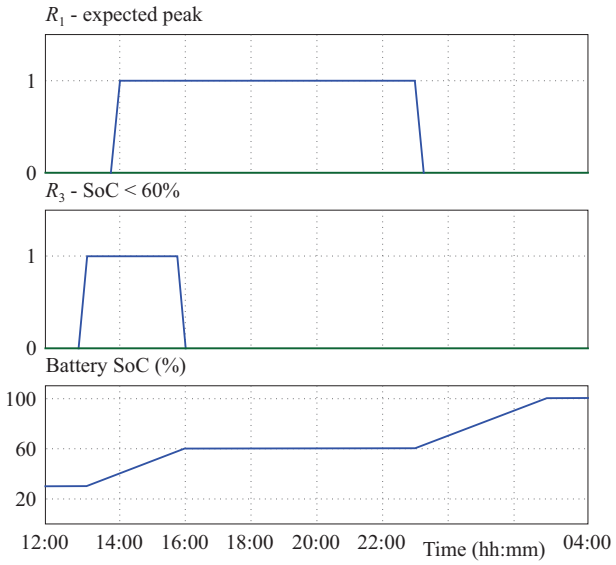


Fig. 3. Example – connection time 13:00; battery SOC 30 %

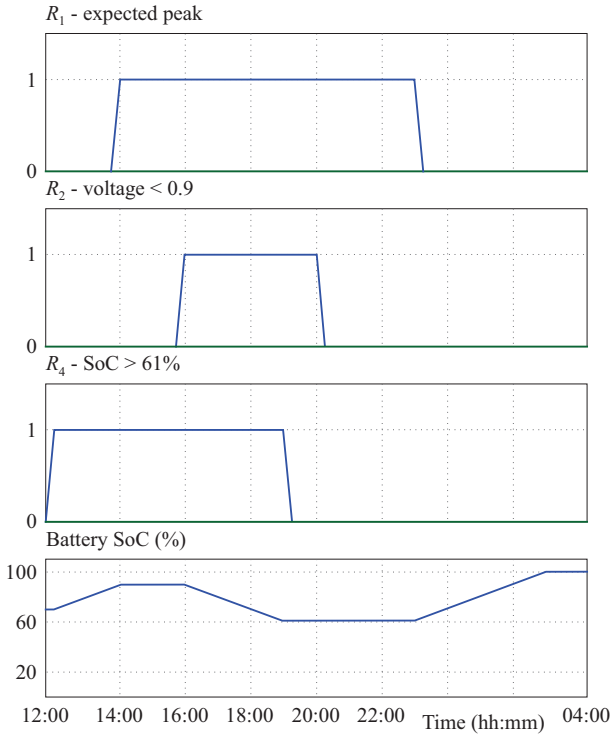


Fig. 4. Example-connection time 12:00; battery SOC 70 %

NO contacts R1/2 and R4/1 are closed. However, the discharging process will not begin. If the phase voltage drops below 0.9 per unit, terminal 63 from the PM is closed and R2 is energized. NO contacts R1/2, R2/1, and R4/1 are closed, and the discharging process starts. The discharging process lasts until the battery SOC reaches 61 %. In this case, terminal 2 from the EVC opens, and R4 will be de-energized. NO contact R4/1 will open and stop the discharging process (the same will happen if the voltage exceeds 0.9 per unit, but in that case, relay R2 is de-energized, and R2/1 will stop the discharge process). Figure 4 depicts an example when the EV is connected to the grid at noon with a battery SOC of 70 %. The voltage is lower than 0.9 per unit from 16:00 to 20:00.

The proposed control solution can be easily implemented inside the EVC microcontroller and the control board. In such a case, only two signals from the PM are needed, and there is no need for relays R1, R2, R3, and R4 because all the logic will be executed by the EVC. A 60% SOC value is taken as an example. This value can be defined in a predefined range. With this attribute, the owner of the EV will have control over how much energy he has in his EV until the peak load from the general household load surpasses. The 0.9 per units voltage value is also taken as an example. Because low-voltage distribution networks have a radial configuration, households that are electrically closer to the supply substation are expected to have higher voltage values compared to households that are at the end of the radial topology. Therefore, households that are electrically closer to the supply node can start discharging their excess energy at higher voltages (*ie* 0.95 per unit). Additionally, to avoid constantly changing the status of contact 63, the operating band of contact 63 should be implemented because of the voltage sensitivity arising from the charging/discharging of the EV.

The proposed solution can be easily implemented at a low cost. Additionally, there is no need for SG infrastructure or communication networks of any kind in the LVDS.

3 Simulation model

A simulation model based on the MC method is developed to investigate the effectiveness of the presented solution for CC and V2G. One MC step (experiment) is a representation of one day with 24 hours duration. Standard EN50160 is used to evaluate the results. According to the standard, the voltage quality is evaluated in weeks. The idea is to test the solution for an integer number of weeks. Therefore, 9 996 days are analyzed equivalent to 1 428 weeks. To better display the EV charging requirements, the day is simulated to start at 07 : 00. Load flow calculations are conducted in 15 minutes intervals. The busload curve is calculated as the sum of two curves: the general household load curve and the EV charging load curve. The simulation model is described in the following subsections.

- Model of EV,
- Household load curve generator,
- Solution implementation.

3.1 Model of EV

To create a model of EVs based on their daily energy needs, the following information for every EV should be provided:

- daily driven distance in km,
- vehicle arrival time = time of connection to the LVDS,

- vehicle type (sedan, van, pickup van, SUV),
- charger type (single-phase or three-phase),
- energy consumption per kilometer,
- battery capacity,
- location (bus) in the LVDS where the EV is connected.

Surveys that record the transportation habits of the population reveal information on the daily driving distances per vehicle. This model used data from the NHTS 2017 survey conducted in the United States [47]. The survey covered more than 900 000 individual trip records. As the aim of this model is to simulate the energy needs of an EV used for households and the light industry, only trip records for vehicle-type sedans, vans, pickup vans, and SUVs are taken into consideration. Then, the daily driven distance for each vehicle (d_i) is calculated as the sum of all recorded individual driven distances per day

$$d_i = \sum_{j=1}^{N} T_{i,j}\,, \tag{1}$$

where N is the total number of trips of vehicle i and $T_{i,j}$ is the distance of the individual trip j of vehicle i.

Participants in the survey [24] recorded the arrival times of all trips made by each vehicle during the day. It is assumed that the owner connects the EV as soon as he arrives from his last trip for the day; therefore, the arrival time of the last trip can be used as an EV connection to the grid time. The distribution of vehicles by type is also obtained from [24]. This information is important because different types of EVs have different battery capacities. Additionally, owing to their different weights, different EVs have different energy consumptions per driven kilometer. Information on the energy consumption of EVs and their battery capacities used in this simulation can be found in [25]. The battery SOC before arrival can be calculated as

$$SOC_i\,(\%) = \begin{cases} 0, & d_i \geq AER_i \\ \dfrac{\lambda_i\, d_i}{B_{cap_i}} 100\,, & d_i < AER_i \end{cases}\,, \tag{2}$$

where λ_i is the energy consumption per driven kilometer, B_{cap_i} is the total battery capacity, and AER_i is the all-electric range of vehicle i. There is insufficient information in the literature regarding EV charger-type distribution (single-phase or three-phase charger type). For this simulation, the type of charger for all the simulated EVs is randomly chosen. It is also assumed that the EVs are connected for charging in a household, the charging current is set to be $I_{ch} = 10\,\mathrm{A}$ [26], and the efficiency of the charger is $\eta = 88\,\%$. The connection point of EVs among different households is randomly chosen. Figure 5 depicts the energy required to fully charge two EVs using different charger types.

3.2 Household load curve generator

Typical household load profiles with 15 min resolution for 12 months are obtained from [27],

$$\begin{gathered} P_{i,j,k} = c_{j,k} \cdot random_{j,k}(\mu_i, \sigma_i)\,, \\ i = 1, 2, \ldots, N_{hh};\ j = 1, 2, \ldots, 96\,;\, k = 1, 2, \ldots, 12 \end{gathered} \tag{3}$$

where index hh stands for "house hold". To capture possible differences in household consumption, certain modifications of the general household load profile are introduced, these modifications are

$$\mu_i = P_{\mathrm{disc},\,i}\,, \tag{4}$$

$$\sigma_i = 0,1 mu_i\,, \tag{5}$$

where $c_{j,k}$ are the coefficients for the time interval j (15 min) and month k. The coefficients are typical for a household load type.

The coefficient is multiplied by a random number from a normal distribution. The mean values of the normal distribution $_i$ are equal to the analyzed household discrete load values (see Table 1). The standard deviation σ_i is set to 10 % of its mean value. Therefore, for the first MC step, we took the daily coefficients for the average day in January and multiplied them with a normally distributed random number for every household. In the second MC step, the daily coefficients for the average day in February are multiplied by a normally distributed random number, and so on. Figure 6 depicts an example of daily load profiles for household 17 for the 35^{th} and 71^{st} MC steps.

3.3 Simulation implementation

Figure 7 depicts the flow chart for the MC simulation for analyzing the effectiveness of the proposed CC and V2G solutions. The analyzed LVDS distributes electricity to a known number of households. According to [24], the average number of vehicles per household is 1.95. Therefore, with a predefined penetration level, the number of EVs can be calculated as

$$N_{EV} = 1.95\, N_{hh}\, \frac{p}{100}\,, \tag{6}$$

where p is the penetration level of EVs in %.

After the number of EVs is calculated, MC simulation began. Every MC step is a representation of one day, and with 9 996 days, the total number of analyzed weeks is 1 428. The day is divided into 96-time intervals, each lasting 15 min. Load flow calculations are conducted for each time interval using the Newton-Raphson method. Finally, the daily load curve for each household is generated using the procedure explained in paragraphon 3.2.

For each EV, a random value for the daily driven distance and arrival time is chosen from [24], as described in paragraph 3.1. The distribution of vehicles based on their type and energy consumption per driven kilometer is also considered. With every MC step, the same number of EVs will have different battery SOC. Since there

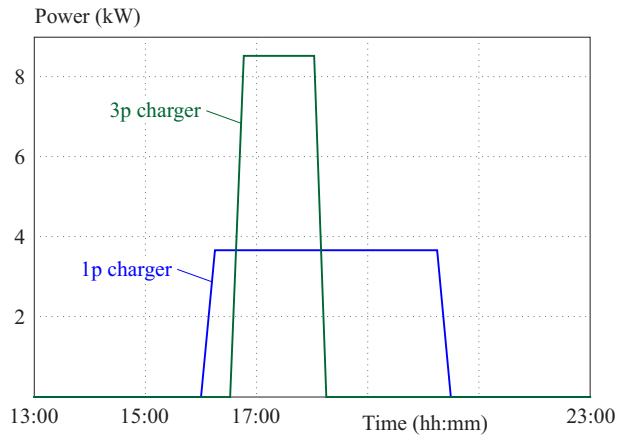


Fig. 5. Energy needs for two EVs with different charger types [25]

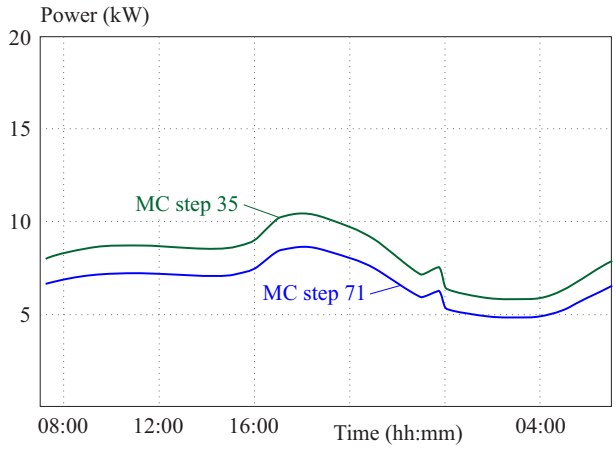


Fig. 6. Household 17-randomized daily load curves for November

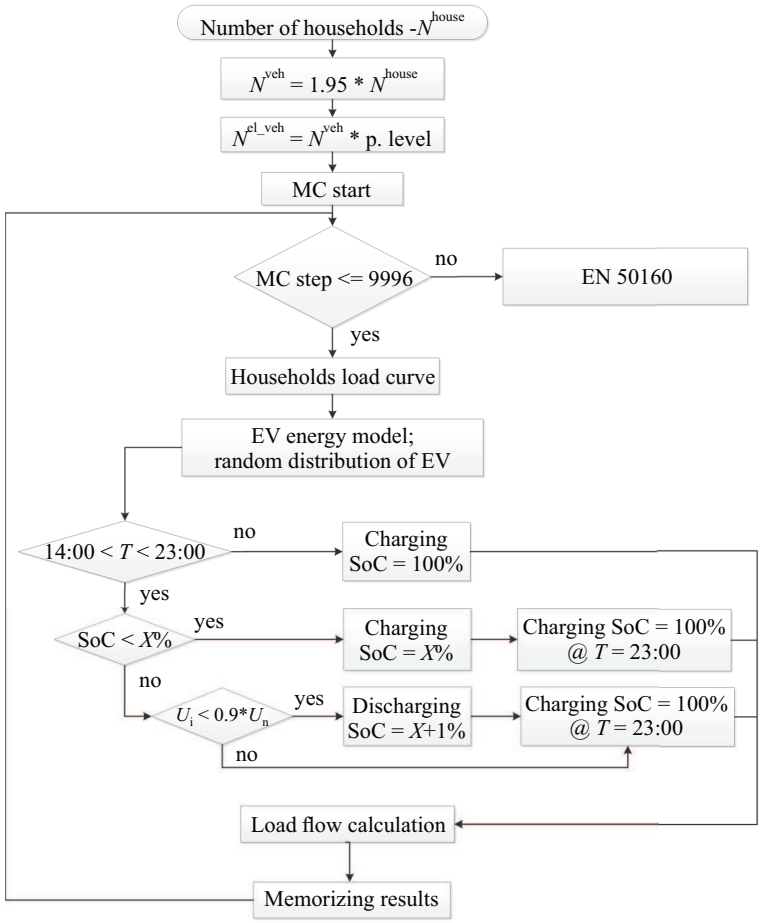


Fig. 7. Computer model flow chart

is no information on which household has an EV, in every MC step, the EVs are randomly distributed among households.

Therefore, in every MC step, for each arriving EV, the SOC, charger type, and connection point (household) are determined. Therefore, the following algorithm is implemented to meet the proposed CC and V2G solutions:

- EVs that arrive from 07:00 to 14:00 and from 23:00 to 07:00, should start charging at 100%.
- EVs that arrive from 14:00 to 23:00 and their $SOC < X\,\%$ start charging to $SOC = X\,\%$.
- EVs that arrive from 14:00 to 23:00 and their $SOC > \{X+1\}\,\%$ start discharging if the bus voltage is lower than 0.9 per units, until $SOC = \{X+1\}\,\%$.

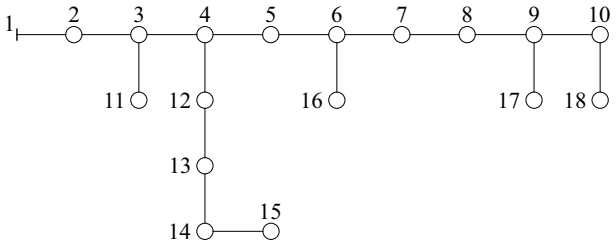


Fig. 8. Radial low voltage distribution network

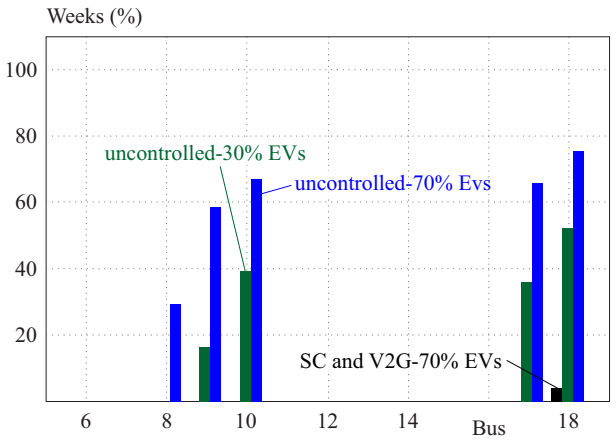


Fig. 9. Percentage of weeks for which EN 50160 is not fulfilled

- EVs that arrive from 14:00 to 23:00 start charging to 100% after 23:00.
- X is a random number from a predefined set and is different for each simulated EV. This number represents the owners acceptable SOC during the peak load period.

4 Results

A low-voltage distribution network based on the CIGRE European test system is used. The network has a radial configuration and supplies electricity to 17 households. The supply transformer had a nominal power $S_n = 500\,\text{kVA}$. Some network components are modified to analyze the effectiveness of the proposed solution. Additional information about the network parameters and household discrete load values is presented in Table 1. Figure 8 depicts the network topology.

In the first case, a 30 % penetration level of EVs is considered. The charging of the EVs is uncontrolled. The standard EN50160 is used to evaluate the voltage quality results. According to the standard, the voltage magnitude must be in the range of ±10 % for more than 95 % of the time for one week. Figure 9 depicts the percentage from 1 428 weeks when the standard is not fulfilled. The voltage magnitudes for households that are electrically far from the supply substation are not satisfactory (buses 9, 10, 17, and 18). Additionally, a scenario with a 70 % penetration level of EVs is simulated. The results from uncontrolled charging are shown in the same figure. Once again, the voltage magnitudes for households that are electrically far from the supply substation are not satisfactory (for bus number 18, for more than 70 % of all weeks analyzed). With the same penetration level of EVs, but now with incorporated CC and V2G solution, the results are far better (for both cases, only bus 18 did not fulfill the standard for less than 5 % of the analyzed weeks).

For further investigation, the load curves from one MC step are analyzed. The simulated EV penetration level is 70 %. In Fig. 10, the black line represents the sum of all households load curves. The blue line represents the energy required to charge all connected EVs. In this case, the CC and V2G solutions are not implemented. The green line represents the total energy supplied by the supply substation. High demand in peak load hours is evident.

In Fig. 11, the black line represents the sum of all general households' load curves. The blue line is the power needed for EV charging, and the red line is the energy returned to the LVDS from V2G. The green line represents the equivalent load curve. It can be noticed that the

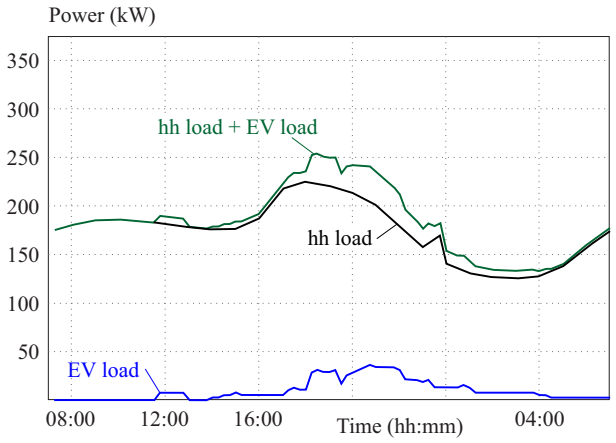


Fig. 10. Load Curves - 70% EVs penetration level, without CC and V2G solution implemented

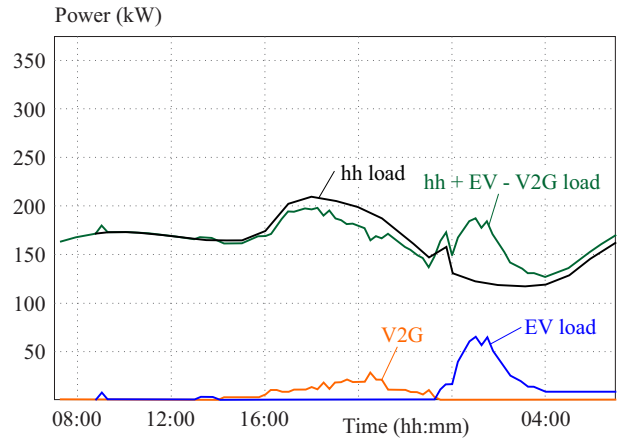


Fig. 11. Load Curves - 70% EVs penetration level, with CC and V2G solution implemented

Table 1. Low voltage distribution network parameters

Line parameters					Load parameters	
From bus	To bus	R (Ω/km)	X (Ω/km)	L (m)	Household number	Load P (kW)
1	2	0.405	0.205	100	1	17
2	3	0.405	0.205	100	2	16
3	4	0.405	0.205	100	3	15
4	5	0.405	0.205	100	4	10
5	6	0.405	0.205	100	5	6
6	7	0.405	0.205	100	6	16
7	8	0.405	0.205	100	7	17
8	9	0.405	0.205	100	8	14
9	10	0.405	0.205	100	9	15
3	11	2.050	0.212	50	10	15
4	12	2.050	0.212	50	11	11
12	13	2.050	0.212	50	12	14
13	14	2.050	0.212	50	13	8
14	15	2.050	0.212	50	14	14
6	16	2.050	0.212	50	15	12
9	17	2.050	0.212	50	16	9
10	18	2.050	0.212	50	17	10

proposed solution helped in reducing the peak load with the help of V2G and achieved peak shaving with the help of the CC. With such a solution implemented, the given LVDS can accept higher EV penetration levels.

5 Conclusions

CC and V2G solutions that will help LVDS operators overcome the problems arising from EV charging are presented in this paper. Smart grid technologies will become a reality in the future. With the help of SG, various optimization techniques for CC can be implemented.

The number of EVs will increase at higher rates than the implementation of SG, especially in suburban LVDS in developing countries with higher wealth inequality. Therefore, we offer solutions based on an already deployed infrastructure (power meter and EV charger) to help distribution system operators overcome problems arising from uncontrolled EV charging.

This solution can be implemented without the presence of SG, which leads to lower costs. Since there is no SG, there are no issues regarding cyber security and data privacy. If SG is not present, the LVDS operator must reinforce the low-voltage network to satisfy the EN50160 standard, which leads to additional spending to facilitate higher EV penetration. The offered solution can smoothen the transition toward more sustainable transportation in urban areas and help evaluate the benefits of V2G and CC even before SG is implemented. Additionally, the developed simulation model proves the effectiveness of the presented solution in peak load shaving and bus voltage improvement in low-voltage distribution networks.

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Received 3 April 2022