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V2g (Vehicle To Grid) Stability And Power Quality

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Abstract
The increasing penetration of renewable energy sources, distributed energy resources (DERs), and electric vehicles (EVs) has created new opportunities for improving the flexibility, reliability, and sustainability of modern power systems. Smart grid technology integrates advanced communication, monitoring, and control systems with conventional electrical networks to enable bidirectional power flow and intelligent energy management. In this context, Demand-Side Management (DSM) and DER integration play important roles in balancing electricity demand, reducing peak loading, and improving the utilization of renewable energy resources. Vehicle-to-Grid (V2G) technology further enhances smart grid functionality by enabling bidirectional energy exchange between electric vehicles and the power grid. Through suitable bidirectional power converters, battery management systems, and energy management systems, EV batteries can supply stored energy to the grid when required while meeting battery operating limits and user mobility requirements. V2G can contribute to peak-load reduction, renewable energy integration, frequency regulation, and voltage support. This chapter presents an overview of conventional and smart grid structures, the major components and benefits of smart grids, DSM strategies, and the role of DERs in modern power systems. It also explains the working principle, bidirectional power flow, system architecture, and interaction between V2G systems and grid operators. The discussion highlights the importance of coordinated energy management, reliable communication, cybersecurity, battery health, and appropriate grid interconnection standards for effective V2G implementation. Finally, potential research directions are identified, including optimized energy management, battery degradation assessment, coordinated grid-support control, and secure communication for large-scale V2G deployment.

Keywords: Smart Grid, Vehicle-to-Grid (V2G), Electric Vehicles, Demand-Side Management, Distributed Energy Resources, Bidirectional Power Flow, Energy Management System, Renewable Energy Integration

I. INTRODUCTION

EVs are driven by electric motors powered by energy stored in energy storage devices (batteries, supercapacitors, fuel cells). Electric Vehicle-to-grid (V2G) technology can be described as a system capable of controlling bi-directional power flow between PEVs and the power grid [1-3]. V2G system refers to PEVs communication with the power grid to avail grid support services by

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either discharging to the grid or throttling their charging rate.V2G technology can avail flexible, cheap, and quick-responding energy storage unit of the EVs battery pack. The incorporation of electric vehicles into the power grid is referred to as a V2G integral system. In [4], V2G can provide ancillary services like load leveling, frequency regulation, energy storage, and the spinning reserve [5].

II. NEED FOR VEHICLE-TO-GRID (V2G)

The rapid growth in the adoption of Electric Vehicles (EVs), increasing electricity demand, and the widespread integration of renewable energy sources have transformed the operational characteristics of modern power systems. Although electric vehicles contribute significantly to reducing greenhouse gas emissions and dependence on fossil fuels, their large-scale charging introduces new challenges related to grid stability, power quality, peak demand, and energy management. Conventional EV charging follows a unidirectional approach in which electricity flows only from the grid to the vehicle. During periods of high charging demand, this one-way energy flow can overload distribution networks, increase peak loads, and negatively affect voltage and frequency stability [2]. To address these challenges, Vehicle-to-Grid (V2G) technology has emerged as an innovative and intelligent solution that enables bidirectional power exchange between electric vehicles and the electrical grid. Vehicle-to-Grid technology allows electric vehicles to function not only as transportation devices but also as mobile distributed energy storage systems. Through bidirectional charging infrastructure, EV batteries can store electrical energy during periods of low demand or high renewable energy generation and discharge stored energy back to the grid during periods of peak demand or system disturbances. This capability transforms EVs into active participants in power system operation, supporting the grid by providing ancillary services such as frequency regulation, voltage support, reactive power compensation, spinning reserve, and peak load management [3].

III. PROBLEM STATEMENT AND MOTIVATION OF THE WORK

The integration of photovoltaic (PV) systems and electric vehicles (EVs) into modern electrical grids has introduced significant challenges related to power quality and grid stability. While PV systems generate renewable energy and EVs serve as both consumers and suppliers through bidirectional power transfer, their combined incorporation creates notable harmonic disturbances. These harmonics adversely affect the performance of the main power system, causing voltage distortion, reduced system efficiency, and non-compliance with established power quality standards. The nonlinear characteristics of power electronic converters in PV inverters and EV charging equipment contribute substantially to these harmonic distortions. The intermittent nature of solar power generation, coupled with the variable and dynamic demand

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from EV charging and discharging, leads to voltage fluctuations and reactive power imbalances within the grid [4].

IV. PROPOSED METHODOLOGY

SOLAR PV INTEGRATED EV CHARGING SYSTEM

The Solar Photovoltaic (PV) Integrated Electric Vehicle (EV) Charging System is an advanced charging infrastructure that utilizes solar energy as the primary power source for charging electric vehicle batteries. This system combines renewable energy generation with electric vehicle charging to reduce dependence on conventional fossil fuel-based electricity, lower greenhouse gas emissions, improve energy efficiency, and promote sustainable transportation. In the proposed research, the Solar PV system is integrated with an EV charging unit through a controlled power electronic converter, where a PID controller and Pulse Width Modulation (PWM) technique are employed to regulate the charging voltage and provide continuous, stable power to the EV battery. The proposed Solar PV integrated EV charging system consists of several interconnected components, including the Solar PV array, DC–DC boost converter, PID controller, PWM generator, EV battery, measurement units, and MATLAB/Simulink environment. Each component performs a specific function to ensure efficient energy conversion and controlled battery charging [5].

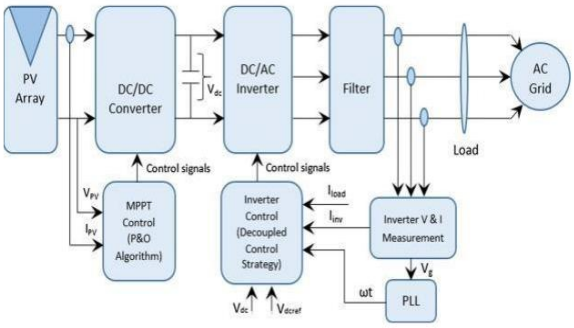


Figure 1. Block diagram of Proposed methodology.

Figure 1 above provides an overview of the research work. This chapter delves into the primary focus of the study: solar energy systems, examining the process from photovoltaic cells to power generation. The MPPT controller determines the duty cycle by analyzing the voltage and current from the solar panels. It uses the Perturb and Observe method to compute the changes in voltage and current, which helps in identifying the new slope of the PV curve and subsequently calculating the D value. At the same time, the dq method PI controller processes inputs such as the DC link voltage (Vdc), grid voltage (Vabc), and grid current (Iabc). This controller is responsible for producing PWM signals for the inverter, ensuring the DC link voltage is

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maintained at the inverter's input and synchronizing the PV power with the main grid which is detailly explained in future chapters [6-10].

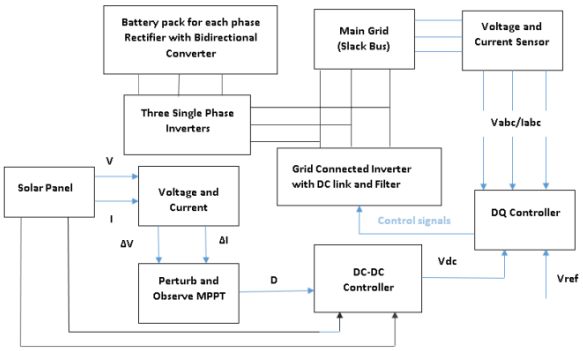


Figure 2 Proposed Integrated PV-EV-Grid Topology with DQ Controller and Bidirectional Power Flow Controller.

The Proposed system effectively addresses power quality issues when a PV generator connects linear, non-linear loads and EV loads to the main grid. The MPPT algorithm, also Photovoltaic (PV) generation system, control mechanism, PWM-based power regulation, and EV system. known as Perturb and Observe (P and O), efficiently supplies power to the grid-side inverter. Additionally, the system mitigates potential voltage spikes at the PCC caused by the growing number of EVs. Harmonics introduced into the PCC by Switched-Mode Power Supply. (SMPS) based converters in charging stations and on-board EV chargers can be reduced using distributed FACTS devices, shunt and series active filters, and hybrid active filters. To proactively manage power quality problems arising from the dynamic integration of numerous EVs into the load, control strategies such as real and reactive power (PQ) methods and direct and quadrature (d-q) methods are incorporated into the distribution system, as illustrated in Figure 2. The proposed configuration, depicted in Figure 2, integrates a DC link voltage regulation loop, a PV-grid synchronization loop with a dq controller, and a twoswitch bidirectional converter to regulate the battery's charging/discharging cycle. These components collectively create a PV-EV-Grid system with enhanced power quality, where the inverter plays a crucial role in effectively resolving power quality issues caused by nonlinear loads. By isolating these variables, precise control of the inverter's voltage and current outputs is achieved, leading to the derivation of synchronous reference frame components. In the block diagram, black lines represent power flow, while blue lines indicate the controller section. The DC link voltage is continuously regulated by the dq controller, which aligns the voltage and phase angle with the grid. A crucial aspect of this control strategy involves utilizing the SVPWM technique generated by the dq controller to produce PWM for the inverter switches, ensuring compliance with grid code requirements. Figure 3

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illustrates the Voltage Regulation process for PV Output utilizing a PI controller. Initially, the three-phase voltage Vabc is transformed from the aforementioned equation to its RMS value. This value is then contrasted with the specified 343V, and a discrepancy is identified. This discrepancy is employed to generate a proportional current that reflects the deviation from 343V. A PI controller processes the error signal and produces an output that specifies the necessary current to eliminate the difference between the Vabc RMS voltage and 343, thereby reducing the Vabc RMS voltage and facilitating the attainment of the target value. The current reference output is positioned in the quadrature axis, or q-component, format as it pertains to reactive power compensation. This is because the PV panel provides only real power, while the grid voltage Vabc consists of both real and reactive power elements.

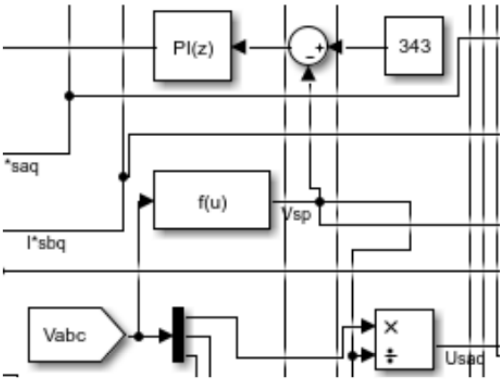


Figure 3 Voltage Regulation Process for PV Output Using PI Controller

The desired reference signal is created by eliminating the reactive component. Lastly, the q component is converted into three-phase a,b,c components through a dq-to-abc transformation, as depicted in Figure 4.

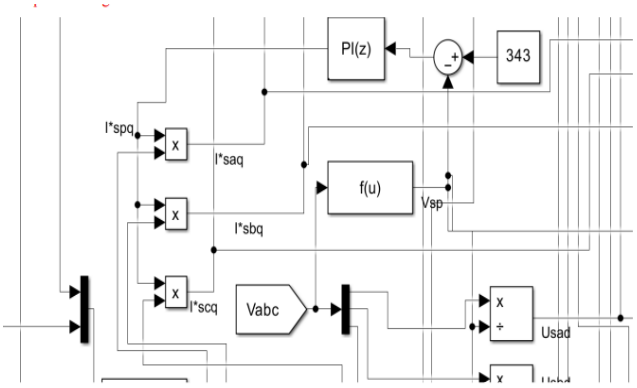


Figure 4. dq to abc Conversion Process

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In a similar manner to how the reactive component of the current is established, the direct axis component is determined by comparing the DC link voltage to its 1600V reference value. The difference is then processed through a PI controller, which applies proportional and integral actions to the error, generating the necessary control signal, which serves as the direct axis component. The PI controller's output is used to derive a, b, and c elements of the direct axis current. The direct axis (d) and quadrature axis (q) are then combined in a summation box with the actual current signal for the area. Each component transforms and generates the required PWM signals to regulate the inverter. This process ensures proper current control and maintains stable system operation. Figure 5 illustrates the control loop for the direct and quadrature axis current components.

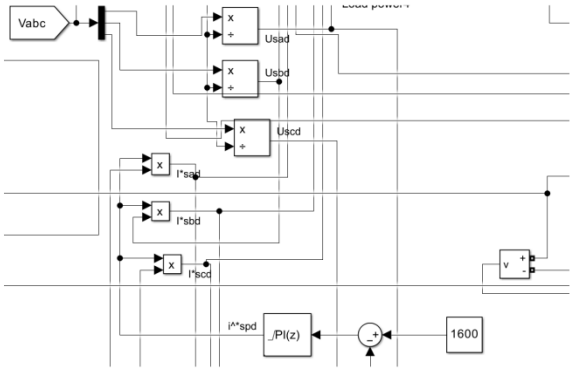


Figure 5 Control Loop for Direct and Quadrature Axis Current Components The difference between the reference and actual current serves as input for the PWM generation block, which produces the necessary inverter gate pulse PWMs. To ensure precise current tracking, the output current of the inverter (i) is compared with the reference currents, denoted as a*, b*, and c*. This process is depicted in the above Figure 4.10.

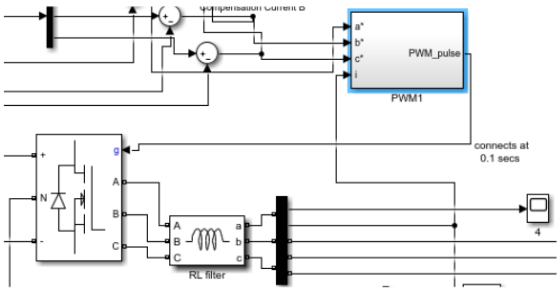


Figure 6 Comparison of Reference Current with Inverter Output Current for PWM Control. The three-phase current (a, b, and c) produced by the inverter is constantly monitored and evaluated against the corresponding reference three-phase currents (a*, b*, and c*). This evaluation is

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crucial for maintaining proper current control and ensuring high power quality. The discrepancy resulting from this comparison is then transmitted to the PWM generation unit, which processes the information to create the necessary PWM signals for the inverter's switches. These signals are utilized to control the inverter, enabling the output current to closely track the reference current.

V. PROPOSED BATTERY CHARGING/DISCHARGING CIRCUIT: CONTROL SYSTEM DESIGN

The control system depicted in Figure 7 incorporates a voltage control loop. This loop measures the DC link voltage and compares it to a predetermined reference value (Vdc-ref) to generate the reference interfacing inductor current (Inf-ref). Additionally, a single-phase phase locked loop (PLL) is employed to maintain a sinusoidal input grid current that is in phase with the grid voltage (Vg), thereby achieving unity power factor. The system continuously compares the reference inverter current (Iinv ref) with the actual inverter current (IN), feeding the resulting error into a Proportional and Resonant Current controller (PR Controller). The output from this PR Controller is utilized to create the necessary PWM signals for managing the switching devices in the stage-1 converter. This methodical approach ensures effective control and regulation of the entire system. The PR Controller, unlike traditional controllers, integrates proportional control with resonance-based methods, offering accurate tracking of the grid current reference and robust suppression of system resonances. This results in improved stability and dynamic response, particularly in situations where grid conditions may fluctuate. Moreover, the PR Controller's inherent ability to address both transient and steady-state performance requirements made it the ideal choice for achieving efficient control and regulation throughout the system.

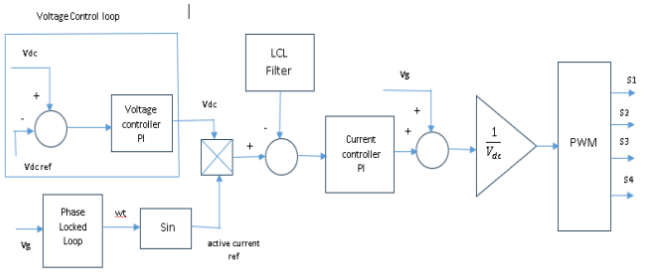


Figure 7 Controller for Bidirectional AC-DC Converter (Stage 1). Figure 8 depicts the control diagram for this system. The process involves comparing the battery current (Ibat) with the reference current (Ibat-ref) using a comparator. The resulting difference generates an error signal, which is then input into the current controller. The current controller's output is based on the disparity between the actual battery charging current (Ibat) and the reference value (Ibat-ref).

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This output directly affects the duty cycle adjustment of the PWM signal for the switches in the stage-2 converter. In contrast, during the boost phase, the electrical flow reverses direction, moving out of the battery. This change in current direction does not affect the rest of the system's arrangement. The bidirectional converter's operation mode, either charging or discharging, is determined by a switch. This switch regulates the flow of power in a controlled fashion, allowing the converter to either store energy in the battery from the grid or release energy to the grid or load. The system's versatility and performance are enhanced through effective switching mechanisms.

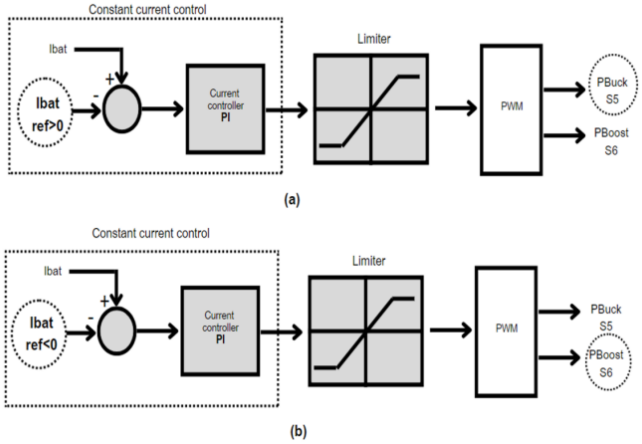


Figure 8 Regulatory system for dual-directional Buck-Boost converter (stage 2): (a) Schematic for battery buck/charging mode regulation; (b) Schematic for battery boost/discharging mode regulation.

VI. SIMULATION RESULT AND DISCUSSION

The model and algorithm developed were evaluated using MATLAB/Simulink simulations. The model underwent testing under varying solar irradiation conditions while maintaining a constant load. Simulations were conducted with a Perturb and Observe MPPT controller, and the resulting solar voltage, current, and power waveforms were documented. Additionally, the controller's tracking efficiency was measured in relation to the irradiation levels.

Waveforms of Grid-Connected PV System Figure. 9 shows the system response to step changes in irradiance every 0.1 seconds, simulating passing cloud conditions. The MPPT controller (P&O) adjusts the duty cycle dynamically. Following each step increase in irradiance, the PV power output stabilizes to the new maximum value within 0.1 second, indicating a fast transient response. The voltage waveform also exhibits a quick settling time of 0.015 second without significant overshoot. This confirms the controller’s ability to track MPP efficiently under dynamic environmental conditions.

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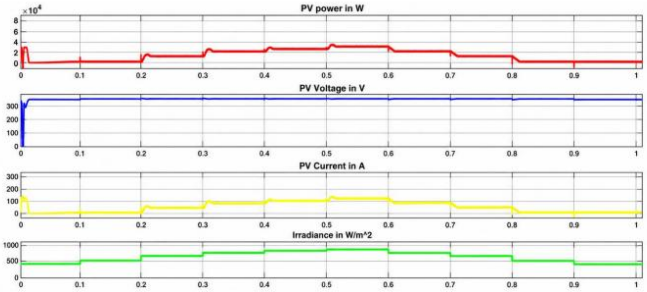


Figure 9 Waveforms of Solar Power, Voltage, Current, and Irradiation in P&O Controlled PV System The P&O controller dynamically adjusted the system to track the maximum power point (MPP) f the solar PV panels effectively. As the solar irradiation levels changed, the corresponding duty cycle and voltage waveforms demonstrated the controller's capability to adapt and maintain optimal power output. These waveforms provide a comprehensive view of how the gridconnected PV system responds to varying solar inputs, ensuring efficient operation and maximum energy harvest under fluctuating irradiation conditions and shown in the below Figure 9.

Simulation Results of dq-Method PI Controller for Voltage Regulation and Reactive Power Compensation in EV-PV Grid Integration

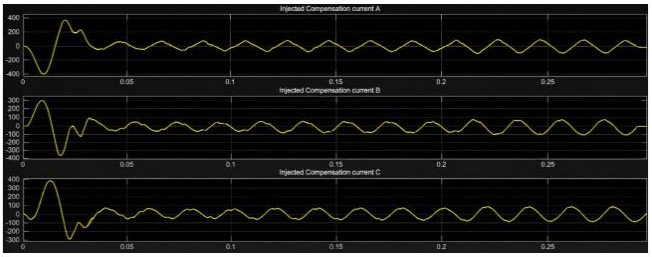


Figure 10 Injected Current from Inverter in Voltage-Regulated Mode for Maintaining Constant DC link Voltage.

During voltage-regulated operation, the inverter injects a steady current into the system to maintain a constant DC link voltage at its input. This injected current primarily serves to counterbalance any fluctuations or perturbations in the DC link voltage, ensuring it remains stable at the designated reference value. The control system of the inverter continuously monitors the DC link voltage and dynamically adjusts the injected current to offset any deviations from the reference voltage. By maintaining a steady DC link voltage, the inverter ensures stable operation, efficient power conversion, and the ability to deliver consistent power to the grid or load.

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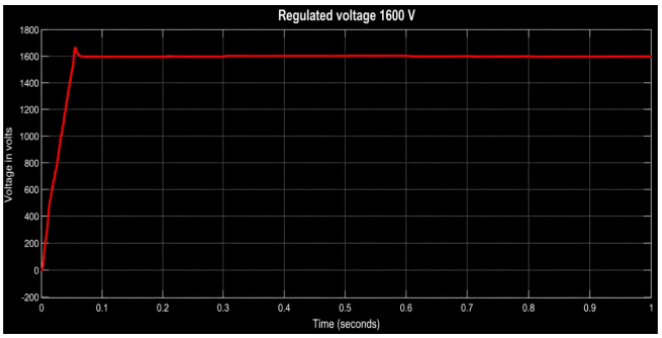


Figure 11 DC Link Voltage Regulation with Reference Voltage of 1600 V.

The PV inverter and grid voltage both exhibit an amplitude of approximately 343V. The presence of a nonlinear load and an electric vehicle (EV) charging station on the grid can introduce distortions, impacting the load voltage. Despite these potential disruptions, the grid current maintains a sinusoidal waveform due to the inverter's injection current. This injected current plays a crucial role in managing reactive power at the grid, thereby ensuring stable power .The combined effect of the dq control loop and Space Vector Pulse Width Modulation (SVPWM) enables the system to actively correct for disturbances caused by the nonlinear loads and EV chargers, maintaining grid voltage and current stability.

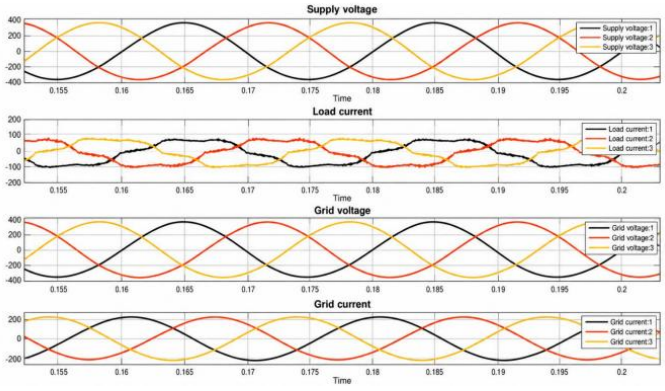


Figure 12 Voltage and Current Stability at the Grid with Reactive Power Control through dq Method PI Controller.

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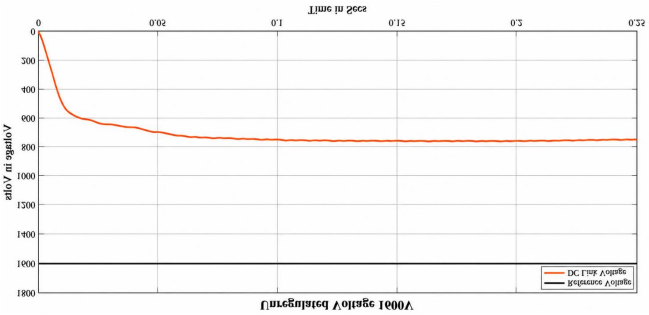


Figure 13 DC Link Unregulated Voltage Regulation with Reference Voltage of 1600 V.

The supply voltage mentioned is the PV inverter output around 343 V and similar amplitude is obtained in the grid voltage also. The non-linear load and the EV connected to the grid the load voltage is as same shown in Figure 5.4. But due to the injection current from the inverter the current at the grid is sinusoidal in nature thus controlling the reactive power at the grid. All though voltage regulation loop is not active and the DC link voltage is not as expected the dq controller has maintained the voltage and the current at the grid to be stable which is as shown in the Figure.13.

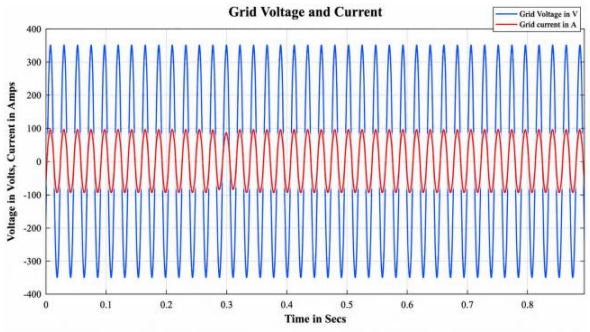


Figure 14 Bidirectional Power Flow Between Vehicle to Grid (V2G) and Grid to Vehicle (G2V).

The bidirectional energy transfer between grid-to-vehicle (G2V) and vehicle-to-grid (V2G) systems is depicted in Figure 14. Figure 15 shows the relationship between voltage and current during the transfer of power from the grid to the vehicle. This graph demonstrates the current's orientation relative to the voltage, offering insights into the dynamics of power flow and its impact on the vehicle's charging process.

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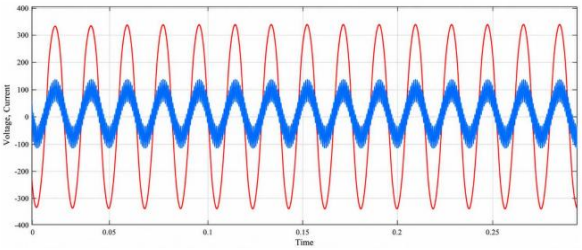


Figure 15 Current-Voltage Dynamics in Vehicle Charging Process.

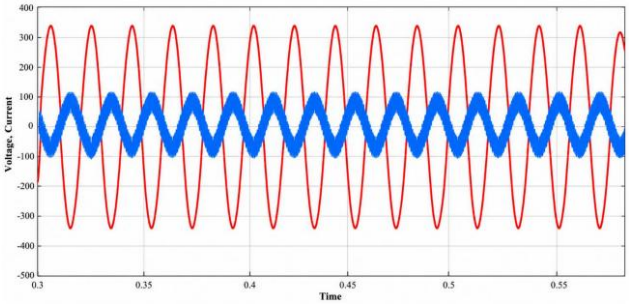


Figure 16 Current-Voltage Dynamics in Vehicle discharging Process.

The standard operating mode is G2V, while V2G is activated based on the load and PV power input, as shown in Figure 17. This diagram illustrates the current direction, which is opposite to the voltage phase in this instance, offering insights into power flow patterns during the vehicle's discharge process back to the grid. Grasping this relationship is crucial for establishing the system's two-way energy flow.

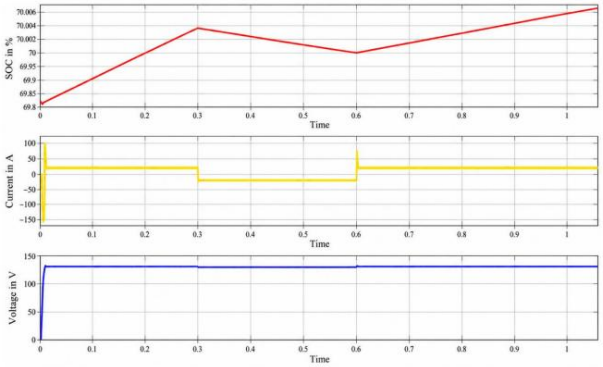


Figure 17 Battery Dynamics: Charging and Discharging Stages with SOC Variation.

VII. CONCLUSION

The proposed system demonstrates effective regulation of the DC-link voltage at the reference value of 1600 V, with a small transient overshoot during startup. The PV power and current responses follow variations in solar irradiance, indicating the system's ability to operate under

changing environmental conditions. The three-phase supply voltage, grid voltage, and current waveforms illustrate the electrical behavior of the integrated system under the simulated operating conditions. The battery state of charge (SOC), current, and voltage responses also show the system's dynamic behavior during charging and discharging transitions. Overall, the simulation results indicate the potential of the proposed control strategy to improve DC-link voltage regulation and support stable power management in a renewable energy-based grid-connected system.

FUTURE SCOPE

1. Advanced control techniques: Implement adaptive, model predictive, or intelligent control strategies to further improve DC-link voltage regulation and transient response.
2. Energy management optimization: Develop an optimized energy management system for coordinating PV generation, battery storage, and grid power exchange.
3. Battery performance analysis: Investigate battery degradation, charging efficiency, lifetime, and SOC estimation accuracy under varying operating conditions.
4. Power quality improvement: Evaluate total harmonic distortion (THD), power factor, and gridcurrent quality under nonlinear loads and changing solar irradiance.
5. Real-time validation: Validate the proposed control strategy using hardware-in-the-loop (HIL) simulation and a laboratory-scale experimental prototype.
6. Robustness assessment: Examine system performance under sudden load changes, irradiance fluctuations, parameter uncertainties, and grid disturbances.

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