Development of a Vehicle-to-Grid (V2G) Energy Management System to Mitigate Local Operational Challenges in Low Voltage Distribution Networks with Photovoltaics

2022 4th Global Power, Energy and Communication Conference (GPECOM) | 978-1-6654-6925-8/22/$31.00 ©2022 IEEE | DOI: 10.1109/GPECOM55404.2022.9815823

Furkan Gunes
Department of Electrical and Electronics Engineering
Marmara University
Istanbul, Turkey
furkangunes14@hotmail.com

Mustafa Alparslan Zehir
Department of Electrical and Electronics Engineering
Marmara University
Istanbul, Turkey
alparslan.zehir@marmara.edu.tr

***Abstract*— Electric vehicles have been rapidly growing, especially in the last 10 years, with sales rates that have nearly doubled every two years. In combination with the evolving technology, parameters such as the driving range, charging power, and battery capacity of vehicles are increasing. It is of great importance that the integration of electric vehicles into existing networks, the possible difficulties they may cause, and the services that can be provided from the vehicle to the grid (Vehicle-to-Grid V2G) can be accurately predicted through detailed analysis. This study aims to prevent local network operational problems related to voltage, which may be encountered in low voltage distribution networks, including solar panels and electric vehicles, with improved power and energy management approaches based on V2G. In a 10-house LV distribution network based on real data, the daily charging behavior of electric vehicles as well as household consumption and solar generation profiles, the effectiveness of a V2G approach that considers the busses that are most effective in solving local voltage problems is investigated. The study provided useful findings for solving local problems, with realistic scenarios and comprehensive analyzes, with the developed vehicle-to-grid power and energy management approaches in low voltage distribution networks including distributed generation from solar energy and electric vehicles.**

Keywords—low voltage distribution network, electric vehicle, solar panel, V2G

I. Introduction

In the last decade, technology for vehicles has improved significantly. Due to the rapid progress in technology, electric vehicle production, use and electric vehicle technology have become widespread all over the world. Normally, China is the biggest sales market; however, by the beginning of the 2020 Europe has taken over this role. In recent years, electric vehicle studies have focused on the integration of electric vehicle charging systems into existing infrastructures, and how electric vehicles can be used more widely. In addition to the seamless integration of electric vehicle charging stations into existing infrastructures, the additional services, and benefits that electric vehicles can offer to the network with the vehicle-to-grid (V2G) approach gain importance. Therefore, this study is mainly focused on solving the problems that occur in low voltage distribution network systems that contain residential customers with photovoltaics via using V2G energy management system

"Vehicle-to-grid services (V2G) are the vehicles' ability to communicate with the electricity grid, its operators or similar external stakeholders, and adjust their charge and even discharge times and power profiles according to the needs of the grid, thus helping the grid to operate" [1]. As stated in [2], smart grid problems are an extremely expanding point of interest with investments from developing countries.

Kumar et all worked on Vehicle to Grid (V2G) and Grid to Vehicle (G2V) charging or discharging modes [3]. According to the study, Electrical Vehicles (EVs) can help the grid through different functions such as V/f regulation and also support load balancing with Demand Side Management (DSM). The authors concluded that voltage and frequency regulation are very important for V2G application due to higher demand in the market and to cope with arising operational problems on the infrastructure. In V2G systems, electrical vehicles' batteries can provide fast regulation to the system. In Kumar et all worked, "V2G mode of EVs with controlled charging/discharging of EVs leads to voltage levels that are in a controlled manner at EV penetration level of 90% with Chinese standards" [3]. It means that V2G systems is definitely effective at mitigating voltage problems that occur in local grids.

V2G systems can benefit both users and network operators or other stakeholders. If it is needed to make a technical definition of the V2G and EV relationship, it expresses a mutually win-win situation for both parties by following a different network policy from the traditional production/consumption methods of the user [4]. From the user's perspective, from an economic point of view, users can buy the electricity required for electric vehicles in periods with a lower price. Also, depending on the V2G process, they can sell it back to their network while electricity with higher prices in the time intervals when electricity tariffs are observed higher [5]. From the producer's point of view, it will make a great contribution in not having to experience power cuts during periods of high usage/demand or having to solve the difficulties in network operation with high-cost methods.

Another study has been done about comprehensive analysis of Vehicle to Grid systems [6], states that unorganized charging situations can induce difficulties for power grid by peak demand and overloading. The authors concluded that V2G systems have two ways that are unidirectional and bidirectional, and in unidirectional systems, there is an energy flow from grid to EV's. Therefore, the operator that works on the grid can track and control the energy flow mechanism also rate and the time interval of charging in order to avoid overloading/underloading situations and variations. Besides local problems, another important aspect is getting adequate energy from resources. The effective use of V2G systems in systems with renewable energy sources can offer additional benefits

In most cases there is connection to a higher level upstream main grid for generating energy. However, in most cases for V2G systems due to the intensity of demand in the grids, it is not possible to use energy efficiently and optimally. High electricity demand is the main issue in most of the field applications. Therefore, a supportive energy source is needed. In the study integration of renewable energy resources (RESs) to the system [7] is considered as part of the scenario. Similar to [7], 10 solar panels for each home are considered. As stated in another study conducted in this context, solar and wind energy is the fastest growing renewable energy type in today's conditions. The electricity production gained from two different technologies varies according to the sun and wind conditions throughout a day[8].

Integrating heat and power networks into the system will have a positive effect on increasing system utilization. In addition, it will be beneficial in reducing total costs and creating flexibility in electricity generation/distribution/consumption [9]. In [10], V2G provides "peak load shaving" in grid profile. Therefore, thanks to the V2G management system at the time when peak load occurs, providing supply from EVs is found as an economical method. When this method is used, it can prevent the overload in the system. Also, EV owners have an advantage that they will gain profits by selling the energy stored in their EVs back to the grid.

In another perspective, Smart grid systems are built on increasing the efficiency of electrical energy use, from production, which is the first step of the process, to the end user (consumption), which is the last step of the process, by effectively incorporating all generation, storage and distribution options covering the model [11]. Along with the smart systems installed in the houses, with the support of renewable energy sources as mentioned above, the users are not only in the position of consuming, but also producing, observing, managing and taking action on their own energy exchange.

Looking at the big picture in order to understand why V2G applications are needed in today's world, it is observed that people spend approximately 90% of their time indoors [12] [13]. Therefore, this situation shows that houses are of great importance in energy production-distribution-consumption.

In this study, the characteristics that distinguish this study from other studies found in the literature are that the study is aimed at solving problems in the local system, rather than the problems across the main network. V2G approach that consider in this study is the most effective approach for solving local voltage problem. With the established vehicle-to-grid power and energy management systems in low voltage distribution networks, including distributed generation from solar energy and electric vehicles, the study contributes valuable insights for tackling local problems with realistic scenarios and extensive analyses. Moreover, the data resolution is 1-minute, solar panels are integrated into the local grid and their coordination with the V2G system, all of which can be considered as the original aspects of the study. Section 2 describes the methodology; Section 3 presents the case study and results. Section 4 discusses the findings and concludes the paper.

II. Methodology

Low voltage network with residential prosumers that own PV and EV is the considered area of use of the solution that is developed (Figure 1).

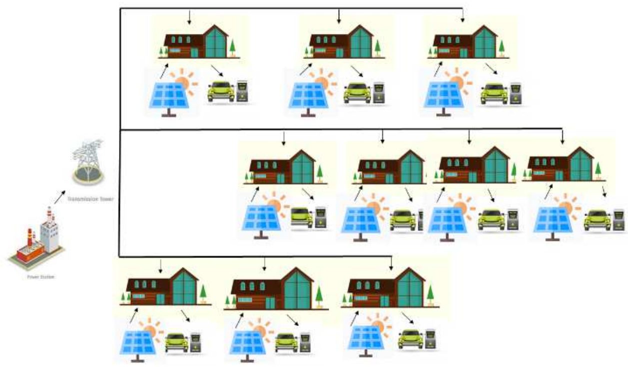

Figure 1: An example distribution network with 10 houses

At the first stage of the study, the Low Voltage Distribution Network Finland Model (Figure 2 and Table 1) is modelled via PSCAD program. The cables in the base model are modeled using series resistance and inductance. Electric vehicles, solar panels and houses have been added as constant power components which can be controlled by reference parameters read from the external files that contain daily power profiles.

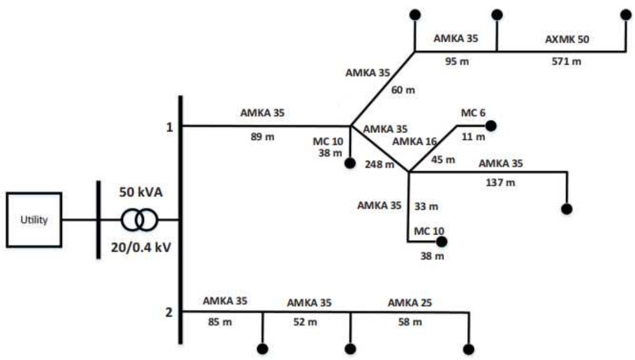

Figure 2. Low voltage distribution network model [14].

TABLE I. R/X Ratios for the Used Cable Types [19]

Cable Type	R/X Ratio (Per km)
AMKA 3x35+50	8.35
AMKA 3x255+30	11.32
AMKA 3x16+25	17.69
AMKA 4x50S	7.28
AMKA 3x10+10	20.8
AMKA 3x6+6	34.22

At the next stage of the study, the Daily Household Demand and Solar Panel Power Profile Production Tool of Loughborough University (CREST Demand Model) is used to stochastically generate household consumption and solar panel power generation profiles [15]. It has been used as a reliable tool in more than 1000 scientific studies, and 1-day home and solar panel power profiles are produced at 1-minute resolution using this free open-source software tool written using macro in Excel.

Various profiles are generated for each house individually, taking into account factors such as the number of people living in it, solar irradiance including cloudiness impacts, the type and number of electrical appliances used in the house, different periods of the week (weekdays-weekends). As a result of these created profiles, the daily household electricity consumption profile is revealed. A sample log profile produced for houses that is without real data and has been produced stockpiled is given in Figure 3.

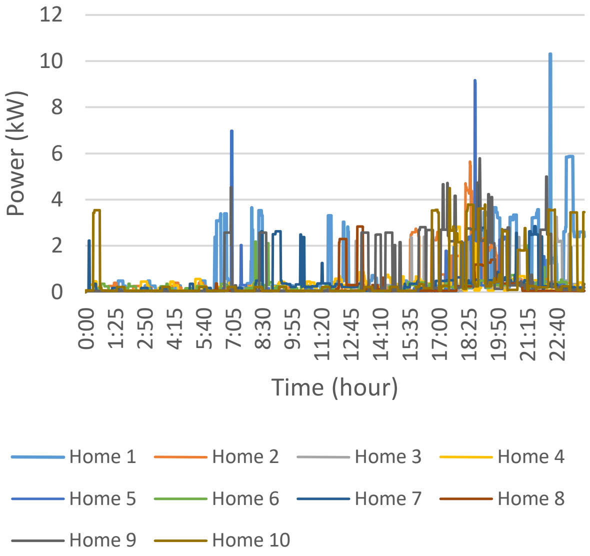

Figure 3. Daily residential demand profiles for 10 houses

In order to reveal the amount of electricity that solar panels will produce, multiple profiles have been created and production data is generated according to the amount of solar irradiation. A 1-day sample profile that has been produced stockpiled without real data is given in Figure 4. A net power profile will be obtained by applying the production and consumption data together. Solar panels have 2 kW installed power for per house An example 1-day profile that produces stockpiled is given in Figure 5.

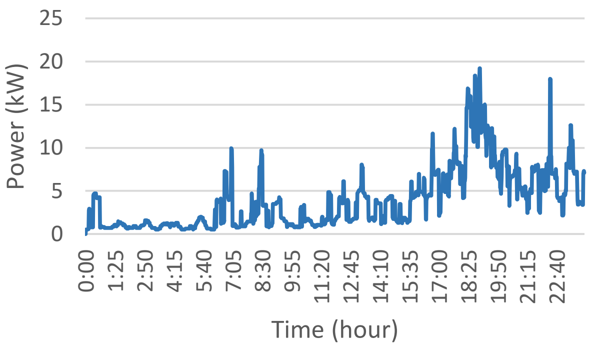

Figure 4. Total consumption power profile

In another phase of the project, the most commonly used electric vehicles in Turkey [16] are considered and their data is created using the methods mentioned below.

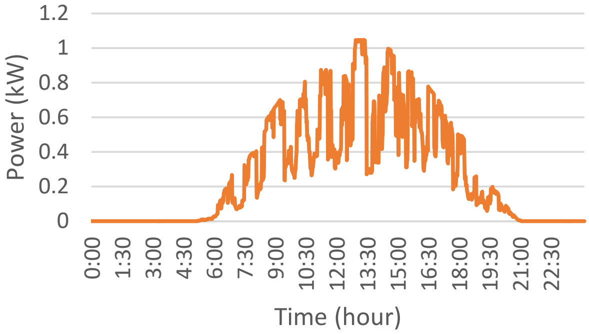

Figure 5. Solar panel power profile

Statistics on vehicle usage profiles of electric vehicle users, how often and in which hour intervals they use, charging times and hours of charging are obtained from sources with past pilot application data [17]. The technical specifications (energy consumption, range, storage capacity) of the vehicles are gathered from the relevant vehicle characteristics database [18]. The specific charging characteristics of each vehicle are determined and analyzed. The charging times, powers, frequencies and types of charging structures are determined per car model.

In Figure 6, an aggregate electrical vehicle power profile that produced stockpiled is shown for 10 cars. Electrical vehicles charge power are variable starting at 3.7 to 7.4 kW. It was observed that electric vehicles were charged in the evening, as the users were usually at home in the evening.

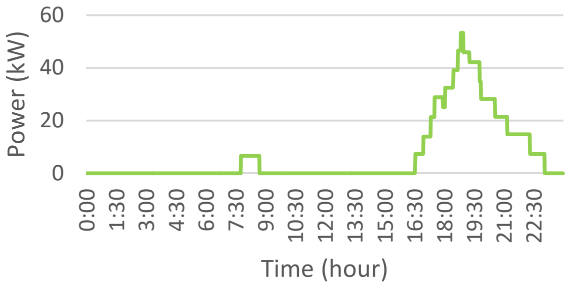

Figure 6: Electrical vehicle profile

The generated data is integrated into the distribution network model that is modeled in the PSCAD program through externally controlled constant power sources, the daily power and voltage graphs for each house are obtained through simulations. In order to apply V2G management system, the main need is knowing the priorities, in other word which EV's charging session to intervene in case of a local voltage problem. A priority chart is needed to be derived showing the interaction between the busses in the distribution network, that will ultimately reveal which house has more impact on which other home in the neighborhood. Therefore, for deriving priorities, a step change of 2 kW of power was realized in each house at different time intervals, making it easy to observe voltage changes. The difference in considered bus voltage per step change in active power of the other buses $\frac{dV}{dP}$, between the recorded voltage after the step change V_{new} and the voltage before the step change V_{old} is calculated. As a result of the output data, the most effective neighboring busses for each bus is listed and sorted.

$$\frac{dV}{dP} = V_{new} - V_{old}$$

For example, after necessary calculation the priority table for House 3 is given below (Table 2). As can be seen from the table, a V2G control action at House 2, is around 3 times more effective compared to House 4, 5, 6 and 7, while power change in House 8, 9 and 10 located in another feeder have no impact on the voltage of House 3.

TABLE II. PRIORITY LIST FOR HOUSE 3

House Name	Compared Voltage Difference per step change of active power
House 3	2.561
House 2	0.920
House 1	0.561
House 6	0.336
House 5	0.336
House 7	0.336
House 4	0.335
House 8	0.000
House 9	0.000
House 10	0.000

V2G will provide solutions to the voltage problems that occur in the network. The methods to be used at this stage are as follows:

1. To provide V2G service for suitable vehicles with dV/dP (usually on the V/kW scale) ratio of unit voltage change per unit power change that can most effectively improve the voltage of the busbar or busbars where the voltage problem occurs,
2. Providing V2G service to vehicles that will most effectively reduce the load of the line part where the problem of line overload occurs,

III. CASE STUDY

In this study, four different scenarios were investigated. In the first scenario only the residential demand of 10 houses are considered in the model. The second scenario included solar panels with 1 kWp of installed power for each house. In the third, main, scenario electrical vehicles are added for every house in addition to PV and the fourth and last scenario V2G management system is applied to the third scenario to mitigate voltage problems. Rather than solely considering the highest and lowest voltage values, the duration of bus voltages inside certain ranges is analyzed in each scenario.

In first scenario only the residential demand of 10 houses is considered. The results are shown in Figure 7. It is seen that the voltage is dominantly between 220 and 230 V. For a very short time period of the day voltages from 207 to 200 V are observed, still in $\pm 10\%$ operation range.

Related voltage ranges and their percentage duration for second scenario is shown in Figure 8. When first and second scenario are compared, a clear shift to 230 and 240 V range can be observed. The reason behind it is that in second scenario there is solar panel for each house. Therefore, these panels effect and increase the voltage value of the houses. The short period overvoltage event happens rarely for tolerable durations in daily operation.

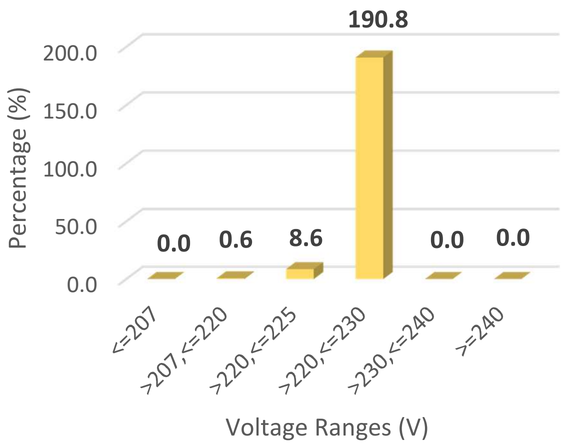

Figure 7. Voltage ranges and percentages for the first scenario

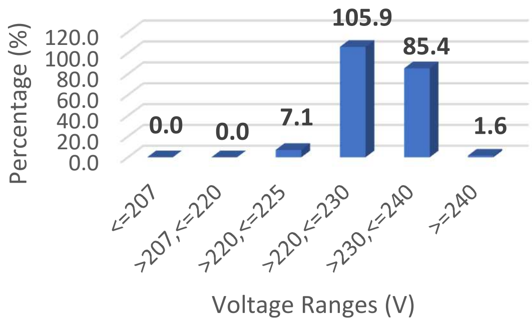

Figure 8. Voltage ranges and percentages for the second scenario

In Figure 9, some under-/overvoltage problems are being seen. Third scenario contains houses, solar panels and electrical vehicles. Therefore, electrical vehicles have big impact on house voltages. Most of the time they decrease the voltages at the buses and this situation causes low voltage problems on the lines. Voltages below 207 V can cause undervoltage relays to trip and household appliances to malfunction or fail. V2G management system is applied in the next scenario to mitigate the long-lasting undervoltage problems.

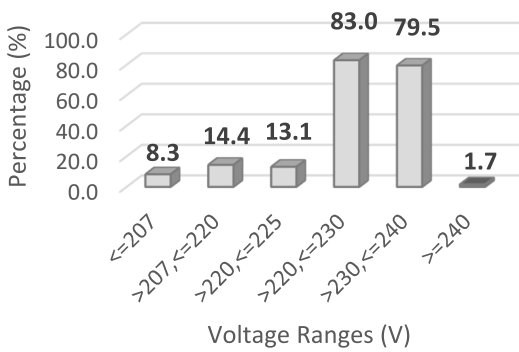

Figure 9. Voltage ranges and percentages for the third scenario

In Figure 10, when the V2G management approach is applied through the day, the low voltage issue in the previous scenario is found to be eliminated. If one of the examples is considered for House 3 that in order to understand how the problem is solved, firstly the problem time interval has been detected. The problem starts at 18.24 and end at 20.22. In order to solve the problem, priority table is used and according to it, the ongoing charging sessions for the electrical vehicles of House 3 and House 2 are stopped at that time intervals. Managing these electrical vehicles solved the low voltage problems in that interval.

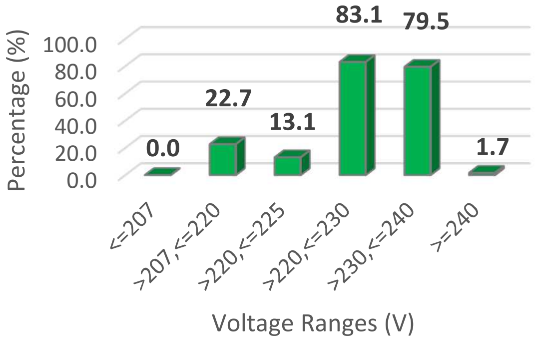

Figure 10. Voltage ranges and percentages for the fourth scenario

Net power profile for houses is showed in Figure 11. For getting net power profile value, it is included electric consumption of house, solar panel power and electrical vehicle charge situation. It said that before, in the evening there are some electrical vehicles charged at the station; therefore, the net power profile is in the negative value ranges.

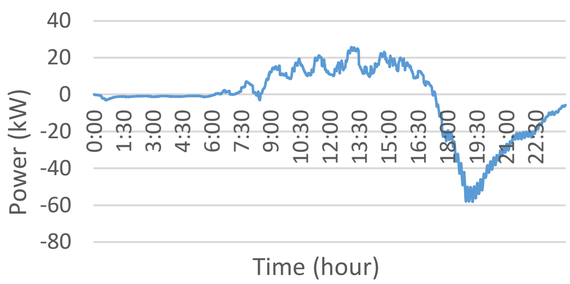

Figure 11. The net power profile of 10 houses with PV and EV

The individual daily voltage profiles of each house in scenario-1 are shown in Figure 12.

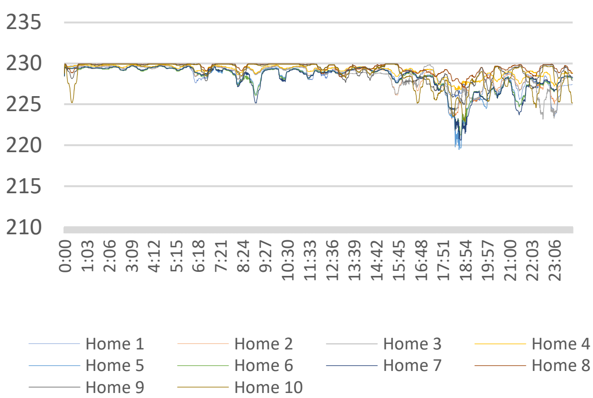

Figure 12. Daily voltage profiles of 10 houses for scenario-1

Daily voltage profiles of each house in scenario-2, when 2 kWp PV is integrated is shown in Figure 13. Voltage values are increased in overall.

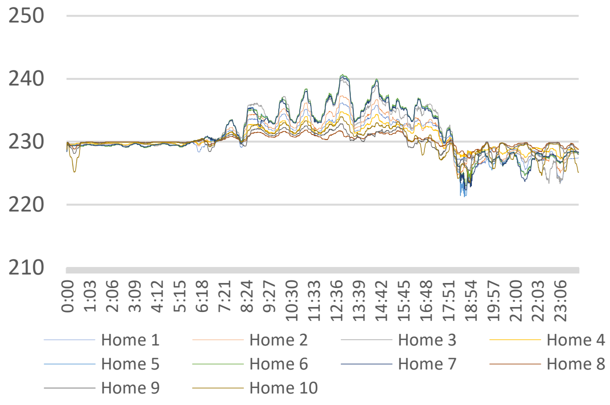

Figure 13. Daily voltage profiles of 10 houses for scenario-2

In Figure 14, voltages of the houses formed during a day are observed. As can be seen in the graph, low voltage voltages of some houses are seen. These houses are also shown in the Figure 15. In order to implement V2G energy management system actions, the ongoing EV charging sessions at the buses that will be most effective at mitigating the voltage problem are stopped or commenced.

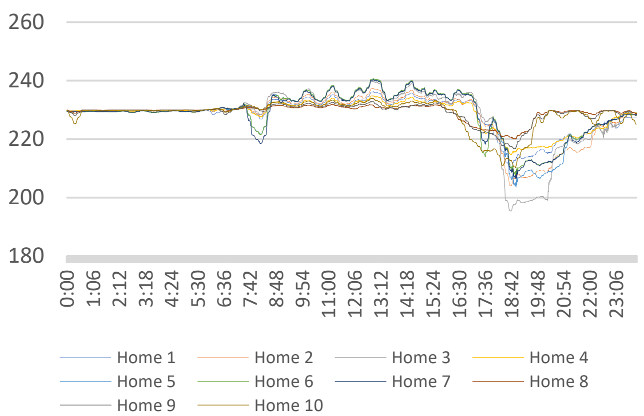

Figure 14. Daily voltage profiles of 10 houses for scenario-3

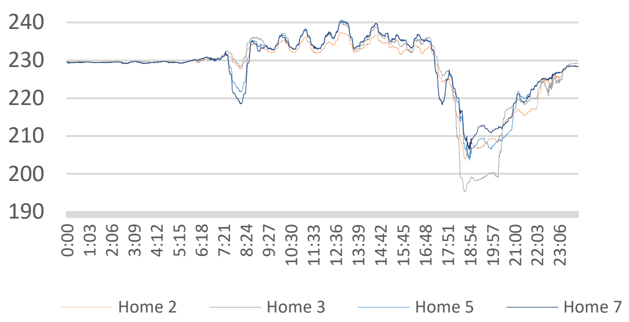

Figure 15. Daily voltage profiles of the 4 houses with the lowest voltage in scenario-3

In Figure 16, the graph is the result of fourth scenario that contains V2G management system. Thanks to V2G, the houses minimum voltage is above 207V, therefore the proposed method was found effective, by interrupting maximum 2 ongoing charging sessions per event.

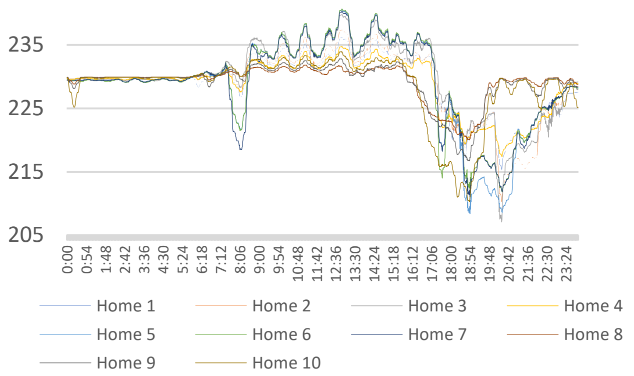

Figure 16. Daily voltage profiles of 10 houses for scenario-4

In Table 3, the overall minimum and maximum voltage values for each scenario are presented. Minimum value firstly increase in the second scenario because of the fact that there are solar panels. However, in the third scenario with electrical vehicles are added; the overall minumum voltage is decreased below operational limits. V2G management approach is implemented in the fourth scenario and the minumum voltage value is increased.

TABLE III. MINIMUM AND MAXIMUM VOLTAGES IN EACH SCENARIO

Scenario Number	Minimum Value (V)	Maximum Value (V)
Scenario 1	219.49	229.96
Scenario 2	231.85	240.69
Scenario 3	195.36	240.69
Scenario 4 (Solution)	207.07	240.69

IV. CONCLUSION

In this study a single-phase low voltage distribution network system that contains 10 houses with photovoltaics and electric vehicles is considered to mitigate undervoltage events through a bus voltage sensitivities based V2G priority approach. During daily operation, in the PV and EV integrated scenario long-lasting undervoltage problems were observed, and these problems were mitigated using V2G energy management system. V2G service manages the charging of the vehicles that are being charged in busses that are the most effective at improving the voltage profile of the bus where the voltage problem occurs. In future works, V2G method including fair management among the EV owners can be applied by producing data covering different time ranges, such as 1 weeks or 1 months, instead of 1 day, to perform analysis on different days and different profiles. The scope of the work can be expanded with models and analytics created using urban networks instead of the rural network used in this study.

ACKNOWLEDGEMENT

This research is funded under the framework of the "2209-A Research Project Support Programme for Undergraduate Students" organized by "The Scientific and Technological Research Council of Turkey (TUBITAK)".

REFERENCES

[1] Cleveland, Cutler J.; Morris, Christopher. 2006. "Dictionary of Energy. Amsterdam: Elsevier", s. 473. ISBN 0-08-044578-0

[2] O. Erdinc, T. D. P. Mendes, and J. P. S. Catalao, "Impact of electric vehicle V2G operation and demand response strategies for smart households," in 2014 IEEE PES T&D Conference and Exposition, 2014, pp. 1–5.

[3] M. Kumar, S. Vyas, and A. Datta, "A review on integration of electric vehicles into a smart power grid and vehicle-to-grid impacts," in 2019 8th International Conference on Power Systems (ICPS), 2019, pp. 1–5.

[4] M. Garcés Quílez, M. Abdel-Monem, M. El Baghdadi, Y. Yang, J. Van Mierlo, and O. Hegazy, "Modelling, analysis and performance evaluation of power conversion unit in G2V/V2G application—A review," Energies, vol. 11, no. 5, p. 1082, 2018.

[5] A. G. Anastasiadis, A. Polyzakis, and G. A. Vokas, "Economic impact of V2G technology in a smart microgrid," 2018.

[6] B. Bibak and H. Tekiner-Moğulkoç, "A comprehensive analysis of Vehicle to Grid (V2G) systems and scholarly literature on the application of such systems," Renew. Energy Focus, vol. 36, pp. 1–20, 2021.

[7] L. Liu, F. Kong, X. Liu, Y. Peng, and Q. Wang, "A review on electric vehicles interacting with renewable energy in smart grid," Renew. Sustain. Energy Rev., vol. 51, pp. 648–661, 2015.

[8] C. B. Robledo, V. Oldenbroek, F. Abbruzzese, and A. J. M. van Wijk, "Integrating a hydrogen fuel cell electric vehicle with vehicle-to-grid technology, photovoltaic power and a residential building," Appl. Energy, vol. 215, pp. 615–629, 2018.

[9] International Energy Agency, Energy technology perspectives 2016: Towards sustainable urban energy systems. Paris Cedex, France: Organization for Economic Co-operation and Development (OECD), 2016.

[10] S. M. Shariff, D. Iqbal, M. Saad Alam, and F. Ahmad, "A state of the art review of electric vehicle to grid (V2G) technology," IOP Conf. Ser. Mater. Sci. Eng., vol. 561, no. 1, p. 012103, 2019.

[11] C. W. Gellings, The smart grid: Enabling energy efficiency and demand response, 1st Edition. Gistrup, Denmark: River Publishers, 2020.

[12] R. Laumbach, Q. Meng, and H. Kipen, "What can individuals do to reduce personal health risks from air pollution?," J. Thorac. Dis., vol. 7, no. 1, pp. 96–107, 2015.

[13] A. Steinemann, P. Wargocki, and B. Rismanchi, "Ten questions concerning green buildings and indoor air quality," Build. Environ., vol. 112, pp. 351–358, 2017.

[14] M. A. Zehir et al., "Impacts of microgrids with renewables on secondary distribution networks," Appl. Energy, vol. 201, pp. 308–319, 2017.

[15] I. Richardson, M. Thomson, D. Infield, and C. Clifford, "Domestic electricity use: A high-resolution energy demand model," Energy Build., vol. 42, no. 10, pp. 1878–1887, 2010.

[16] Ö. Gönül, A. C. Duman, and Ö. Güler, "Electric vehicles and charging infrastructure in Turkey: An overview," Renew. Sustain. Energy Rev., vol. 143, no. 110913, p. 110913, 2021.

[17] J. Quiros-Tortos, L. Ochoa, and T. Butler, "How electric vehicles and the grid work together: Lessons learned from one of the largest electric vehicle trials in the world," IEEE Comput. Applic. Power, vol. 16, no. 6, pp. 64–76, 2018.

[18] Electric Vehicle Database. "All electric vehicles". http://ev-database.org Last Access Date: 19 December 2021

[19] H. Laaksonen, P. Saari, and R. Komulainen, "Voltage and frequency control of inverter based weak LV network microgrid," in 2005 International Conference on Future Power Systems, 2005, pp. 6 pp. – 6.