

Investigations and Validation of PV-Powered Unified Power Quality Conditioner for Electric Vehicle Smart Charger in Standard AC/DC Hybrid Microgrid Test System



S. Sumana and R. Dhanalakshmi

Abstract It is well known that increase of nonlinear load such as electric vehicles (EVs) has become the key aspect in booming the power quality (PQ) issues in the power distribution grid. The application of AC/DC hybrid microgrid has become one of major trends in power transmission and distribution. The electric vehicle smart charger in the hybrid AC/DC microgrid (MG) causes PQ issues in the power system and also at the customer end. To uphold the quality of the power according to its standard, series of devices called custom power devices (CPDs) are accustomed. Unified power quality conditioner (UPQC) provides better solution in resolving the PQ-related issues and is emerged as powerful tool in enhancing the standards of power that is supplied to the end user. Novelty in this paper is the analysis of PQ issues due to the penetration of EVs in AC/DC hybrid microgrid and its compensation by photovoltaic (PV)-powered UPQC. The simulation is carried out in MATLAB 2017b platform. Based on the action of UPQC, outcomes are analyzed for three different cases. In each case, three scenarios are discussed based on the charging condition of EV smart charger in both the modes of system operation, i.e., when it is coupled to the grid and also in off-grid mode. Comparative investigation is achieved on the Performance of the PV powered UPQC for compensating the PQ issues caused by the EV charger in AC/DC hybrid microgrid test system and as well as in the standard IEEE 14 bus microgrid (MG) system for validation.

Keywords AC/DC hybrid microgrid · PV-powered UPQC · EV charger · Dynamic load · IEEE 14 bus

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1 Introduction

The hypothesis of PQ is explaining the efficacy of the power grid to supply authentic, absolute electricity to customers [1]. In modern power system, some standards such as IEEE and IEC indicate the importance of power quality [2–5]. A correlation between benchmarks related to PQ concept is represented in [6, 7]. Effect of most frequently used power electronic devices in modern distribution network is discussed in [8]. Due to the rapid growth of the Distributed Generation (DG) units to the grid, which increases the power quality issues, this would be the new topic of research in upcoming years. Several examinations were performed on diminishing the argumentative impact of nonlinear loads mainly power electronic (PE)-based DGs in microgrids, despite the fact that still much upgradation has to be done in this area [9–12]. A new configuration of AC/DC microgrid which comprises generation together with storage that is interconnected with AC and DC loads has emerged as one of the best infrastructures which can provide the integration of AC/DC technologies [13, 14]. A decisive review has been accomplished on PQ issues due to nonlinear loads in AC/DC hybrid microgrid and also suggested that still there is room for improvement [15–17]. The future trend of transportation sector is that conventional vehicles are replaced by electric vehicle (EV). Charging of EVs both in grid-coupled and island means of working, of power system using PV and wind, is considered in [18]. Basically, PE converter alike EV chargers are nonlinear load, its characteristics not only disturb the voltage configuration of the system but also initiate harmonics in the current, and the elimination of harmonics by UPQC using modified optimization techniques is presented in [19, 20]. Mitigation of power quality by multi-level inverter while using the electric vehicles is presented in [21]. The custom power device whose construction is based on the fundamentals of p–q theory and is emerged as most promising device in intensifying the PQ of both voltage as well as current is unified power quality conditioner (UPQC). Considering to the effective standards of the component existing in UPQC, it can be applied to both single and for three-phase supplies, but there arises stability issues when three individual single-phase apparatuses are resemblant to get a three-phase UPQC [22]. Numerous ways of solving the power quality problems using UPQC when it is connected to grid and off-grid have been studied, but these solutions are not turned as global solution [23–26]. Still, a promising solution is required for power quality intensification in the area of hybrid microgrid using custom power devices. The gaps explored from the above researches in diminishing the PQ riddles owing to the variation caused by unpredictable loads in distribution system are as follows: (i) Though review suggests the advantages of hybrid AC/DC microgrid in energy system, but the invent of power electronics devices modified the load characteristics of customer. Therefore, investigation on PQ issues in hybrid AC/DC MGs is still an area of research. (ii) Several ways of resolving the power quality problems using UPQC when it is connected to grid and off-grid have been studied, but these solutions are not turned as global solution. Still, a promising solution is required for PQ enrichment in the area of hybrid AC/DC microgrid using custom power devices in the presence of nonlinear loads.

In this work, the proposed system power quality is enhanced by using two-level inverters, i.e., UPQC when the EVs are connected as load. Simulation is performed in MATLAB 2017b context for three cases and three scenarios for each case. The results are validated in IEEE 14 bus microgrid environment. The novelty of this work is as follows: (i) Designing of hybrid AC/DC MG by modeling the DC grid using PV with effective converter, (ii) Modeling of PV-powered UPQC for enhancement of power quality in hybrid AC/DC microgrid, (iii) Modeling of EV charger and dynamic load, (iv) Testing and validating the PV-based UPQC under the standard IEEE 14 bus microgrid test environment for power quality issues caused by EV charger and dynamic load. This paper is mainly organized into three sections: Sect. 1 provides introduction about power quality issues due to the EV charger, hybrid AC/DC microgrid architecture, and custom power devices. In Sect. 2 block diagram of the proposed network and standard IEEE 14 bus system, its control scheme and design of the dynamic load are discussed in comprehensive. Section 3 provides the outcome and discussion of the proposed evaluating system and the standard IEEE 14 bus system.

2 Proposed Methodology

PQ issues of the proposed system as a consequence of penetration of EV smart charger and dynamic loads are analyzed for grid coupled as well as in off-grid mode. The analysis is carried in the following way: At first, the proposed analysis system is examined for three cases and three scenarios with EV smart charger and the same system is validated in standard IEEE 14 bus microgrid model distribution system.

Figure 1 represents the schematic outline of proposed hybrid AC/DC MG system. The comprehensive narration of the schematic structure is discussed in this way.

2.1 Modeling of AC Grid System

The principal AC grid is modeled in MATLAB tool by way of a configurable three-phase voltage source, a switch, a three-phase 200 kVA distribution transformer with a minimal power capacity of 1 MVA and delta-star connected. This traditional AC distribution network comprises distribution conduit, operating, susceptible, and harmonic loads. The loads, i.e., three commercially available EVs with single-phase 16 A (230 V) charger and 24 kWh lithium-ion (Li-ion) battery are placed at the tail end of the distribution lines. Also, a dynamic load of 45 kW resistive load (15 kW per phase) tractable per single phase in 1 kW steps is placed at the end of distribution lines.

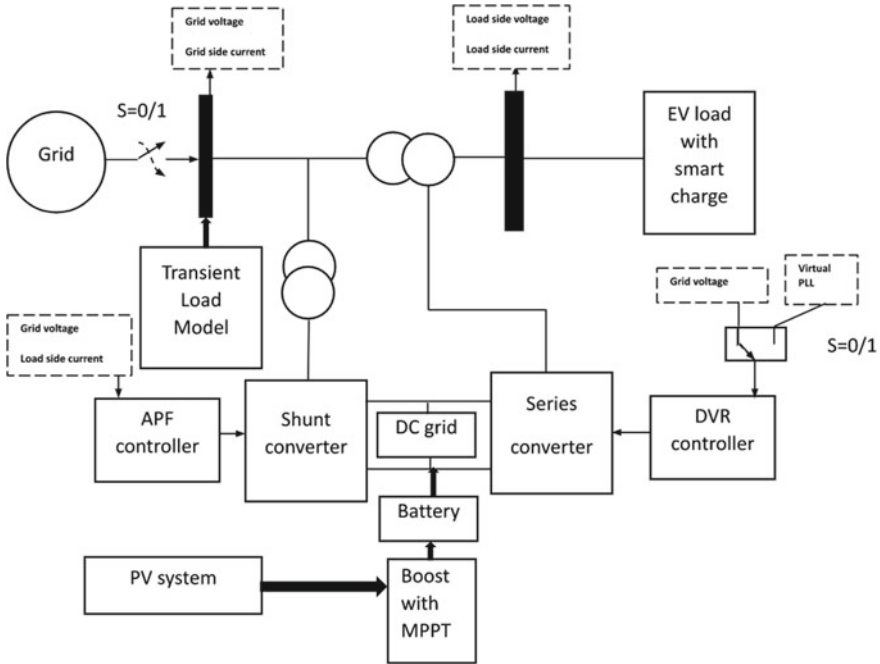


Fig. 1 Block diagram of proposed AC/DC hybrid microgrid system

2.2 Modeling of DC Distribution System

For the DC microgrid, the primary source of energy is the PV arrays that gives the utmost beneficial power, with a magnitude of 800 V in the DC network using a step-up DC/DC converter. The simulated DC segment of the AC/DC hybrid MG comprises 700 kW PV arrays that are controlled by Perturb and observe maximum power point (MPPT) tracing approach and a 600 V/500 Ah Li-ion battery [27].

2.3 Load

The operation of EV battery charge controller is like a droop controller. The EV intelligent charge regulator directs prescribed current to the charger as per electric mains' voltage dip state. It is a unidirectional charger whose charging rate can be modulated between 6 and 16 A. Figure 2 shows the closed-loop system of smart EV charger.

- A simple transient load of 45 kW is considered in this test system and is made it to run for 1 s. At initial, the 1/6th of 45 kW is connected. Then, the 2/6th time the 2/6th of the load is connected. The notion is given as the numerical model [28].

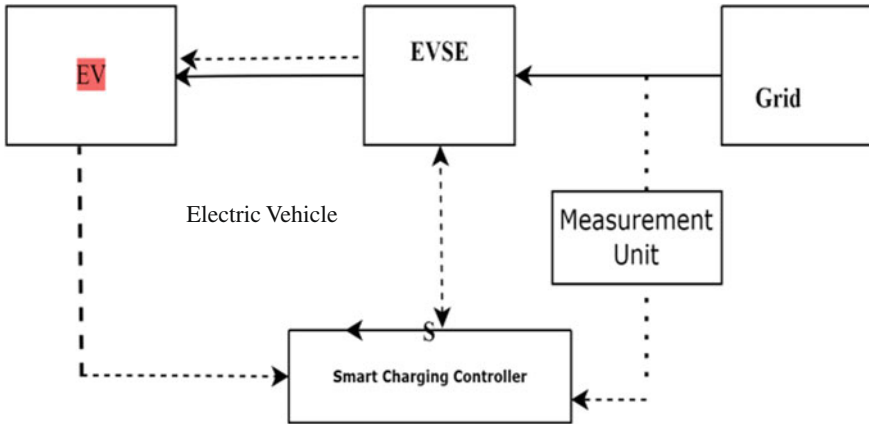


Fig. 2 Control scheme of EV smart charger

$$P_{load}(i) = \left(\frac{i}{6}\right) * P; \text{ here } i = 1, \dots, 6; P \text{ is the load.} \tag{1}$$

2.4 Proposed Approach

If the switch $S = 1$ then the proposed AC/DC hybrid microgrid operates in grid attached mode which indicates that three phase locked loop (PLL) is active, which is shown in the schematic diagram in Fig. 1. If $S = 0$ then the proposed system operates in islanded mode. The power from the DC grid to the load through the UPQC, which functions as the synchronizing inverter. The energy to the DC grid is supplied by solar panel which is attached to the DC/DC converter, which in turn ties up with battery storage. This configuration contributes the steady DC link potential. Synchronizing inverter, i.e., UPQC avails this voltage for the enhancement of PQ in grid-connected way and converts the DC to AC in off-grid manner.

2.5 Control Scheme

The UPQC is a combo of shunt active power filter (SAPF) and series-controlled inverter, i.e., DVR. UPQC resolves PQ problems related to voltage and current.

Figure 3 shows the regulation strategy of UPQC. The control method of APF identifies the estimated values and generates the required compensation alert. These signals are then linked with hysteresis controller and the desired control signals are initiated. Similarly, series-connected DVR determines the signal associated with

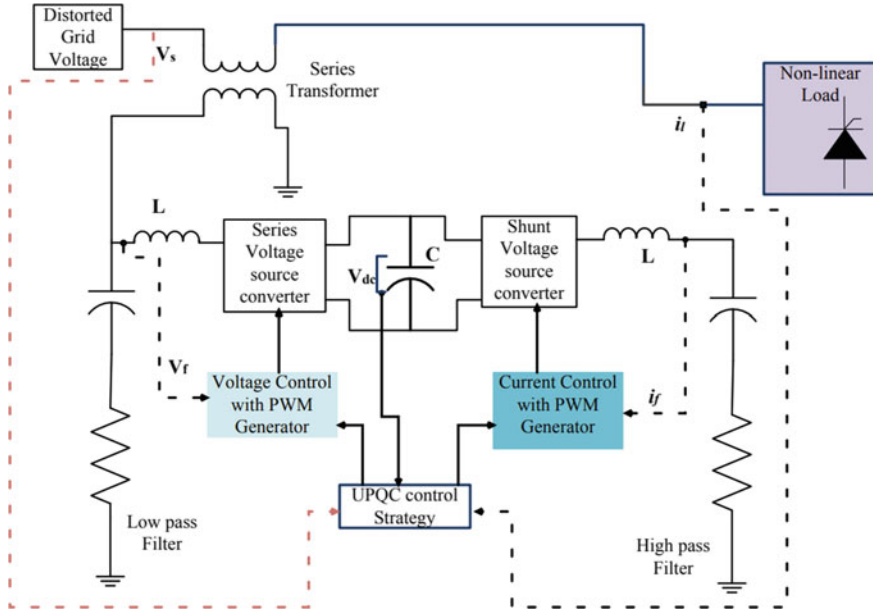


Fig. 3 Control scheme of UPQC

input voltage for sag/swell identification. This identified signals are then fed in pulse duration modulation regulator and the desired gate signals are originated.

2.6 Modeling of AC/DC Hybrid Microgrid in IEEE 14 Bus System

IEEE 14 bus system is test bed which constitutes a simple estimation of the United States (US) Electric Power system. It includes 14 buses, 5 generators, and 11 loads.

One-line illustration of IEEE 14 bus MG model distribution network is represented in Fig. 4. The main grid is of 69 kV, 100 MVA electrical transmission system, with X/R ratio of 10, which in turn is stepped down to a voltage of 13.8 kV. In this work, Bus number 13 is of 13.8 kV which is stepped down to 220 V using a step-down transformer. Buses which is indicated in blue color are 13.8KV and indicated in green color are of 220V. The green color buses 2 and 5 represents the voltage at distribution side, which forms the DC grid. Bus 13 is the AC grid, and the PV-powered UPQC is connected between Buses 2 and 5. The simulation is carried out in MATLAB 2017b environment, for three cases and three scenarios with EV load and dynamic load. The consequence of including PV-powered UPQC is examined in the standard IEEE 14 bus platform. MATLAB 2017b is considered for analyzing and indicating the simulation results [27, 28]. Figure 4 represents the IEEE 14 bus system modelled as

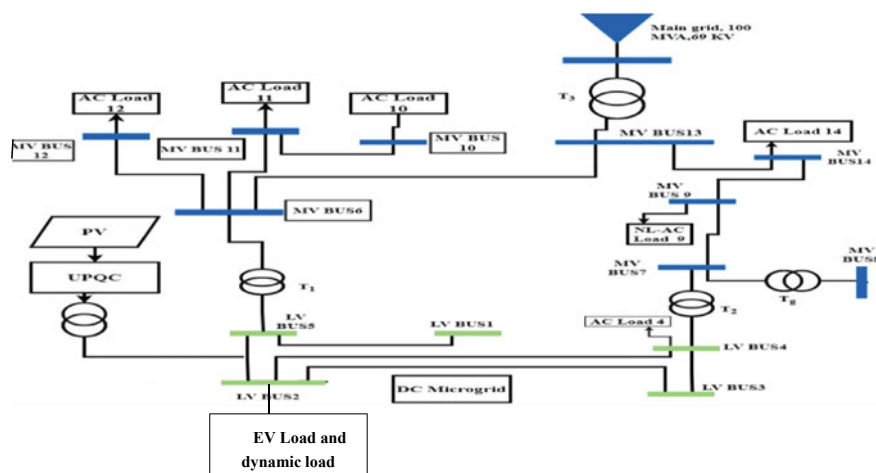


Fig. 4 AC/DC hybrid microgrid in IEEE 14 bus environment

hybrid AC/DC MG with PV powered UPQC. The loads in the IEEE 14 bus system are EV and dynamic load.

3 Results and Discussion

3.1 Performance Analysis of UPQC in AC/DC Hybrid Microgrid System

The analysis is carried out in MATLAB 2017b software package for analyzing problem solving capability of UPQC for three cases and in each case four scenarios depending on the smart EV charging action both when coupled to the grid as well as in islanded manner of the suggested hybrid MG system.

The three cases are as follows: **Case 1:** In the absence of UPQC and the EV, smart charger is attached at the load side, and in this case, distribution network works in grid-connected fashion. **Case 2:** In this case, system is grid connected, UPQC is brought in action, and EV charger is at the load side. **Case 3:** In this case, system works in off-grid mode, and both UPQC and the smart EV charger are connected to the system.

The three scenarios are analyzed depending on the working of smart EV charger:

Scenario 1 (SCN 1): When smart EV charger is in charging mode with minimum charging current of 6 A for all the three phases.

Scenario 2 (SCN 2): The smart EV charger is in charging condition but only at two phases.

Scenario 3 (SCN 3): The smart charger is in charging condition only at single phase [28].

Scenario 1, Case 1: EV smart charger is in charging mode with minimum of 6 A current

It is noticed from Fig. 5 that in the absence of UPQC, smart charger has helped to boost the voltage at the grid side, but every second increase in the dynamic load increases the smart charger current to maintain the grid voltage. In this case, the grid voltage is maintained at 194 V.

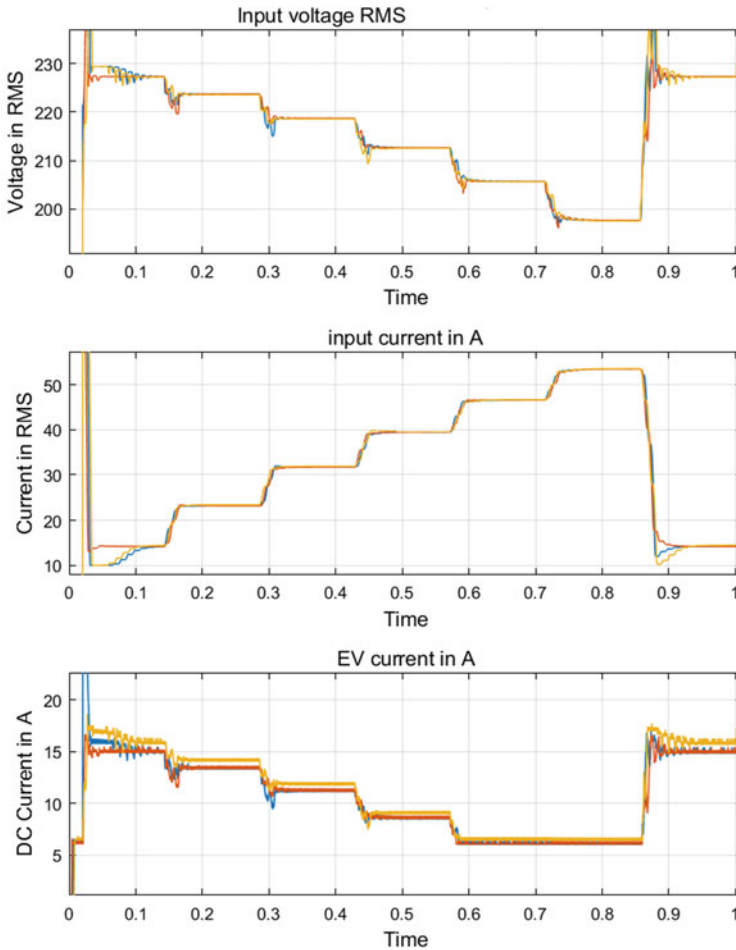


Fig. 5 Voltage, current of grid and EV current in RMS value: SCN 1, Case 1

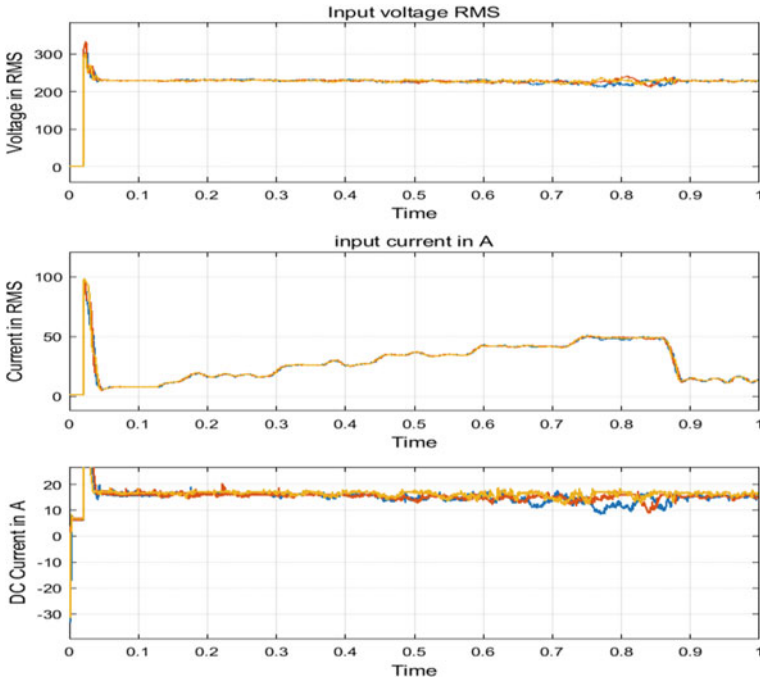


Fig. 6 RMS values of voltage and current of grid and EV current: Scenario 1, Case 2

Scenario 1, Case 2: The UPQC is connected to the network and the smart EV charger is in charging condition

In Case 2, the combination of UPQC and the smart EV charger action maintains the voltage at 220 V which is shown in Fig. 6.

Scenario 1, Case 3: In Case 3, the system is detached from the grid, but the UPQC is connected to the system

It can be seen from Fig. 7 that the smart charger work efficiently and maintains the grid voltage to 230V in case 3.

The values of EV current, grid voltage, current and voltage harmonics, power factor of scenario 1 for all the three cases are estimated and is tabulated in Table 1.

Scenario 2: The smart EV charger is in action at two phases only

The proposed system is tested under unstable status. Here, smart EV charger and the transient load operate at two phases. This invents instability in the system.

In Case 1, i.e., in the absence of UPQC, the voltage is slightly improved to 196 V. The voltage is improved slightly compared to Scenario 1. In Case 2, UPQC and smart EV charger action maintain the grid voltage at 220 V, i.e., within the safer limit. The grid is detached and the outcomes are same as Scenario 1 in Case 3. The values of

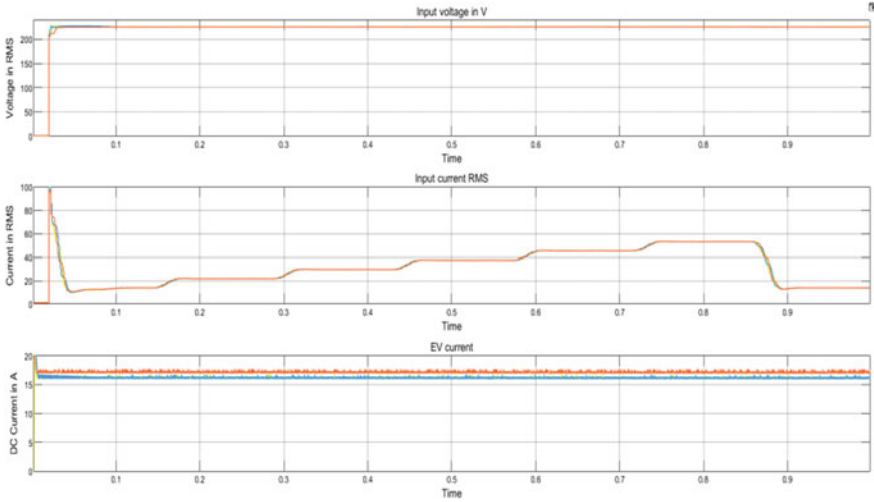


Fig. 7 Voltage, current of grid and EV current in RMS: Scenario 1, Case 3

Table 1 Comparative analysis of AC/DC hybrid microgrid system [26]

Cases	Parameters	SCN 1	SCN 2	SCN 3
Case 1	Grid voltage (V)	194	196	199
	Grid current (A)	55	55	56
	Percentage voltage THD	19.52	5.38	12.21
	Percentage current THD	20.38	3.81	3.95
	EV charger current (A)	6	6	6
	P.f (min)	0.5	0.65	0.72
Case 2	Grid voltage (V)	220	210	213
	Grid current (A)	50	35	28
	Percentage voltage THD	4.39	4.07	1.72
	Percentage current THD	4.06	6.13	5.08
	EV charger current (A)	9	9	10
	P.f (min)	0.78	0.84	0.8
Case 3	Grid voltage (V)	220	220	220
	Grid current (A)	30	30	28
	Percentage voltage THD	2.59	5.38	0.47
	Percentage current THD	3.29	3.81	5.61
	EV charger current (A)	9	9	9
	P.f (min)	0.95	0.94	0.93

grid voltage, EV current, voltage and current harmonics, power factor of Scenario 2 for all the three cases are tabulated in Table 1.

Scenario 3: EV smart charger is in action with only single phase

The Scenario 3 discusses the unbalancing due to EV charger in charging condition for only one phase. The C phase is connected with dynamic load which creates the sag in voltage. In Case 1, the grid voltage is little bit compensated; it reached up to 199 V, because of the connection of EV smart charger, but it is not within safer limit. In Case 2, the UPQC and smart EV charger are connected and the voltage is steady between the phases. The RMS value of voltage is 213 V. PV based DC grid provides the power to the load through UPQC and the voltage is maintained at 220V within safe limit in the islanding operation of case 3. The values of grid voltage, EV current, voltage and current harmonics, power factor of scenario 2 for all the three cases are tabulated in Table 1.

Three colors in the graph indicate three-phase colors (i.e., R Y B or A B C).

3.2 Performance Analysis of UPQC in Standard IEEE 14 Bus Microgrid Model Distribution System

Scenario 1, Case 1: EV charger is in charging state with minimal current of 6 A in all the three phases and the UPQC is not connected.

Due to the EV charger in charging state, the grid voltage is managed at 106 V which is shown in Fig. 8. The grid current is 103 A and the EV current is 6 A.

Scenario 1, Case 2: EV smart charger is in operation with minimum current of 6 A in all the three phases and the UPQC is connected to the system.

In Case 2, when UPQC is brought into action, there is an improvement in the voltage. Due to the effect of UPQC, the RMS value of voltage is maintained at 127 V and decreases the current to 100 A which is shown in Fig. 9.

Scenario 1, Case 3: EV smart charger is in charging mode, and the UPQC is attached to the system, but the grid is disconnected from the main supply.

In Case 3, during island mode, PV-powered UPQC maintains the grid voltage to nearly equal RMS value of the voltage, i.e., at 120 V which is shown in Fig. 10. All other parameters such as power factor, EV current, Voltage and current harmonics are in safer limit and is tabulated in Table 2.

Scenario 2: EV smart charger operates at two phases only

The proposed system is tested under unbalanced condition in standard IEEE 14 bus microgrid environment. This scenario functions for only two phases. In Case 1 without UPQC, there is voltage sag, and it is maintained at 104 V, whereas in Case 2 and Case 3, in the presence of UPQC system, voltage is maintained at its RMS value. All remaining parameters are within the limit as tabulated in Table 2.

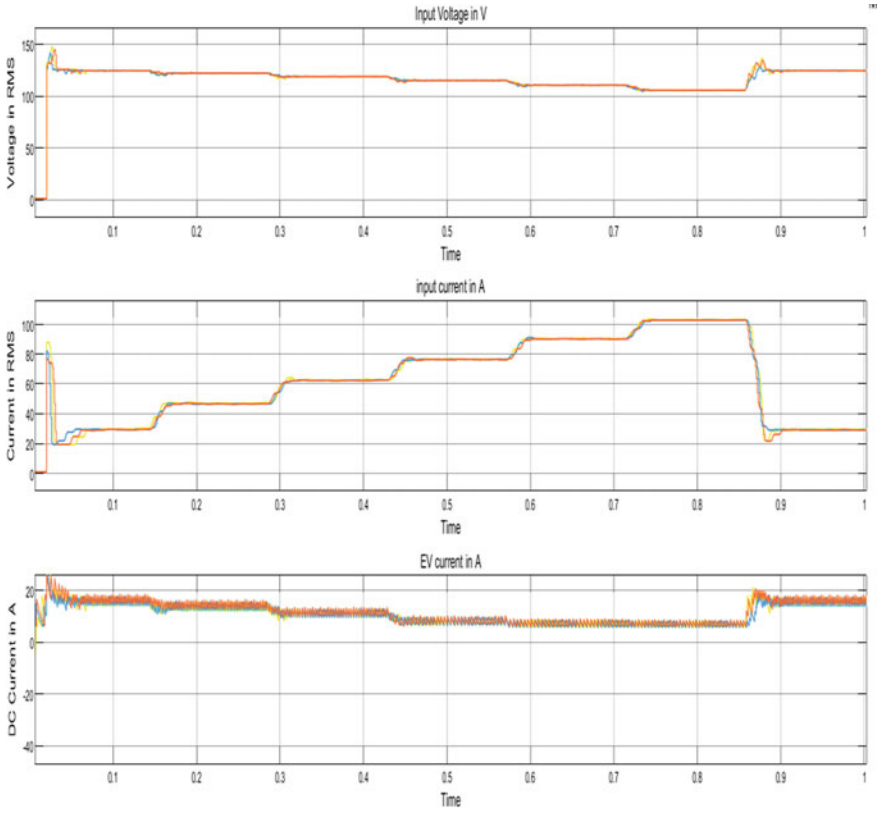


Fig. 8 RMS voltage and current of grid and EV current: Scenario 1, Case 1

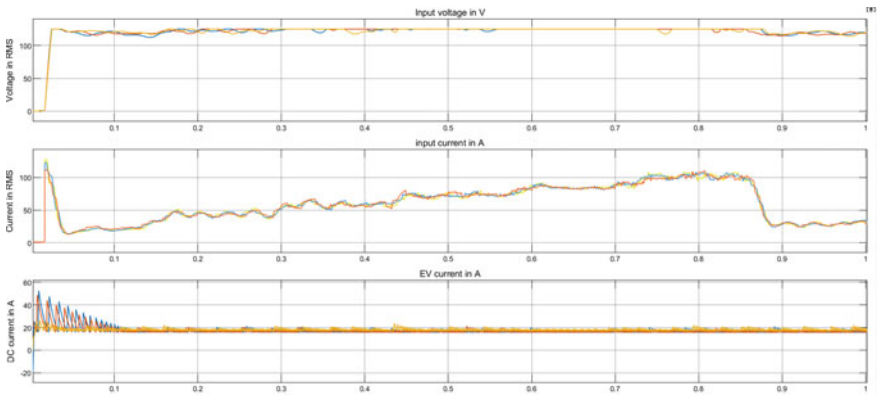


Fig. 9 Voltage and current of grid in RMS: Scenario 1, Case 2

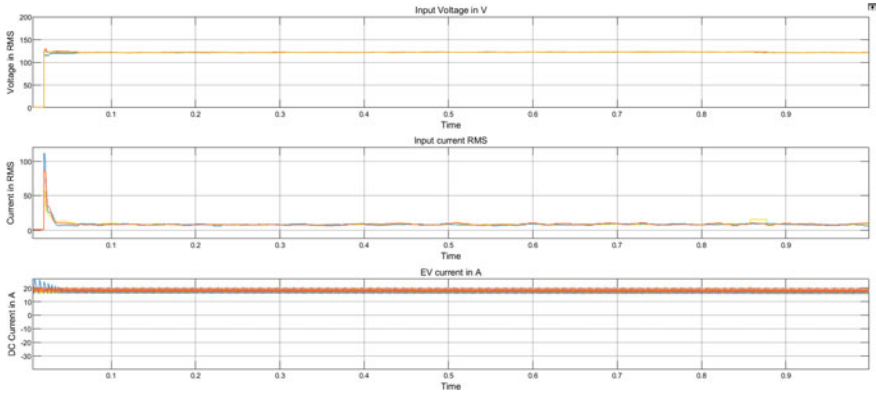


Fig. 10 RMS values of voltage and current of grid and EV current: Scenario 1, Case 3

Table 2 Comparative analysis of scenarios in IEEE 14 bus

Cases	Parameters	Scenario 1	Scenario 2	Scenario 3
Case 1	Grid voltage (V)	106	104	104
	Grid current (A)	103	98	100
	Percentage voltage THD	4.91	4.6	4.6
	Percentage current THD	2.39	4.64	2.39
	EV charger current (A)	6	6	6
	P.f (min)	0.7	0.5	0.72
Case 2	Grid voltage (V)	127	127	125
	Grid current (A)	96	80	50
	Percentage voltage THD	1.91	3.85	2.25
	Percentage current THD	5.55	4.02	6.07
	EV charger current (A)	16	16	16
	P.f (min)	0.5	0.5	0.8
Case 3	Grid voltage (V)	121	123	121
	Grid current (A)	10	12	10
	Percentage voltage THD	3.52	9.44	4.27
	Percentage current THD	4.58	4.58	6.40
	EV charger current (A)	16	16	12
	P.f (min)	0.5	0.65	0.7

Scenario 3: The smart charger is in charging condition at only one phase

The Scenario 3 operates at only one phase, where both the loads are connected at C. In the absence of UPQC (Case 1), there is voltage sag, and even though smart charger is in charging mode, it can able to maintain 104 V, whereas in Case 2 and

Case 3, in the presence of UPQC system, voltage is maintained at its RMS value. All remaining parameters are within the limit as tabulated in Table 2.

4 Conclusion

PQ issues due to the penetration of EV charger in the proposed AC/DC hybrid microgrid system is analyzed for three cases and three scenarios. PV-powered UPQC is capable of resolving these issues in the grid system. System is analyzed for both in coupled to grid as well as in island modes.

Voltage and harmonic-related issues have raised in the grid system due to the attachment of EV smart charger. These analyses are done for grid-coupled and isolated mode with and without PV-powered UPQC. From the results, it is evident that voltage levels are improved, power factor is also in the acceptable limit, and also voltage and current harmonics are also within the safer range. Power quality issues due to EV charger are also analyzed and tested for the same cases and scenarios in the standard IEEE 14 bus microgrid environment. The results of all scenarios for the three cases are tabulated for the proposed AC/DC hybrid microgrid network in Table 1, and the validated results for the standard IEEE 14 bus microgrid environment are listed in Table 2. From these outcomes, it is evident that voltages are below the RMS value (i.e., below 200 V in test system and it is below 120 V in the standard system) for Case 1 (i.e., when UPQC is not inaction). There is an improvement in the voltage stability both in test as well as in standard IEEE 14 bus system when UPQC is connected (i.e., in Case 2). In the off-grid mode, the DC power is supplied to the load via battery. The PV and accumulator are acting at one time to satisfy both EV and the transient load. UPQC is performed well comparatively in off-grid mode, i.e., in Case 3. In both the system power factors, EV currents are in acceptable limit. Thus, the performance of PV-powered UPQC is validated in standard IEEE 14 bus microgrid and provides better performance.

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