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THE IMPACT OF PLUG-IN HYBRID VEHICLES IN LOW-VOLTAGE DISTRIBUTION SYSTEMS USING A MONTE CARLO SIMULATION

VPLIV PRIKLJUČNIH HIBRIDNIH VOZIL NA NIZKONAPETOSTNE DISTRIBUCIJSKE SISTEME Z UPORABO METODE MONTE CARLO

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Keywords: Plug-in Hybrid Electric Vehicle, Power Quality, Non-Deterministic Approach, Voltage Deviations, Power Losses, Distribution Systems.

Abstract

The growing presence and randomness of renewable-based Distributed Generation, such as solar, photovoltaic, and wind power, and heavy Plug-in Hybrid Electric Vehicle loads in residential distribution grids result in both a higher degree of imbalance and a wide range of voltage fluctuations. When increasing the number of Plug-in Hybrid Electric Vehicles that are simultaneously charged, the additional unpredicted load may cause several problems to the current grid in terms of voltage deviations, thermal overloads, power losses, increased aging of transformers and lines, decreased quality of supply, and power outages. This paper proposes an approach that models Plug-in Hybrid Electric Vehicles' behaviour and performs power flow analysis on CIGRE low voltage benchmark grid to investigate the impact on the current distribution grid.

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Povzetek

Vse večja prisotnost proizvodnje, ki temelji na obnovljivih virih energije, kot je sončna, fotovoltaična in vetrna energija, njena naključna porazdeljenost ter velike obremenitve priključnih hibridnih električnih vozil (EV) v stanovanjskih distribucijskih omrežjih povzročajo tako višjo stopnjo neravnovesja kot širok razpon nihanj napetosti. S povečanjem števila priključnih hibridnih EV, ki se sočasno polnijo, lahko dodatna nepredvidljiva obremenitev povzroči več težav trenutnemu omrežju – to so odstopanja napetosti, toplotne preobremenitve, izguba moči, hitrejše staranje transformatorjev in vodov ter zmanjšana kakovost oskrbe in izpad električne energije. V članku predlagamo pristop, ki modelira obnašanje priključnih hibridnih električnih vozil in izvaja analizo pretoka moči na nizkonapetostnem referenčnem omrežju CIGRE ter na ta način omogoča raziskavo vplivov EV na trenutno distribucijsko omrežje.

1 INTRODUCTION

Distribution System Operators (DSOs) are responsible for operating their grid to follow a predicted demand with unidirectional power flows only. Most of the conventional distribution grids are of the radial type with different configurations and loads. They have one objective: to offer a quality of supply under certain technical and economic parameters that offer efficient and reliable grid operation. *[1]-[2]* Due to the fast development of power electronic technologies, the presence of Distributed Generation (DG) and connected Plug-in Hybrid Electric Vehicles (PHEVs), the bi/multi-directional power flow distribution grid is growing rapidly, which raises the question: Are the current conventional distribution grids ready for these new rapidly-growing types of loads? *[3]*
The advancements in transportation electrification have changed the structure of traditional car manufacturing processes. This kind of rapid and increased development in the transportation electrification sector requires large-scale research and evaluation in order to measure the capability of the current conventional distribution systems to withstand the increased presence of PHEVs. *[4]*

PHEVs are continuously opening up new perspectives and numerous possibilities. *[5]* These types of vehicles currently present on the market not only reduce pollution, but can also help in conserving natural resources. PHEV technology is one of the most promising forms of technology for reducing petroleum consumption associated with reducing the use of internal combustion engine vehicles, and they are seen as an opportunity to provide environmentally-friendly vehicles for transportation that do not release greenhouse gases into the atmosphere or cause smog. From an energy policy point of view, electro-mobility offers the opportunity to achieve the objectives of decarbonisation and decentralisation of electricity sources. *[6]*

As one of the types of Electric Vehicles (EVs), PHEVs are recharged through a plug connected to the electric power grid. *[4]* Hence, PHEVs are changing the conventional load profile. *[7]-[8]* The main issues caused by their growing presence are mainly related to power quality. Power quality is a predominant aspect of the efficiency and security of grids and is likely to be strongly affected by PHEV development over the forthcoming years. *[9]*

'Power Quality' refers to providing a near sinusoidal voltage and current waveforms for the power grid at the rated magnitude and frequency. *[10]* Factors such as voltage and frequency variations, imbalance, interruption, flicker, and harmonics can determine power quality. As the number of PHEVs that are randomly charged on the grid is increasing rapidly, the unpredicted load profile may pose several problems to the current conventional grid in terms of voltage deviations, thermal overloads, power losses, increased aging of transformers and lines, decreased quality of supply and power outages. It is thus of great importance to investigate power quality concerns in distribution grids when considering PHEVs.

The impact of PHEVs on the grid's parameters can be consequential or inconsequential depending on the number of PHEVs attached to the grid, the grid's characteristics, and the PHEV's charging features. To conclude that supplied energy is of acceptable quality, the parameters that define it must be within limits defined by the DSO distribution regulation. *[11]*

With the increased presence of PHEVs, and moving beyond the aforementioned problems associated with the quality of the distributed electric energy, the problem relating to the increased aging of transformers and lines is also significant. The solution to this problem is mainly focused on grid reinforcement. Researchers studying this problem have concluded that a large economic investment will be needed for the proposed solution. Different studies have proposed strategies as an economical alternative to grid reinforcement. *[1]* One of the proposed strategies involves PHEV charging schemes as an alternative for supporting the grid and enhancing both the efficiency and the reliability of the distribution grid. Numerous research studies show that intelligent integration, namely smart PHEV charging, can lower the impact on the power grid or provide different ancillary services. *[12]* The ancillary services provided by PHEVs are associated with the mode of discharging their batteries, i.e. discharging the stored energy for peak power shaving and spinning reserves. *[13]* On the other hand, the available energy stored in PHEVs can relieve the distribution grid from overloading at certain times or allow the grid to charge more PHEVs at any time of the day, including during peak hours. Introducing storage devices like PHEVs may result in revolutionary changes to the distribution grid, *[14]* such as voltage support, providing backup power in case of interruption, reducing losses, and postponing the need for distribution grid reinforcements.

The way the distribution grid is connected and operated to provide power to a load that changes every minute requires a time analysis to see the effect on the grid, especially with changing household loading and the timing of PHEVs cycles of charging and discharging or, in other words, demand response. *[15]* The main purpose of this paper is to analyse a specific grid configuration where feeders, conductors, transformers and substations, DGs, and PHEVs perform well while simultaneously maintaining a radial configuration and the desired supply quality. *[16]*

2 PROBLEM FORMULATION

The problem of connecting the injections generated by PHEVs in the distribution grid for 24-hour analysed intervals and analysing the power quality parameters is defined in this section using MATLAB functions.

The PHEV types used in this simulation are defined in Table 1. *[8]* There are four different groups of PHEVs, with each group containing three different PHEVs according to their All-Electric Range (AER). The AER is defined as the possible distance driven by a PHEV with a fully charged battery. *[4]* Table 1 also shows the battery capacity of PHEVs with an AER of 48, 64, and 96 km, respectively. The data shows that a PHEV's battery capacity can vary from 7.78 kWh to 27.44 kWh.

In order to precisely define the PHEVs referred to in this paper, the battery's State of Charge (SOC) has to be determined as one of the required parameters. SOC is a calculation estimate that gives a rough estimate of the state of energy in the battery pack. *[4]* This paper defines the battery SOC as a random value between 0.3 and 0.9 of the battery capacity. These values reflect the minimum energy that must be stored in the PHEV's battery and the maximum energy up to which the PHEV's battery can be charged.

Table 1: *PHEVs battery capacity data*

Vehicle type	**$PHEV_{48}$[kWh]**	**$PHEV_{64}$[kWh]**	**$PHEV_{96}$[kWh]**
Compact sedan	7.78	10.34	15.51
Mid-size sedan	8.95	11.93	17.89
Mid-size SUV	11.33	15.11	22.67
Full-size SUV	13.72	18.29	27.44

$$\Delta SOC = 0.9 - 0.3 = 0.6 \tag{2.1}$$

$$A = rand[0,1] \tag{2.2}$$

$$\Delta SOC' = A \cdot \Delta SOC + 0.3 \tag{2.3}$$

If the battery SOC of the PHEV is < 0.5, the vehicle attached to the grid has be charged or, in other words, take energy from the grid. Conversely, if the battery SOC is > 0.5 and < 0.9, then the vehicle must discharge or inject energy into the grid.

$$PHEV = \begin{cases} \text{charging:} & SOC < 0.5 \\ \text{discharging:} & 0.5 < SOC < 0.9 \end{cases} \tag{2.4}$$

The following parameters defining the PHEVs are the arrival and departure times of PHEVs. The arrival and departure times determine their availability during the 24-hour analysed interval. The arrival time and departure time of the PHEVs have been randomly chosen from real-life databases. *[17]* Suppose the value of the departure time is lower than that of the arrival time. In this case, the departure time of the vehicle is considered to be within the next day, which falls outside of the analysed interval. The departure time is thus rounded up to midnight or the last hour of the analysed interval. After determining the needed parameters, we can generate the injection of the PHEVs during the 24-hour analysed interval.

$$ATime = rand[DataBase] \tag{2.5}$$

$$DTime = rand[DataBase] \tag{2.6}$$

$$DataBase = 01{:}00, 02{:}00, \ldots.24{:}00 \tag{2.7}$$

$$DTime = \begin{cases} DTime; DTime > ATime \\ 24{:}00; DTime < ATime \end{cases} \tag{2.8}$$

In terms of the grid load, the paper uses real-life data from the site *Elektrodistribucija DOOEL. [18]* The loading data applies to households with and without electric heating during 2021. Annual data for the scale of 24-hour distribution has been extracted for this simulation. Figure 1 presents a daily diagram of the households loading with electric heating and without electric heating, respectively, during 24 hours with its minimum, maximum, and mean values according to the legends shown on the diagrams.

Based on the analysis, the load curves connected to the grid nodes are randomly selected between the highest and lowest values from the load profile curve area shown in Figure 1. Considering all of the uncertain variables in this paper, a Monte Carlo simulation is used to solve the power flow analysis in each iteration. A new loading curve is generated for every grid node, and the methodology is repeated for every iteration.

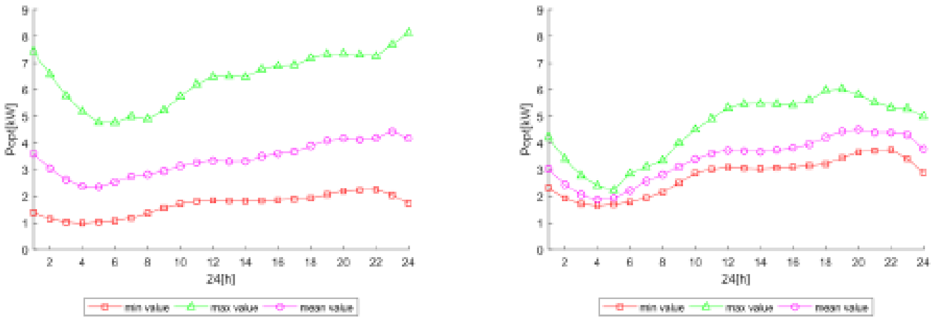

Figure 1: *Domain of the household loading curves – left with electric heating (Case One) and right without electric heating (Case Two)*

- Case 1: Household with electric heating

$$P_{value,h_i,case1} = rand[P_{min\ value,h_i,case1}, P_{max\ value,h_i,case1}] \quad (2.9)$$

$$h_i = 1,2,3\ldots.24 \quad (2.10)$$

- Case 2: Household without electric heating

$$P_{value,h_i,case2} = rand[P_{min\ value,h_i,case2}, P_{max\ value,h_i,case2}] \quad (2.11)$$

$$h_i = 1,2,3\ldots.24 \quad (2.12)$$

The characteristic values that determine the loading data are presented in Table 2. It can be noticed that the loading values attached to the grid are within the interval of 0.9914 kW to 8.1298 kW for households with electric heating. While again, for households without electric heating, the loading values attached to the grid are within the interval of 1.6492 kW to 6.0206 kW.

In this paper, in order to analyse the injection of PHEVs into the distribution grid and the characteristics that define the power quality, the CIGRE benchmark low voltage grid is used. *[20]* The grid's topology is presented in Figure 2, with household loads connected to every grid node.

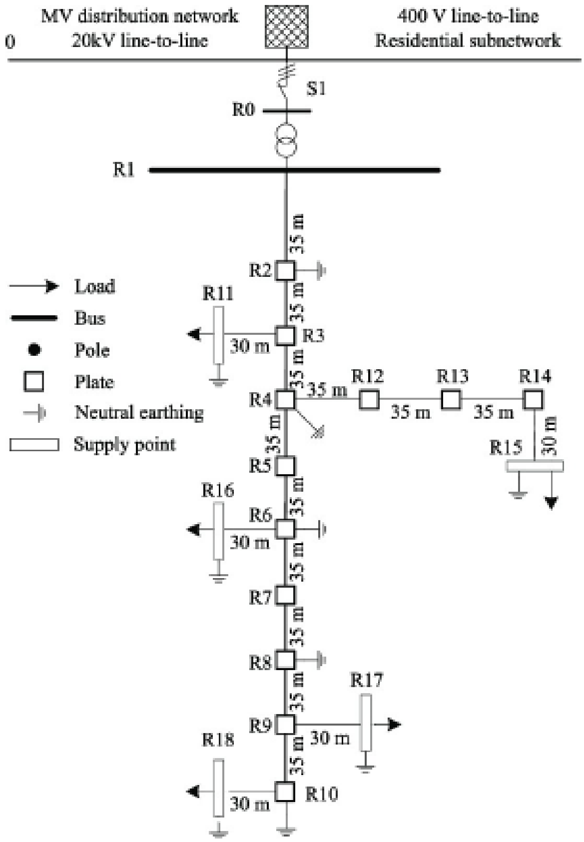

Figure 2: CIGRE *Benchmark low voltage grid*

Table 2: *Household loading data*

h_{no}	With electric heating			Without electric heating		
	min [kW]	max [kW]	mean [kW]	min [kW]	max [kW]	mean [kW]
1	1.3883	7.4191	3.6039	2.3096	4.2115	3.0264
2	1.1536	6.5703	3.0390	1.9192	3.3929	2.4341
3	1.0278	5.7731	2.6180	1.7099	2.7751	2.0563
4	0.9914	5.1797	2.3705	1.6492	2.3962	1.8760
5	1.0332	4.7751	2.3439	1.6969	2.2351	1.9304
6	1.0819	4.7651	2.5352	1.7812	2.8479	2.2125
7	1.1811	4.9939	2.7336	1.9385	3.0982	2.5695
8	1.3583	4.8876	2.8093	2.1587	3.3362	2.8082
9	1.5612	5.2129	2.9471	2.5006	3.9948	3.1012
10	1.7215	5.7407	3.1316	2.8639	4.4958	3.3943
11	1.8143	6.2004	3.2678	3.0182	4.9054	3.6079

12	1.8520	6.4862	3.3325	3.0810	5.3181	3.7169
13	1.8315	6.5069	3.3030	3.0469	5.4679	3.6963
14	1.8228	6.4792	3.3098	3.0324	5.4789	3.6669
15	1.8376	6.7738	3.4915	3.0571	5.4663	3.7338
16	1.8596	6.8856	3.5979	3.0936	5.4246	3.8048
17	1.8909	6.9139	3.6771	3.1458	5.5919	3.9519
18	1.9282	7.1817	3.8842	3.2078	5.9616	4.2007
19	2.0656	7.3305	4.0904	3.4363	6.0206	4.4399
20	2.2005	7.3505	4.1649	3.6608	5.8126	4.5026
21	2.2284	7.3101	4.1181	3.7072	5.5252	4.3869
22	2.2481	7.2631	4.1809	3.7400	5.3398	4.3885
23	2.0472	7.6929	4.4291	3.4057	5.2919	4.3145
24	1.7388	8.1298	4.1697	2.8927	5.0012	3.7669

The Power Flow analysis of the low-voltage distribution grid is made using a suitable mathematical model. *[21]* The Power Flow analysis determines the power distribution in the grid branches and voltages in the grid's nodes.

3 CASE STUDY

The case study consists of two different case studies depending on the loading attached to the grid. Case One consists of loading data with electric heating, while Case Two consists of loading data without electric heating. The simulation for each case is performed once when there are PHEVs injections attached to the distribution grid and once when there are no PHEVs injections attached to the distribution grid in order to compare the results between the two Cases for the branch's active power loss and node voltage drop. For every node of the CIGRE Benchmark low voltage distribution grid, a new injection for the 24-hour analysed interval from one randomly chosen PHEV is created, and a new curve for the loading profile is generated depending on the analysed case. Since the grid has 18 nodes, 17 new PHEV injections are generated, 17 different loading profiles are generated, and one power flow analysis is performed. Node R1 does not form part of the analysis. The result from one iteration is a 24-hour probability distribution (PD) for the branch's active power loss and the node's voltage drop interval.

The simulation for Case One with PHEV injections attached to the distribution grid and Case One without PHEV injections attached to the distribution grid is performed 10,000 times to provide detailed information regarding the PD of the branch's active power losses and the node voltage magnitudes. The same procedure is then repeated for Case Two.

As mentioned earlier, this paper considers the Monte Carlo method for solving the power flow simulation. The values subject to analysis are randomly sampled during a Monte Carlo simulation. Each set of samples is called an iteration, and the resulting outcome from each sample is recorded. Here, the results recorded are the branch active power losses and node voltages. With the Monte Carlo simulation performed hundreds or thousands of times, the result is a probability distribution of possible outcome values of the branch active power losses and node voltages. As a result, the Monte Carlo simulation provides a much more comprehensive view of what may happen.

The desired output of the power flow analysis is the domain of the active power losses in the grid, presented by its min, max, and mean values, and the domain of the voltages in the nodes, respectively. It is expected that when the active power loss value in the grid is maximum, the node voltages values are minimum due to high values of the loading.

The comprehensive presentation of the generated PHEV injections represented by their minimum, maximum, and mean values is presented in Figure 3.

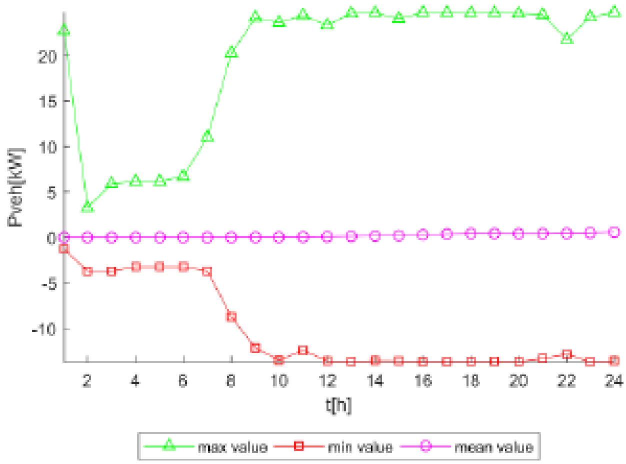

Figure 3: *Domain of the generated PHEVs injections*

From the presented data of the generated injections, we note that the domain of the PHEVs attached to the grid is between 24.6939 kW and -13.7191 kW. The results for active power losses and node voltages for Case One after the simulation are presented in Figure 4 and Figure 5, respectively.

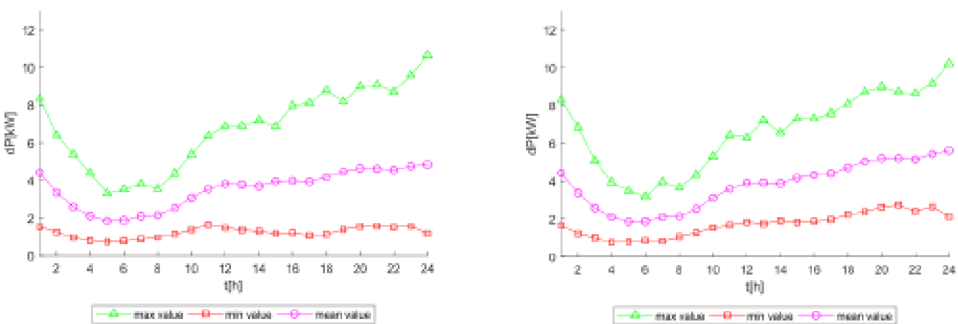

Figure 4: *Active power losses - left without PHEVs, right with PHEVs – Case One (with electric heating)*

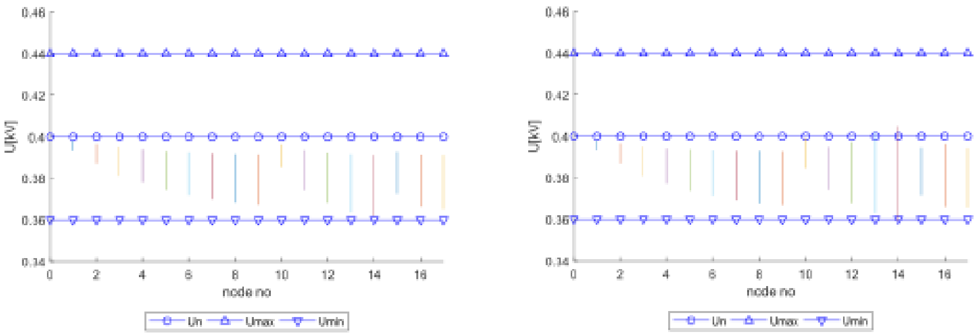

Figure 5: *Histogram of node voltages - left without PHEVs, right with PHEVs – Case One (with electric heating)*

Next is the simulation for Case Two. The results for active power losses and node voltages for Case Two are presented in Figure 6 and Figure 7, respectively.

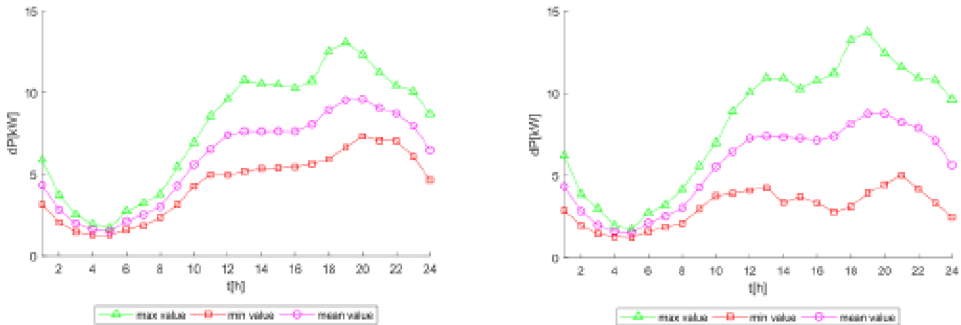

Figure 6: *Active power losses - left without PHEVs, right with PHEVs – Case Two (without electric heating)*

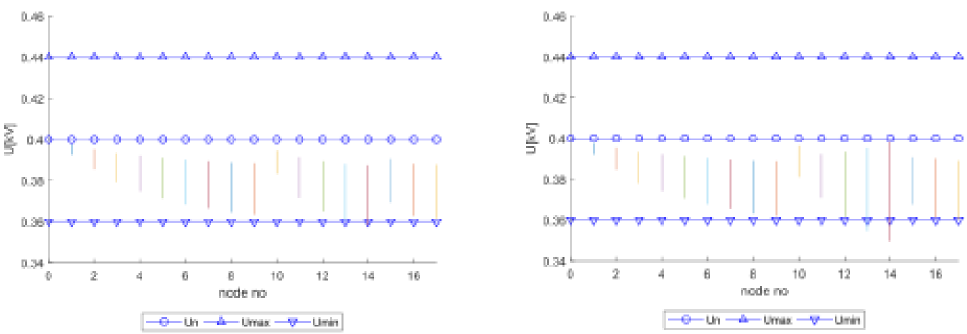

Figure 7: *Histogram of node voltages - left without PHEVs, right with PHEVs – Case Two (without electric heating)*

From the presented results for Case One, the domain of the grid active power losses with and without PHEVs is mainly overlapped. The domain of the active power losses consists of larger values when no PHEVs are connected to the grid, which is unlike when PHEVs are connected to the grid, as confirmed by the presented results. When we analyse the scenario without PHEVs, the curves of the active power losses generally follow the curve of the loading profile, something which is not the case when we analyse the scenario with connected PHEVs. In such cases, the active power losses curve follows the same trend but with certain peak shaving, depending on the PHEVs injections. As for the results of the node voltages for Case One and the given constraints, almost all are beneath the nominal grid voltage (0.4 kV). However, besides this, all of the values are in the DSOs given constraints of ΔU = ± 10%, with and without connected PHEVs, respectively. From the presented results, we note a deviation of voltage magnitudes, which is more significant when PHEVs are connected to the grid and somewhat smaller when PHEVs are absent. When PHEVs are connected, the distribution grid performs well while maintaining both a radial configuration and the desired supply quality as defined by the DSO distribution regulation. Unlike Case One, Case Two is characterised by a different domain of the household loading curves, which means that the domain of the grid active power losses with and without PHEVs will differ. The domain of the active power losses in Case Two consists of slightly larger values than in Case One. According to the presented results, it is characterised by the same diversity both when PHEVs are connected to the grid and when PHEVs are absent. As for the results of the node voltages for Case Two, a difference in voltage magnitudes is noted from the presented results. When PHEVs are absent, the voltage magnitudes are lower the nominal grid voltage (0.4 kV), but nevertheless fulfil the DSO's given constraints of ΔU = ± 10%. This is not the case when PHEVs are connected to the grid. In this case, one node, Node No 14, did not fulfil the DSOs given constraints ΔU = ± 10%. All the other voltage magnitudes are beneath the nominal grid voltage (0.4 kV). In this case, the households connected to that node will face a slight malfunction resulting in lowered power quality determined by several factors, such as voltage and frequency variations, imbalance, interruption, and flicker.

4 CONCLUSION

The increasing presence of PHEVs in daily life is inevitable. Their presence in the years that follow will increase exponentially. According to the presented results, PHEVs will impact the current distribution grid. These impacts can be significant or insignificant, depending on the number of PHEVs attached to the grid, grid characteristics, and PHEV charging features. This is despite the negative impact of PHEVs' charging/discharging cycles on battery life.

Technical and economic factors must also be considered when reducing the impact of PHEVs on the distribution grid. The proposed methods align with integrating new charging schemes and coordinating their charging and discharging cycles. *[22]* With the smart charging of PHEVs, the peak from charging PHEVs will be shifted to periods with a lower peak from the household loading. The characteristic of PHEV for bi/multi-directional power flow can be used as a strategy for regulating the grid voltage. The active power control can also adjust the operation of PHEV charging, while the reactive power control can inject reactive power into the grid to support the network voltage. The proposed methods should be the subject of further research.

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Nomenclature

ΔSOC	domain of the PHEVs state of charge
A	A random value between 0 and 1
$\Delta SOC'$	State of Charge assigned to the PHEV
$ATime_{veh}$	random value for the arrival time of the PHEV from the Data Base
$DTime_{veh}$	random value for the departure time of the PHEV from the Data Base
Data Base	Data Base with values for arrival and departure time for the PHEVs
$P_{value,\, hi,case1}$	value for the load in each hour randomly chosen between the min and the max values of the load profile curve area for Case One
$P_{value,\, hi,case2}$	value for the load in each hour randomly chosen between the min and the max values of the load profile curve area for Case Two
h_i	each hour of the analysed interval