Novel aggregated controller of wind and PV based grid connected charging station for electric vehicle

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Article Info

Article history:

Received Dec 20, 2022
Revised Apr 25, 2023
Accepted May 7, 2023

Keywords:

Aggregated controller
Electric vehicles
Grid to vehicle to grid
Hardware-in the–loop
OPAL-RT modules
Wind

ABSTRACT

Novel technologies are adopting electric vehicles (EVs) day-by-day due to increasing interest in EVs. The charging process of EVs is a very important aspect when it is connected to the utility grid. Generally charging of an EV can be done at either home or in charging stations were connected to the utility grid. More harmonics and nonlinear currents are injecting into the utility grid during the charging process of the battery due to the existence of converters for power conversion in charging stations of EVs, which generally affects the quality of the power. In this situation, supplying the power to the utility grid from batteries existing in the vehicle through the charging station will provide a better solution and will charge again when there is less demand on the grid. Further using renewable energies in the charging stations can provide reliable power for both vehicles as well as the utility grid. To achieve better performance and maintain power quality at load bus, an aggregated controller is proposed in this paper. Moreover, reloading conditions are also incorporated to renewable energy sources under disconnection of the utility grid to maintain power balance. Hardware-in the–loop (HIL) based extensive results by using OPAL-RT modules are examined in this article under many situations to validate the proposed method.

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1. INTRODUCTION

Electric vehicles (EVs) are becoming popular day by day and attracting many people throughout the world due to its benefits both economically as well as reducing pollution. Due to increasing the number of EVs on the road every day, establishment of many charging stations is required. The charging process of the EV through the charging station is a very important aspect while it is connected to the utility grid. Because of the existence of power converters in charging stations/electric vehicles, many harmonics will be injected into the utility grid which results causes' poor power quality at load buses where other loads are connected [1]–[3]. Therefore, a proper controller is required in the charging station to reduce this effect. Further, there will be a peak load every day on the utility grid. During this peak load, the generation of all units will be suffered and this leads to increasing the cost of electricity production. Therefore, energy storage devices such as batteries which lead to high cost and maintenance should be maintained in some key places. On the other hand, many people are using EVs for going to offices, institutions, and industries, where they can keep charging for a long time till they return [1]. During this time period, sufficient time will be available to get charging and discharging of batteries, hence the utility grid can take some power from batteries in EVs during the peak load demand. This technology can satisfy local load demand at load bus then again batteries can recharge during low demand. Then there will be no effect or problem for operators of EVs since batteries can get full recharge. Hence this kind of system can provide quality and reliable power to load buses as well as reduce peak load demand on the utility grid with very less cost [1], [3].

The charging stations receive power from the utility grid when it is required. However, there may be an isolated mode where the charging station is disconnected from the utility grid for a number of reasons including daily power cuts, and faults. during this situation, the EVs connected in charging stations cannot get charging. To avoid this problem and to make the system more eco-friendly, locally placed hybrid photovoltaic (PV) – wind based power generation systems are integrated to charging stations [4]–[6]. Actually, this configuration will be more effective since sufficient space is available for installation of PV-wind based electricity generation systems. However, due to absence of internal batteries in the charging station, the loading must be performed during islanded mode of operation. During a normal scenario, the converter interfaced between grid and charging station must maintain power balance among PV, wind, batteries in EVs and utility grid through proper energy management system [7], [8]. An aggregated controller is designed in this paper to fulfill all the above tasks and the objectives of this research work are listed below: i) Integrate PV-wind based power generation system to establish a charging station; ii) Operate loading mode during islanding mode; iii) Design an aggregated controller for managing power bidirectional power flow between charging station-batteries-utility grid; iv) Design a hardware-in the loop (HIL) for analyzing the performance of the system.

2. SYSTEM DESCRIPTION

The layout of the utility grid connected two charging stations is shown in Figure 1. The system consists of two charging stations where one is having integration of renewable energy sources and other is a simple charging station without integration of any alternative sources. There will be an option to transfer power from batteries to the utility grid. Hence different directions of power flows are depicted in Figure 1. When selecting the bidirectional flow (where EVs are connected in charging stations for a long time), the batteries used in EVs can able to supply power to the utility grid during peak load and again charge the batteries during light load conditions. In the same manner, the hybrid PV and wind generation will be used for charging the batteries which are connected in charging stations, further the excess power will be fed to the utility grid. Each renewable energy source is having its own maximum power point tracking devices for their best utilization. Each charging station is employed with its own proposed aggregated controller to manage the direction of power flow between grid and charging station depending on requirement. Usually, a bidirectional converter is employed in charging stations (1 and 2). Hence the converter controller should work for reducing harmonics injected to the utility grid like an active filter [2].

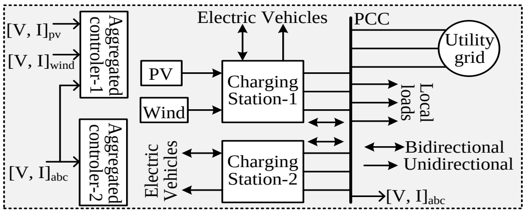


Figure 1. Layout of utility grid connected charging stations with aggregated controllers

3. ENERGY MANAGEMENT SYSTEMS AT CHARGING STATIONS

Every charging station has its own energy management system [9], however the bidirectional power flow-based energy management system can deliver the best performance where vehicles are keeping charging for more hours [1]. Charging stations employed with wind-PV systems can provide reliable supply to vehicles during all conditions [9], [10]. These kinds of charging stations are commonly established in office premises, institutions, and universities, where employees can keep charging for a long time. The batteries used in electric vehicles can be used to produce power for maintaining peak load demand on grid when it is required and again it can be charged due to availability of sufficient time. Hence, bidirectional power flow of battery controller as well as converter controller of charging station should be developed to maintain aggregated control. Effective controllers of both battery converter and converter in charging stations are designed to maintain an aggregated energy management system for charging stations in this paper. Hence, two controllers are implemented in this paper as shown in Figure 2 is for the controller used in the charging station and controller showing Figure 3 is for controller used in vehicles to manage charging/discharging of the battery. Figure 2 is implemented for AC to DC converter to manage flow of active power from both the directions (i.e., vehicle to grid and grid to vehicle) based on requirement of power flow. It can be possible by comparing the direct axis component of voltage with per unit i.e., ‘1’. At the same time the controller can help to compensating for reactive power demanded by local loads and also mitigate the nonlinear effect on the grid. Hence the reactive component of voltage (i.e., v_q) is compared with zero reference signals. The error is given to proportional and integral controllers (PI controllers) to generate reference signals of currents. The required PWM signals are generated by a PWM generator as shown in Figure 2. The V_{abc} represents grid voltages (V_g) & I_{abc} refers to grid currents required by the charging station.

The controller depicted in Figure 2 is able to minimize the nonlinear load effect on the utility grid due to the AC to DC converter which is used in charging stations to charge electric vehicles. Once achieved stable DC link voltage, the proper converter is required to make charging and discharging of the battery which is used to drive EV(s). The bidirectional DC to DC converter is proposed in this paper along with its controller which is shown in Figures 3(a) and 3(b) respectively. The “2ω” oscillations will be presented in DC-Link voltage due to nonlinear load on the grid. The “2ω” oscillations can be tracked by subtracting DC link voltage with pure DC voltage by low pass filter (LPF). These oscillations need to be circulated in DC-to-DC converter, and then the effect of nonlinear load can be minimized on the grid. This is achieved by comparing the “2ω” component to its reference value ‘zero’ and the error signal further given to the PI controller for generating equivalent oscillations which can allow DC to DC bidirectional converter as shown in Figure 3. The reference current of the battery-bank is obtained through a PI controller to decide the direction of power flow. Required switching pulses are generated by comparing reference and actual battery current. In order to consider the life of the battery, the SoC of the battery is incorporated with a controller of DC-to-DC converter to prevent it from over charging and discharging situations. Switches Q_1 and Q_2 are used in the converter for managing charging and discharging respectively. Hence the converter can allow power flow in a bidirectional way by controlling dc-link voltage at its reference value. The aggregated energy management system will decide the direction of power flow and can set the voltage reference value for different EVs which can be connected for charging in the same charging station.

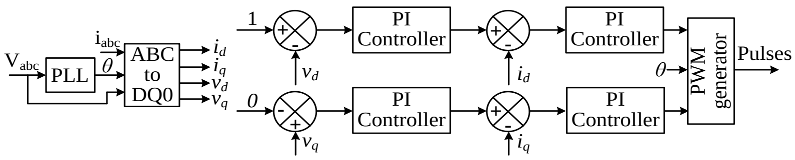


Figure 2. AC to DC converter controller used in charging station

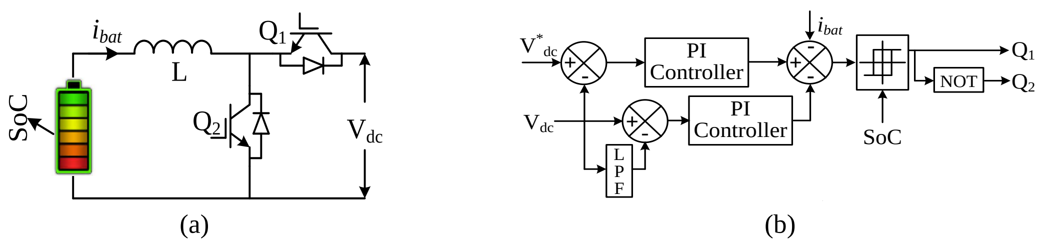


Figure 3. Bidirectional DC to DC converter: (a) DC to DC converter and (b) controller

4. CONTROL OF MOTOR IN ELECTRICAL VEHICLE

Generally multiple vehicles will be charged from a charging station and there is a chance of using different kinds of motor drives in vehicles [11]. Some vehicles are operating with induction motors, and some are with BLDC motors. However, the most popular drive is the BLDC motor used recently [12], [13]. Hence, the controller to drive the electric vehicle is considered in this paper is BLDC motor. For an effective operation, a MRAC based sliding mode controller of the BLDC motor is implemented [14]–[17] for testing the performance of the drive. However, while charging, the vehicle will be in standalone mode and while running there is no chance of charging. The MRAC model for speed estimation is shown in Figure 4 for the basic and implemented model on BLDC motor [18]–[25].

$$v_{ab} = R(i_a - i_b) + L\frac{d}{dt}(i_a - i_b) + e_a - e_b \quad (1)$$

$$v_{bc} = R(i_b - i_c) + L\frac{d}{dt}(i_b - i_c) + e_b - e_c \quad (2)$$

$$v_{ca} = R(i_c - i_a) + L\frac{d}{dt}(i_c - i_a) + e_c - e_a \quad (3)$$

$$T_e = \frac{e_a i_a + e_b i_b + e_c i_c}{\omega} \quad (4)$$

Generally,

$$i_a = -i_b \quad \text{and} \quad i_c = 0, \quad (5)$$

similarly, back EMFs are $e_a = -e_b$ and $e_c = 0$, therefore,

$$T_e = \frac{2e_a i_a}{\omega_r} \quad (6)$$

the back EMFs of BLDC motor are proportional to the electric speed of the rotor because of the rotor is having permanent magnet and it is denoted by (6)-(9).

$$e_a = k_e \omega \quad (7)$$

$$\omega = \frac{v_{ab} - 2Ri_a - 2L\frac{di_a}{dt}}{2k_e} \quad (8)$$

In steady state, $\frac{di_a}{dt} = 0$

$$\omega = \frac{v_{ab} - 2R_s i_a}{2k_e} \quad (9)$$

Here, the back EMF's coefficient is denoted by 'k_e'. The 'DQ' reference frame equations of BLDC motor can be expressed as:

$$\psi_{ds} = L_{ds} i_{ds} + L_{ad} i_{dr} + \psi_{fd} \quad (10)$$

$$\psi_{qs} = L_{qs} i_{qs} + L_{aq} i_{qr} \quad (11)$$

$$\psi_{dr} = L_{dr} i_{dr} + L_{ad} i_{ds} + \psi_{fd} \quad (12)$$

$$\psi_{qr} = L_{qr} i_{qr} + L_{aq} i_{qs} \quad (13)$$

$$e_a = \frac{k_e}{2}\omega_m F(\theta_e) \quad (14)$$

$$e_b = \frac{k_e}{2}\omega_m F\left(\theta_e - \frac{2\pi}{3}\right) \quad (15)$$

$$e_c = \frac{k_e}{2}\omega_m F\left(\theta_e + \frac{2\pi}{3}\right) \quad (16)$$

$$T_e = \frac{k_t}{2}\left[F(\theta_e) i_a + F\left(\theta_e - \frac{2\pi}{3}\right) i_b + F\left(\theta_e + \frac{2\pi}{3}\right) i_c\right] \quad (17)$$

$$\frac{d}{dt}\begin{pmatrix} i_a \\ i_b \\ \omega_m \\ \theta_m \end{pmatrix} = \begin{pmatrix} -\frac{R}{L} & 0 & 0 & 0 \\ 0 & -\frac{R}{L} & 0 & 0 \\ 0 & 0 & -\frac{k_f}{J} & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix}\begin{pmatrix} i_a \\ i_b \\ \omega_m \\ \theta_m \end{pmatrix} + \begin{pmatrix} \frac{2}{3L} & \frac{1}{3L} & 0 \\ -\frac{1}{3L} & \frac{1}{3L} & 0 \\ 0 & 0 & \frac{1}{J} \\ 0 & 0 & 0 \end{pmatrix}\begin{pmatrix} v_{ab} - e_{ab} \\ v_{bc} - e_{bc} \\ T_e - T_{pm} \end{pmatrix} \quad (18)$$

$$\frac{d\omega_{ref}}{dt} = -a_m\omega_{ref} + b_m v_x \tag{19}$$

$$T_e = \sum_{n=1}^{3} \frac{2}{3} I_m M i_m \, sin^2(2\theta + \pi_n) = I_m \widehat{M} i_n \tag{20}$$

$$\frac{de}{dt} = -a_m e + \left(a_m - \frac{B}{J}\right)\omega + \frac{\widehat{M}i_m}{J} I_m^* - b_m v_x + \frac{T_{pm}}{J} + \frac{1}{J}\sum_{n=1}^{Nr}(h_n \, sin(2n\theta) + g_k \, cos(2k\theta)) \tag{21}$$

where, rotor inertia constant represented as 'J' and friction coefficient is taken as 'k_f'. The parameters 'M, b_m, a_m, h_n, g_k, n', and 'k' are constants. The values of K_p and K_i are the gains of PI controller. Finally,

$$I_m^* = \frac{J}{\widehat{M}i_m}\left[\left(\frac{B}{J} - a_m\right)\omega + b_m v_x - \frac{T_{pm}}{J} - \frac{1}{J}\sum_{n=1}^{Nr}(h_n \, sin(2n\theta) + g_k \, cos(2k\theta))\right] \tag{22}$$

(a) (b)

Figure 4. MRAC implementation on BLDC motor, (a) basic MRAC and (b) MRAC of BLDC

The reference speed signal will be compared with motor actual speed which is estimated by MRAC model and error will be given to sliding mode control for generating reference dc-current signal as shown in Figure 5. Once obtained the required reference dc-current from the SMC, required switching pulses for the converter to drive BLDC motor can be easily generated by using control method as shown in Figure 6.

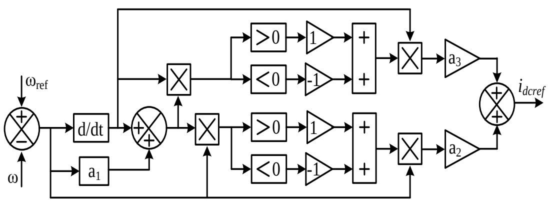


Figure 5. Sliding mode controller to estimate dc-current

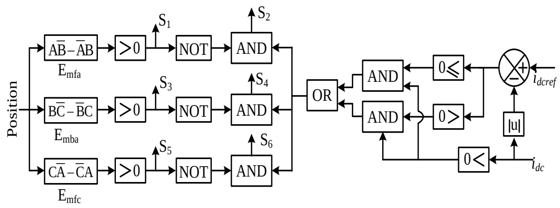


Figure 6. Converter controller to drive BLDC motor

5. RESULTS AND DISCUSSIONS

The real time simulator (RTS) is able to deliver a real-time operation by simulating dynamic equations of the system to be fast enough to deliver the output similar to the real network. Due to the acceptance of the RTS process worldwide for testing and development of power system control schemes, the OPAL-RT technologies based RTS configuration has been considered in this paper to obtain the results. In order to implement HIL setup, researchers have used two RTS modules designed by OPAL-RT technologies connected back-to-back in a loop. The system is divided into two parts as plant and controller. The unit-1 consists of the complete plant model and another unit is used for dumping the controllers with the help of MATLAB. Both the units are facilitated with analog and digital cards for their interconnection to form a loop. The analog signals are going from plant to control and digital signals are coming from control to plant. The MATLAB installed laptop is used to get extensive results for presenting in this section. The model setup of HIL with the help of two OPAL RT modules is shown in Figure 7. The proposed model shown in Figure 1 is divided into plant and controller. Further the results are presented in the following situations.

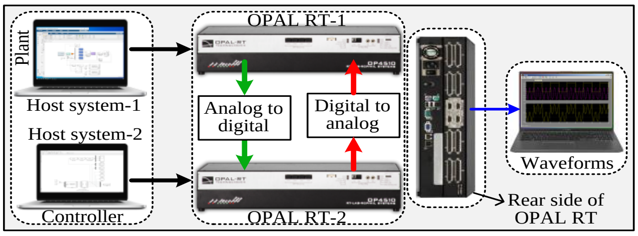
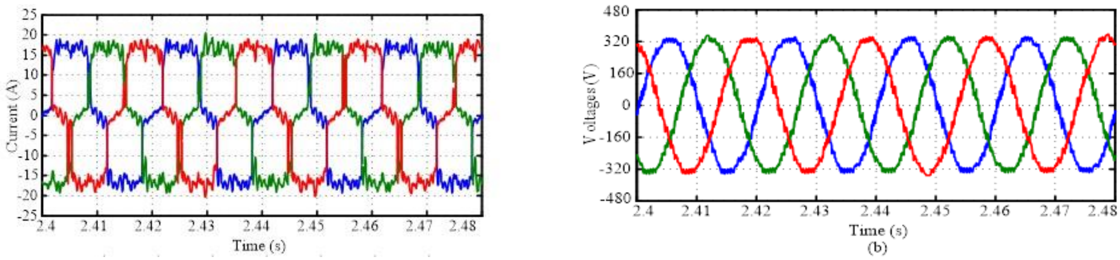


Figure 7. HIL setup

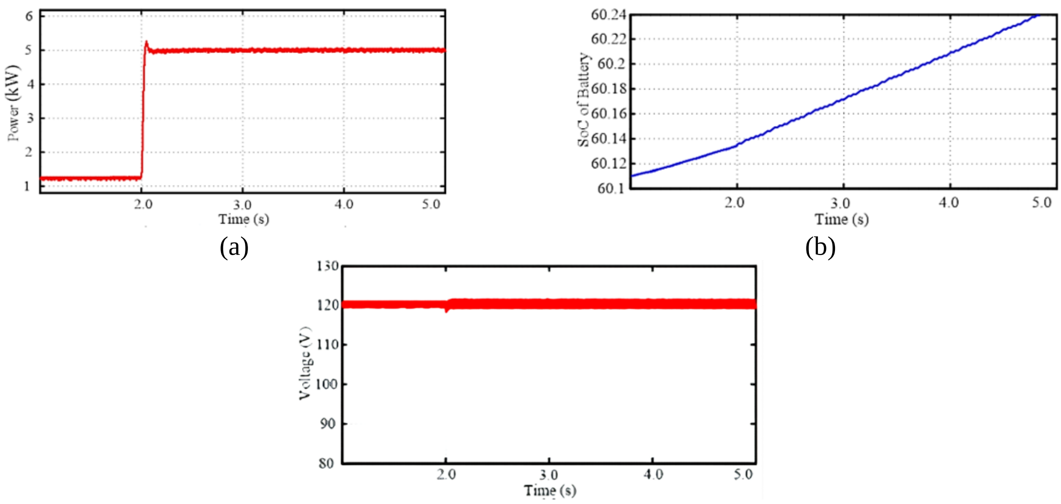
Assume multiple vehicles are connected in charging stations and all vehicles are drawing nonlinear current due to the existence of converters. Figure 8(a) shows the profile of nonlinear load current which is drawn from the utility grid. However, the controller of the charging station tries to make them sinusoidal grid currents as depicted in Figure 8(b). Hence the controllers can reduce the effect of nonlinear load on utility grid mainly where renewable energy sources are integrated.



(a) (b)

Figure 8. Grid (a) currents and (b) voltages

The proposed model is now tested for changing the number of EVs connected at charging-stations. Assumes many numbers of electric vehicles are connected suddenly at t=2.0 sec as shown in Figure 9(a). During this operation, the SoC of all the vehicles (represented in average) will be suddenly increasing as it is depicted in Figure 9(b). However, there is not much change or effect on DC-link voltage which is quickly stabilized as shown in Figure 9(c) with the help of proposed controllers. The controller of the DC-to-DC converter is working effectively and plays a key role in stabilizing the dc-link at its reference value.



(a) (b) (c)

Figure 9. Response of (a) power, (b) SoC, and (c) voltage at DC-link in charging station

The electric vehicle is tested now under running condition to enhance the performance of BLDC motor drive. The reference speed of the motor is reduced from 1800 to 700 rpm at t = 3 sec. However, to achieve realistic performance, the change is considered with slow dynamics not as a sudden step, because of sudden step change cannot be possible in the running condition of the electric vehicle. The MRAC of the motor can also estimate the speed of the BLDC motor. However, the controllers are having their own delay in response time and respective response(s) on the motor speed is depicted in Figure 10. Due to faster tracking response by SMC than PI, the response with the SMC is having the significant priority to use in electric vehicles.

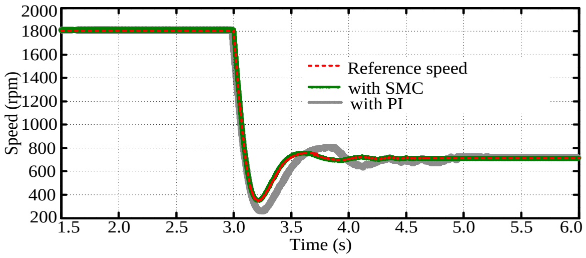


Figure 10. Speed of BLDC motor

The system is tested under grid off mode (isolated mode). During no power from the grid, ordinary charging stations (charging station-1 in Figure 1) will fail to provide charging. However, the proposed system (charging station-1 in Figure 1) has the facility of integration of renewable energy sources. The changes in total power generated by PV plus wind and load are considered as per the figure shown in Figure 11(a). Under this scenario, the battery is working to maintain the power balance between load and the generation. The charging of the battery represented by negative power and positive refers to discharge (sometimes local loads are connected which are most prior loads exp. hospitals). The response of voltage at dc-link which is regulated by the battery is presented in Figure 11(b). Moreover, there is a major rise and dip occurred in dc-link voltage because of huge changes in load, however these are very nominal and acceptable. During this process, RMS voltages of 3-phase are provided in Figure 11(c) which shows a stable response.

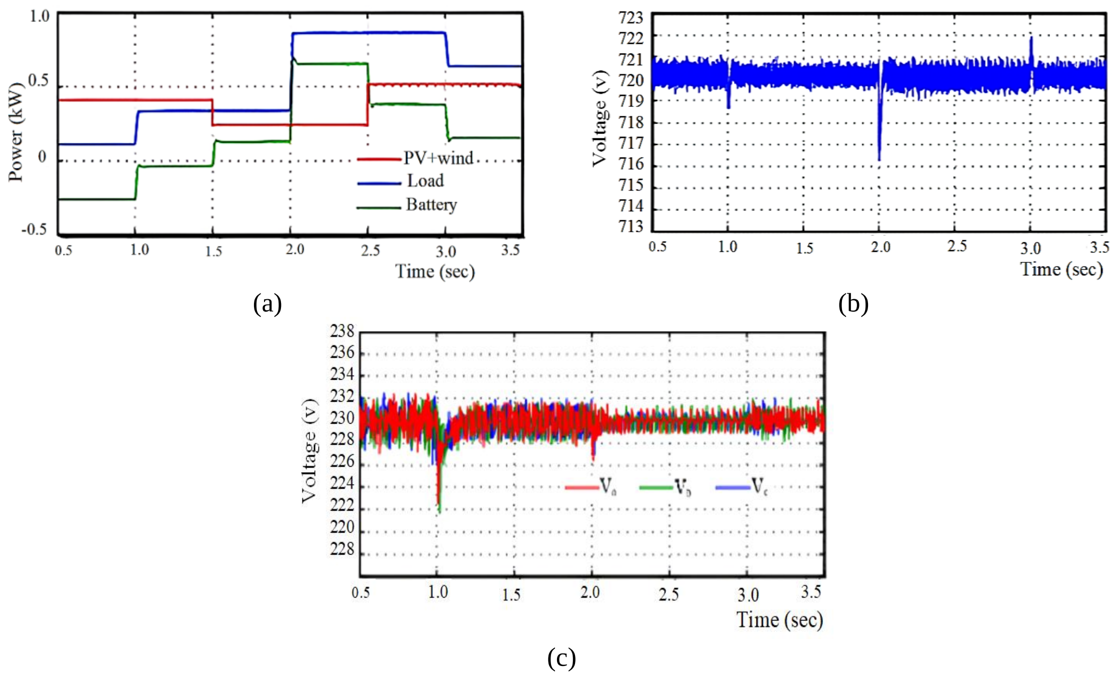


Figure 11. Proposed system performance in isolated mode: (a) various powers, (b) voltage at dc-link, and (c) 3-phase RMS voltages

6. CONCLUSION

The aggregated energy management system with novel control configuration of charging stations is presented in this paper. Sliding mode controller-based BLDC motor drive is included for testing the electric vehicle during running operation. The renewable energy sources are integrated to the system for power generation during grid off mode. The hybrid system can provide reliable power during all the conditions. Extensive HIL based results are examined in this paper to validate the proposed method. From the results, it is concluded that the performance of the proposed system is quite satisfactory under various conditions.

REFERENCES

[1] S. A. Amamra and J. Marco, "Vehicle-to-Grid Aggregator to Support Power Grid and Reduce Electric Vehicle Charging Cost," *IEEE Access*, vol. 7, pp. 178528–178538, 2019, doi: 10.1109/ACCESS.2019.2958664.

[2] Z. Zhang and K. T. Chau, "Pulse-Width-Modulation-Based Electromagnetic Interference Mitigation of Bidirectional Grid-Connected Converters for Electric Vehicles," *IEEE Transactions on Smart Grid*, vol. 8, no. 6, pp. 2803–2812, 2017, doi: 10.1109/TSG.2016.2541163.

[3] I. Sami *et al.*, "A bidirectional interactive electric vehicles operation modes: Vehicle-to-grid (V2G) and grid-to-vehicle (G2V) variations within smart grid," *2019 International Conference on Engineering and Emerging Technologies, ICEET 2019*, 2019, doi: 10.1109/CEET1.2019.8711822.

[4] A. Balal and M. Giesselmann, "PV to Vehicle, PV to Grid, Vehicle to Grid, and Grid to Vehicle Micro Grid System Using Level Three Charging Station," *IEEE Green Technologies Conference*, vol. 2022-April, pp. 25–30, 2022, doi: 10.1109/GreenTech52845.2022.9772041.

[5] V. Khare, C. J. Khare, S. Nema, and P. Baredar, "Modeling, cost optimization and management of grid connected solar powered charging station for electric vehicle," *International Journal of Emerging Electric Power Systems*, vol. 23, no. 4, pp. 587–603, 2022, doi: 10.1515/ijeeps-2021-0240.

[6] G. Rituraj, G. R. C. Mouli, and P. Bauer, "A Comprehensive Review on Off-Grid and Hybrid Charging Systems for Electric Vehicles," *IEEE Open Journal of the Industrial Electronics Society*, vol. 3, pp. 203–222, 2022, doi: 10.1109/OJIES.2022.3167948.

[7] J. Tabatabaei, M. Samiei Moghaddam, and J. Mohammadi Baigi, "Rearrangement of electrical distribution networks with optimal coordination of grid-connected hybrid electric vehicles and wind power generation sources," *IEEE Access*, 2020, doi: 10.1109/ACCESS.2020.3042763.

[8] K. Sarita *et al.*, "Power Enhancement with Grid Stabilization of Renewable Energy-Based Generation System Using UPQC-FLC-EVA Technique," *IEEE Access*, vol. 8, pp. 207443–207464, 2020, doi: 10.1109/ACCESS.2020.3038313.

[9] S. Singh, P. Chauhan, and N. J. Singh, "Feasibility of Grid-connected Solar-wind Hybrid System with Electric Vehicle Charging Station," *Journal of Modern Power Systems and Clean Energy*, vol. 9, no. 2, pp. 295–306, 2021, doi: 10.35833/MPCE.2019.000081.

[10] R. Baghel, H. K. Ghritlahre, R. N. Patel, A. Sahu, A. Patel, and M. K. Verma, "Design and performance improvements of solar based efficient hybrid electric vehicle," *International Journal of Emerging Electric Power Systems*, vol. 23, no. 4, pp. 513–521, 2022, doi: 10.1515/ijeeps-2021-0247.

[11] Q. Gao, X. Zhang, and H. Pan, "Day-ahead and real-time congestion scheduling method for distribution network with multiple access to electric vehicle charging piles," *International Journal of Emerging Electric Power Systems*, 2022, doi: 10.1515/ijeeps-2021-0347.

[12] C. M. Rahul Charles and J. S. Savier, "Bidirectional DC-DC converter fed BLDC motor in electric vehicle," *Proceedings of the 2021 1st International Conference on Advances in Electrical, Computing, Communications and Sustainable Technologies, ICAECT 2021*, 2021, doi: 10.1109/ICAECT49130.2021.9392394.

[13] B. V. R. Kumar and K. Sivakumar, "Design of a new switched-stator BLDC drive to improve the energy efficiency of an electric vehicle," *Proceedings of the IEEE International Conference on Industrial Technology*, pp. 532–537, 2017, doi: 10.1109/ICIT.2017.7915414.

[14] S. Sashidhar, V. Guru Prasad Reddy, and B. G. Fernandes, "A Single-Stage Sensorless Control of a PV-Based Bore-Well Submersible BLDC Motor," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 7, no. 2, pp. 1173–1180, 2019, doi: 10.1109/JESTPE.2018.2810506.

[15] Y. Shao, R. Yang, J. Guo, and Y. Fu, "Sliding mode speed control for brushless DC motor based on sliding mode torque observer," *2015 IEEE International Conference on Information and Automation, ICIA 2015 - In conjunction with 2015 IEEE International Conference on Automation and Logistics*, pp. 2466–2470, 2015, doi: 10.1109/ICInfA.2015.7279700.

[16] J. R. B. A. Monteiro, C. M. R. Oliveira, and M. L. Aguiar, "Sliding mode control of brushless DC motor speed with chattering reduction," *IEEE International Symposium on Industrial Electronics*, vol. 2015-September, pp. 542–547, 2015, doi: 10.1109/ISIE.2015.7281525.

[17] P. Malla and M. T. Scholor, "Sliding Mode Speed Control of Induction Motor Using SVPWM Technique for Hybrid Electric Vehicles Sliding Mode Speed Control of Induction Motor Using SVPWM Technique for Hybrid Electric Vehicles Priyanka Malla," *International Journal of New Technologies in Science and Engineering (IJNTSE)*, vol. 8, no. 1, pp. 1–7, 2022, [Online]. Available: www.ijntse.com

[18] A. K. Yarlagadda and V. Verma, "A Five Level Switched Capacitor Multi-Level Inverter with Soft Charging and Reduced Switching Loss," *2022 IEEE 2nd International Conference on Sustainable Energy and Future Electric Transportation, SeFeT 2022*, 2022, doi: 10.1109/SeFeT55524.2022.9909390.

[19] A. K. Yarlagadda and V. Verma, "Asymmetric MLDCL Inverter with Reduced Number of DC Sources Using LEN for PV Applications," *2022 IEEE IAS Global Conference on Emerging Technologies, GlobConET 2022*, pp. 152–157, 2022, doi: 10.1109/GlobConET53749.2022.9872364.

[20] A. K. Yarlagadda and V. Verma, "Single Phase 17-Level Asymmetric CHB Multilevel Inverter Using Fundamental Switching Frequency Modulation," *2022 2nd International Conference on Emerging Frontiers in Electrical and Electronic Technologies, ICEFEET 2022*, 2022, doi: 10.1109/ICEFEET51821.2022.9847957.

[21] B. Mukhopadhyay, R. K. Mandal, and D. Das, "Optimum Hourly Energy Scheduling in Interconnected Renewable Microgrids," *2023 IEEE IAS Global Conference on Renewable Energy and Hydrogen Technologies, GlobConHT 2023*, 2023, doi: 10.1109/GlobConHT56829.2023.10087595.

[22] P. Pan and R. K. Mandal, "Fault Detection and Classification in DC Microgrid Based on Convolutional Neural Network," *2022 2nd International Conference on Emerging Frontiers in Electrical and Electronic Technologies, ICEFEET 2022*, 2022, doi: 10.1109/ICEFEET51821.2022.9848336.

[23] A. K. Singh, R. Raushan, R. K. Mandal, and M. W. Ahmad, "A New Single-Source Nine-Level Quadruple Boost Inverter (NQBI) for PV Application," *IEEE Access*, vol. 10, pp. 36246–36253, 2022, doi: 10.1109/ACCESS.2022.3163262.

[24] A. Kumar, R. K. Mandal, R. Raushan, and P. Gauri, "Design and Analysis of the Gate Driver Circuit for Power Semiconductor Switches," *2020 International Conference on Emerging Frontiers in Electrical and Electronic Technologies, ICEFEET 2020*, 2020, doi: 10.1109/ICEFEET49149.2020.9186960.

[25] S. Yadav, R. K. Mandal, and G. K. Choudhary, "Determination of appropriate location of superconducting fault current limiter in the smart grid," *2014 International Conference on Smart Electric Grid, ISEG 2014*, 2015, doi: 10.1109/ISEG.2014.7005580.

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