Integrated proportional-integral control for enhanced grid synchronization and power quality in photovoltaic-electric vehicle systems

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ABSTRACT

Photovoltaic (PV)-grid with electrical vehicle penetration introduces harmonics to the main power system. This paper explores the disturbances introduced due to both PV and electric vehicles (EVs) in the grid. PV acting as the source and EV acting as both the load and the source introduces harmonics to the main grid. The combined harmonics from both the PV and EV are controlled using the integrated DQ controller on the voltage source converter (VSC) that connects to the grid from the PV source. The real and reactive power is controlled in a decoupled manner to obtain better control of the harmonic reduction introduced in the grid. This study investigates the use of proportional-integral (PI) control techniques to develop an integrated controller that can effectively handle both PV synchronization and power quality when using electric vehicles. To reduce harmonics in the grid current, the study combines multicarrier space vector pulse width modulation (SVPWM) with PI control on the grid-connected converter through a dual-control loop system devoted to PV grid synchronization, with one loop specifically addressing EV battery charging control. DQ method yields a total harmonic distortion (THD) of 2.74% for voltage and 3.44% for current according to the IEEE 519 standards.

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1. INTRODUCTION

The integration of electric vehicles (EVs) and solar photovoltaic electricity into the grid is transforming the current energy environment and paving the way for intelligent and sustainable urban energy systems. Even though this integration offers a promise to lessen reliance on conventional energy sources and reduce emissions, it also causes intricate issues with power quality and grid synchronization. This integration creates intricate problems with power quality and grid synchronization, even if it has enormous potential to reduce dependency on traditional energy sources and reduce carbon emissions. There are several obstacles, including the intermittent nature of solar energy and the nonlinearity due to high-speed switching power electronic devices for EV charging. To guarantee smooth and dependable operation, harmonics, voltage, and current variations in the grid require regulation. To maximize the integration of photovoltaic (PV) and EV technologies into current energy infrastructures, power quality issues introduced in the grid due to their integration needs to be addressed.

Different penetration levels of the PV energy into the power grid analyzed with different inverter topologies including voltage source converter (VSC) [1]. The stochastic nature of the inverters makes it an impeccable choice for small, medium and large scale grid connections. Different topologies of PV grid inverters are discussed according to the capacity it can produce according to the topological variation, shading effect, and cost [2]. Although the PV integration uses the synchronization technique the passives filters like RL and LCL filter are necessary for steady current regulation in the point of common coupling (PCC). The advantages of LCL filter over RL filter is discussed in detail for better power quality in grid connected systems [3]. However, resonance issues in LCL filters necessitate efficient active damping methods; a two-DOF PID control mechanism is proposed [4] to achieve around 98% damping. Model predictive controller (MPC) is used as the inverter controlling for voltage and current regulation in the microgrid configuration [5]. According to IEEE 1547.1 and IEEE 519 standards, three-level HCC is advised in order to address SF variation issues and enhance control performance [6]. Additionally, VSC-based distribution static compensator (DSTATCOM) systems can be used to decrease grid distortion, imbalance, harmonics, and voltage variations. These developments in control schemes and inverter topologies highlight how grid-connected photovoltaic systems are changing and how important they are to sustainable energy solutions.

Researchers successfully combined solar photovoltaic (PV) and wind energy with a Li-ion battery to create an AC charging station in a recent study [7]. Bidirectional electricity flow was made possible by this grid-connected station, allowing for the import and export of electricity. Further research in [8] concentrated on creating novel control strategies designed for grid-connected solar power plant fast charging stations. The study investigated ways to improve multi-port charging stations. A different study that was highlighted in [9] presented a charging approach that purposefully broke up the charging time into intervals. The objective of this strategy was to reduce energy expenses by minimizing the peak energy usage of electric vehicle (EV) fleets during the day. In charging infrastructure contexts, traditional two-level DC-DC converters which are recognized for their ease of use and high efficiency have been extensively addressed. These converters, in particular, use buck and boost converter topologies. But these converters can't handle the medium and high voltage levels found in fast-charging stations; this puts additional strain on the switching components and necessitates the use of more expensive parts. As a durable alternative, multi-level (ML) converters have gained favor in response, providing benefits such as decreased switching losses, lower output voltage distortion, and lessened device strain [10]-[14]. These features offer ML converters as a feasible option for medium and high-voltage applications in charging infrastructure by facilitating more cost-effective and efficient operations. Power quality problems in single-phase and three-phase electrical systems, such as harmonics and reactive power requirements, have been the subject of numerous configurations and methods [15]. Preview study [16] investigates the charging dynamics of plug-in electric vehicles (PEVs) within residential solar PV systems in an effort to address voltage imbalances and power quality issues. These problems are addressed by the introduction of a battery management system, particularly when dealing with intermittent PV power. It outlines a strategy that entails charging the battery during periods of peak PV power availability and draining it during periods of peak demand. In this regard, the assessment of hosting capacity which stands for the energy supplied to the network without sacrificing power quality is conducted. Enabling vehicle-to-grid (V2G) coordination in a PV-integrated grid environment is investigated in conjunction with intelligent electrical charging for EVs, which includes a data mining technique and driver assistance application [17]. The paper emphasizes power quality issues while acknowledging the difficulties distribution systems face from the growing use of renewable energy sources (RES) and dynamic electric vehicle loading [18]. P-V curves, EV charging stations (EVCS), and vehicle-to-grid technology (V2G) are used to evaluate the grid impact during PV and EV penetration. This is followed by a thorough power quality assessment [18]. A demand response (DR) study presents a local energy community (LEC) management approach that synchronizes the selection of V2G participants with DR using a preference modeling algorithm [19]. Considering different V2G percentages and capabilities, the paper also discusses the overall grid-level effects of individual vehicle frequency regulation [20], offering insights into the best V2G integration for overall grid frequency regulation.

The effective use of DER-generated energy, energy storage systems (ESS), and EVCS to transfer loads from the main grid through the integration of an energy management system for microgrid models is investigated [21]. The paper recognizes that big DC components might cause problems like transformer core saturation and winding heating, which is why transformer-less inverter technology is being investigated as a potential solution. Reinforcement learning-based efficient scheduling algorithms are emphasized for enhanced and self-sufficient electric vehicle charging systems (EVCS). Particle swarm optimization (PSO) and other algorithms are used in a study to minimize power loss and voltage imbalances in a bipolar DC distribution grid (DCDG) scenario with probabilistic EV charging loads [22]. The development of EV charging methods is examined, with a focus on the advantages for users and networks of bidirectional power transmission (car-to-grid) [23]. The specific control mechanisms of these chargers, particularly for vehicle-to-residence scenarios, are illustrated by simulations that show how effective control strategies may be implemented [24]. Furthermore, efforts are given [25] to optimize microgrid operations in the event of the worst-case renewable energy failures. In order to minimize energy loss, load shedding, and the utilization of electric vehicles and energy storage systems (EV/EES) in worst-case scenarios, a two-level model with mixed-integer quadratic programming (MIQP) is utilized. It is known that during the energy revolution, there has been a continuous shift toward grid decentralization, highlighting the importance of micro grids and the imperative need for an efficient energy management system (EMS) [26]. The article cites several articles [27]-[36] that address the integration of electric vehicles with the grid. Citing solar research studies that improve power tracking and stability, it acknowledges the expansion of PV power plants and the benefits that go along with them.

The cumulative harmonic distortion introduced due to the introduction of both the bidirectional power from the EV and PV to the grid needs to be controlled. This paper attempts the DQ controller to control the harmonics thus introduced by controlling the pulse width modulation (PWM) of the VSC that interfaces between the PV and the grid. The grid side current has to be kept with good shape since the disturbance in grid current would disturb all the loads connect at the point of common coupling (PCC). MATLAB simulation with PV-grid connected to the bidirectional EV load that can both get and deliver power to the grid is developed and the DQ controller is applied to maintain the stability in both voltage and current at the grid. A thorough analysis of the findings is included in the paper, along with data tabulations for scenarios combining EV operations with linear and nonlinear loads.

2. POWER QUALITY IMPROVEMENT USING DQ CONTROLLER

Electric vehicles are penetrating incrementally the distribution system, and it is bound to grow further in future. Scenarios where communities introduce renewable energy into the distribution system is evolving with the awareness on sustainability. Electric vehicle (EV) and renewable energy sources (RES) are both source of power quality issues to the distribution system. Since EVs have battery based energy storage, inrush of current to batteries cause the voltage stability issues in the distribution transformer outputs. While renewable energy resources due to its intermittent supply and unsynchronized voltage and frequency need to synchronize with the distribution system. This paper develops the power quality controller that manages both the EV and PV integration with the distribution system and bidirectional operation of EVs with the change in load scenarios. Decoupled control of all the real and reactive power component of the system is controlled using the DQ controller. Scenarios of vehicle to grid (V2G) and grid to vehicle (G2V) is simulated using MATLAB in the photovoltaic (PV) integrated system. Power quality issues introduced due to EV and PV integration to the distribution generation including voltage imbalance, total harmonic distortion and power factor are eliminated.

The approach takes a holistic approach to address power quality concerns brought on by the increasing grid integration of electric vehicles (EVs) and solar photovoltaic installations. This method necessitates the use of a bidirectional power flow controller to control battery charging and discharge. Additionally, a grid-side converter maintains grid synchronization and controls the DC link voltage under the direction of a DQ controller. Using the DQ controller's SVPWM method ensures grid code compliance. The perturb and observe (P&O) maximum power point tracking (MPPT) feature of the system ensures an efficient power supply to the grid-side inverter while managing a variety of loads. In order to handle possible voltage interruptions at the PCC brought on by a rise in EVs, mitigation solutions include distributed flexible AC transmission system (FACTS) devices, active and hybrid filters, and advanced control approaches. A robust PV-EV-grid system that can accurately control the voltage and current outputs to handle power quality issues caused by non-linear loads and the dynamic addition of EVs to the distribution system is created by this integrated method, with the inverter serving as the key component.

2.1. Electric vehicles and solar PV systems

The study's main component is the solar photovoltaic generator, which is made up of solar cells and connecting parts. The range of materials available for solar cells has grown from silicon to include low-cost, highly efficient organic compounds. As EVs and PV systems become more prevalent, power electronics devices with higher switching frequencies are added to the grid. Grid interruptions could be caused by these devices, which include grid-side converters for PV integration and bidirectional converters for battery charging and discharging.

2.2. Control strategies for integrating the grid

A comprehensive control strategy is recommended by the study to effectively address the power quality issues. While a bidirectional power flow controller runs as a single loop to manage battery charging and discharging, a DQ controller manages a grid-side converter. This DQ controller ensures the constant maintenance of the DC link voltage by synchronizing the voltage and phase angle with the grid. A key part of this control technique is using the SVPWM method that the DQ controller generates to deliver PWM for the inverter switches in compliance with grid code criteria.

2.3. Handling power quality challenges

With a PV generator linking linear and non-linear loads to the main grid, the designed system can handle power quality problems well. The grid-side inverter is fed power efficiently by the MPPT algorithm, which is also referred to as perturb and observe (P&O). Furthermore, the mitigation of potential voltage spikes in the PCC due to the increasing number of EVs is covered. Switched-mode power supply (SMPS) based converters, which are used in charging stations and on-board EV chargers, add harmonics into the PCC. Distributed FACTS devices, shunt and series active filters, and hybrid active filters can all be used to cut down on these harmonics. In order to proactively manage power quality issues resulting from the dynamic introduction of a significant number of EVs into the load, control approaches such as real and reactive power (PQ) methods and direct and quadrature (d-q) methods are included into the distribution system as shown in Figure 1. The proposed setup, as shown in Figure 1, combines a DC link voltage regulation loop, a PV-grid synchronization loop with a DQ controller, and a two-switch bidirectional converter to manage the battery's charging/discharging cycle. Together, these components provide a PV-EV-grid system with improved power quality, in which the inverter plays a key role in effectively resolving power quality issues brought on by non-linear loads. By separating these variables, the inverter's voltage and current outputs may be carefully controlled, which leads to the derivation of synchronous reference frame components. Black lines in the block diagram represent power flow, while blue lines designate the controller portion.

The MPPT controller uses the measured voltage (V) and current (I) from the solar panel to determine the duty cycle (D). Using the perturb and observe (P&O) method, the MPPT controller calculates the gradient voltage (ΔV) and current (ΔI) to determine the new slope of the PV curve. This produces a D value. The DQ controller simultaneously incorporates as inputs the observed values of DC link voltage (Vdc), grid voltage (Vabc), and grid current (Iabc). The DQ controller generates PWM signals for the inverter in order to maintain the DC link voltage at the inverter input and synchronize PV power with the main grid. This intricate process guarantees a seamless integration of solar energy into the grid system, underscoring the efficacy of the proposed system architecture. The proportional and integral gains are derived as in (1) and (2).

$$P_G = k_{pg} * error \tag{1}$$

$$P_I = k_{ig} \int_0^t (error)dt \tag{2}$$

The Park's transformation applied to convert the abc to dq conversion as defined in (3).

$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\omega t) & \cos(\omega t - \frac{2\pi}{3}) & \cos(\omega t + \frac{2\pi}{3}) \\ -sin(\omega t) & -\sin(\omega t - \frac{2\pi}{3}) & -\sin(\omega t + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} va \\ vb \\ vc \end{bmatrix} \tag{3}$$

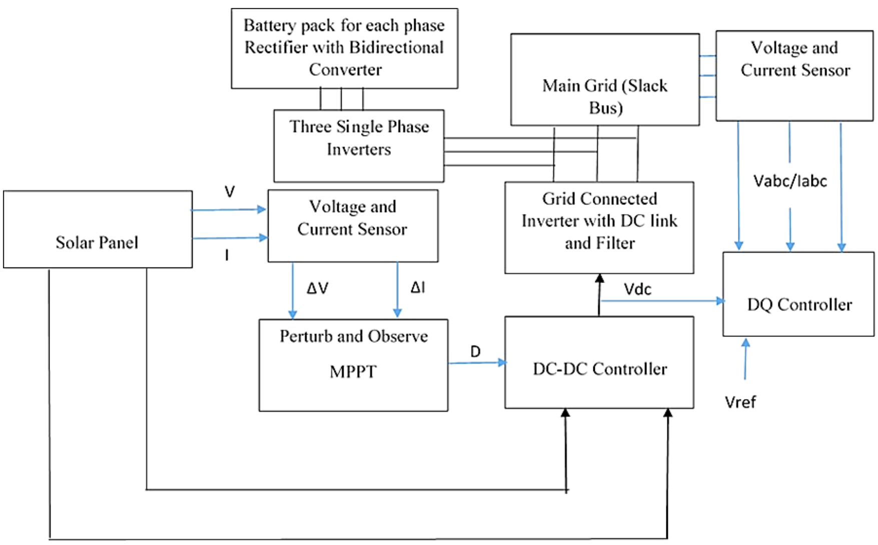

Figure 1. Integrated PV-EV-grid topology with bidirectional power flow controller and DQ control

The (4) outlines the inverse Park transformation, which converts dq coordinates to abc coordinates. This transformation is used to generate the reference current for the SVPWM converter or hysteresis control. The PWM signals in the inverter are generated by comparing the reference current with the actual current.

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos(\omega t) & -\sin(\omega t) & 1 \\ \cos(\omega t - \frac{2\pi}{3}) & -\sin(\omega t - \frac{2\pi}{3}) & 1 \\ \cos(\omega t + \frac{2\pi}{3}) & -\sin(\omega t + \frac{2\pi}{3}) & 1 \end{bmatrix}\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} \quad (4)$$

As illustrated in Figure 2, the DC link set point is established by performing a subtraction, and the PI regulator produces an output to minimize the error between the measured voltage and the actual voltage.

The above said DQ method is applied on the PV connected inverter connecting to the grid. The voltage regulation at the DC link of the PV inverter and the decoupled real and reactive power control of the grid PCC power is carried out using the controller. Reference current thus generated from the controller is given as the reference current to generate the inverter PWM. This PWM thus generated would control the inverter in such a way that the real and reactive power is kept intact to obtain power quality improvement in the grid PCC.

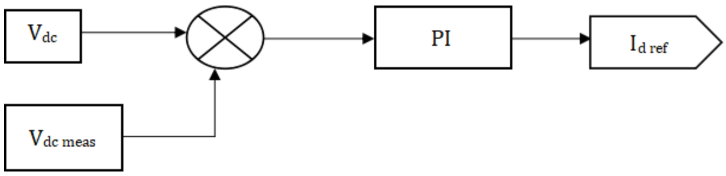

Figure 2. DC voltage regulation

3. RESULTS AND DISCUSSION

The MATLAB simulation for an integrated grid system with PV, EV, and nonlinear loads contains a complicated controller discussed in the previous section. This simulation aims to evaluate the system's performance in all possible ways and improve it. The simulation specifications are shown in Table 1, which also includes information on the PV irradiation variation, transformer, grid code, solar panel array, and linear and nonlinear loads. The main conclusions and outcomes of the simulation are explained in more detail in the following. Batteries are essential for storing solar-generated energy in photovoltaic systems. Direct current can be converted to three-phase alternate current with the help of an inverter. The charge controller is essential for controlling redundant discharge and overcharging depending on the state of charge (SOC) threshold. By including both independent topologies and conventional grid-connected PV systems, the simulation highlights the two-way energy exchange between the grid and the PV system. The utility grid, voltage source inverter (VSI), and transformer of the grid-connected PV module increase the complexity of the system. The simulation takes into consideration dynamic load fluctuations and potential impacts on the system's overall performance as PV power integration into the grid increases. It also looks at how renewable energy sources (RES) and nonlinear loads can be integrated into the power grid, with a focus on how this could affect the quality of power that is provided to customers. Power quality problems are taken into consideration, particularly in light of the difficulties that electric vehicles that are connected to the distribution system present. MATLAB simulation developed is simulated with the parameters as given in Table 1.

Table 1. Simulation parameters

Component	Parameter	Specification
PV	Open circuit voltage per panel	64.2 V
	Short circuit current per panel	5.96 A
	Voltage at maximum power point	54.7 V
	Current at maximum power point	5.58 A
	Parallel panels	6
	Series panels	48
Grid	440 V, 50 Hz	
Linear load		80 KW
Boost converter		Input = 400 V/output = 700 V
Inverter		Three level/SVPWM
PHEV battery		110 V/50 Ah

These problems include losses in the power grid and electromagnetic interference brought on by PQ disturbances. To realize the power quality improvement in the PV-grid with EV loads the grid current is maintained sinusoidal even when the load current is disturbed. The DQ controller contributes in improving the overall power quality of the grid integrated with PV and loaded with EV. The grid voltage and the voltage at the PCC are similar although the grid is loaded with the non-linearity of both EV battery load and a rectifier load. Figure 3 shows the voltage from the grid and the PCC to be similar. The current at the load is disturbed with deadbeat in the waveform while the current at the grid is found to be sinusoidal thus maintaining the power quality.

Bidirectional power flow control is a key component of the technique for controlling battery charging and discharging. Figure 4 shows possible scenarios in which energy moves from photovoltaic cells and the grid to batteries during periods of excess supply, and from the battery pack to loads during periods of increased demand. The battery pack's bidirectional current flow is illustrated, demonstrating how the current is received from the battery in the opposite direction.

Figure 4 shows the bidirectional power flow between vehicle to grid (V2G) and grid to vehicle (G2V). The relationship between voltage and current when power is transferred from the grid to the vehicle is shown in Figure 5. The graph illustrates the direction of the current in relation to the voltage in this particular circumstance, providing information about the dynamics of power flow and its effect on the vehicle's charging process. The relationship between current and voltage when power is transferred from the vehicle to the grid is shown graphically in Figure 4. The graph illustrates the direction of the current that is out of phase with the voltage in this specific case, providing information about the power flow dynamics during the vehicle's process of discharging back to the grid. Determining the system's bidirectional energy flow requires an understanding of this relationship. In order to comprehend the dynamics of the system, battery performance during charging and discharging operations is essential. The SOC variation and current direction during these actions are shown in Figure 5, which sheds light on the behavior of the battery.

The grid to vehicle mode is the usual mode of operation while the V2G is triggered according to the load and PV power delivered as shown in Figure 6. Due to the switch between the G2V and V2G architecture happening in different time periods it can be observed that the battery state of charge (SOC) starts increasing from the initial SOC of 70%. While the direction changes at 30% of the total time of 1 sec and again at 70% of the total time. Figure 7 shows the battery dynamics which includes both the charging and discharging stage of the EV battery. The second waveform shows the reversal of the current to the battery. Negative current indicates the discharge operation of the battery.

The PV power, voltage, current, and irradiation dynamics are as given in Figure 8. The power generated from the irradiation variation along with the voltage variation is depicted. Additionally, Figure 8 illustrates the power response with the DQ controller in the PV-EV-grid topology. Due to the variation in irradiation, load variation and battery charge discharge variation the power curves of the load, PCC, and PV in wattage is given in Figure 9. The power responses at the load, PCC, and PV inverter output demonstrate the system's adaptability to power quality problems.

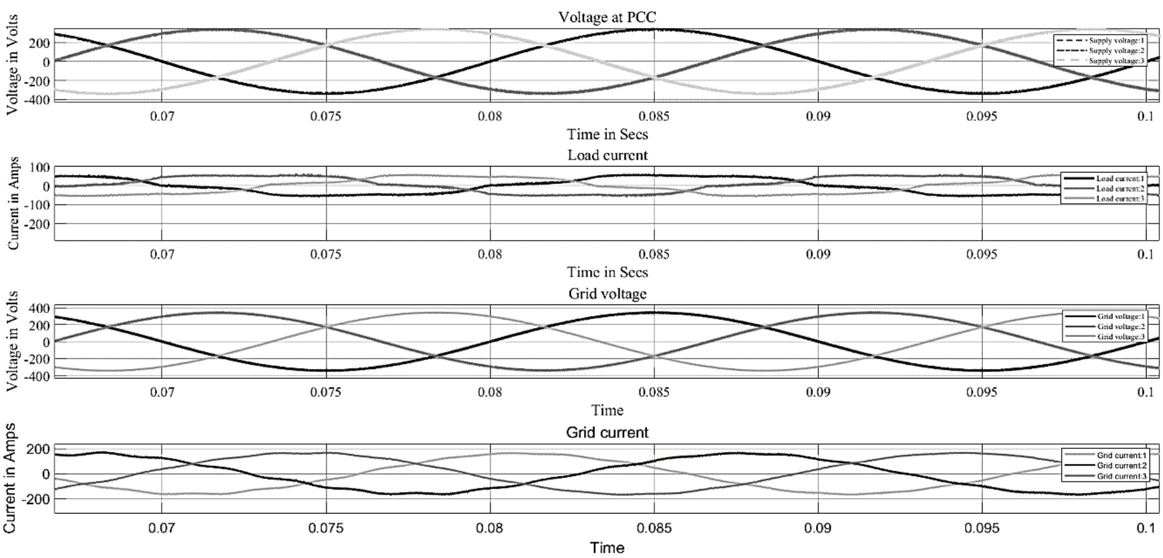

Figure 3. Grid and PCC voltage, load, and grid current

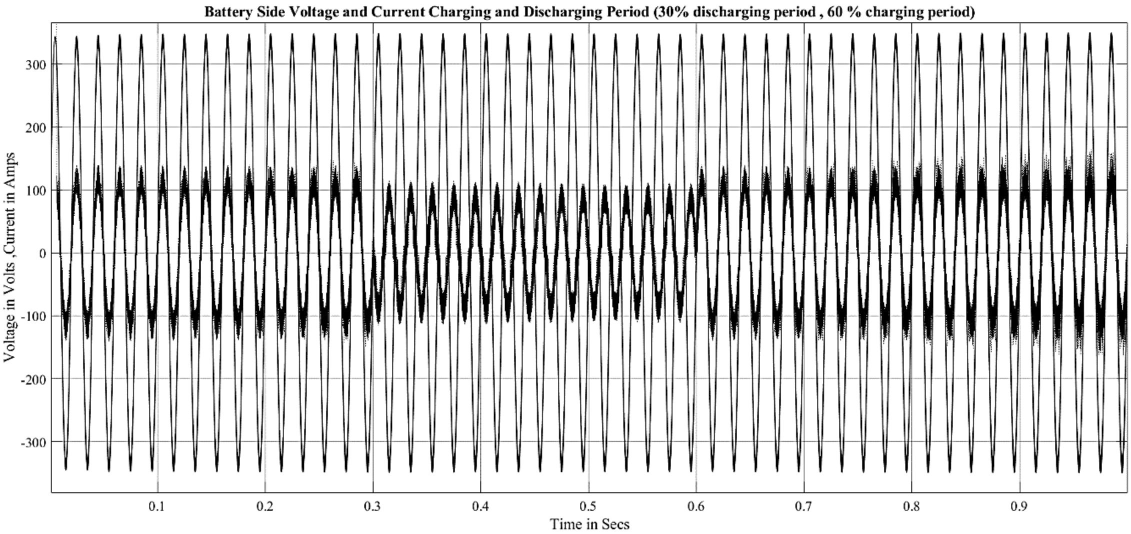

Figure 4. Bidirectional power flow in PHEV system

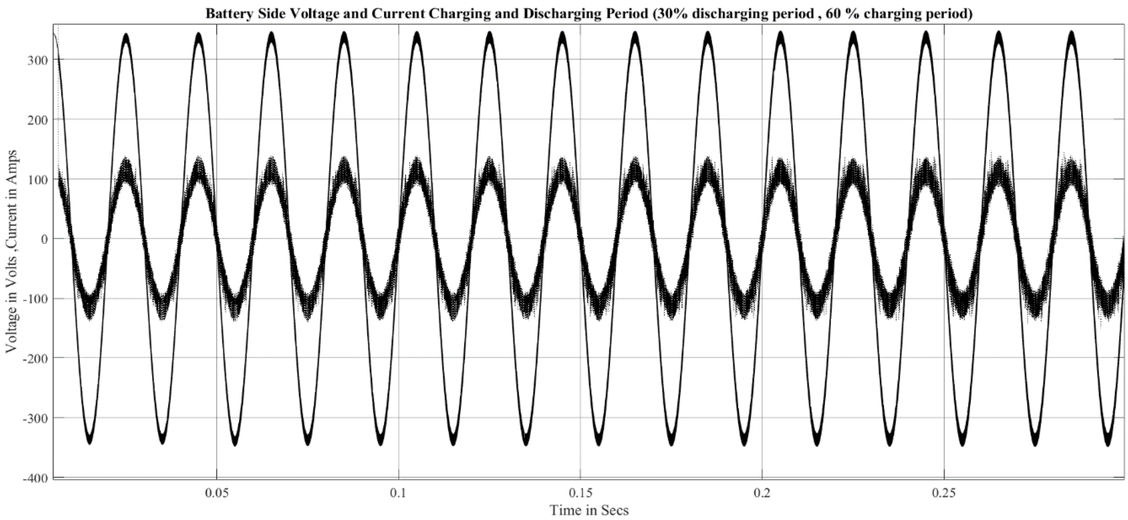

Figure 5. Current in phase with voltage grid to vehicle

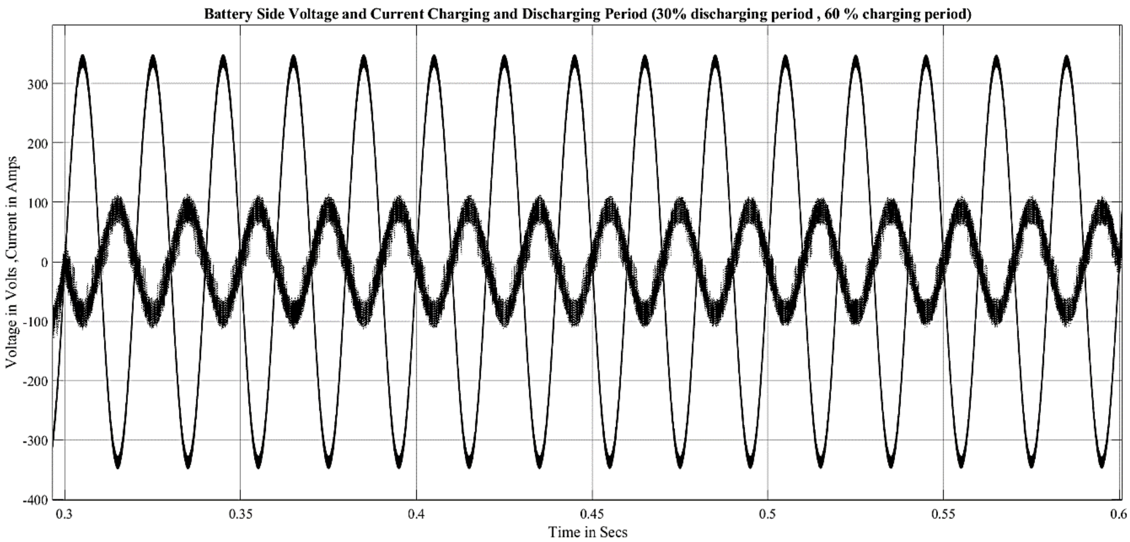

Figure 6. Current out of phase with voltage vehicle to grid

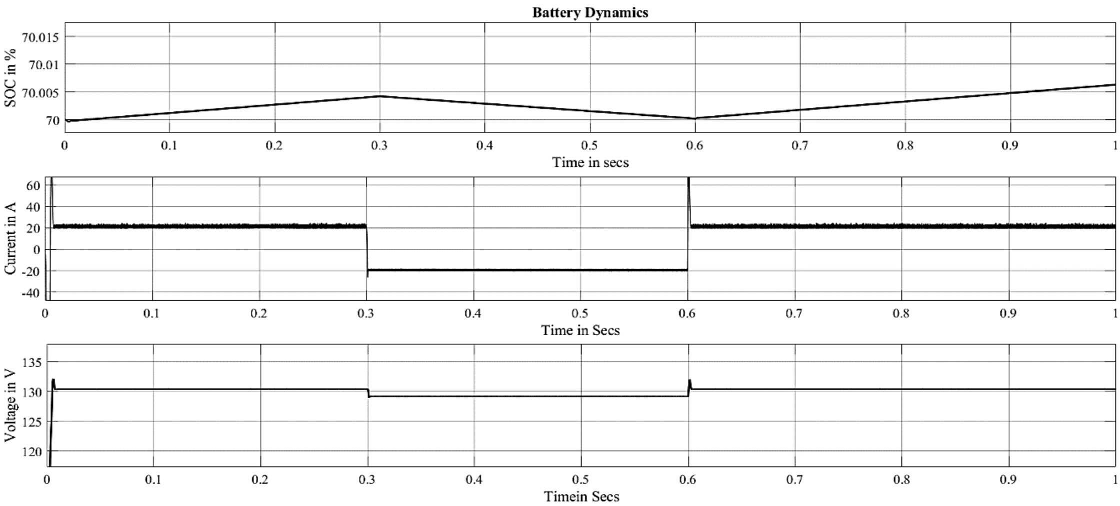

Figure 7. Battery performance and state of charge variation

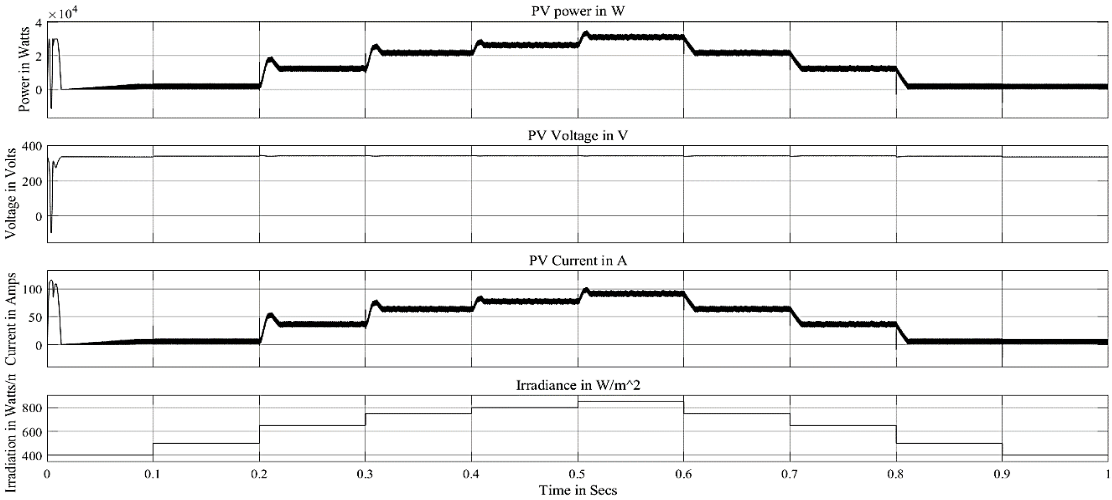

Figure 8. PV dynamics

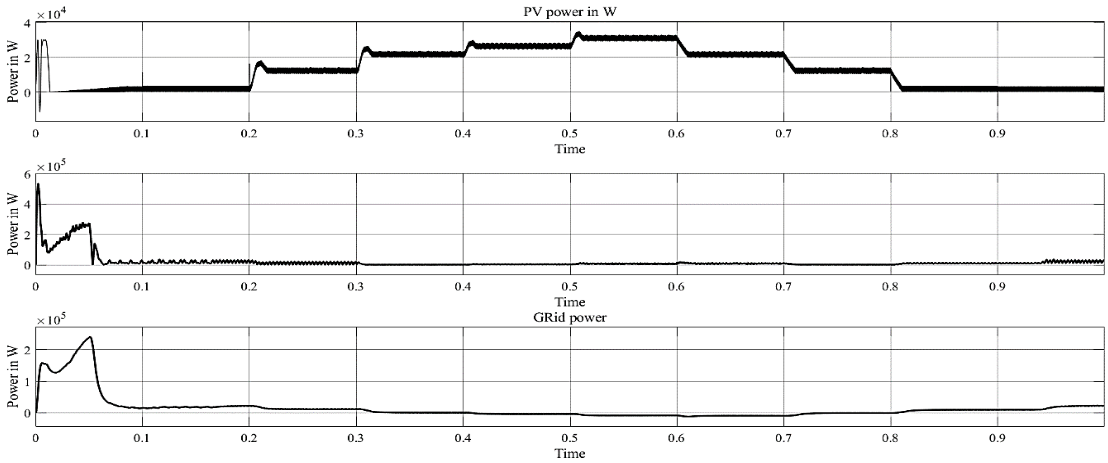

Figure 9. Power responses in PV-EV-grid topology with DQ controller

Since total harmonic distortion (THD) is considered as the performance indicator for the implementation the THD obtained at the grid current is considered and checked whether it complies with the IEEE standards. The

THD values for the case with a proportional-integral (PI) controller 2.74% for grid voltage, 3.44% for grid current, and 15.66% for load current are within the limits defined by the IEEE 519 standards, guaranteeing that the power delivered to linked devices and loads satisfies defined quality requirements. Power quality improvement of the PV integrated grid with EV load is attained using the DQ controller.

4. CONCLUSION

The PV-EV-grid integration, which is regarded as the modern standard in power systems, is evaluated for how well it handles power quality issues. The developed method, which used two control loops one for bidirectional power flow between the grid and electric vehicles and another for grid synchronization with voltage regulation was able to accomplish a 2.74% current THD and 3.44% voltage THD. Current THD dropped significantly with the installation of multicarrier SVPWM and PI control, from 15.66% in the load to 3.44%. This THD decrease demonstrates how well the suggested controller improves power quality. Though there is still an opportunity for development, the system's performance might be further enhanced by including more sophisticated intelligent controllers, which are renowned for their increased resilience and efficiency. In order to fulfill changing power quality standards, the PV-EV-grid integration, which is representative of a smart grid paradigm in modern power systems, is ready for improvement and advancement.

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