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

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Abstract:

In this project, to provide incessant charging during islanded, grid-connected and DG-connected modes, a solar PV (Photovoltaic) array, a Battery Energy Storage (BES), a Diesel Generator (DG) set and a grid-based EV Charging Station (CS) are used .The charging station is mainly designed to charge the Electric Vehicle (EV) battery using a solar PhotoVoltaic (PV) array and a BES. However, the charging station intelligently takes power from the grid or DG (Diesel Generator) set in the event of an empty storage battery and inaccessible solar PV array generation. However, in order to achieve optimum fuel efficiency under all loading conditions, the power from the DG collection is drawn in a way that often operates at 80-85% loading. In addition, the charging station controls generator voltage and frequency without a mechanical speed controller in conjunction with the storage battery. In addition, to obtain ceaseless charging, the PCC (Point of Common Coupling) voltage is synchronized to the grid/generator voltage. In order to improve the operating efficiency of the charging station, the charging station also conducts the vehicle to grid active/reactive power transfer, vehicle to home and vehicle to vehicle power transfer. Using the Matlab/Simulink software, the operation of the charging station is validated

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

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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].

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 utilized 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.

Verification of a new energy control strategy for dynamic voltage restorer by simulation

M. R. Banaei and S. H. HosseiniTo restore the load voltage, dynamic voltage restorer (DVR), which installed between the supply and a sensitive load, should inject voltage and active power from DVR to the distribution system during voltage sag. Due to the limit of energy storage capacity of DC link, it is necessary the minimize energy injection from DVR. In this paper the techniques of the supply voltage sag compensation in a distribution feeder are presented. In addition, a new concept of restoration technique is suggested to inject minimum energy for a given apparent power of DVR.

II. SYSTEM DESCRIPTION

Operation with batteries

At night, an off-grid PV system may use batteries to supply loads. Although the fully charged battery pack voltage may be close

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to the PV panel's maximum power point voltage, this is unlikely to be true at sunrise when the battery has been partially discharged. Charging may begin at a voltage considerably below the PV panel maximum power point voltage, and an MPPT can resolve this mismatch.

When the batteries in an off-grid system are fully charged and PV production exceeds local loads, an MPPT can no longer operate the panel at its maximum power point as the excess power has no load to absorb it. The MPPT must then shift the PV panel operating point away from the peak power point until production exactly matches demand. (An alternative approach commonly used in spacecraft is to divert surplus PV power into a resistive load, allowing the panel to operate continuously at its peak power point.)

In a grid connected photovoltaic system, all delivered power from solar modules will be sent to the grid. Therefore, the MPPT in a grid connected PV system will always attempt to operate the PV modules at its maximum power point.

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.

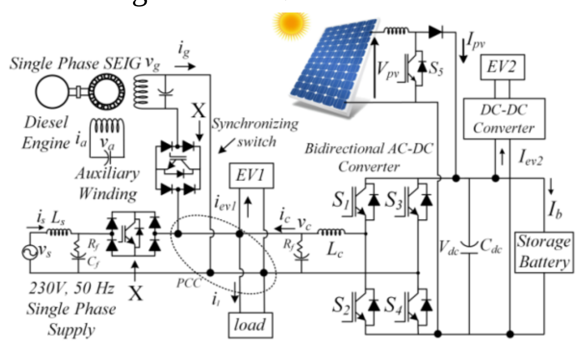

Fig. 1 Topology of charging station

DG set:

A diesel generator is the combination of a diesel engine with an electric generator (often an alternator) to generate electrical energy. This is a specific case of engine-generator. A diesel compression-ignition engine often is designed to run on fuel oil, but some types are adapted for other liquid fuels or natural gas.

Diesel generating sets are used in places without connection to a power grid, or as emergency power-supply if the grid fails, as well as for more complex applications such as peak-lopping, grid support and export to the power grid.

Proper sizing of diesel generators is critical to avoid low-load or a shortage of power. Sizing is complicated by the characteristics of modern electronics, specifically non-linear loads. In size ranges around 50 MW and above, an open cycle gas turbine is more efficient at full load than an array of diesel engines, and far more compact, with comparable capital costs; but for regular part-loading, even at these power levels, diesel arrays are sometimes preferred to open cycle gas turbines, due to their superior efficiencies.

The packaged combination of a diesel engine, a generator and various ancillary devices (such as base, canopy, sound attenuation, control systems, circuit breakers, jacket water heaters and starting system) is referred to as a "generating set" or a "genset" for short.

Set sizes range from 8 to 30 kW (also 8 to 30 kVA single phase) for homes, small shops and offices with the larger industrial generators from 8 kW (11 kVA) up to 2,000 kW (2,500 kVA three phase) used for large office complexes, factories. A 2,000 kW set can be housed in a 40 ft (12 m) ISO container with fuel tank, controls, power distribution equipment and all other equipment needed to operate as a standalone power station or as a standby backup to grid power. These units, referred to as power modules are gensets on large triple axel trailers weighing 85,000 pounds (38,555 kg) or more. A combination of these modules are used for small power stations and these may use from one to 20 units per power section and these sections can be combined to involve hundreds of power modules. In these larger sizes the power module (engine and generator) are brought to site on trailers separately and are connected together with large cables and a control cable to form a complete synchronized power plant. A number of options also exist to tailor specific needs, including control panels for autostart and mains paralleling, acoustic canopies for fixed or mobile applications, ventilation equipment, fuel supply systems, exhaust systems, etc. Diesel generators, sometimes as small as 200 kW (250 kVA) are widely used not only for emergency power, but also many have a secondary function of feeding power to utility grids either during peak periods, or periods when there is a shortage of large power generators.

Ships often also employ diesel generators, sometimes not only to provide auxiliary power for lights, fans, winches etc., but also indirectly for main propulsion. With electric propulsion the generators can be placed in a convenient position, to allow more cargo to be carried. Electric drives for ships were developed prior to World War I. Electric drives were specified in many warships built during World War II because manufacturing capacity for large reduction gears was in short supply, compared to capacity for manufacture of electrical equipment. Such a diesel-electric arrangement is also used in some very large land vehicles such as railroad locomotives.

Grid support:

Emergency standby diesel generators, for example such as those used in hospitals, water plant, are, as a secondary function, widely used in the US and, in the recent past, in Great Britain to support the respective national grids at times for a variety of reasons. In the UK the tenders known as the Short Term Operating Reserve have exhibited quite variable prices, and from 2012 the volume of demand-side participation, which mainly entails the use of on-site diesels, has dropped as the tendered prices fell. Some 0.5 GWe of diesels have at times been used to support the National Grid, whose peak load is about 60 GW. These are sets in the size range 200 kW to 2 MW. This usually occurs during, for example, the sudden loss of a large conventional 660 MW plant, or a sudden unexpected rise in power demand eroding the normal spinning reserve available.

This is beneficial for both parties - the diesels have already been purchased for other reasons; but to be reliable need to be fully load tested. Grid paralleling is a convenient way of doing this. This method of operation is normally undertaken by a third party aggregator who manages the operation of the generators and the interaction with the system operator.

These diesels can in some cases be up and running in parallel as quickly as two minutes, with no impact on the site (the office or factory need not shut down). This is far quicker than a base load power station which can take 12 hours from cold, and faster than a gas turbine, which can take several minutes. Whilst diesels are very expensive in fuel terms, they are only used a few hundred hours per year in this duty, and their availability can prevent the need for base load station running inefficiently at part load continuously. The diesel fuel used is fuel that would have been used in testing anyway.

In Great Britain, National Grid can generally rely upon about 2 GW of customer demand reduction via back-up diesels being self-dispatched for about 10 to 40 hours a year at times of expected peak national demand. National Grid does not control these diesels - they are run by the customer to avoid "triad" transmission network use of system (TNUoS) charges which are levied only on consumption of each site, at the three half-hours of peak national demand. It is not known in advance when the three half-hours of peak national demand (the "triad" periods) will be, so the customer must run his diesels for a good deal more half-hours a year than just three.

The total capacity of reliably operable standby generation in Britain is estimated to be around 20 GW, nearly all of which is driven by diesel engines. This is equivalent to nearly 29% of the British system peak, although only a very small fraction will ever be generating at the same time. Most plant is for large offices blocks, hospitals, supermarkets, and various installations where continuous power is important such as airports. Therefore, most is in urban areas, particularly city and commercial centers. It is estimated that around 10% of plant exceeds 1 MW, about 50% is in the 200 kW-1 MW range, and the remaining 40% is sub-200 kW. Although it is growing, only a very small proportion is believed to be used regularly for peak lopping, the vast majority just being only for standby

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generation. The information in this paragraph is sourced from section 6.9 of the government report: "Overcoming Barriers to Scheduling Embedded Generation to Support Distribution Networks"

A similar system to Great Britain's Short Term Operating Reserve operates in France. It is known as EJP; at times of grid stress, special tariffs can mobilize at least 5 GW of diesel generating sets to become available. In this case, the diesels prime function is to feed power into the grid.

During normal operation in synchronization with the electricity net, power plants are governed with a five percent droop speed control. This means the full load speed is 100% and the no load speed is 105%. This is required for the stable operation of the net without hunting and dropouts of power plants. Normally the changes in speed are minor. Adjustments in power output are made by slowly raising the droop curve by increasing the spring pressure on a centrifugal governor. Generally this is a basic system requirement for all power plants because the older and newer plants have to be compatible in response to the instantaneous changes in frequency without depending on outside communication.

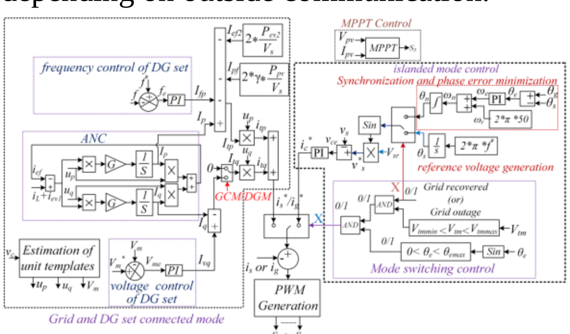

Fig. 2 Unified control of VSC for standalone and grid and DG set connected mode

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 minimization of voltage error using proportional integral (PI) controller. The error minimization and reference current generation is expressed as,

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

(1)

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

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III 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,

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

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,\

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

Where, Ip and Iq are the active and reactive currents of EV, and Ief2 and Ipf are the feed-forward term of the EV2 and the PV array. Ifp and Ivq are the frequency and voltage regulators terms used in the DG set connected mode. Ief2 controls the vehicle to grid power transfer of the EV. Ipf 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,

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

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Where up and qp are synchronizing signals of the DG set or grid voltage (vg or vs). Using the sensed and the reference current of grid/DG set, the switching signals are generated using hysteresis controller as shown in Fig. 2.

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,

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

(5)

Where $Vme = Vm * -Vm$ and the zvi and zvp are the PI controller gains.

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

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

(6)

Where fe is the error in frequency and zkfp, zfi 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.

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.

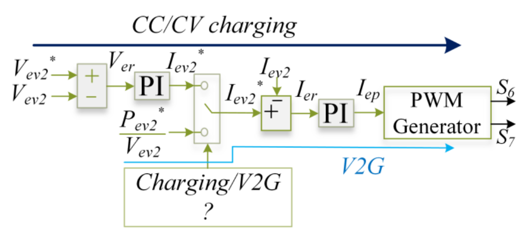

Fig. 3 EV2 control for CC/CV charging and V2G power transfer

The reference charging current is estimated as,

$$I^*_{ev2}(s) = I^*_{ev2}(s-1) + z_{evp}\{V_{er}(s) - V_{er}(s-1)\} + z_{evi}V_{er}(s)$$

(7)

Where, Ver is the EV battery voltage error and zevp and zevi 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,

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

(8)

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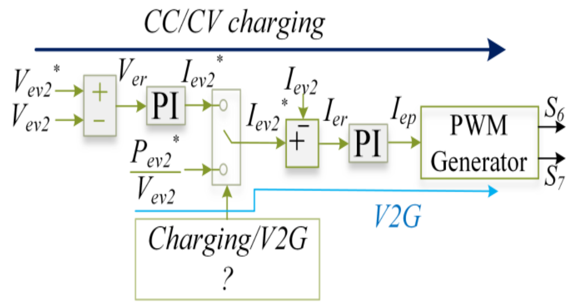

Fig. 3 EV2 control for CC/CV charging and V2G power transfer

Where Ier is battery current error and zep and zei 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,

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

Where Δθ is phase difference, and zpa and zia 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.

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/m2 to 300 W/m2. 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 > SOCmin. After, the complete discharge of the battery, the controller connects the CS to the grid after the synchronization. At 0.79s, the CS has started drawing power from grid. After this point, CS is supported by the DG set due to unavailability of grid and storage battery power as shown in Fig. 4. From Fig. 4, it is observed that the charging station is

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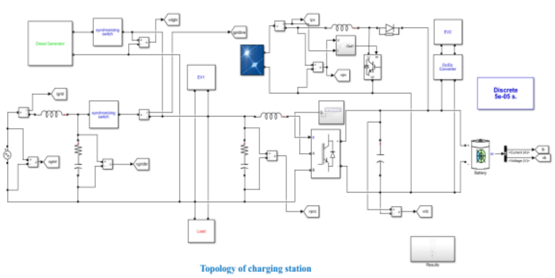
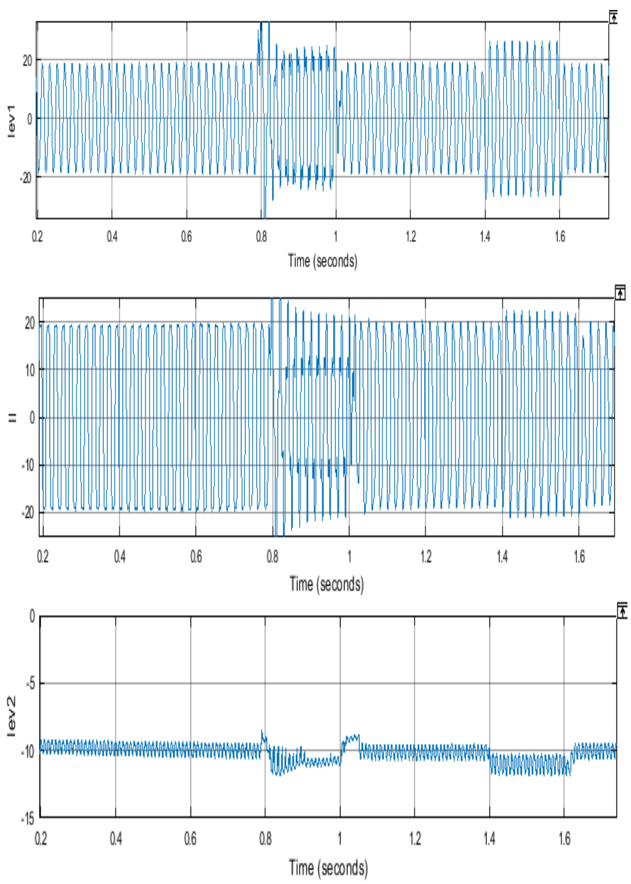
automatically changing the modes depending upon the generation and demand.

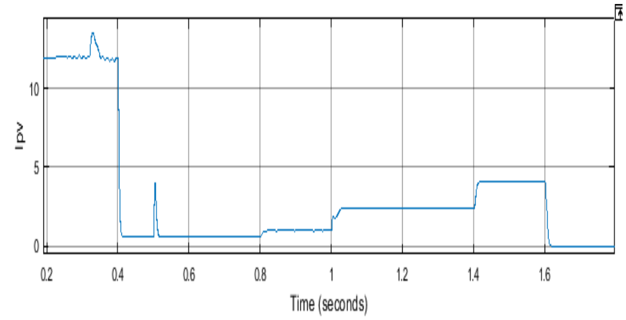
Screenshots.



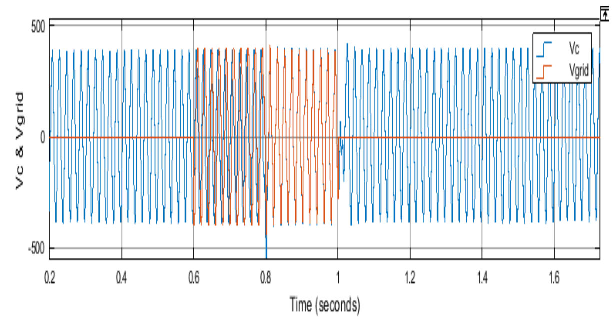
Schematic diagram



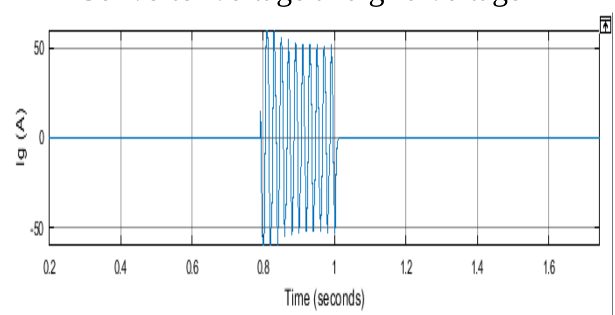
Ev1 current, load current, ev2current



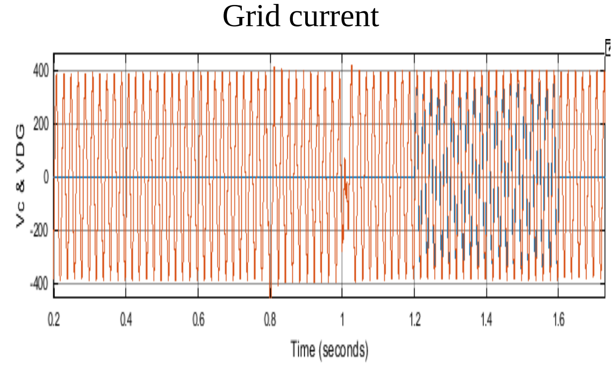
PV panel current, battery current



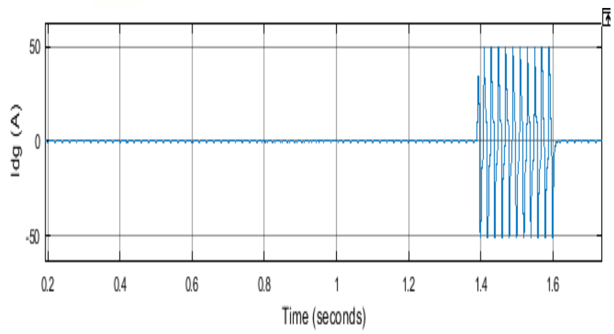
Converter voltage and grid voltage



Grid current



Converter and dg set voltage



Dg set current

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 dynamicsconditions 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.

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