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Implementation of Solar PV- Battery and Diesel Generator Based Electric Vehicle Charging Station

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***Abstract*— In this paper, a solar PV (Photovoltaic) array, a battery energy storage (BES), a diesel generator (DG) set and grid based EV charging station (CS) is utilized to provide the incessant charging in islanded, grid connected and DG set connected modes. The charging station is primarily designed to use the solar photovoltaic PV array and a BES to charge the electric vehicle (EV) battery. However, in case of exhausted storage battery and unavailable solar PV array generation, the charging station intelligently takes power from the grid or DG (Diesel Generator) set. However, the power from DG set is drawn in a manner that, it always operates at 80-85% loading to achieve maximum fuel efficiency under all loading conditions. Moreover, in coordination with the storage battery, the charging station regulates the generator voltage and frequency without a mechanical speed governor. It also ensures that the power drawn from the grid or the DG set is at unity power factor (UPF) even at nonlinear loading. Moreover, the PCC (Point of Common Coupling) voltage is synchronized to the grid/ generator voltage to obtain the ceaseless charging. The charging station also performs the vehicle to grid active/reactive power transfer, vehicle to home and vehicle to vehicle power transfer for increasing the operational efficiency of the charging station. The operation of the charging station is experimentally validated using the prototype developed in the laboratory.**

***Index Terms*— EV Charging Station, Solar PV Generation, Power Quality, DG Set.**

I. Introduction

Currently, electric vehicles (EVs) are recognized as one of the most efficient modes of transportation with zero trailing emission. Considering the advantage of EVs, 3 million vehicles are already deployed on the road, and it is expected to cross 100 million by 2030 [1]. However, the execution of proposed plan demand for huge charging infrastructure and enormous electrical energy. Moreover, EVs can only be sustainable when the electrical energy required for charging is generated from renewable and sustainable energy sources. However, the use of fossil fuels for electricity generation, does not reduce the emission but merely shift it from vehicles to the power plant. Therefore, the use of renewable energy sources for electricity generation can completely eliminate the emission and provides an environmental benefit. Among various available renewable energy sources, solar PV array, wind energy, hydro energy and fuel cell based energy, solar PV based generation is a most feasible solution for EV charging because it is available almost everywhere irrespective of the rural or urban region [2]. As far as the Indian region is concerned, it is available almost throughout the year. On the contrary to the solar PV array, the wind and hydro energies are location specific. The wind energy is mostly useful in the coastal region, and hydro energy is useful for hilly region.

Though, the renewable energy based charging stations are the most feasible solution for the EV charging, however, their integration to the existing charging system introduces the additional power conversion stage, which increases the complexity and power loss in the system. Moreover, each conversion stage needs an individual controller, which needs to be integrated with the existing control. Therefore, it is imperative to design an integrated system with multifunctional and multimode operating capability, for which a unified control and coordination between the various sources are essential.

Many efforts have been made to develop the renewable energy based charging station. Ugirumurera et al. [3] have discussed the importance of renewable energy for the sustainability of the EV charging station. Mouli et al. [4] have utilized the solar power for charging of EVs using the high power bidirectional EV charger. However, the designed charger does not provide the AC charging. Monterio et al. [5] have presented a three port converter for integrating PV array with the EV charger. However, the designed charger does not consider the current distortions in the grid current created by the charger. Singh et al. [6] have proposed a modified z-source converter for designing of PV array/grid connected EV charger. However, the charger is not designed for the islanded mode of operation. Therefore, it cannot provide the EV charging in absence of grid. Chaudhari et al. [7] have discussed a hybrid optimization model for managing the battery storage such that the running cost of charging station can be minimized and the solar PV array power is utilised maximally. Kineavy et al. [8] have proposed to use the on-site PV generated power (deployed on the commercial building) in coordination with the EV charging station for maximum utilisation of solar PV array (under uncertainties) with less impact on the grid. Zhang et al. [9] have studied the optimal scheduling of the EV charging station in workplace with dual charging modes. The PV array powered charging station (CS) is also suitable for the onsite deployment for the best quality of service at a minimum cost while reducing the grid impact of charging [10]. Kandasamy et al. [11] have investigated the loss of life of a storage battery used with the commercial building based solar PV array system. The wind energy powered CS is also beneficial for EV due to its availability in both day and night time, and many publications are available in this area [12]-[14].

EVs nowadays are also used as a distributed energy resource for providing various ancillary services due to the huge amount of energy stored in EV batteries. Singh et al. [15] have presented a PV array based CS for providing charging facility along-with the vehicle-to-grid reactive/active power, active power filtering and vehicle-to-home. Saxena et al. [16] have implemented a grid tied PV array system for EV and residential application. Razmi et al. [17] have proposed the power management strategy with multi-mode control of an integrated residential PV-storage battery system for both grid-connected and islanded operation. Erdinc et al. [18] and Kikusato et al. [19], Hafiz et al. [20] have presented the smart household operation such that EV can be used as a storage for providing

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the vehicle-to-home and vehicle-to-grid operation for the benefits of both utility and the consumer.

The detailed analysis of reviewed literature, advocates that the work presented in the area of renewable energy based charging station, are mostly focusing on the optimization of different aspects of charging such as the size of the renewable energy sources, size of the storage unit, vehicle driving pattern, charging time, charging cost, charging scheduling etc. However, in present scenario only few publications have actually implemented the charging station using renewable energy sources. Moreover, the performance of charging station under real circumstances, is also less discussed.

Moreover, in most of the literature, the performance of CS, is discussed only in either grid connected mode or islanded mode. However, due to the single mode of operation in grid connected mode, the solar PV panel becomes unusable if the grid is not available even if the sun (solar irradiance) is available. Similarly, in islanded mode, the PV power is disturbed by the intermittency of solar irradiance. Therefore, a storage battery is required for mitigating the effect of variable solar irradiance. However, in case of the fully charge storage battery, the maximum power point tracking (MPPT) has to be disabled to avoid the overcharging of the storage battery.

Therefore, in this paper, a PV array, grid, energy storage and DG set supported CS is presented, which operates in islanded, grid connected and DG set connected modes, so that the PV array energy is utilized for all operating conditions.

Some publications [15] have discussed both islanded and grid connected modes. However, these two modes are controlled separately and the automatic mode switching between two modes are not presented. Therefore, without automatic mode switching capability, the PV array power is to be interrupted and the charging of the EV is not to be continuous. Therefore, in this paper, an automatic mode switching logic is presented, so that the controller automatically switches between different operating modes depending on the power generation of PV array and the charging demand of EV.

Due to the unavailability in the night and the intermittent nature of the PV array, storage battery with PV array is used for continuous and reliable operation of CS. However, due to the limited storage capacity of the storage battery, it is hardly possible to provide backup all the time. Therefore, the CS needs support of the grid in case of PV array energy is unavailable, and energy storage is also discharged.

However, due to the limited availability of grid, especially in remote areas, the DG set may be required for maintaining the continuity of the charging. However, the DG set performance is affected by the type of loading, and it is not utilised to its full capacity. Generally, the DG sets are designed for very limited amount of harmonics in the load current [21]. Therefore, the DG set performance is severely affected by the EV charging, due to presence of harmonics in the EV current because the charger of the EV generally uses rectifier followed by a power factor correction circuit and a DC-DC converter for step down. However, in this paper, the DG set is always loaded to at least 80% of the rated value because the harmonics and reactive current requirement of the EV charger are provided by the voltage source converter (VSC).

The major contributions in this paper, are as follows.

- Design and experimental validation of PV array, energy storage and DG set supported grid integrated CS, which uninterruptedly supports both DC and AC charging of EVs.
- Design of a unified controller, which enables the charging station to operate in islanded, grid connected and DG set connected modes without changing the hardware and using only a single VSC.
- Design of a mode switching logic using which, the charging station changes the mode seamlessly to provide the continuous charging.
- Design of control strategy for vehicle-to-vehicle (V2V) power transfer for charging the EV and vehicle-to-grid (V2G) power transfer for supporting the grid.
- Active power filter operation of the charging station for mitigating the grid current harmonics, so that the power exchange takes place at unity power factor. This is required for the compliance of the charging station with the IEEE-519 standard.
- Strategy for regulating the frequency and voltage of DG set without mechanical automatic voltage regulator.
- Strategy to feed the surplus PV array generated power into the grid for avoiding the overcharging of the storage battery.

II. System Description

The presented charging station, as shown in Fig. 1, uses a solar PV array, a storage battery, a DG set and grid energy to charge the EV and to feed the load connected to charging station. The solar PV array is connected at DC link of voltage source converter (VSC) through a boost converter and a storage battery is connected directly to DC link. The grid, a single phase SEIG (Self Excited Induction Generator), an EV and a nonlinear load, are connected on the AC side of VSC through a coupling inductor. A ripple filter at PCC, is used to eliminate the switching harmonics from the grid and the generator current and to make these currents sinusoidal. An excitation capacitor is connected to the auxiliary winding of the SEIG. A small capacitor is also connected across the main winding of the SEIG. A synchronizing switch is used between grid/DG set and PCC for controlled connection/ disconnection of charging station to grid/DG set.

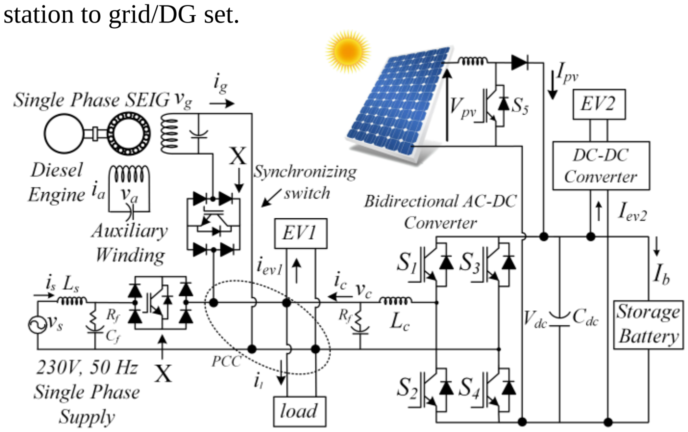

Fig. 1 Topology of charging station

III. Control Strategies

Various control strategies used in the CS, are discussed here.

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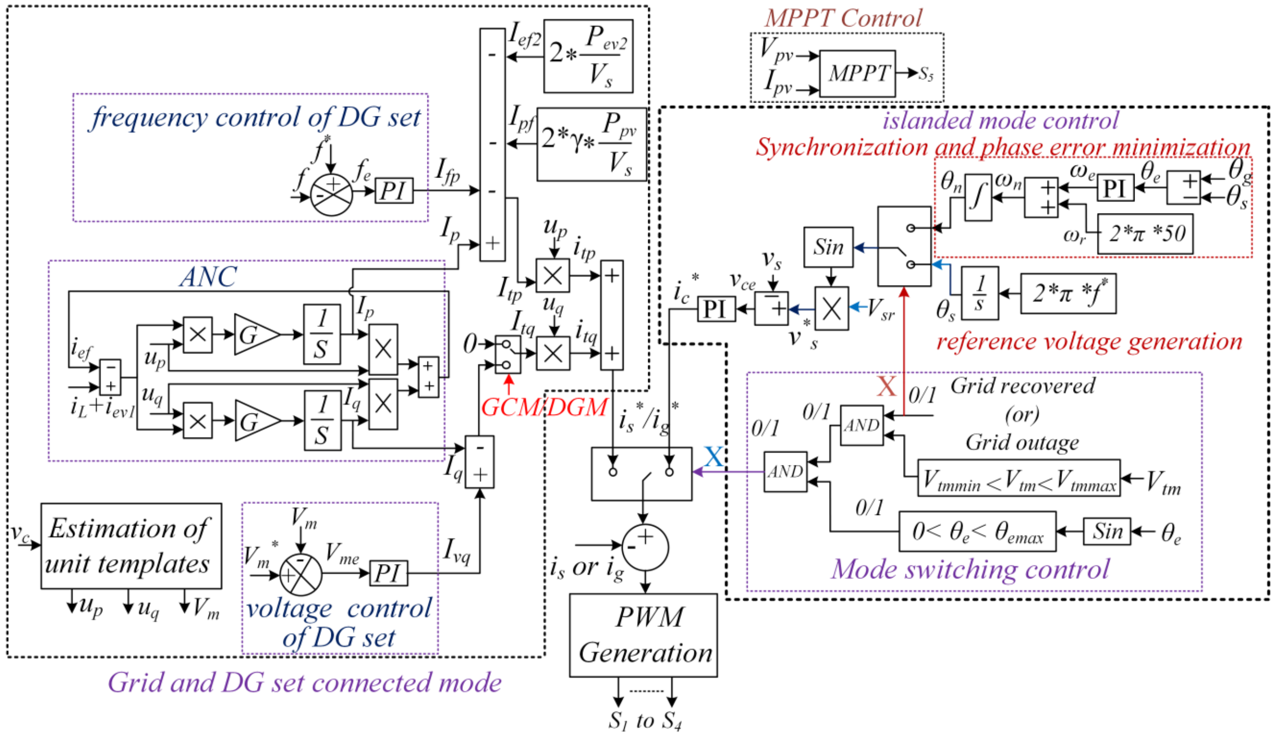

Fig. 2 Unified control of VSC for standalone and grid and DG set connected mode

A. Control of VSC in Islanded Mode (Absence of DG Set and Grid)

The islanded control of the CS ensures the stable operation of the CS in absence of the grid, which means the AC as well as the DC charging of the EV remains intact along with the undisturbed solar power generation. The DC charging and the solar PV generation can be managed by the storage battery without much modification in the control. However, the AC charging needs a separate controller for VSC using which the local voltage reference is generated, because in absence of the grid no voltage reference is available. Therefore, the islanded controller generates the internal voltage reference of 230V and 50 Hz as per the logic presented in Fig. 2, which integrates the frequency and pass through the sin for generating the reference voltage. The generated reference is compared with the terminal voltage of the converter, which ultimately gives the reference converter current after minimisation of voltage error using proportional integral (PI) controller. The error minimisation and reference current generation is expressed as,

$$i_c^*(s) = i_c^*(s-1) + z_{pv}\{v_{ce}(s) - v_{ce}(s-1)\} + z_{iv} v_{ce}(s) \quad (1)$$

The reference current after comparison with sensed converter current and after passing through hysteresis controller generates the gate signals of the converter.

B. Control of VSC in DG Set or Grid Connected Mode

In grid connected mode, the controller task is to decide the amount of power to be exchanged with the grid. In DG set connected mode, DG set operates in constant power mode for achieving maximum fuel efficiency. However, in both cases, the controller has to compensate the harmonic and reactive current demand of the EVs, which is achieved by estimating the reference current of the grid or the DG set from the EV current. In grid connected condition, the reference current is estimated by considering only the active current of the EV current. However, in DG set connected mode, the reference DG set current is estimated using both reactive and active currents of the EV. In this work, an adaptive notch cancellation (ANC) [22] extracts the fundamental frequency current of the EV. Further with the sample and hold logic, the fundamental current at every zero crossing of quadrature and in-phase unit template, gives the active and reactive current, respectively.

Now, the total active and reactive currents in grid connected mode are as,

$$I_{sp} = I_p - I_{ef2} - I_{pf} \quad (2)$$
$$I_{sq} = 0$$

In grid connected mode, only active current of EV is considered and the reactive current is considered zero for achieving unity power factor operation. However, in DG set connected mode, both active and reactive current components of EV are used.

Now, total active and reactive current in DG set connected mode is as,

$$I_{sp} = I_p - I_{ef2} - I_{fp} - I_{pf} \quad (3)$$
$$I_{sq} = I_{vq} - I_q$$

Where, I_p and I_q are the active and reactive currents of EV, and I_{ef2} and I_{pf} are the feed-forward term of the EV2 and the PV array. I_{fp} and I_{vq} are the frequency and voltage regulators terms used in the DG set connected mode. I_{ef2} controls the vehicle to grid power transfer of the EV. I_{pf} is the PV array feed-forward term in grid-connected mode, which controls the overcharging of the storage battery. Since the energy storage is directly interfaced to DC link, the storage battery cannot be charged in CC/CV mode. However, it can be ensured that the storage battery does not get over charged in any condition. In grid connected condition, overcharging of storage battery is protected by feeding the solar PV generated power into the grid. This is achieved by adding the solar PV array feed-forward term in the grid connected mode control as shown in Fig. 2. A variable gain 'γ' is also multiplied with the feed-forward term, which decides the percent of PV array power fed into grid. Constant 'γ' is defined between 0-1, which is decided by the SOC information of the storage battery. Therefore, if the storage battery is fully charged, the 'γ' takes the value as '1'. However, in case of fully drained storage battery, the 'γ' becomes '0'.

Finally, the estimated reference current of grid or DG set is as,

$$i_s^* or\ i_g^* = I_{tp} \times u_p + I_{tq} \times u_q \tag{4}$$

Where u_p and q_p are synchronizing signals of the DG set or grid voltage (v_g or v_s). Using the sensed and the reference current of grid/DG set, the switching signals are generated using hysteresis controller as shown in Fig. 2.

C. DG Set Control for Voltage and Frequency

For operating the DG set at single point, the frequency and voltage of DG set are regulated using decoupled control of VSC. In decoupled control, the frequency is regulated by the active power and the voltage is regulated by reactive power. Therefore, two PI controllers are used for voltage and frequency regulations. The PI control for voltage regulation is given as,

$$I_{vq}(s) = I_{vq}(s-1) + z_{vp}\{V_{me}(s) - V_{me}(s-1)\} + z_{vi}V_{me}(s) \tag{5}$$

Where $V_{me}=V_m^*-V_m$ and the z_{vi} and z_{vp} are the PI controller gains.

Similarly, the discerate expression of the frequency PI controller is as,

$$I_{fp}(s) = I_{fp}(s-1) + z_{fp}\{f_e(s) - f_e(s-1)\} + z_{fi}f_e(s) \tag{6}$$

Where f_e is the error in frequency and zk_{fp}, z_{fi} are PI gains.

The outputs of the frequency and voltage controllers are added in grid connected control as shown in Fig. 2. However, the outputs of these controllers become zero in grid connected mode as the voltage and frequency of the grid remain regulated.

D. Control of EV2

EV connected at DC link through a DC-DC converter is controlled in constant current/constant voltage (CC/CV). Until the terminal voltage of the EV battery reaches the voltage corresponding to the full charge condition, the EV charges in CC mode. However, after reaching near to the desired terminal voltage in nearly full charge condition, the charging of the EVs is shifted in CV mode. Here, the CC/CV mode of charging is controlled using two PI controllers as shown in Fig. 3. The outer voltage loop gives reference current for current control stage.

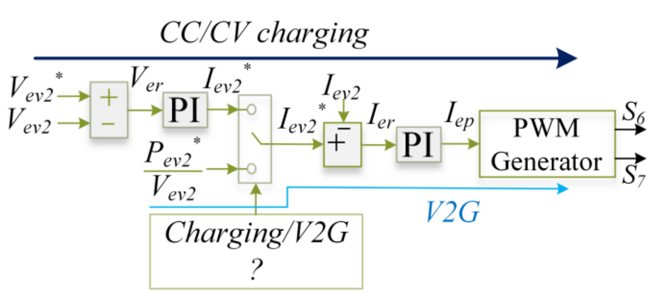

Fig. 3 EV2 control for CC/CV charging and V2G power transfer

The reference charging current is estimated as,

$$I_{ev2}^*(s) = I_{ev2}^*(s-1) + z_{evp}\{V_{er}(s) - V_{er}(s-1)\} + z_{evi}V_{er}(s) \tag{7}$$

Where, V_{er} is the EV battery voltage error and z_{evp} and z_{evi} are the controller gains.

Using the reference and sensed battery currents, the switching signals of the converter are derived using the PI controller and PWM generator. The PI controller for duty cycle calculation is expressed as,

$$d_{ev}(s) = d_{ev}(s-1) + z_{ep}\{I_{er}(s) - I_{er}(s-1)\} + z_{ei}I_{er}(s) \tag{8}$$

Where I_{er} is battery current error and z_{ep} and z_{ei} are controller gains.

For the V2G power transfer, the EV2 battery is discharged on the basis of the reference power and the controller takes the alternate path as shown in Fig. 3. The reference power controls the EV2 feed-forward term in Fig. 3.

E. Synchronization and Switching Control

Since the charging station operates in many modes, depending upon the generation and the charging demand, the design of mode changing strategy is necessary, so that the switchover from one mode to another mode becomes smooth and the charging remain undisturbed. Islanded to grid connected and islanded to DG set connected modes are such conditions for which the mode switching logic is designed. In this strategy, at first the phase difference between the two voltages are acquired and controller brings two voltages in same phase for the purpose of synchronization. For this the PI controller changes the frequency of the VSC generated voltage in islanded condition using the logic shown in Fig. 2. The PI controller for phase minimization is given as,

$$\Delta\omega(s) = \Delta\omega(s-1) + z_{pa}\{\Delta\theta(s) - \Delta\theta(s-1)\} + z_{ia}\Delta\theta(s) \tag{9}$$

Where $\Delta\theta$ is phase difference, and z_{pa} and z_{ia} are controller tuning parameters.

Fig. 2 also shows the conditions for which the CS operates in islanded mode and under which condition, the mode transition has to be done. On fulfilling, all the requirements of synchronization, the control logic generates the enabling signal X='1', for the synchronizing switch.

IV. Results And Discussion

The performance of the CS is discussed with both simulation and experimental results.

A. Simulation Results

Simulated results shown in Fig. 4, present the uninterruptible operation of the CS. Initially, the CS is operating in the islanded mode, and the PV array power is fed for charging the EVs connected at PCC. Since the PV array generation is exceeding the EVs charging demand, the surplus generation is stored in the energy storage. At 0.32s, the solar irradiance changes from 1000 W/m^2 to 300 W/m^2. Due to which, the PV array power reduces, and the storage battery starts discharging to keep the charging uninterruptible. At 0.48s, the storage battery discharges, as the PV array power becomes zero. After this, the storage battery completely supports the charging, as long as the SOC > SOC$_{min}$. After, the complete discharge of the battery, the controller connects the CS to the grid after the synchronization.

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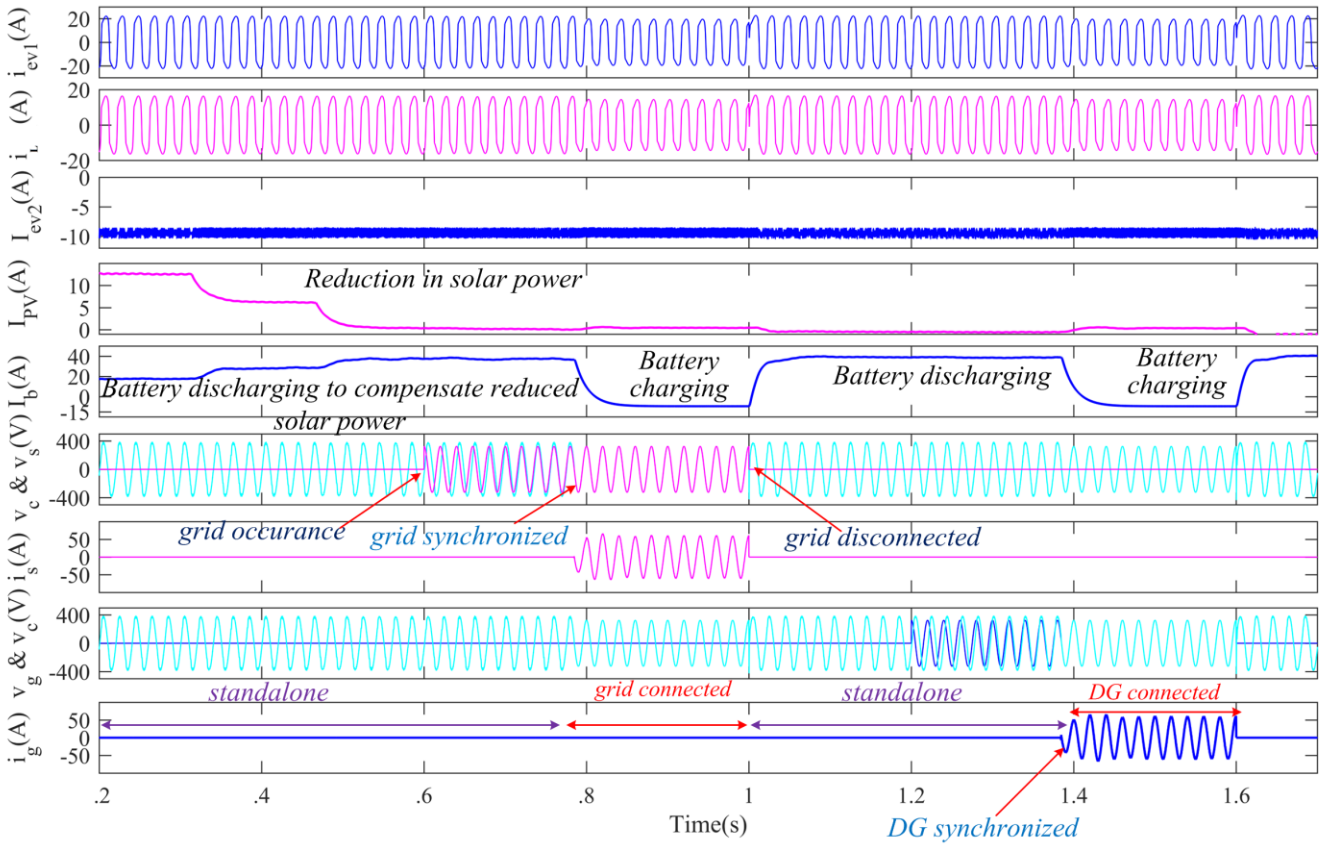

Fig. 4 Simulation results showing the different modes of operation

At 0.79s, the CS has started drawing power from grid. After this point, CS is supported by the DG set due to unavailibility of grid and storage battery power as shown in Fig. 4. From Fig. 4, it is observed that the charging station is automatically changing the modes depending upon the generation and demand.

B. *Experimental Results*

The photograph of the developed experimental setup in the laboratory is shown in Fig. 5. Test results of charging station, are shown in Figs. 6-12. For a hardware implementation, a solar PV simulator (TerraSAS) is used as a solar PV array. A lead-acid battery of 360V, 14Ah is used as an energy storage. A nonlinear load connected at PCC, is realized using a diode bridge rectifier followed by the resistive and inductive load on the DC side of the rectifier. However, an EV is connected at PCC through the charger. A 3.7 kW, single phase, two winding SEIG, is used as a diesel engine driven generator. An excitation capacitor of 144 μF is connected across the auxiliary winding of the SEIG to generate the rated voltage across main winding at no-load. A 7.5kW SCIM (Squirrel Cage Induction Motor) driven by variable frequency drive is used as a prime mover of the DG set. The control algorithm of the CS station, is implemented using the digital controller (dSPACE-1006).

I. *Performance under Steady State Operating Condition*

The CS performance under steady state conditions verifies the power balance capability and power quality maintenance capability of the charging. Since the charging station operates in many modes depending upon the power generation and charging demand, the steady state results are discussed for three cases, (1) islanded mode: EV charging using solar PV array, (2) grid connected charging, (3) DG set connected charging.

1) *EV Charging in Grid Connected Mode (Unavailable PV Array Power)*

In grid connected mode, the power drawn from the grid, is at UPF even though the load connected at PCC is nonlinear as shown in Figs. 6 (a), (b).

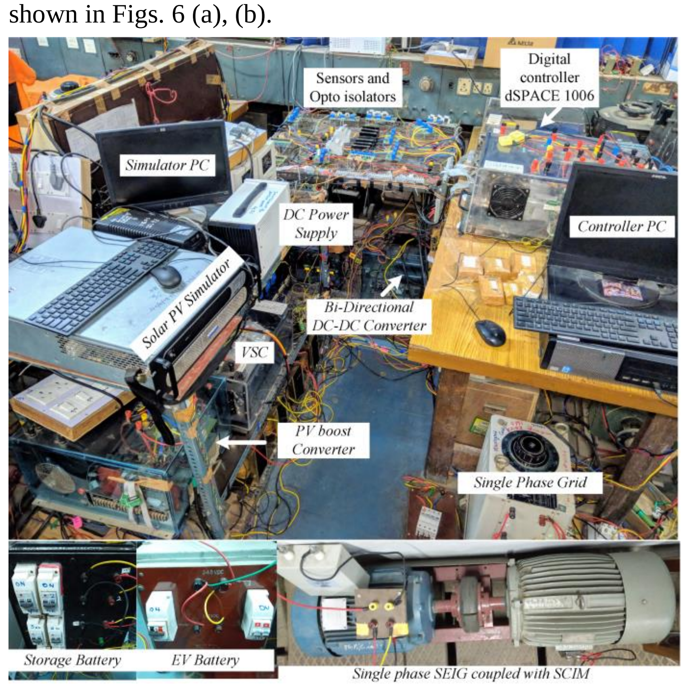

Fig. 5 Experimental setup

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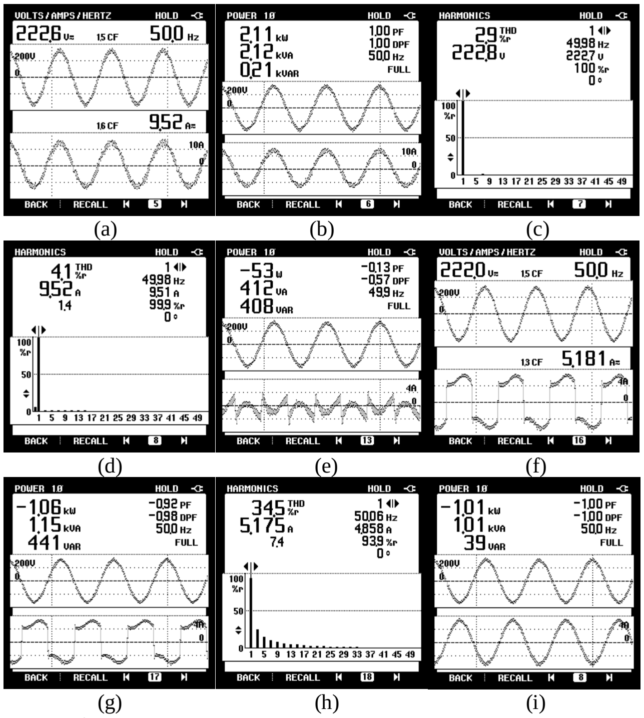

Fig. 6 Performance under grid connected mode, (a) v_s and i_s, (b) grid power, (c)-(d) THDs of v_s and i_s, (e) VSC power, (f) v_c and i_L,(g) load power, (h) THD of i_L ,(i) EV power

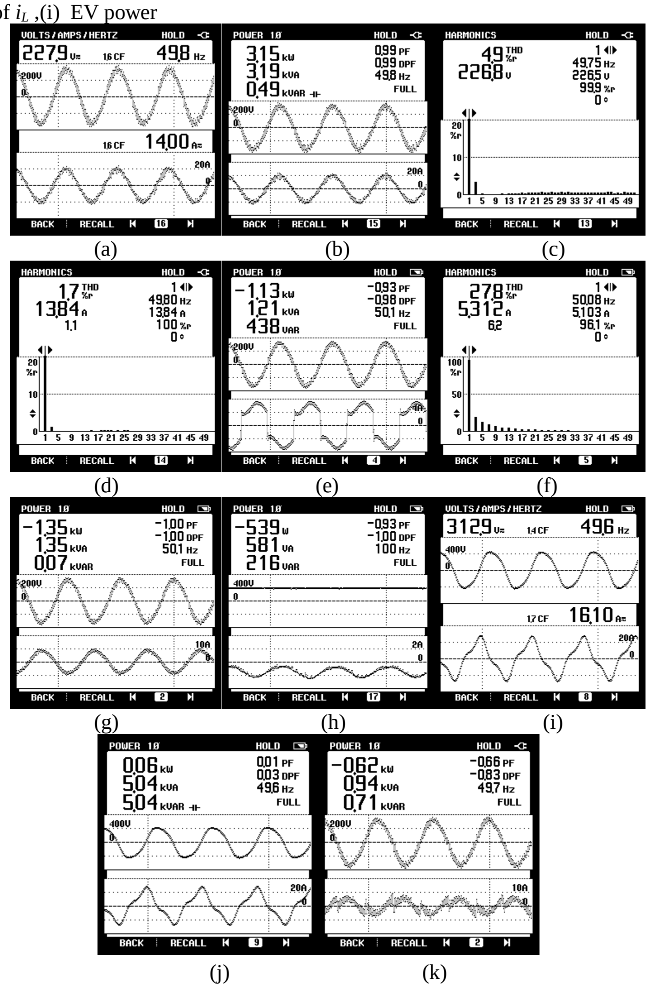

Fig. 7 Performance of the charging station when DG set is feeding load, charging EV and charging storage battery, (a) v_g and i_g , (b) generator power, (c)-(d) THDs of i_g and v_g, (e) load power, (f) THD of i_L, (g) EV power, (h) battery power, (i) v_a and i_a, (j) auxiliary winding power, (k) VSC power

The harmonic current demand of the nonlinear load, is supplied by VSC as shown in Fig. 6(e). The THDs of grid voltage (v_s) and current (i_s) are 2.9% and 4.1% as shown in Figs. 6 (c)-(d). The load and EVs voltage, current, and power, are shown in Figs. 6 (f)-(i).

2) *EV Charging in DG Set Connected Mode (Absence of both Grid and PV Array Generation)*

The DG set is feeding load, charging EV and charging storage battery when the solar PV array generation and grid, are not available, and the storage battery is also discharged. In this condition, the DG set is always operated at 80-85% of the loading so that the efficiency of the diesel engine remains maximum. A 3.7kW DG set is generating 3.15 kW electrical energy. The generator voltage (v_g), current (i_g) and their total harmonic distortions (THDs) are shown in Figs. 7(a)-(d). Out of 3.15 kW of generated power, the nonlinear load is taking 1.13kW and EV is taking 1.35kW. The voltage (v_c), current (i_L) and power of the nonlinear load, are shown in Fig. 7 (e). Whereas, the voltage (v_c), current (i_{ev}) and power of the EV, are shown in Figs. 7(h)-(i). Remaining power of the DG set is stored in the storage battery. The voltage (V_b), current (I_b) and power of the storage battery, are shown in Fig. 7(h). The THD of the load current (i_L) is 27.8% as shown in Fig. 7 (f). Though the DG set is supplying the nonlinear load, the THD of the generator current (i_g) is only 1.7%. This is because the harmonics current required by the nonlinear load is supplied by the VSC as shown in Fig. 7(k). Here, the storage battery ensures that the DG set always operates at 80-85% of loading. In case, the combined demand of the EV and load, exceeds 80-85% loading of the DG set; the storage battery discharges its energy to supply the extra power demand. The storage battery also helps in regulating the generator frequency at 50Hz by maintaining the active power balance. The voltage (v_a) and current (i_a) of the auxiliary winding of the generator, are shown in Figs. 7 (i)-(j). From Figs. 7 (i)-(j), it is seen that the excitation capacitor is supplying the reactive power to maintain the voltage of the generator.

II. CS Performance under Dynamic Conditions

The behavior of the hybrid CS is validated in islanded, grid connected and DG set connected mode under the irradiance disturbance and EV charging current change.

1) Performance in Islanded Mode Operation

In islanded mode, the CS operation is disturbed by the solar irradiance change and EV current change, and the energy storage compensates for all disturbances. Figs. 8 (a)-(b) are showing that the change in irradiance is affecting the PV array generation and energy storage is actively compensating the reduction in PV generated power, so that the EV charging remain undisturbed. The same is exhibited by the undisturbed EV current.

Similarly, under disturbance in charging current of one EV, the charging of another EV is not getting disturbed. Moreover, the PV generation also remains stable. Figs. 8 (c)-(d) show the performance at the step variation in charging current of EV2.

Figs. 8(e)-(f) show the performance under the variation in AC charging current of EV. From Figs. 8 (c)-(f), it is verified that the storage battery is compensating the power imbalance occurring due to the disturbance in EV charging current. Along

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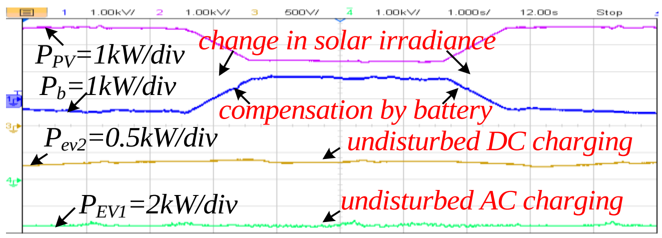
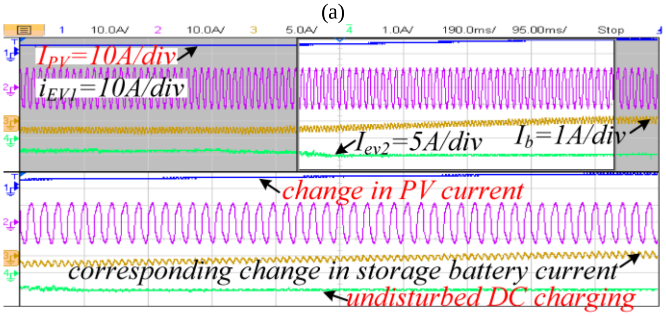
with the change in solar irradiance level, the EV is also connected or disconnected. In this condition also, the storage battery takes care of the change in demand at charging station as shown in Fig. 8(g).

2) Performance in GCM

In GCM, the performance under the variation in AC charging demand of EV are exhibited in Figs. 9 (a)-(b). The change in AC charging demand is affecting only the grid power. However, the PV generation remains constant as shown in Figs. 9 (a)-(b). The CS behavior during the change in irradiance are exhibited in Figs. 9 (c)-(d).



(a)



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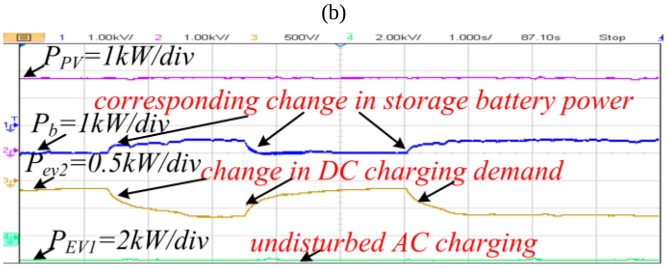
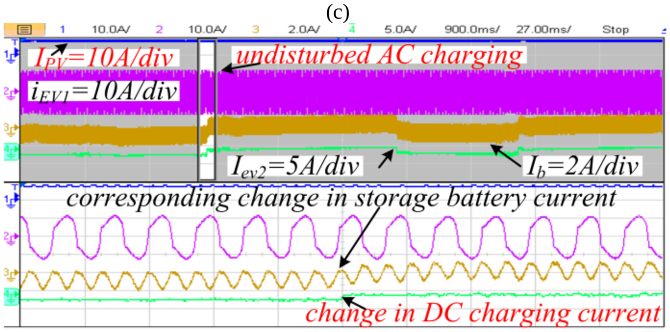
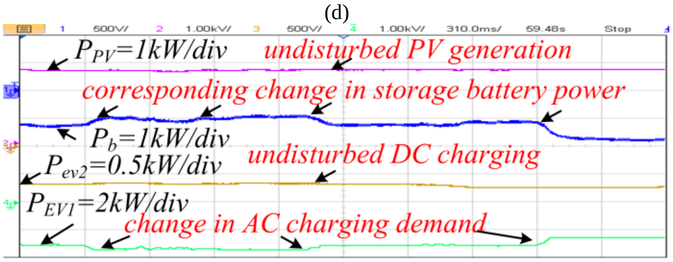


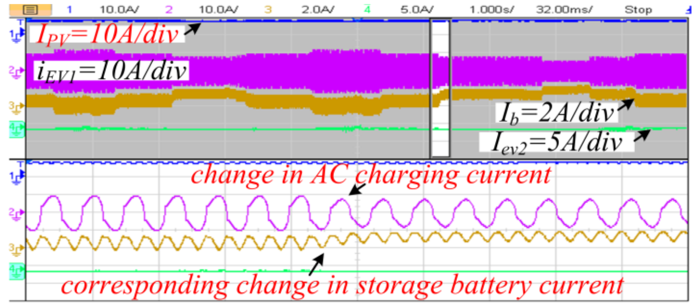
(c)



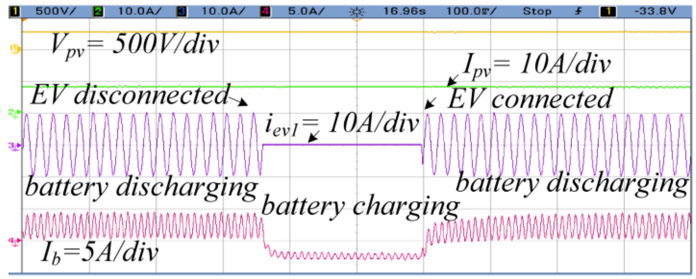
(d)



(e)



(f)



(g)

Fig. 8 Dynamic performance in islanded mode, (a)-(b) under solar irradiance change, (c)-(d) under change in DC charging (EV3) demand, (e)-(f) under change in AC charging (EV1) demand, (g) under EV connection/disconnection

Under the disturbance in irradiance level, PV array generated power is changing. Consequently, the power fed into the grid is changing to balance the active power. However, the charging of the EV remains undisturbed under irradiance change as exhibited in Figs. 9 (c)-(d). The vehicle-to-grid (V2G) power transfer capability of the CS is shown in Fig. 9 (e). Due to the discharging of the EV2 battery power, the power fed into the grid increases. However, PV array generation and AC charging of the EV remain undisturbed.

3) Performance Under DG Set Connected Mode

To show the efficient operation of DG set under all loading conditions, the load at PCC is changed as shown in Fig. 10 (a). The DG set current (i_g) remains undisturbed under the load change. Moreover, the voltage (v_g) and frequency of the DG set, are also regulated at the reference values. However, the power balance under load change is maintained by the storage battery. This is observed by the change, in the battery current (I_b) with the change in load current (i_L). Fig. 10 (b) shows that the VSC current (i_c) also changes with the change in the nonlinear load. However, the DC link voltage (V_{dc}) and the charging current of the EV (iev), do not change.

4) Automatic and Uninterruptible Mode Switching Performance of Charging Station

The performance of the synchronization of grid voltage (v_s) to the PCC voltage (v_c) is shown in Figs. 11 (a)-(b). Fig. 11 (a) shows that the on the occurrence of the grid, the control of the charging station first synchronizes the grid voltage to the PCC voltage. After that, the grid starts feeding the demand at PCC and charges the storage battery. Fig. 11(b) shows the performance of control loop as discussed in Fig. 2 and generation of the control signal "X" for the bidirectional switch. Fig. 11 (b) shows that the load current remains undisturbed under synchronization/de-synchronization process.

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5) *Performance of V2G Reactive Power Support and Active Filtering*

Fig. 12 (a) shows the performance under step change in reactive power demand. Due to the step change in the reference reactive power (Q_{ref}) from -1kVAR to 1kVAR, the grid current (i_g) becomes lagging from leading. Fig. 12(b) shows the harmonic compensation capability of CS. It is observed that the grid current becomes sinusoidal after the compensation, which is same as the load current without compensation.

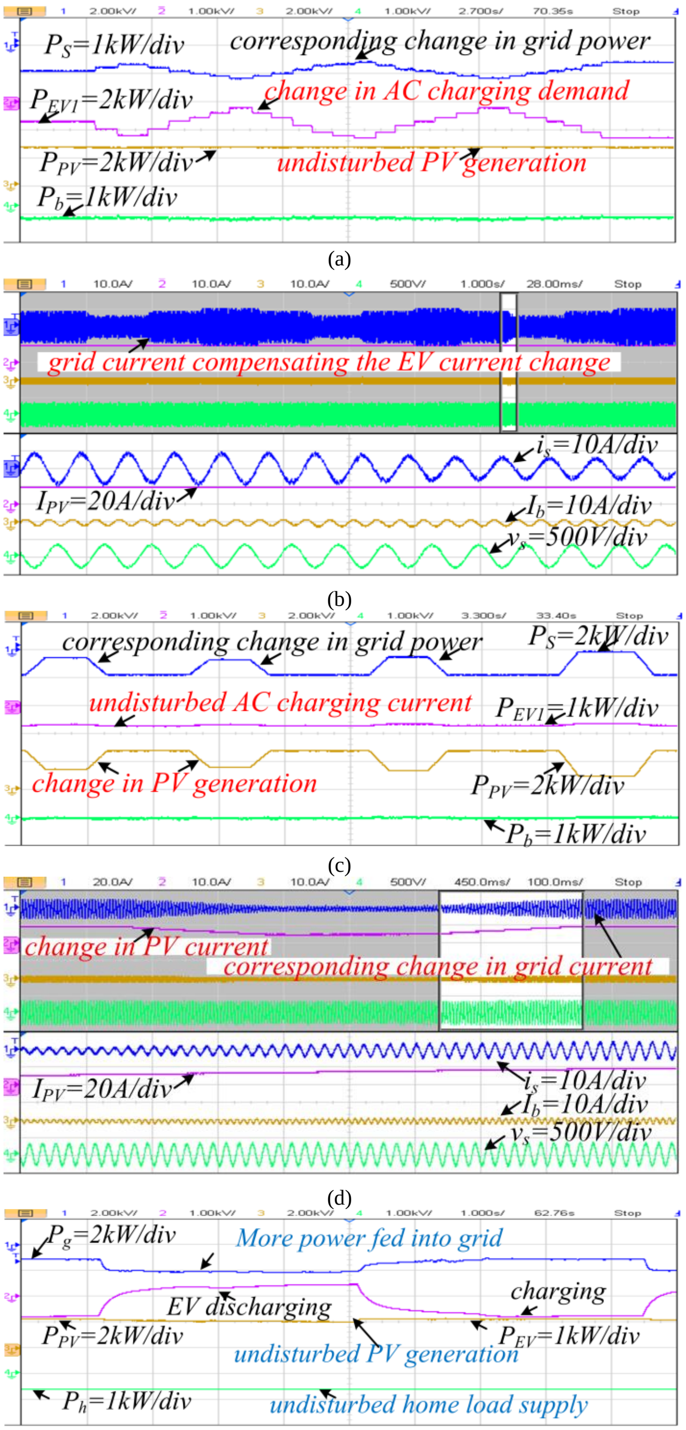

Fig. 9 Dynamic performance in grid connected mode, (a)-(b) under change in AC (EV1) charging demand, (c)-(d) under solar irradiance change, (e) under change in DC charging (EV2) demand (V2G)

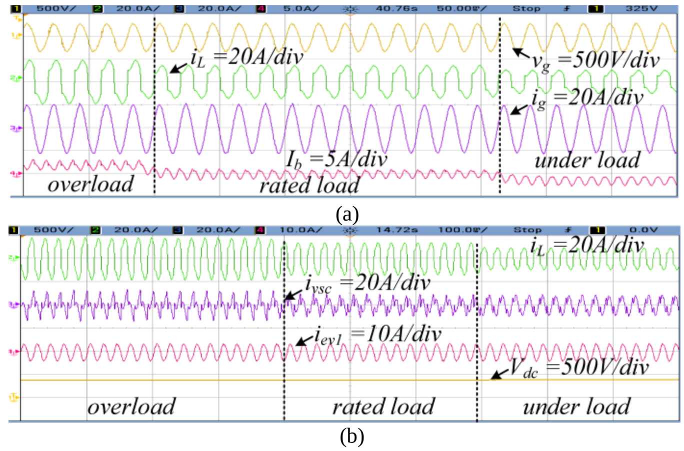

Fig. 10 Dynamic performance of the charging station with DG set, (a)-(b) under load change

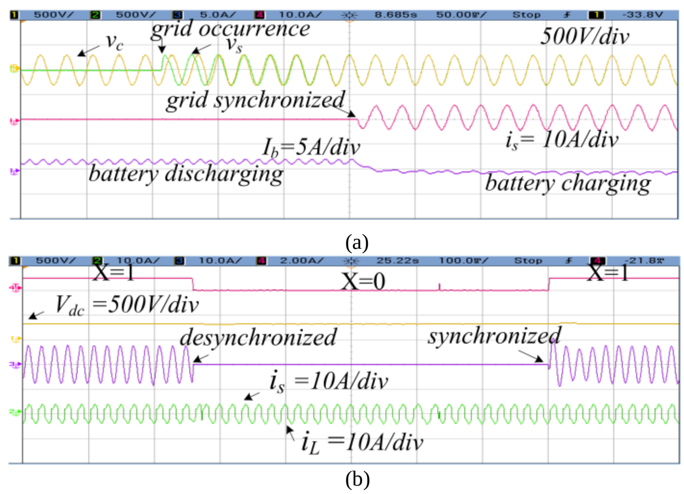

Fig. 11 Automatic and uninterruptible mode switching (a) synchronization of grid voltage with PCC voltage, (b) generation of signal X=0/1

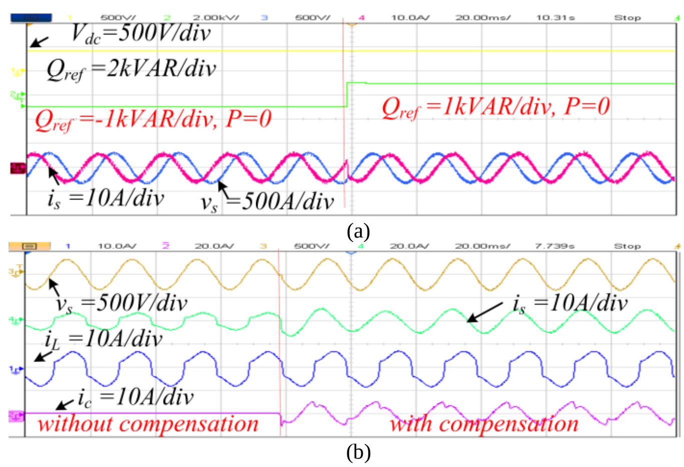

Fig. 12 Performance of charging station (a) under V2G reactive power compensation, (b) under active filtering

V. Conclusion

An implementation of PV array, storage battery, grid and DG set based charging station has been realized for EV charging. The presented results have verified the multimode operating capability (islanded operation, grid connected and DG set connected) of the CS using only one VSC. Test results have also verified the satisfactory operation of charging station under different steady state conditions and various dynamics

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conditions caused by the change in the solar irradiance level, change in the EV charging current and change in the loading. The operation of charging station as a standalone generator with good quality of the voltage, has been verified by the presented results. Whereas, test results in DG set or grid connected mode, have verified the capability of ANC based control algorithm to maintain the power exchange with the grid at UPF or the optimum loading of the DG set. Moreover, the islanded operation, grid connected and DG set connected operations along with the automatic mode switching have increased the probability of MPP operation of the PV array and optimum loading of DG set along with increasing the charging reliability. The IEEE compliance operation of the charging station with voltage and current THD always less than 5% verifies the effectiveness of the control. Form the above mentioned point, it can be concluded that this charging station with the presented control have the capability to utilize the various energy sources very efficiently and provides the constant and cost effective charging to the EVs.

REFERENCES

[1] International Energy Agency-Global EV Outlook 2018- Towards cross-modal electrification. [Online] Available: https://webstore.iea.org /download/direct/1045?fileName=Global_EV_Outlook_2018.pdf

[2] International Energy Agency- Renewables 2O18 - Analysis and Forecasts to 2O23 [Online]. Available: https://webstore.iea.org/ download/summary/2312?fileName=English-Renewables-2018ES.pdf.

[3] J. Ugirumurera and Z. J. Haas, "Optimal Capacity Sizing for Completely Green Charging Systems for Electric Vehicles," *IEEE Trans. Transportat. Electrificat.*vol. 3, no. 3, pp. 565-577, Sept. 2017.

[4] G. R. Chandra Mouli, J. Schijffelen, M. van den Heuvel, M. Kardolus and P. Bauer, "A 10 kW Solar-Powered Bidirectional EV Charger Compatible With Chademo and COMBO," *IEEE Trans, Power Electron.*, vol. 34, no. 2, pp. 1082-1098, Feb. 2019.

[5] V. Monteiro, J. G. Pinto and J. L. Afonso, "Experimental Validation of a Three-Port Integrated Topology to Interface Electric Vehicles and Renewables With the Electrical Grid," *IEEE Trans. Ind. Informat*., vol. 14, no. 6, pp. 2364-2374, June 2018.

[6] S. A. Singh, G. Carli, N. A. Azeez and S. S. Williamson, "Modeling, Design, Control, and Implementation of a Modified Z-Source Integrated PV/Grid/EV DC Charger/Inverter," *IEEE Trans. Ind. Electron.*, vol. 65, no. 6, pp. 5213-5220, June 2018.

[7] K. Chaudhari, A. Ukil, K. N. Kumar, U. Manandhar and S. K. Kollimalla, "Hybrid Optimization for Economic Deployment of ESS in PV-Integrated EV Charging Stations," *IEEE Trans. Ind. Informat.*, vol. 14, no. 1, pp. 106-116, Jan. 2018.

[8] F. Kineavy and M. Duffy, "Modelling and design of electric vehicle charging systems that include on-site renewable energy sources," in *IEEE 5th Int. Symp. Power Electron. For Distributed Gene. Syst. (PEDG)*, Galway, 2014, pp. 1-8.

[9] Y. Zhang, P. You and L. Cai, "Optimal Charging Scheduling by Pricing for EV Charging Station With Dual Charging Modes," *IEEE Trans. Intelligent Transportat. Syst.*, vol. 20, no. 9, pp. 3386-3396, Sept. 2019.

[10] Y. Yang, Q. Jia, G. Deconinck, X. Guan, Z. Qiu and Z. Hu, "Distributed Coordination of EV Charging With Renewable Energy in a Microgrid of Buildings," *IEEE Trans. Smart Grid*, vol. 9, no. 6, pp. 6253-6264, Nov. 2018.

[11] N. K. Kandasamy, K. Kandasamy and K. J. Tseng, "Loss-of-life investigation of EV batteries used as smart energy storage for commercial building-based solar photovoltaic systems," *IET Electrical Systems in Transportation*, vol. 7, no. 3, pp. 223-229, 9 2017.

[12] A. Tavakoli, M. Negnevitsky, D. T. Nguyen and K. M. Muttaqi, "Energy Exchange Between Electric Vehicle Load and Wind Generating Utilities," *IEEE Trans. Power Sys.*, vol. 31, no. 2, pp. 1248-1258, 2016.

[13] 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*, Early Access.

[14] P. Liu, J. Yu and E. Mohammed, "Decentralised PEV charging coordination to absorb surplus wind energy via stochastically staggered dual-tariff schemes considering feeder-level regulations," *IET Gene., Trans. & Distri.*, vol. 12, no. 15, pp. 3655-3665, 28 8 2018.

[15] B. Singh, A. Verma, A. Chandra and K. Al-Haddad, "Implementation of Solar PV-Battery and Diesel Generator Based Electric Vehicle Charging Station," in *IEEE Int. Conf. Power Electronics, Drives and Energy Systems (PEDES)*, Chennai, India, 2018, pp. 1-6.

[16] N. Saxena, B. Singh and A. L. Vyas, "Integration of solar photovoltaic with battery to single-phase grid," *IET Generation, Transmission & Distribution*, vol. 11, no. 8, pp. 2003-2012, 1 6 2017.

[17] H. Razmi and H. Doagou-Mojarrad, "Comparative assessment of two different modes multi-objective optimal power management of micro-grid: grid-connected and stand-alone," *IET Renewable Power Generation*, vol. 13, no. 6, pp. 802-815, 2019.

[18] O. Erdinc, N. G. Paterakis, T. D. P. Mendes, A. G. Bakirtzis and J. P. S. Catalão, "Smart Household Operation Considering Bi-Directional EV and ESS Utilization by Real-Time Pricing-Based DR," *IEEE Trans. Smart Grid*, vol. 6, no. 3, pp. 1281-1291, May 2015.

[19] H. Kikusato, K. Mori, S. Yoshizawa, Yu Fujimoto, H. Asano, Y. Hayashi, A. Kawashima, S. Inagaki, T. Suzuki, "Electric Vehicle Charge-Discharge Management for Utilization of Photovoltaic by Coordination between Home and Grid Energy Management Systems," *IEEE Trans. Smart Grid*, Early Access.

[20] F. Hafiz, A. R. de Queiroz and I. Husain, "Coordinated Control of PEV and PV-based Storages in Residential System under Generation and Load Uncertainties," *IEEE Trans. Ind. Applica.*, Early Access.

[21] R. W. Wies, R. A. Johnson, A. N. Agrawal and T. J. Chubb, "Simulink model for economic analysis and environmental impacts of a PV with diesel-battery system for remote villages," *IEEE Trans. Power Systems*, vol. 20, no. 2, pp. 692-700, May 2005.

[22] R. R. Chilipi, N. Al Sayari, A. R. Beig and K. Al Hosani, "A Multitasking Control Algorithm for Grid-Connected Inverters in Distributed Generation Applications Using Adaptive Noise Cancellation Filters," *IEEE Trans. Energy Conversion*, vol. 31, no. 2, pp. 714-727, June 2016.

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