An Improved Energy Management Strategy for a DC Microgrid including Electric Vehicle Fast Charging Stations

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***Abstract*—The number of electric vehicles (EVs) on the road is expected to continue to increase during the next decades due to various factors such as the rapid progress in EV technology and decreasing battery prices. The prolonged battery charging process, which is one of the main problems that affects the increased EV penetration, makes the fast charging units more attractive and efficient option for the charging stations. In this study, a control strategy for a DC microgrid including electric vehicle fast charging station (EVFCS) and distributed generation units is presented to examine the impacts of EVFCS on the grid as well as their potential contributions to the system operation in the case of considering the vehicle-to-grid (V2G) technology. It is especially aimed to mitigate the voltage sag and swell problems by using the EV battery as a DC source of a distribution static compensator (D-STATCOM) device. Simulation studies in MATLAB Simulink/SimPower systems show that considerable improvements can be achieved from the perspective of distribution system operation such as improved voltage quality and from the perspective of end users such as decreased charging durations.**

Keywords—Electric vehicles, fast charging stations, microgrid, distributed generation, V2G.

I. INTRODUCTION

Recent technological advances and anticipated economic and environmental benefits have significantly increased the number of electric vehicles (EVs) on the road at the last decade. According to Energy Outlook and International Energy Agency (IEA), the EV number is expected to reach 250 million by 2030 [1]. One of the main barriers that hinders the full potential of increased EV penetration is the limited charging rate of EV charging units, which generally causes long charging periods. For instance, traditional EV charging units, namely, level 1 and level 2 chargers can fully charge a depleted battery between four and sixteen hours, which is only feasible for overnight or charging at work [2]. Therefore, the level-3 DC EV fast charging units, which have the capability of charging an EV in less than 30 minutes come into prominence recently; however, the high charging power value of these units brings additional burden on the power grids [3]. Besides, these units might still contribute to the carbon emission indirectly as a large portion of the energy requirement of EV charging stations (EVCS) is supplied by power grids. Also, the nonlinear characteristics of EVCSs affect the power quality by causing voltage fluctuations and power losses [4]. These problems are especially of great importance for the residential level-3 DC EV fast charging units as they are connected to the distribution networks directly.

In order to alleviate the negative effects of the abovementioned problems, the electric vehicle fast charging stations (EVFCSs) have been recently used in microgrid environments coupled with distributed generation. García-Triviño et al. [5] proposed a decentralized control method for a grid-connected microgrid consisting of two EVFCSs, photovoltaic (PV) panels and an energy storage system (ESS) to maintain the medium voltage DC bus voltage and the state-of-charge (SOC) of ESS within predefined thresholds. A similar DC microgrid structure including EVCSs with slow and fast charging modes, a PV system and an electrochemical storage system was considered in [6] and an EVCS power management strategy based on power limitation and driver choices was proposed. The potential of integrating EVFCSs and a PV system in a microgrid architecture was investigated in [7] in terms of economic benefits. Another PV- and ESS-integrated DC microgrid was considered by Wang et al. [8] and a decentralized primary control method based on the adaptive droop control of the ESS was developed for less frequent grid connection and higher PV penetrations. Wang et al. presented a model-based continuous differentiable charging approach for EVCSs in microgrids with the aim of reducing the charging time without scarifying battery health [9]. Another DC microgrid structure including PV rooftops, ESSs and EVFCSs was considered in [10] with the targeted innovations for both system manager and end-user.

As can be seen from the studies mentioned above, in the case of using EVFCSs in a microgrid environment, which has the capability of effectively managing energy exchanges with the power grid and among its components, the energy

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requirements of the EVFCSs can be provided with less power losses and higher economic benefits while also limiting the peak-to-average load ratio. In addition to these studies mainly aiming to decrease the impacts of EVFCSs on the grid, the use of the available energy in the batteries of EVs connected to EVFCSs, which is called vehicle-to-grid (V2G) technology, has been also investigated in several recent studies for the purpose of supporting the distribution system operation. Ahmad et al. [11] presented an energy management method based on switching mechanism among trading markets for public EVCSs integrated with a microgrid and dealt with the balancing of total load demand and generated power by also considering V2G. An EVCS equipped with a PV array, an ESS and a diesel generator was used in [12] with the objective of providing the required charging energy in both islanded and grid-connected modes. Rodrigues et al. [13] proposed a holistic V2G coordinated approach for EVs in unbalanced smart microgrid environments in order to support the network by using the available stored energy in EVs. Salvatti et al. [14] presented an energy management approach for microgrids containing an EV parking lot, PV arrays and dynamic loads, in which PV production and load demand predictions are used to optimize the EVs' charging and discharging profiles. Another control and scheduling approach for charging and discharging of EVs was developed in [15] to enable the integration of a high number of EVs in a microgrid. For the purpose of protecting the EV batteries and saving their lifetime during the grid connections, a V2G scheduling approach based on frequency control was proposed in [16].

As seen from the literature reviewed above, several studies have considered the use of V2G technology for supporting the grid; however, none of these studies investigated the possibility of using EV battery in V2G mode as a DC voltage source in a distribution static compensator (D-STATCOM) system to further improve power quality. Motivated by this fact and by the results presented in the literature showing that EVs can considerably contribute to the flexibility of distribution systems in microgrid environments, and that EVFCSs have been gaining growing interest in the recent years, a low-voltage DC microgrid including level-3 EVFCS, solar PV arrays and a diesel generator as distributed generation units is considered in this study. A control strategy based on adaptively controlling the converters of distributed generation units and EVFCSs is proposed by also considering V2G technology for EVFCSs with the objectives of providing flexibility in the distribution system operation, decreasing the EV charging times and mitigating the impacts of voltage sag and swell in the distributed grid.

The contributions of the study are twofold:

1) A control strategy for a low-voltage DC microgrid including distributed generation units and level-3 EVFCS with V2G technology is considered.

2) The idea of using a battery storage system as a DC source of a D-STATCOM device, which was proven as an effective approach in the literature [17], [18], is extended for the batteries of EVs for the first time in the literature.

The rest of this paper is organized as follows: Section II describes the system structure considered in the study and Section III elucidates the proposed control strategy. Section IV describes the EV battery-integrated D-STATCOM. The case studies and simulation results are presented in Section V. Finally, the last section highlights the concluding remarks.

II. SYSTEM DESCRIPTION

A DC microgrid is considered in the study due to its advantages for EVFCSs compared to AC microgrid on especially improving the peak performance of the public grid without increasing the grid capacity. Besides, PV arrays are deployed as distributed generation units in the proposed structure since the installation of wind turbines necessitates the availability of adequate locations and large premises, which is a major challenge in urban areas. Also, the prospects of using PV power for charging applications are very diverse as the power production from PV arrays offers greater flexibility for the integration with the EVFCSs while the unstable nature of wind speed makes it less granulated for charging applications as compared to PV systems. In addition, a diesel generator connected to the PV source is used to provide the necessary means of support to the PV system at various time intervals. The coordinated operation of the PV-diesel generator offers a reasonable way to eliminate the need for energy storage device in terms of the system economics.

In this study, a low-voltage DC microgrid including EVFCS and distributed generation units is considered as shown in Fig. 1. The proposed system uses a solar PV array with standard conditions (1000W/m^2 irradiance, 25^{o}C temperature), a diesel generator set and grid energy to charge the EVs connected to EVFCS.

The proposed system parameters are given in Table I. The detailed model of PV arrays and diesel generator can be found in [19], [20]. In the proposed model structure, the PV string is connected to the DC link through a DC/DC converter and the EVFCS is linked to the DC bus through bidirectional DC/DC charger. The electrical grid, diesel generator and other loads are connected to the DC link through individually controlled AC/DC inverters. The inverters' control are modulated in this system through the pulse width modulation (PWM) signals generated by the inner current and voltage loop PI controller based on the design introduced in [21]. It is noted that a PWM-PI controller is used in the proposed model structure since it is one of the most widely used methods in the control of inverter-based microgrids; however, any improved method such as model predictive control can be easily implemented for different objectives.

III. DECENTRALIZED CONTROL SYSTEM BASED ON PI CONTROLLERS

In the study, a decentralized control system (DCS) is adopted, which means that each component of the charging station works independently from the rest of the system. Thus, independent controllers based on PI systems are developed for the power converters of the diesel generator and the grid. This control system is preferred as it allows an easy integration of new elements to the EVFCSs without affecting on the other elements of the system.

With regard to the PV system, as the main objective of the boost converter is to track the maximum power point of the PV array by regulating the solar panel terminal voltage using the power voltage characteristic curve, PV is assumed to work in the maximum power point tracking (MPPT) so that PI control is not necessary.

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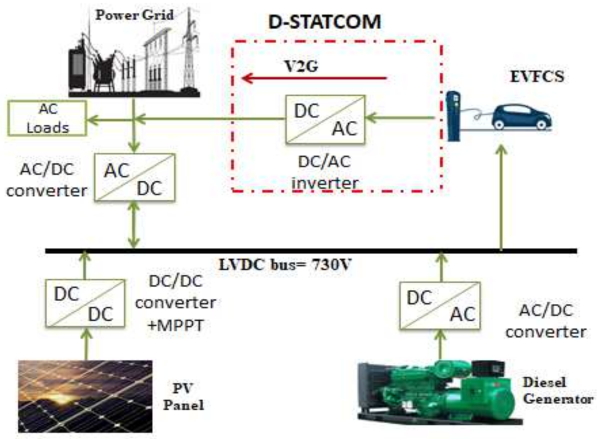

Fig. 1. Schematic diagram of the proposed system.

TABLE I. EVFCS input parameters

Parameter	Values	Parameter	Values
P_{PV}	170 kW	X/R ratio	7
P_{diesel}	300 kW	P_{EV}	103.8 kW
V_{bat}	480 V	Battery capacity	100 Ah
V_{grid}	400 V	Battery initial *SOC*	60%
f_{grid}	50 Hz	Battery response time	1e-3 Sec

The main goal of this decentralized control is to maintain the LVDC bus voltage in a reference range and keep the power balance in the EVFCS. The LVDC bus is optioned by controlling the output of the diesel generator, PV system and grid at the voltage reference.

III.A. Inverters control

The control objective of the voltage source AC/DC inverter is to maintain 730V DC-bus voltage for EVFSC. When energy production or load demand changes, the DC-bus voltage is adjusted to the constant value so as to observe the power balance within the system and to exchange power between the microgrid and the grid. A dq control theory is proposed in this study using three PI controllers. It consists of one outer voltage loop and two current loops. Synchronization with the grid and diesel voltage is performed through a phase locked loop (PLL) [20].

Fig.2 illustrates the proposed inverter control system, in which the DC bus voltage is controlled by the d-axis outer loop and the active AC current is controlled by the inner loop. The reactive current IQ is set to zero. The PLL system uses the AC source voltage as an input and the output VD, and frequency signals are obtained for use in the dq frame inverter control [21]. The proportional K_p and integral K_i gain of PI controller are 0.5 and 200, which are obtained using the trial-and-error method.

III.B. EV charger control

The EV battery charger control is designed based on the model described in [24]. The battery, power converter and controller are the three key components of the charging system. The control system consists of PI controllers, and the PWM generator is used to provide pulses to the IGBTs of the DC/DC converter, as shown in Fig. 3.

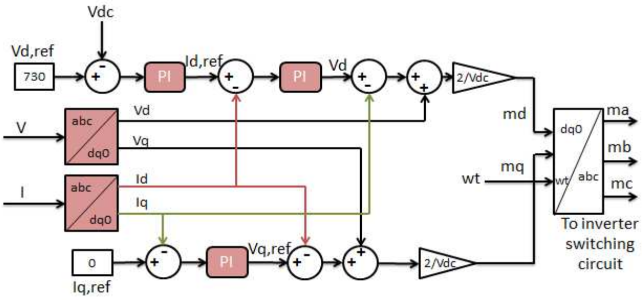

Fig. 2. Inverter control system [21].

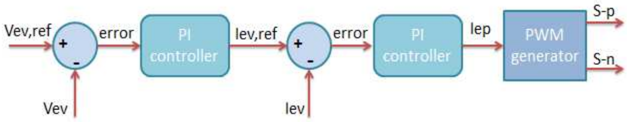

Fig. 3. Constant current battery charger control [12].

Depending on the desired charging method, two identical control approaches can be implemented: constant current (CC) and constant voltage (CV). CC strategy is a unified control method that is equivalent to use the battery as a current source and the output of PI controller defines the boost-mode operation of the EV charger. While CV strategy is equivalent to use the battery as voltage source and the output of PI controller defines the buck-mode operation of the EV charger [21], [24]. In this study, a CC control methodology is implemented to operate the battery as a current source. The PI controller parameters are 5 (K_p) and 0.0005 (K_i), respectively. Eqs. (1-4) show the algorithm that could perform PWM charger mode organically.

$$V_{ev-error} = V_{ev-ref} - V_{ev} \quad (1)$$

$$I_{ev-ref} = V_{ev-error}\left(\frac{K_i}{s} + K_p\right) \quad (2)$$

$$I_{ev-error} = I_{ev-ref} - I_{ev} \quad (3)$$

$$I_{ep} = I_{ev-error}\left(\frac{K_i}{s} + K_P\right) \quad (4)$$

where V_{ev} is the EV battery voltage, I_{ev} is the battery current of the EV, I_{ep} is the pulse current and V_{ev-ref} and I_{ev-ref} are the reference EV battery charger voltage and current, respectively.

IV. VOLTAGE SAG/SWELL MITIGATION WITH EV BATTERY-INTEGRATED D-STATCOM

As EV battery with V2G can be used for peak shaving or valley falling and it contributes significantly to grid stability [18], EV battery in V2G mode can also be used as DC voltage source in D-STATCOM device to improve power quality. In order to have flexible charging or discharging rates as shown in Fig. 4, the charging and discharging are separated at the AC-DC converter stages [25]. The system consists of bidirectional DC-DC converter and two AC/DC converters for two-way operation.

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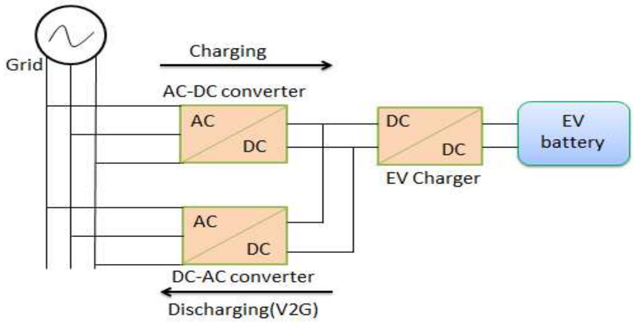

Fig. 4. Block diagram of EV Charger and V2G integrator.

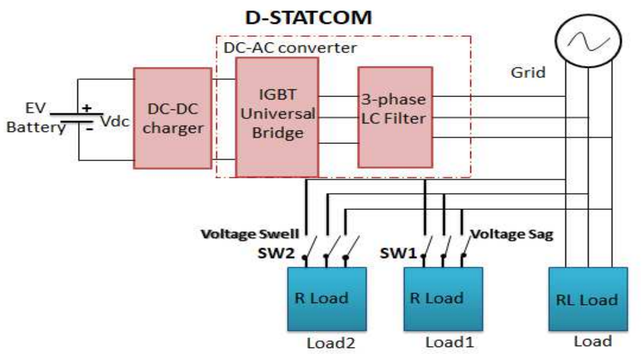

Fig. 5. Block diagram of D-STATCOM connected to the 3-phase distribution line.

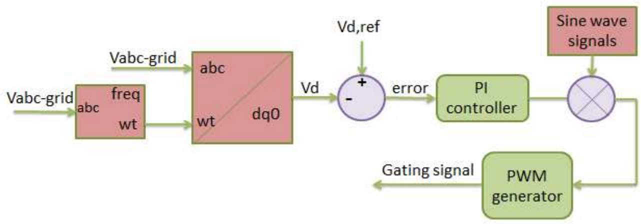

Fig. 6. PI Control scheme designed for the D-STATCOM.

TABLE II. D-STATCOM parameters

Parameter	Values	Parameter	Values
Filter resistor	0.6419 Ω	Inverter resistance	1 mΩ
Filter capacitor	7.89 µF	PI controller (Kp)	0.025
Filter inductor	0.0064 H	PI controller (Ki)	0.00025

D-STATCOM is a shunt-connected power electronics-based device, which is generally connected near the load at the distribution systems to mitigate power quality problems such as voltage sag, voltage swell and harmonics[26]. In general, D-STATCOM consists of four main parts, namely, voltage source inverter (VSI), LC filter, control circuit and DC source, as shown in Fig. 5.

In this work, EV is proposed as a DC source for the D-STATCOM and PI controller shown in Fig. 6 is proposed to regulate the required terminal voltage at the PCC where the sensitive loads are connected under system disturbances. The D-STATCOM and PI controller design procedure are adapted from [26] and the obtained parameter values are presented in Table II.

V. SIMULATION RESULTS

EVFCS decentralized control strategy simulation with on-board charging and discharging (D-STATCOM) modes is performed in MATLAB/Simulink environment. Three different energy sources are utilized for charging EVFCS based on a LVDC bus. Moreover, the results of using a D-STATCOM grid connected in V2G (discharge) mode for voltage regulation are presented with PI control to maintain the point of common coupling voltage at a nominal value when a voltage sag or swell occurs on grid voltage.

V.A. Charging of EV battery

Battery SOC and current variations for the EV battery during charging mode for a period of 1 second are shown in Fig. 7. Fig. 7(a) and Fig. 7(b) refer to the battery SOC and charge current of 192 A. Besides, Figure 8 shows the desired DC bus voltage of 730 V, which is obtained under three charging sources. EVFCS is operated between 0 and 1 seconds, and the EV is simultaneously connected and charged from all the microgrid energy sources at the first 0.52 seconds.

The PV and diesel generator are disabled from 0.52 to 1 seconds, and the EV is charged by drawing energy from the utility grid. Figure 8 also depicts the DC bus voltage response to the shifting of the energy sources. The voltage variation is less than 80 V in that case and it is stabilized in less than 0.2 seconds.

V.B. EV battery integrated D-STATCOM for voltage sag/swell mitigation

In this work, EV battery is proposed as a power supply to drive the D-STATCOM during discharging mode to mitigate voltage sag/swell. As shown in Fig. 9 and Fig. 10, the voltage sag is appeared in the period from 0.2 to 0.4 seconds when 20 kW heavy load (Load1) is added to the system by switching SW1. In this case, the voltage drops by almost 24.3% with respect to the reference rms value (from 317 V to 240 V). At 0.4 seconds, the SW1 is opened and stays throughout the rest of the simulation.

On the other hand, voltage swell is occurred in the period from 0.6 to 0.8 seconds when 20 kW heavy load (Load2) is turned off by switching SW2. In that case, the voltage on the power line increases by almost 38.1% with respect to the reference rms value (from 317 V to 438 V) and at 0.8 seconds, the SW2 is closed and stays throughout the rest of the simulation. The percentage of sag/swell for the system is calculated by Eq. (6):

$$\text{sag, swell}(\%) = \frac{V_{rms}(vol) - V_{sag,swell}(vol)}{V_{rms}(vol)} \times 100 \qquad (1)$$

Based on Fig. 11 and Fig. 12, it is clear that the voltage sag/swell problems are mitigated when the proposed EV battery-connected D-STATCOM with PI voltage control strategy is injected in the distribution grid. During these periods, the EV will act as a DC source and begin to discharge its stored energy, as shown in Fig. 13(a). As a result, the EV voltage decreases and the EV current increases to compensate

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the voltage drop during voltage sag period as shown in Fig. 13(b) and Fig. 13(c), respectively. In the contrary, the EV voltage increases and the current decreases to help the recovery of the voltage to its normal value (i.e., 300 V) during voltage swell period.

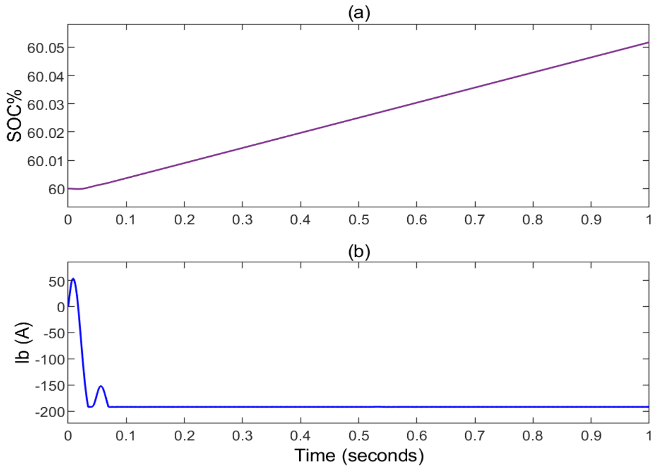

Fig. 7. Variation of EV battery variables for charging operation: (a) battery SOC, (b) battery current.

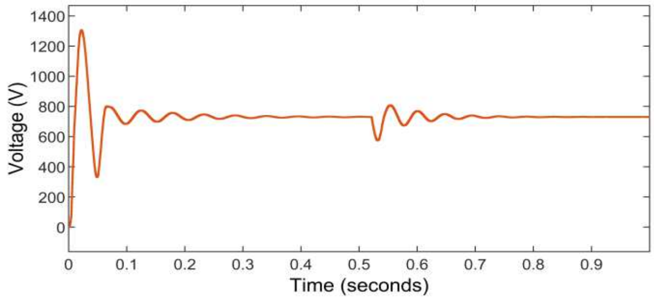

Fig. 8. DC bus voltage for different charging modes.

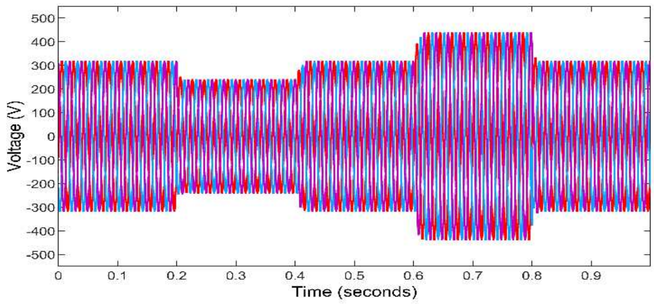

Fig. 9. Three phase voltage profile at load point.

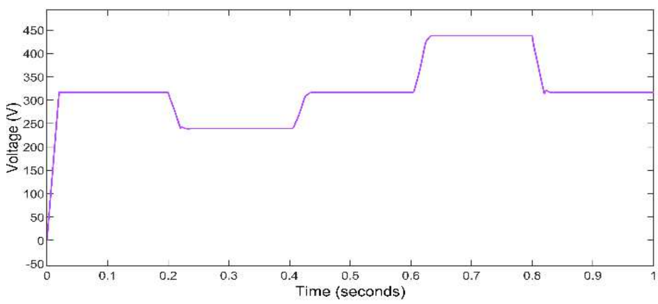

Fig.10. Voltage profile in (rms) at load point.

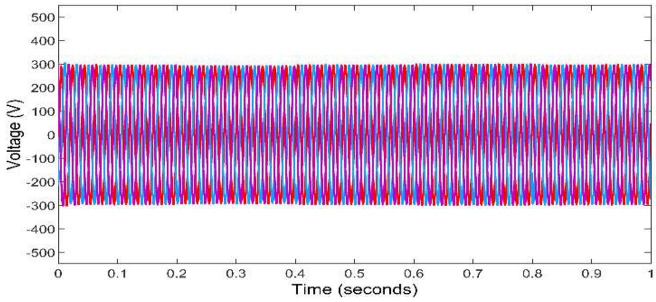

Fig. 11. Three phase voltage profile at load point with D-STATCOM.

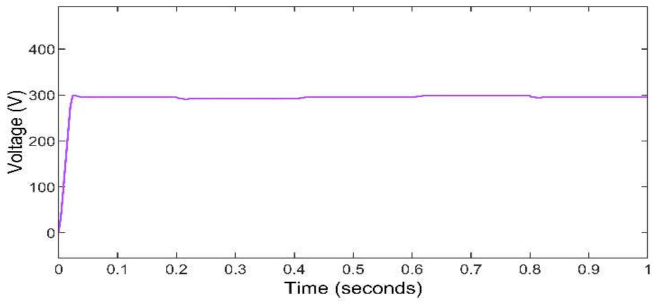

Fig. 12. Voltage profile in (rms) at load point with D-STATCOM.

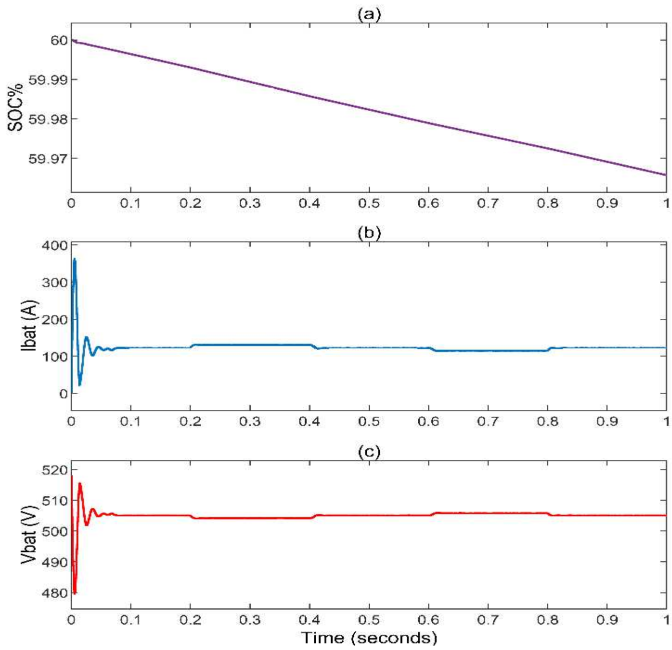

Fig. 13. EV battery results for discharging operation: (a) battery SOC, (b) battery current, and (c) battery voltage.

VI. CONCLUSION

This study presents the idea of using a simplified model of decentralized PI control with renewable energy for fast charging modes in order to reduce grid reliance and make the system less polluted. The PI controllers are used to control the converters of two system components independently to achieve a coordinated operation. Besides, the idea of using an EV battery as a DC source for a D-STATCOM device to mitigate voltage sag/swell is considered in this paper. The D-

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STATCOM is built by integrating the PI control system and the implementation of the model in MATLAB/Simulink and SimPower Systems is described in detail. The results of the simulation studies conducted show that the proposed V2G system can be utilized to effectively overcome the power quality problems by reducing voltage sag and swell problems. As a future direction, the effectiveness of the proposed strategy is planned to be validated in a larger power grid including a higher number of components.

REFERENCES

[1] I. G. E. Outlook, "to Electric Mobility." IEA: Paris, France (2019).

[2] M. Nour, H. Ramadan, A. Ali, and C. Farkas, "Impacts of plug-in electric vehicles charging on low voltage distribution network," in *2018 International Conference on Innovative Trends in Computer Engineering (ITCE)*, 2018, pp. 357–362.

[3] X. Gong and J. Rangaraju, "Taking charge of electric vehicles-both in the vehicle and on the grid," *Texas Instruments, Dallas, TX, USA*, pp. 1–13, 2018.

[4] A. K. Karmaker, S. Roy, and M. R. Ahmed, "Analysis of the impact of electric vehicle charging station on power quality issues," in *2019 International Conference on Electrical, Computer and Communication Engineering (ECCE)*, 2019, pp. 1–6.

[5] P. García-Triviño, J. P. Torreglosa, L. M. Fernández-Ramírez, and F. Jurado, "Decentralized fuzzy logic control of microgrid for electric vehicle charging station," *IEEE J. Emerg. Sel. Top. Power Electron.*, vol. 6, no. 2, pp. 726–737, 2018.

[6] D. Wang, F. Locment, and M. Sechilariu, "Modelling, Simulation, and Management Strategy of an Electric Vehicle Charging Station Based on a DC Microgrid," *Appl. Sci.*, vol. 10, no. 6, p. 2053, 2020.

[7] L. Yang and H. Ribberink, "Investigation of the potential to improve DC fast charging station economics by integrating photovoltaic power generation and/or local battery energy storage system," *Energy*, vol. 167, pp. 246–259, 2019.

[8] S. Wang, L. Lu, X. Han, M. Ouyang, and X. Feng, "Virtual-battery based droop control and energy storage system size optimization of a DC microgrid for electric vehicle fast charging station," *Appl. Energy*, vol. 259, p. 114146, 2020.

[9] S. Wang, K. Kuang, X. Han, Z. Chu, L. Lu, and M. Ouyang, "A model-based continuous differentiable current charging approach for electric vehicles in direct current microgrids," *J. Power Sources*, vol. 482, p. 229019, 2021.

[10] M. Dicorato, G. Forte, M. Trovato, C. B. Muñoz, and G. Coppola, "An integrated DC microgrid solution for electric vehicle fleet management," *IEEE Trans. Ind. Appl.*, vol. 55, no. 6, pp. 7347–7355, 2019.

[11] F. Ahmad, M. S. Alam, S. M. Shariff, and M. Krishnamurthy, "A cost-efficient approach to EV charging station integrated community microgrid: A case study of Indian power market," *IEEE Trans. Transp. Electrif.*, vol. 5, no. 1, pp. 200–214, 2019.

[12] B. Singh, A. Verma, A. Chandra, and K. Al Haddad, "Implementation of solar PV-battery and diesel generator based electric vehicle charging station," *IEEE Trans. Ind. Appl.*, 2020.

[13] Y. R. Rodrigues, A. C. Z. de Souza, and P. F. Ribeiro, "An inclusive methodology for Plug-in electrical vehicle operation with G2V and V2G in smart microgrid environments," *Int. J. Electr. Power Energy Syst.*, vol. 102, pp. 312–323, 2018.

[14] G. A. Salvatti, E. G. Carati, R. Cardoso, J. P. da Costa, and C. M. de O. Stein, "Electric vehiclesenergy management with V2G/G2V multifactor optimization of smart grids," *Energies*, vol. 13, no. 5, p. 1191, 2020.

[15] O. Egbue and C. Uko, "Multi-agent approach to modeling and simulation of microgrid operation with vehicle-to-grid system," *Electr. J.*, vol. 33, no. 3, p. 106714, 2020.

[16] Q. Yang *et al.*, "An improved vehicle to the grid method with battery longevity management in a microgrid application," *Energy*, vol. 198, p. 117374, 2020.

[17] M. C. Falvo, L. Martirano, and D. Sbordone, "D-STATCOM with energy storage system for application in Smart Micro-Grids," in *2013 International Conference on Clean Electrical Power (ICCEP)*, 2013.

[18] D. Leskarac, M. Moghimi, J. Liu, W. Water, J. Lu, and S. Stegen, "Hybrid AC/DC Microgrid testing facility for energy management in commercial buildings," *Energy Build.*, vol. 174, pp. 563–578, 2018.

[19] A. M. Humada, M. Hojabri, S. Mekhilef, and H. M. Hamada, "Solar cell parameters extraction based on single and double-diode models: A review," *Renew. Sustain. Energy Rev.*, vol. 56, pp. 494–509, 2016.

[20] M. K. Siddiqui, M. A. Mallick, and A. Iqbal, "Performance analysis of closed loop control of diesel generator power supply for base transceiver (BTS) load," 2019.

[21] F. M. Shakeel and O. P. Malik, "Vehicle-To-Grid Technology in a Micro-grid Using DC Fast Charging Architecture," in *2019 IEEE Canadian Conference of Electrical and Computer Engineering (CCECE)*, 2019, pp. 1–4.

[22] P. García-Triviño, J. P. Torreglosa, L. M. Fernández-Ramírez, and F. Jurado, "Control and operation of power sources in a medium-voltage direct-current microgrid for an electric vehicle fast charging station with a photovoltaic and a battery energy storage system," *Energy*, vol. 115, pp. 38–48, 2016.

[23] Y. Shan, J. Hu, K. W. Chan, Q. Fu, and J. M. Guerrero, "Model predictive control of bidirectional DC–DC converters and AC/DC interlinking converters—A new control method for PV-wind-battery microgrids," *IEEE Trans. Sustain. Energy*, vol. 10, no. 4, pp. 1823–1833, 2018.

[24] A. Arancibia and K. Strunz, "Modeling of an electric vehicle charging station for fast DC charging," in *2012 IEEE International Electric Vehicle Conference*, 2012, pp. 1–6.

[25] N. Koduri, S. Kumar, and R. Y. Udaykumar, "On-board Vehicle-to-Grid (V2G) integrator for power transaction in smart grid environment," in *2014 IEEE International Conference on Computational Intelligence and Computing Research*, 2014, pp. 1–4.

[26] S. A. Zulkifli, A. M. Mohammed, and F. Y. Tascikaraoglu, "Study Case: D-STATCOM in Low-Cost Hardware in the Loop for Voltage Sag Mitigation," in *2021 IEEE International Conference in Power Engineering Application (ICPEA)*, 2021, pp. 30–34.

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