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Installation of an Electric Vehicle Charging Station Using a Diesel Generator and Solar PV Batteries

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Abstract: This study enables continuous charging in islanded, grid-connected, and distributed generation (DG) set-connected modes through a system comprising a battery, a diesel generator set, a battery energy storage system (BESS), a solar photovoltaic (PV) array, and a grid-based electric vehicle (EV) charging station. The main purpose of the charging station is to recharge the EV battery using the solar PV array and the BESS. However, if the storage battery is depleted and solar power is unavailable, the charging station intelligently draws electricity from the grid or the diesel generator.

To ensure optimal fuel efficiency, power from the DG set is utilized to maintain an operating load of 80–85% under various conditions. The charging station also manages the generator's voltage and frequency alongside the storage battery, removing the need for a mechanical speed governor. Additionally, it guarantees that power drawn from the grid or DG set operates at a unity power factor (UPF), even under nonlinear loads. The Point of Common Coupling (PCC) voltage is synchronized with the grid or generator voltage to ensure continuous charging.

Moreover, the charging station facilitates active and reactive power transfers between vehicles, residences, the grid, and other vehicles, enhancing operational efficiency.

Index Terms: DG set, electricity quality, solar PV generation, and EV charging stations.

• INTRODUCTION

Electric vehicles (EVs) are increasingly recognized as one of the most efficient modes of transportation, primarily because they produce no exhaust emissions. Currently, there are three million registered EVs on the road, with projections suggesting that this number could reach 100 million by 2030【1】. However, the widespread adoption of EVs requires a substantial amount of electrical power and a robust charging infrastructure. For EVs to be considered truly sustainable, the electricity used for charging must come from renewable and sustainable sources. Generating electricity from fossil fuels merely shifts emissions from vehicles to power plants, rather than eliminating them. In contrast, utilizing renewable energy sources can significantly reduce emissions and enhance environmental sustainability. Among the available renewable energy options, solar photovoltaic (PV) generation stands out as the most practical for EV charging, as it is consistently accessible in various locations, whether urban or rural. Other renewable sources include wind, hydro, and fuel cells, but solar PV is particularly advantageous in the Indian subcontinent, where it can be harnessed nearly year-round. Unlike solar energy, wind and hydro power are often location-specific, with coastal areas benefiting most from wind energy.

Using renewable energy-based charging stations is the most practical approach for electric vehicle (EV) charging. However, incorporating an additional power conversion stage into the existing charging system can complicate the design and lead to increased power losses. Moreover, each conversion stage requires a dedicated controller for effective current management. Therefore, it is essential to develop an integrated system capable of operating in multiple modes, which demands centralized control and coordination among the various energy sources.

There has been considerable interest in developing renewable energy-powered charging stations. Grimier et al. [3] highlighted the importance of renewable energy for the sustainability of EV charging infrastructure. Mouli et al. [4] utilized solar energy for EV charging through a high-power bidirectional charger; however, their design does not support AC charging. Monterio et al. [5] introduced a three-port converter to connect a photovoltaic (PV) array with an EV charger, but their approach does not address the current distortions introduced into the grid. Singh et al. [6] proposed a modified z-source converter for a PV array/grid-connected EV charger, but it is not designed for island mode operation, meaning it cannot facilitate EV charging when the grid is unavailable.

Chaudhari et al. presented a hybrid approach that optimizes battery storage management to maximize the output of the solar PV array while minimizing the operational costs of the charging station. Keavy et al. [8] recommended integrating the EV charging station with on-site PV generation (installed on commercial buildings) to optimize solar PV utilization while mitigating grid impacts under uncertain conditions. Zhang et al. conducted a study on the optimal scheduling of EV charging stations with dual charging modes in workplace settings, emphasizing the need for PV array-powered charging stations to minimize grid impact and provide cost-effective service【10】. Additionally, Kandasamy and colleagues investigated the performance of a storage battery used in conjunction with solar PV array technology on commercial buildings. Wind energy-powered charging stations also offer benefits for EVs, as they can provide energy around the clock, and numerous studies have explored this topic 【12] - [14】.

Due to their substantial energy storage capacity, electric vehicle (EV) batteries are increasingly being utilized as distributed energy resources, offering a variety of ancillary services. Singh et al. [15] described a photovoltaic (PV) array-based charging station (CS) capable of providing charging functions along with vehicle-to-grid (V2G) reactive and active power, active power filtering, and vehicle-to-home (V2H) capabilities. Saxena et al. [16] installed a grid-tied PV array system for EV and residential applications, while Razmi et al. [17] developed a home-integrated PV-storage battery system with multi-mode control that can function in both islanded and grid-connected configurations. Erdinc et al., Kusto et al., and Hafiz et al. [20] discussed smart home operations where EVs can act as storage units, enabling V2H and V2G operations to benefit both utilities and customers.

A thorough review of the literature indicates that research on renewable energy-based charging stations has largely focused on optimizing various charging parameters, such as the sizing of storage units and renewable energy sources, vehicle driving patterns, charging durations, costs, and scheduling. However, there have been relatively few publications that implement charging stations utilizing renewable energy, with limited attention given to their practical performance.Moreover, most studies primarily examine the performance of charging stations in either islanded or grid-connected modes. When operating in grid-connected mode, the solar PV panel becomes ineffective during periods of grid unavailability, despite the presence of sunlight (solar irradiance). Similarly, irregular solar radiation can disrupt PV energy production in island mode. Therefore, a storage battery is essential to mitigate the impacts of fluctuating solar irradiation. Additionally, when the storage battery reaches full charge, the maximum power point tracking (MPPT) must be disabled to prevent overcharging.This study proposes a charging station supported by grid energy, energy storage, and a diesel generator set (DG set) to maximize the utilization of PV array energy across all operational conditions. This charging station can function in grid-connected, DG set-connected, and islanded modes.

Numerous studies [15] have examined both grid-connected and islanded models; however, these two modes are typically managed separately, lacking automatic mode switching capabilities. Consequently, when transitioning between modes, the power generated by the PV array must be disconnected, preventing continuous EV charging without automatic mode transition. This work introduces an automatic mode-switching logic that allows the controller to seamlessly switch between different operating modes based on the PV array's power generation and the EV charging requirements.

To ensure consistent and reliable operation of the charging station (CS), storage batteries are used in conjunction with PV arrays, especially since solar power is intermittent and unavailable at night. However, the limited capacity of the storage batteries makes it impossible to provide continuous backup. Therefore, the CS requires grid support when both the PV array and energy storage are depleted.

In isolated locations, diesel generator sets (DG sets) may be necessary to maintain charging continuity due to limited grid availability. However, the performance of DG sets is often underutilized and can be adversely affected by the load type. DG sets are typically designed to handle very low load harmonic currents [21]. Since EV chargers frequently incorporate rectifiers, power factor correction circuits, and DC-DC converters for voltage regulation, the presence of harmonic currents in EV charging can significantly impair DG set performance. Nonetheless, in this study, the configuration ensures that the DG set operates at a minimum load of 80% of its rated capacity, as the voltage source converter (VSC) compensates for the harmonics and reactive currents required by the EV charger.

The key contributions of this paper are outlined below:

- **Design and Experimental Verification**: The paper presents the design and experimental validation of a grid-integrated charging station (CS) that facilitates continuous DC and AC charging for electric vehicles through the integration of energy storage, a diesel generator set (DG set), and a PV array.

- **Single Controller Operation**: It introduces a single voltage source converter (VSC) that allows the charging station to function seamlessly in islanded, grid-connected, and DG set-connected modes without requiring any hardware modifications.

- **Mode Switching Algorithm**: An innovative algorithm for mode switching is developed, enabling the charging station to transition smoothly between different operational modes to ensure continuous charging.

- **Control Strategies for Power Transfer**: The paper details the creation of control strategies for vehicle-to-grid (V2G) power transfer to support the grid and vehicle-to-vehicle (V2V) power transfer for EV charging.

- **Active Power Filtering**: The charging station incorporates an active power filter to minimize harmonic currents in the grid and ensure that power exchanges occur at unity power factor, thereby ensuring compliance with IEEE-519 standards.

- **Voltage Regulation with DG Sets**: The frequency of the DG sets is regulated using an automated mechanical voltage regulator to maintain consistent voltage levels.

- **Excess Power Management**: A strategy is implemented to channel any excess power generated by the PV array back into the grid, preventing overcharging of the storage battery.

• SYSTEM DESCRIPTION

The proposed charging station, depicted in Fig. 1, is designed to charge electric vehicles (EVs) and supply power to connected loads using a combination of a solar PV array, a storage battery, a diesel generator (DG) set, and grid electricity. The solar PV array is linked to the voltage source converter (VSC) DC link via a boost converter, while the storage battery is directly connected to the DC link. On the AC side of the VSC, a coupling inductor connects the EV, a single-phase self-excited induction generator (SEIG), a nonlinear load, and the grid. A ripple filter is employed to convert the grid and generator currents at the Point of Common Coupling (PCC) from switching harmonics to sinusoidal currents. The excitation capacitor is connected to the auxiliary winding of the SEIG, and a small capacitor is also connected across the primary winding of the SEIG. To facilitate regulated connection and disconnection of the charging station from the grid and DG set, a synchronizing switch is integrated between the grid/DG set and the PCC.

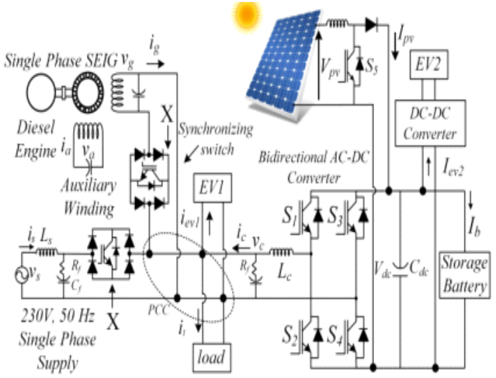


Fig. 1 Topology of charging station

• CONTROL STRATEGIES

Various control strategies used in the CS are discussed here.

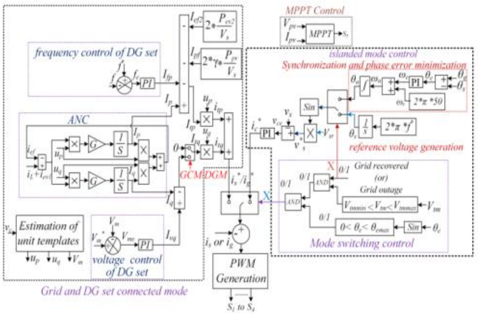


Fig.2 Unified control of VSC for standalone and grid and DG set connected mode

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

Thanks to its islanded control capabilities, the charging station can function reliably even when the grid is unavailable, ensuring continuous solar electricity output and EV charging in both AC and DC modes. With minimal adjustments to the control system, the storage battery can effectively manage both DC charging and solar PV generation.

However, since a grid connection is required to establish any voltage reference, an independent VSC controller is necessary for AC charging to create a local voltage reference. Consequently, the islanded controller produces an internal voltage reference of 230 V at 50 Hz, as illustrated in Fig. 2, which generates the reference voltage by multiplying the frequency by the sine function. The reference converter current is determined by comparing the generated reference with the converter's terminal voltage, following the minimization of voltage error using a proportional integral (PI) controller. The processes for error minimization and reference current generation can be expressed as follows:

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

Once the reference current is compared to the measured current, it generates the gate signals for the converter.

- **Control of VSC in DG Set or Grid Connected Mode**

In grid-connected mode, the controller calculates the amount of electricity to be exchanged with the grid. To enhance fuel efficiency, the DG set operates in constant power mode while connected. However, the controller must address the reactive and harmonic current demands of the EVs in both scenarios. To achieve this, it uses the current from the EV to estimate the reference current for either the grid or the DG set. When the EV is connected to the grid, only the active current is considered for determining the reference current. In contrast, when in DG set-connected mode, the reference current is calculated using both the reactive and active currents of the EV.

Presently, when connected to the grid, the total active and reactive currents are as follows:

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

Only an EV's active current is considered, with the reactive current being considered as zero, to achieve unity power factor functioning in grid connected mode. But when the DG set is connected, the EV's active and reactive current components are both utilised.

The connected DG set's current total active and reactive current is as follows:

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

In this context, \(I_p\) and \(I_q\) represent the active and reactive currents of the EV, while \(I_{ef2}\) and \(I_{pf}\) are the feed-forward terms for the EV and the PV array, respectively. The designations \(I_{fp}\) and \(I_{vq}\) refer to the voltage and frequency regulators used in DG set-connected mode. The term \(I_{ef2}\) regulates the power transfer from the EV to the grid, while the feed-forward term \(I_{pf}\) from the grid-connected PV array helps prevent overcharging of the storage battery.

Since the energy storage system is directly connected to the DC link, charging the storage battery in constant current/constant voltage (CC/CV) mode is not possible. However, measures can be taken to ensure that the storage battery does not become overcharged. In a grid-connected setup, feeding excess solar PV energy into the grid prevents overcharging of the storage battery. This is accomplished by incorporating the solar PV array feed-forward term into the grid-connected mode control, as illustrated in Fig. 2.

A variable gain, denoted as \(\alpha\), is multiplied by the feed-forward term to determine the percentage of PV array energy fed into the grid. The state of charge (SOC) data of the storage battery defines the range of this constant \(\alpha\), which varies from 0 to 1. When the storage battery is fully charged, \(\alpha\) equals 1, and when the battery is completely depleted, \(\alpha\) drops to 0.

Lastly, the predicted reference current for the grid or DG set is as follows:

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

where the grid voltage synchronizing signals (vg or vs) or the DG set are up and qp. A hysteresis controller uses the detected and reference currents from the grid/DG set to generate the switching signals, as shown in Fig. 2.

- **DG Set Control for Voltage and Frequency**

The frequency and voltage of the DG set are managed to operate at a single point by use of decoupled management of VSC. Reactive power controls the voltage in a decoupled control system, whereas active power controls the frequency. As a result, voltage and frequency are controlled by two PI controllers. This is the PI control for voltage regulation:

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

where Vme=Vm * -Vm and zvi and zvp are the gains of the PI controller.

Likewise, the differentiated expression for the frequency PI controller is as follows:

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

where fe is the frequency error and zkfp and zfi are PI gains.

Figure 2 illustrates how grid-connected control integrates the outputs of the voltage and frequency controllers. However, since the grid's voltage and frequency are still controlled when it is connected to the grid, the outputs of these controllers become zero in this mode.

D **Control of EV2**

The DC-DC converter facilitates the connection between the electric vehicle (EV) and the control strategy known as constant current/constant voltage (CC/CV). Initially, the EV charges in CC mode until its battery terminal voltage reaches the predetermined value that signifies a full charge. Once the EV approaches this terminal voltage, indicating that it is nearly fully charged, the charging process transitions to CV mode. As illustrated in Fig. 3, two PI controllers are employed to manage the CC/CV charging method. The external voltage loop generates a reference current for the current control phase.

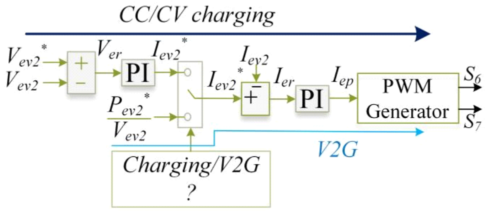


Fig. 3 EV2 control for CC/CV charging and V2G power transfer

The reference charging current that is anticipated is

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

where Zevp and Zevi are the controller gains and Ver is the EV battery voltage error. The switching signals for the converter are produced by the PI controller and PWM generator using the reference and measured battery currents. The expression for the duty cycle calculation PI controller is,

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

where Ier is the battery current error and zep and zei are the controller gains.

Based on the reference power, the EV2 battery is utilized for the V2G power transfer, and the controller follows the erroneous path depicted in Fig. 3. This figure illustrates how the EV2 feed-forward term is managed in relation to the reference power.

- **Synchronization and Switching Control**

The charging station operates in various modes depending on the generation capacity and charging requirements, necessitating the development of a mode-switching strategy to ensure smooth transitions and continuous charging. These scenarios include operation in both grid-connected and DG set modes, for which the logic for mode transitions has been established. This approach involves synchronizing the two voltages by aligning their phases, but only after the controller determines the phase difference between them. In islanded conditions, the PI controller adjusts the frequency of the voltage generated by the VSC to achieve this synchronization, as illustrated in Fig. 2. The expression for the PI controller used for phase minimization is as follows:

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

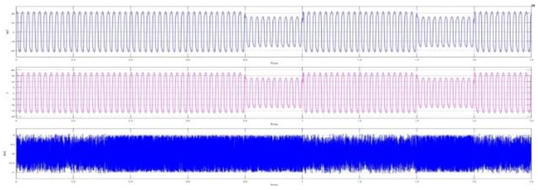
In this context, the phase difference is denoted as \(\Delta \phi \), while \(z_{pa} \) and \(z_{ia} \) represent the tuning parameters of the controller. Fig. 2 further depicts the conditions under which the charging station operates in islanded mode and indicates when a mode shift is necessary. Once all synchronization conditions are met, the control logic produces an enabling signal \(X = 1 \) for the synchronizing switch.

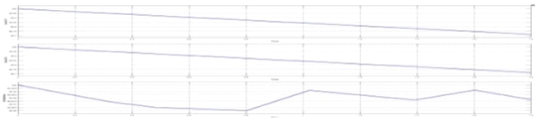
RESULTSAND DISCUSSION

Real and simulated results are utilised to analyse the performance of the CS.

- **Simulation Results**

The simulation results presented in Figure 4 indicate that the charging station (CS) operates continuously without interruptions. Initially, while in islanded mode, the PV array supplies power to charge the electric vehicles (EVs) connected to the Point of Common Coupling (PCC). However, as the demand for EV charging exceeds the power generated by the PV array, any excess generation is stored in the energy storage system. At 0.32 seconds, the solar irradiance drops from 1000 W/m² to 300 W/m². Consequently, to maintain continuous charging, the storage battery begins to deplete, and the output from the PV array decreases. When the PV array's power output reaches zero, the storage battery is exhausted in 0.48 seconds. If the state of charge (SOC) of the battery is greater than the minimum SOC, charging can continue. Once the battery is fully depleted, the controller synchronizes the CS with the grid.





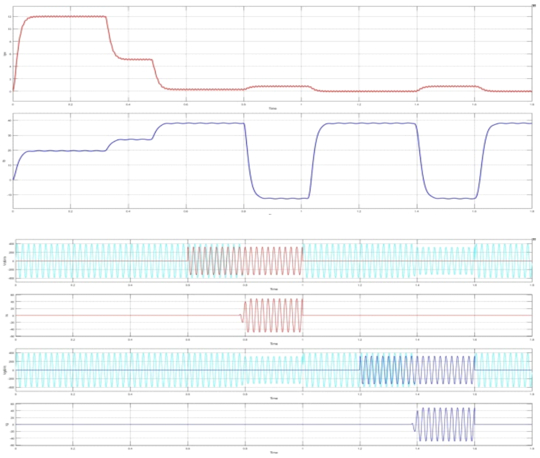


Fig. 4 Simulation results showing the different modes of operation

The CS began using grid electricity at 0.79 seconds. The DG configuration as depicted in Fig. 4 supports CS because there is no longer any grid or storage battery power available after that. As illustrated in Fig. 4, the charging station automatically shifts modes based on generation and demand.

CONCLUSION

A grid-connected diesel generator (DG) set, storage battery, PV array, and electric vehicle charging station have been successfully implemented. The charging station has demonstrated the capability to operate in island mode, grid-connected mode, and DG set-connected mode using a single voltage source converter (VSC). Test results indicate that the charging station operates effectively across various steady-state conditions and dynamic scenarios, including fluctuations in solar irradiation, EV charging currents, and load variations. It functions as a standalone generator with excellent voltage quality, as confirmed by the data presented.

In both DG set and grid-connected modes, the ANC-based control algorithm has proven effective in maintaining power exchange with the grid at a unity power factor (UPF) or optimal loading for the DG set. The successful integration of islanded operation, grid connectivity, and DG set connectivity, along with automatic mode switching, has enabled optimal loading of the DG set and ensured the PV array operates at its maximum power point (MPP), enhancing charging reliability. The performance of the charging station complies with IEEE standards, with total harmonic distortion (THD) for voltage and current consistently below 5%. This demonstrates that the charging station can efficiently utilize multiple energy sources while providing electric vehicles with a reliable and cost-effective charging solution.

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