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Research Paper

A CONJUGATE GRADIENT CONTROL METHOD FOR GRID-TIED PV SYSTEMS SUPPORTING DISTORTION-FREE, CONTINUOUS BIDIRECTIONAL EV CHARGING

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ABSTRACT

This work proposes an advanced control strategy for a grid-connected photovoltaic (PV) system enabling continuous and distortion-free bidirectional electric vehicle (EV) charging. The system integrates a standalone solar PV array with an AC grid through a multifunctional voltage-source converter (VSC), while the EV battery interfaces with the DC bus of the converter. To achieve robust power regulation and superior power quality, a novel adaptive controller based on the conjugate gradient method is developed. The controller dynamically optimizes the switching signals of the VSC to maintain sinusoidal grid currents, minimize harmonic distortion, and support seamless bidirectional energy flow between the grid, PV array, and EV battery. MATLAB/SIMULINK simulations validate the effectiveness of the proposed approach, demonstrating enhanced system stability, improved tracking performance, rapid convergence, and significant reduction in current distortion under changing irradiance and load conditions..

Keywords: Electric vehicle(EV), PV system, Power Quality

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I.Introduction

The rapid global growth of electric vehicles (EVs) and renewable energy technologies has brought significant attention to the development of intelligent, sustainable, and high-quality EV charging infrastructures. Among various renewable energy sources, solar photovoltaic (PV) systems have emerged as one of the most promising solutions due to their abundance, low operating cost, and environmentally friendly characteristics. Integrating solar PV systems with EV charging not only reduces the load on the utility grid but also supports clean transportation and decentralized energy management. However, the dynamic and intermittent nature of solar energy, combined with the nonlinear charging characteristics of EV batteries, introduces substantial challenges in maintaining continuous, stable, and distortion-free power flow.

Bidirectional EV charging stations further complicate the power control problem since they must support both grid-to-vehicle (G2V) charging and vehicle-to-grid (V2G) discharging modes. These stations are required to ensure reliable energy exchange between the PV system, the AC grid, and the EV battery while maintaining high-quality power at the point of common coupling (PCC). In this environment, the voltage-source converter (VSC) plays a critical role in regulating power flow, mitigating harmonics, correcting the power factor, and ensuring that the charging process remains distortion-free. Therefore, developing an advanced and robust control algorithm for the VSC is essential for achieving optimal system performance.

Conventional control strategies such as proportional–integral (PI) control and synchronous reference frame-based methods exhibit limitations when subjected to rapidly changing irradiance, fluctuating grid conditions, and variable EV charging demands. These controllers often suffer from slow dynamic response, steady-state errors, and reduced effectiveness in suppressing harmonics. As a result, they cannot ensure the level of reliability required for modern PV-powered bidirectional charging systems.

To overcome these issues, this research introduces a novel adaptive control technique based on the conjugate gradient method (CGM). The conjugate gradient algorithm is a powerful optimization approach widely recognized for its fast convergence characteristics, numerical stability, and capability to handle large-scale dynamic systems. When applied to the control of a grid-connected PV charging

station, the CGM-based controller continuously updates its parameters to track reference signals more accurately, reduce power losses, minimize harmonic distortion, and maintain a smooth transition between operational modes. The adaptive nature of this method enables superior performance compared to classical approaches, especially under non-linear, time-varying, and uncertain operating conditions.

In this study, a grid-connected solar PV array is interfaced with the AC grid through a multifunctional VSC, while an EV battery is connected to the DC bus to enable bidirectional charging. The proposed conjugate gradient-based controller is implemented within the VSC control loop to ensure sinusoidal grid currents, unity power factor operation, and distortion-free EV charging. The performance of the overall system is analyzed using MATLAB/SIMULINK, where various real-world scenarios are simulated including sudden irradiance changes, dynamic EV demand, and disturbances in the grid.

The simulation results demonstrate that the proposed method significantly enhances power quality, improves dynamic response, and ensures uninterrupted bidirectional EV charging regardless of environmental or grid variations. The conjugate gradient-based control methodology offers a flexible, robust, and efficient solution suitable for modern smart-grid and renewable-powered transportation infrastructures.

Fig. 1 shows the schematic of the PV-APF controlled EVCS. It has a lithium-ion battery, dc–converter and a VSC, ripple filter (RF), dc side capacitor, and interface inductor. The output voltage of ac/dc converter is calculated. The dc voltage magnitude should be suitably adjusted since a lower dc voltage reduces switching losses while a high dc voltage increases dynamic control.

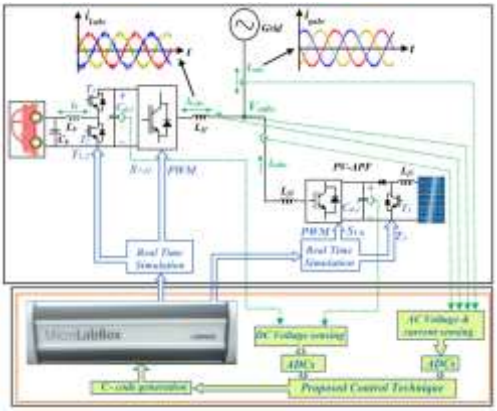


Figure.1Schematic of PV-APF with EVCS

II. Methodology

The proposed methodology focuses on the design, modeling, and control of a grid-connected photovoltaic (PV) system with bidirectional electric vehicle (EV) charging using a Conjugate Gradient Method (CGM)-based controller. The main aim is to achieve continuous, distortion-free bidirectional EV charging while ensuring optimal utilization of renewable energy and stable operation of the DC bus.

1. System Architecture

The system consists of the following main components:

1. Solar PV Array – Converts solar irradiance into DC power.
2. Bidirectional DC–DC Converter – Interfaces the EV battery with the DC bus, enabling both charging and discharging.
3. DC Bus – Acts as a common link between PV array, battery, and voltage-source inverter (VSI).
4. Voltage Source Converter (VSC) – Connects the DC bus to the AC grid, ensuring synchronization and grid-compliant voltage.
5. EV Battery – Stores energy from PV or grid and supplies energy to loads or back to the grid.
6. Conjugate Gradient Controller – Regulates power flow, maintains DC bus voltage, and ensures distortion-free output.

The Solar Energy Conversion System (SECS) consists of:

- Solar PV panel
- DC–DC boost converter
- Maximum Power Point Tracking (MPPT) controller

A schematic of the SECS is shown in Figure 1. The MPPT controller operates in two modes depending on the battery's State of Charge (SOC):

1. **MPPT Mode:** When the battery SOC is below SOCmax_\text{max}max, the MPPT extracts maximum power from the PV panel.

2. **OFF-MPPT Mode:** When SOCmax_\text{max}max is reached, the MPPT is disabled to reduce solar generation and prevent battery overcharging.

The P–V characteristics under different irradiance levels (400–1200 W/m²) at 25°C are illustrated in Figure 3. At an irradiance of 1000 W/m², the maximum power of the PV panel reaches approximately 66 W at 17.6 V.

The PV panel power is given by:

The MPPT algorithm flowchart (Figure 4) regulates the duty cycle of the DC–DC boost converter to ensure maximum power extraction [7].

III. PERTURB AND OBSERVE MPPT IN MICRO GRID

Maximum Power Point Tracking (MPPT) is essential in microgrids with renewable energy sources, particularly **solar PV systems**, to ensure that the photovoltaic array always operates at its maximum power output under varying irradiance and temperature conditions. Among various MPPT techniques, the **Perturb and Observe (P&O) method** is widely used due to its **simplicity, effectiveness, and ease of implementation** in real-time systems.

1. Principle of P&O Method

The **Perturb and Observe (P&O) MPPT algorithm** works by periodically **perturbing (changing) the operating voltage** of the PV array and observing the resulting change in output power:

1. **Perturbation:** The PV voltage is slightly increased or decreased.
2. **Observation:** The change in PV output power (ΔP\Delta PΔP) is monitored.
    - If the **power increases**, the perturbation continues in the same direction.
    - If the **power decreases**, the perturbation direction is reversed

The Perturb and Observe technique works by continuously perturbing the operating point of a photovoltaic system and observing the corresponding change in power output. The technique is used for maximum power point tracking (MPPT), which involves adjusting the operating point of the system to maintain it at the maximum power point (MPP) for a given set of environmental conditions.In the Perturb and Observe technique, the operating point of the photovoltaic system is perturbed by adjusting the voltage or current of the system and observing the resulting change in power output. If the power output increases, the operating point is moved further in that direction, and if the power output decreases, the operating point is moved in the opposite direction. This process is repeated until the maximum power point is reached.The Perturb and Observe technique can be implemented using a microcontroller or other electronic device that monitors the power output of the photovoltaic system and adjusts the operating point accordingly. The system can be programmed to adjust the operating point at regular intervals or in response to changes in the environmental conditions.

One potential issue with Perturb and Observe is that it can sometimes cause the system to oscillate around the maximum power point, resulting in reduced efficiency. To address this problem, modified versions of the technique, such as Incremental Conductance, have been developed that maintain a constant ratio between the incremental change in power output and the incremental change in voltage or current, reducing the likelihood of oscillations.Overall, the considered as infeasible solution. On another hand, in a fully decentralized control each unit is controlled by its local controller without knowing the situation of others. The fully decentralized control is also irrelevant in this context due to strong coupling between the operations of various units in the system. A compromise between those two extreme control schemes can be achieved by means of a hierarchical control scheme consisting of three control levels: primary, secondary, and tertiary

IV. SYSTEM CONFIGURATION

Fig. 1 shows the schematic of the PV-APF controlled EVCS. It has a lithium-ion battery, dc– converter and a VSC, ripple filter (RF), dc side capacitor, and interface inductor. The output voltage of ac/dc converter is calculated. The dc voltage magnitude should be suitably adjusted since a lower dc voltage reduces switching losses while a high dc voltage increases dynamic control**.**

The PWM generator produces switching signals for the VSC switches based on the voltage obtained in the “abc” variables. Battery charging methods determine dc–dc converter control strategy. Trickle, pulsed, constant voltage, constant current, constant current constant voltage, and other charging controls have been implemented [34]. Most

of the time, EV batteries are charged with the constant current constant voltage method. When the SOC of the battery reaches 80%, the charging mode changes from constant current to constant voltage. The last 20% of the battery takes three times as long to charge in the constant voltage mode as in the constant current mode [33]. The dc–dc converter, therefore, employs an MSCC control approach. For V2G and G2V operations, the MSCC control system employs the SOC and mode selection signal to calculate the reference current. A protection signal is also incorporated into this system to prevent the battery from being overcharged or severely discharged. Fig. 4 shows the conjugate gradient algorithm for the reference current generation and the corresponding equations are as follows.

The term "grid" can refer to a variety of different things depending on the context, but in general, a grid is a system of interconnected elements that work together to accomplish a particular goal. In the context of power generation and distribution, the grid refers to the network of power lines, substations, transformers, and other infrastructure that allows electricity to be generated at power plants and transmitted to homes and businessesVSIs are widely used in microgrids due to their ability to generate stable AC voltage waveforms.

A variable speed wind turbine is used in this system. The characteristics of the wind turbine is shown in Figure. 5; the Cp for various wind speeds at different pitch angles. A permanent magnet synchronous generator is selected for its low maintenance and low operational cost. The generator output is dependent on the wind speed. The three-phase output of the generator is rectified using a diode rectifier and then the voltage level is increased with the help of a DC-DC boost converter as shown in Figure.

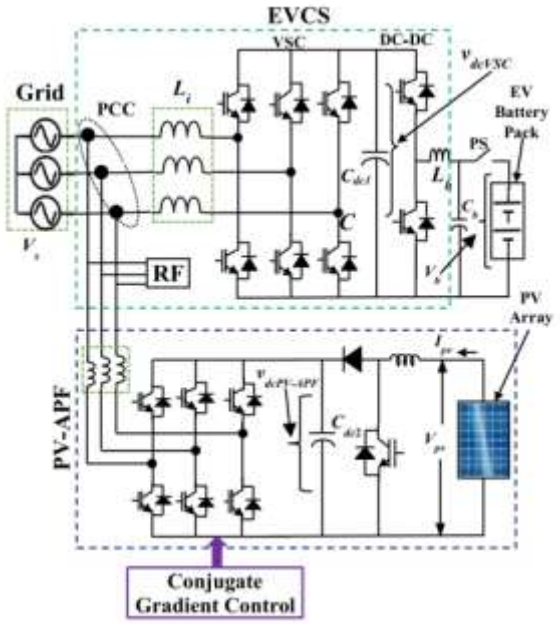


Figure :2 System configuration

DC to AC power conversion is the result of power switching devices, which are commonly fully controllable semiconductor power switches. The output waveforms are therefore made up of discrete values, producing fast transitions rather than smooth ones. For some applications, even a rough approximation of the sinusoidal waveform of AC power is adequate. Where a near sinusoidal waveform is required, the switching devices are operated much faster than the desired output frequency, and the time they spend in either state is controlled so the averaged output is nearly sinusoidal. Common modulation techniques include the carrier-based technique, or Pulse-widthmodulation, space-vector technique, and the selective-harmonic technique.

Current source inverters are used to produce an AC output current from a DC current supply. This type of inverter is practical for three-phase applications in which high-quality voltage waveforms are required.

A relatively new class of inverters, called multilevel inverters, has gained widespread interest. Normal operation of CSIs and VSIs can be classified as two-level inverters, due to the fact that power switches connect to either the positive or to the negative DC bus. If more than two voltage levels were available to the inverter output terminals, the AC output could better approximate a sine wave. It is for this reason that multilevel inverters, although more complex and costly, offer higher performance.

Each inverter type differs in the DC links used, and in whether or not they require freewheeling diodes. Either can be made to operate in square-wave or pulse-width modulation (PWM) mode, depending on its intended usage.

Square-wave mode offers simplicity, while PWM can be implemented several differen

- ways and produces higher quality waveforms.

Voltage Source Inverters (VSI) feed the output inverter section from an approximately constant-voltage source.

The desired quality of the current output waveform determines which modulation technique needs to be selected for a given application. The output of a VSI is composed of discrete values. In order to obtain a smooth current waveform, the loads need to be inductive at the select harmonic frequencies. Without some sort of inductive filtering between the source and load, a capacitive load will cause the load to receive a choppy current waveform, with large and frequent current spikes.

Proportional-Integral controller mode results from the combination of the proportional and the integral mode. Certain advantages of both control actions can be obtained from this mode. This mode is also called as the proportional plus reset action controller. Equations for the proportional mode and integral mode. The proportional gain, by design, also changes the net integration mode gain, but the integration gain, can be independently adjusted. It is understood that the proportional offset occurred, when a load change required a new nominal controller output, and this could not be provided except by a

fixed error from the set point. In the present mode, the integral function provides the required new controller output, thereby allowing the error to be zero after a load change. The integral feature effectively provides a ‘reset’ of the zeroerror output, after the load change occurs. At time t1 a load change occurs, that produces the error. The accommodation of the new load condition requires a new controller output. The controller output is provided through a sum of proportional plus integral action that finally leaves the error at zero. The proportional part is obviously just an image of the error.When the error is zero, the controller output is fixed at the value that the integral term had, when the error reduced to zero. This output is given by pt(0) simply because we choose to define the time at which observation starts, as t = 0. If the error is not zero, the proportional term contributes a correction and the integral term begins to increase or decrease the accumulated

5. Simulation Results

In this case, the photovoltaic (PV) system operates at its maximum capacity of 28 kW. Half of this power (14 kW) is allocated to the electric vehicle (EV) load, maintaining a steady voltage of 760 V at the voltage source converter (VSC), while the remaining 14 kW is fed into the grid.

When the battery's state of charge (SOC) drops to a critical level, the MSCC control initiates a mode transition, enabling the EV to supply power back to the grid in vehicle-to-grid (V2G) mode. During this stage, the total power delivered to the grid, combining contributions from both the EV and PV system, reaches 41.5 Kw.

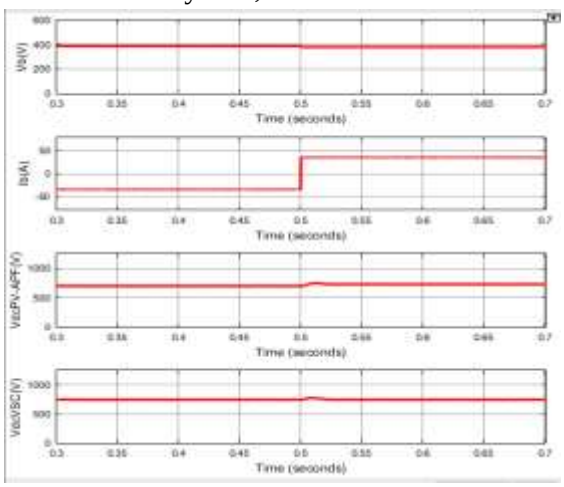


Figure:3.Waveforms of Vsabc, Isabc, ILabc, Icabc with constant irradiance

6. Conclusion

The proposed solar PV-powered Electric Vehicle Charging System (EVCS) integrates a Photovoltaic Active Power Filter (PV-APF) to enable distortion-free charging while supporting bidirectional power flow in Vehicle-to-Grid (V2G) and Grid-to-Vehicle (G2V) modes. The system methodology can be broken down into the following components The project introduces a solar PV-powered electric vehicle charging system (EVCS) that ensures distortion-free charging by incorporating a PV-APF in key operating modes. It begins by outlining the design of the future PV-APF of integrated EVCS, which is regulated using a conjugate gradient of adaptive network algorithm. The system performance is evaluated under sudden variations in solar PV irradiance. Simulation results confirm the efficient operation of the EVCS in both V2G & G2V modes. Furthermore, tests conducted under different irradiance conditions demonstrate that the conjugate

gradient of control strategy surpasses conventional methods in maintaining stable voltage on the PV-APF's DC bus. In both V2G and G2V modes, the total harmonic distortion (THD) remains below 5%. Additionally, the results validate a seamless transition between V2G and G2V modes, highlighting the system's reliability.

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