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A Simulation Study for Power Quality Enhancement in EV Chargers using SCP-NLMF method

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Abstract
Power quality enhancement in EV chargers is essential to reduce harmonics, improve power factor, and maintain voltage stability due to the nonlinear nature of power electronic converters. It ensures grid reliability, regulatory compliance and efficient operation under high-power and fast-charging conditions. This research work focus on the design of multifunctional charging system of electric vehicles (EVs) comprising grid connection, EV batteries and residential loads. The system is designed with two way converter to control the charging and discharging of batteries and to keep the DC bus voltage constant in Electric Vehicles. A voltage source converter (VSC) is connected to the grid. It operates smoothly as it is able to control nonlinear local loads that are non-uniform. The discharging and charging process regulates the voltage and the current profiles depending on the battery state of charge (SOC). A sparse constrained proportionate normalized least mean fourth (SCP-NLMF) algorithm is used in this research work to gain better control over the system. The strategy minimizes the mean square error (MSE) by minimizing the convergence slowdown at the later stages and enhancing the estimation of the active load current component. The accuracy of SCP-NLMF approach and the effectiveness of the suggested charging system is demonstrated using MATLAB/SIMULINK
Keywords: *Bidirectional Converter, Voltage Source Converter, Electric Vehicles, Multipurpose EV Charger, Nonlinear Loads.*

1. Introduction
Dulichand Jaraniya et.al [1] introduced a grid-based multifunctional EV charging system with SCP-NLMF-based control to provide efficient battery charging/discharging, stable DC bus regulation, enhanced dynamic response, and validated operation under a variety of nonlinear loads In order to serve UN SDG-7, Umashankar Subramaniam et al. [2] developed a coordinated control system of solar-integrated EV charging stations. To maintain unity power factor and low harmonics and ensure smooth communication between the grid, PV array and chargers, their technology utilizes two SOGI loops. Hardware checks enhanced stability and reduction of losses. To allow efficient V2G operation, Subia Meraj et al. [3] reviewed modern control strategies and converter architecture of bidirectional wireless EV charging. Their studies show even in the presence of such issues as coil misalignment or delays in communication, they have a higher power flow, high efficiency, and enhanced grid stability. Izviye Fatimanur Tepe et al. [4] proposed a bidirectional fast-charging station that is G2V and V2G-supportive, which operated using model predictive control. The simulations of a DC microgrid demonstrate more adaptability and more storage resource utilization. The presented work in [5] formulates a human evolutionary optimization algorithm (IHEOA) to optimally integrate EV charging infrastructure, renewable distributed generation and compensation devices into the distribution systems and to obtain the best convergence and significant losses, voltage deviation

and greenhouse gas emissions reduction in G2V and V2G conditions. A systematic study of high-gain, multi-input, non-isolated converters was made by Rajulapati and Prabhakar [6,7] and trade-offs between the complexity and performance of the circuits were highlighted. To give the separate management of the voltage, current and power, Tingting He et al. [8] introduced a finite control set MPC approach, which replaces the dynamic DC voltage strategy with PI-based references. The higher speed of response and the quality of steady-state are shown through experiments. Based on the criteria of THD and switching frequency, Jitendra Kumar Singh et al. [9] investigated various hysteresis current control methods of grid connected inverters, and validated the performances of the methods by simulations and prototype tests. To regulate the DC-link and make the two-way power flow in G2V and V2G modes possible, Deepak Kumar et al. [10] modelled an isolated multi-stage bidirectional EV charger, and developed controllers based on the state-space averaging. In the case of four leg VSIs in solar grid systems, O. V. S. R. Varaprasad et al. [11] presented a three level hysteresistance current control method that minimizes switching variation, and also controls harmonic, reactive power and imbalance. Pattan Muthukumar et al. [12] looked at the efficiency and regulatory performance of a number of EV bidirectional converter topologies as well as the control mechanisms involved. Ab-dullah Berkay Bayindir et al. [13] enhanced the reliability of DC-DC chargers and guaranteed the accurate prediction of switching-state even during model changes in combination with inverse MPC and online RLS-based parameter estimation. Ali Sharida et al. [14] extended the use of IMPC and improved robustness in the face of uncertainty by performing adaptive RLS estimation to real-time model three-phase T-type rectifiers. To attain improved dynamic dynamics and the efficient power sharing, Mahmoud F. Elmorshedy [15] introduced a co-ordinated FCS-MPC approach towards hybrid DC microgrids that integrate solar and wind sources. Gusti Arif Hanifah Pawitan et al. [16] used a lookup-table-based MPC to trade state-of-charge of an ESS and operating constraints using ultra capacitor experiments. Shafiqur Rehman et al. [17] in their techno-economic research of hybrid PV-wind-BSS systems discovered the best combinations with zero emissions and applied MPC to enhance the quality of the grid. Similar outcomes were also found by Ahmed Hamed Ahmed Adam et al. [18] who encouraged the use of hybrid renewable microgrids using MPC to improve voltage regulation and harmonic reduction. Ahmed Y. Farag et al. [19] demonstrated a single stage multiport converter that allows effective integration of AC and DC microgrids with two way power flow and high power density. To improve the voltage regulation, Ramesh Kumar et al. [20] designed an independent microgrid with a dish-Stirling generator and refined PI/PID controllers through PSO, MBA and GWO. Tehseen Ilahi et al. [21] proposed a rapid off-board EV charger with high efficiency and thermal performance by using GaO3 devices with the aid of SPICE, TCAD and Simscape models. To make the EV chargers act as a shunt active power filter, Ahmed Elottri et al. [22] came up with BD-SMC control which was experimentally tested in both steady and faulted grid conditions. Stefano Barsali et al. [23] demonstrated better grid-forming droop and VSM control, better resilience, and black-start performance, and discussed the role of chargers as grid-support assets in the assessment of high-power EV stations.

2. System Architecture

2.1. EV Charging Circuit Architecture

The grid-connected electric vehicle charging system is a multipurpose system that is connected to a DC microgrid. The topology ensures the power quality of non linear loading cases and allows the power to flow in both directions between the utility grid and the EV batteries and local AC loads.

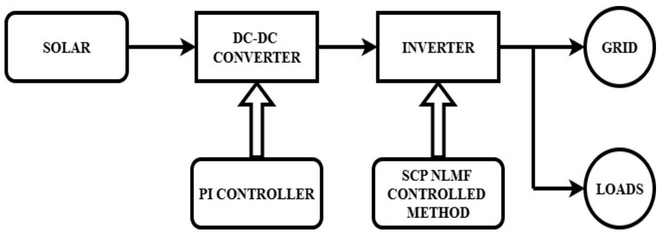

Figure 1 Block Diagram of EV Charging Circuit

The EV batteries are then interfaced to the DC microgrid by individual bidirectional DC-DC converters. These converters have controlled

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discharging and charging depending on the state of charge (SOC) of the EV batteries and the operating requirements. The converters regulate the charging current when the grid is used to charge the vehicle (G2V) to ensure effective and safe charging of the battery. The converters, on the other hand, permit the transmission of power between the EV batteries and the DC microgrid in vehicle-to-grid (V2G) or vehicle-to-home (V2H) configuration. The DC microgrid is developed by linking all DC converters outputs to one DC bus. To enable energy buffering, reduce the fluctuation of voltages and hold a constant DC link voltage in the dynamic operating condition and load variation, a DC link capacitor is implemented over the DC bus. This design provides a stable operation of DC buses and makes it possible to charge a large number of EVs at once.

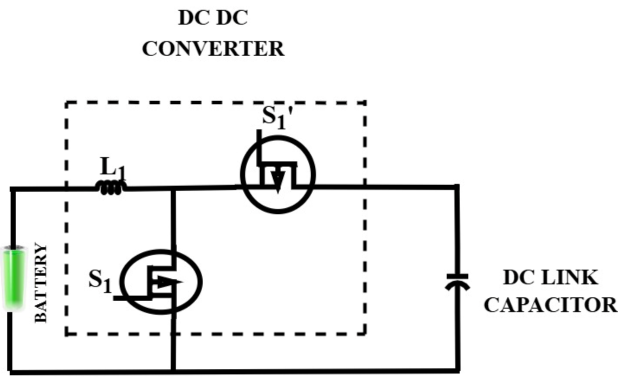

Figure 2 Schematic of Bidirectional DC-DC Converter

The DC microgrid will be linked to the AC side through a three phase voltage source inverter (VSI). The inverter has six regulated semiconductor switches that convert the DC power into three-phase AC power. The inverter will be synchronized to the electric grid and capable of delivering non-linear loads. In order to increase the system performance, an adaptive control strategy is used which is based on the sparse constrained proportionate normalized least mean fourth SCP-NLMF method. This method reduces convergence properties in addition to reducing the mean square error MSE by accurately predicting the active component of the load current. Thus, the given control method guarantees high dynamism responsiveness, efficient harmonic compensation, and stability in operation in different load and EV charging/discharging situations.

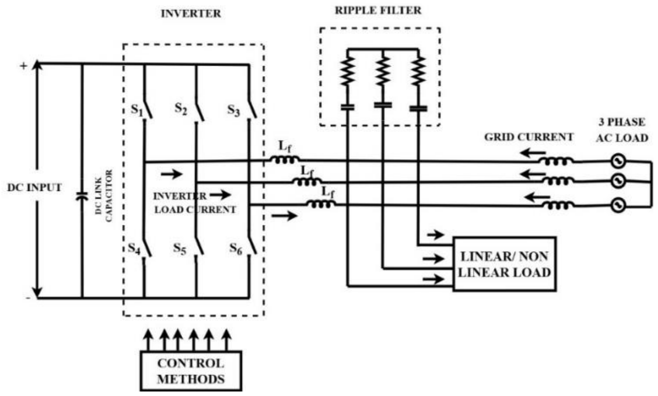

Figure 3 Grid Interfaced with 3 Leg Voltage Source Converter

The proposed architecture offers a small and effective design of Multi EV charging, bi-directional power flow and power quality improvement, and is applicable to the future smart grid and microgrid systems.

2.2. Design of Charging System

Fig. 4 shows that the charging system is connected with the grid, EV battery and Non linear loads. The grid gives power to the EV charger, as well as the nonlinear load, via a diode bridge rectifier and RL network. The bidirectional converter and grid-side voltage source converter (VSC) both have a common DC-link capacitor, thus allowing the VSC to convert the AC power on the grid to DC power to charge the electric vehicle. This power is removed to the EV battery via a smoothing inductor through the bidirectional converter. In order to reduce high-frequency grid distortion, small ripple filter circuits with low capacitance and intermediate resistance are used.

3. Selection of Parameters for The Charging System

Specifications taken from [1] to simulate are given below:

Battery input Voltage = 240V

Battery input Current = 20Ah

Minimum inductance of bidirectional converter, Lb=2.5 mH

Internal resistance of EV battery, Rp =10 kΩ

Internal capacitance of EV battery, Cp =22548 F

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Filter Resistance Rf = 10Ω
Filter Capacitance Cf=10μf

4. Principle of Operation

To offer regulated power flow among the utility grid, EV batteries, and local AC loads, the three-phase voltage source inverter (VSI) and bidirectional DC-DC converter are coordinated in the proposed multifunctional EV charging system.

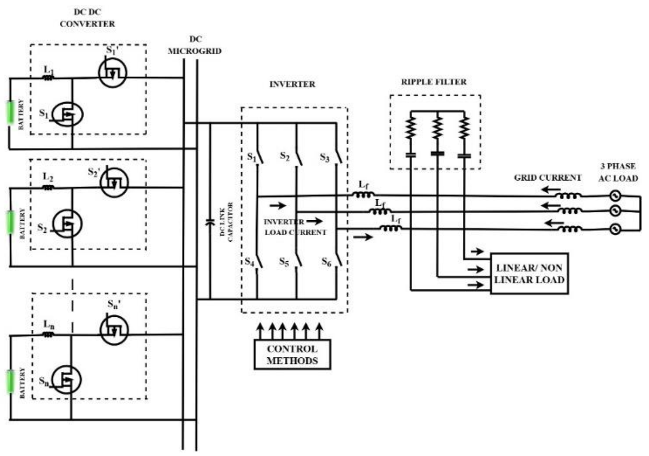

Figure 4 Topology of EV-Integrated DC Microgrid with Bidirectional Power Flow

4.1.Grid-to-Vehicle (G2V) Operation

VSI is an active rectifier that uses electrical energy of the utility grid in the charging mode. It transforms three-phase AC supply into regulated DC supply and also can maintain sinusoidal grid currents and operation over nearly a unity power factor. The DC output is regulated and connected to the DC microgrid and a DC-link capacitor maintains a constant bus voltage. Individual bidirectional DC converters in the buck mode charge each EV battery by regulating the charging voltage and current depending on the state of charge (SOC) of the battery.

4.2. Vehicle to Grid / Vehicle to Load Operation.

When in the charging mode, the voltage source inverter (VSI) is an active rectifier that absorbs power on the utility grid and transforms the three-phase AC supply to regulated DC power without causing grid currents to become sinusoidal and the power factor to be almost unity. The controlled DC output drives the DC microgrid and a DC-link capacitor is used to stabilize the bus voltage. The charging of each EV battery is performed using a single bidirectional DC to DC converter in buck mode that charges the battery depending on the state of charge (SOC). The bidirectional converters are used in discharging mode where boost mode is used to allow controlled power flow between the batteries and the DC microgrid. The regained energy may be fed back into the grid using the VSI or it may be fed to local AC loads. In this mode VSI is used as an inverter feeding regulated active power into the grid, and grid synchronized with the quality accepted standards of the power. The synchronized operation of the VSI and DC-DC converters guarantees that there is no discontinuity between operating regimes, DC-link voltage is constant under dynamic operation, and that the converters can be used in bidirectional mode to provide vehicle-to-grid and vehicle-to-load operation. Moreover, a battery health protection and real-time monitoring systems are used to reduce harmonics, improve the efficiency and reliability of the whole system.

4.3. DC Microgrid and DC-Link Voltage Control.

The microgrid is a DC platform where the inverter and a number of EVs can share power. The DC-link capacitor reduces voltage changes caused by changes in dynamic loads or a change in charging and discharging mode. This will ensure consistent DC bus voltage, which will guarantee stable system operation and allow operation of multiple EVs at the same time.

4.4. Power Quality Improvement and AC Load Supply.

Besides supplying three-phase linear loads, the VSI eliminates the impact of nonlinear loads connected at the point of common coupling. VSI minimizes the harmonics as well as the reactive power requirement, which is induced by the nonlinear loads by adding the appropriate level of current. Consequently, the level of harmonic distortion is reduced and the power factor is increased and the grid currents remain sinusoidal.

4.5. Control Strategy and Switching Mechanism.

One of the most common control strategies used in grid-connected converters and motor drive systems are - The Synchronous Reference Frame (SRF) control and the Phase-Locked Loop (PLL) based control. Three-phase AC quantities are converted into

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a rotating d-q reference frame in SRF control moving in step with the grid or rotor and sinusoidal signals are converted to DC components which are easier to control with PI controllers. PLL is normally employed together with SRF to monitor the phase and frequency of the grid in order to synchronize. Though these methods provide stable and reliable steady-state performance, PLL-based methods can cause delays and lower stability in the case of weak, distorted or dynamic disturbances of the grid. Adaptive algorithms like the Least Mean Squares (LMS) and the Least Mean Fourth (LMF) are able to offer greater flexibility in a dynamic and noisy setting. LMS reduces the average squared error between the desired and actual signal by a simple gradient-based update rule and it is simple to compute at low cost. Its performance however is highly dependent on parameter tuning. LMF builds on this idea by reducing the fourth power of the error to increase sensitivity to larger deviations and increase robustness in impulsive noise. LMF is associated with increased computational costs and can be subject to stability issues when not properly designed due to large signal variations. A more effective and holistic measure is the Sparse Constrained Proportionate Normalized Least Mean Fourth (SCP-NLMF) control measure which is a hybrid approach to the LMF framework which incorporates sign-correlation and normalization capabilities. It reduces the mean square error between the extracted fundamental component and the input signal and also it is stable even with extreme disturbance and distortions. Fast convergence is one of its key strengths that allow the company to respond more quickly to changes in operating modes and provides better dynamic accuracy than the LMS and LMF methods. Also, the power normalization improves stability at large signal conditions and the sign-correlated update decreases the computational complexity. SCP-NLMF has a faster convergence rate, greater robustness and enhanced steady-state performance as compared to other variants like sparsity based NLMF techniques which might have slower adaptation rate. Thus, SCP-NLMF is the most effective control method. SCP-NLMF control is used in EV chargers to enhance the quality of power by reducing harmonic levels, current distortion and anomalies in the waveforms caused by power electronic converters. The controller has a constant check of grid voltage, charger current and reference signals to check the difference between the desired sinusoidal behavior. The instantaneous error is determined by subtracting the measured electrical quantities against the ideal reference values which contain the distortion and transient effects. The algorithm also employs the fourth-order error function as opposed to conventional square-error minimization and is more robust in impulsive disturbance and non-Gaussian noises. The input signal energy scale controls the adaptive update step and eliminates the possibility of unstable changes in coefficients when the amplitude of the signal changes during charger operation. The different controller parameters are then assigned different gains according to their magnitude which allows more dominant distortion components to be corrected at a faster rate. The update rule is added with a sparsity con-constraint to eliminate insignificant coefficients paying control attention to large scale harmonics and disturbances. The controller inherently prioritizes the superior nonlinear effects and removes the small variations to enhance the mitigation efficiency of harmonics. The technique improves the rate of convergence and tracking which guarantees the stable behavior of chargers in case of load or grid changes. SCP-NLMF control combines normalization, proportionate learning, fourth-order adaptation and sparsity enforcement to result in better grid compliance of EV chargers and reduce THD. The primary aim is to control the exchange of power between the grid, the EV battery and the household loads. Under this charging system, the EV battery is charged and discharged depending on the demand of the system and the control strategy modifies the current direction of the battery. The controller is thus meant to accommodate various functions, such as the control of the DC-AC converter and the control of the EV battery storage. The SCP-NLMF algorithm allows the correct synchronization of the voltage source converter (VSC) with the grid while the bidirectional converter ensures the required DC bus voltage and helps to approximate the grid voltage phase, amplitude, and the fundamental components of load currents. The SCP-NLMF based control

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approach is used to control the flow of power in the charging system by properly isolating the basic constituent of load current and rejecting harmonic, noise and disturbances. This is an adaptive method that uses phase voltage data to create unit templates of each phase which are used as normalized sinusoidal references to create grid-synchronized currents. The perceived line voltages are handled to estimate the value of the point of common coupling (PCC) voltage and in phase unit templates are derived by normalizing each phase voltage to this value. These templates are then combined with adaptive SCP-NLMF algorithm to predict the active component of the load current with regard to weight. The algorithm optimizes the weight in an iterative fashion with a variable step size that is based on the current error and the amplitude of the input signal and enables quicker convergence and stability. To create sparsity a zero-attracting term is added to make sure that only the essential component is highlighted and irrelevant harmonics and noise are reduced. After determining the basic weight components of each phase, the mean active weight of the three-phase load currents is computed and added to a term that indicates the state of battery related weight, indicating whether the battery is charging or discharging. This battery element is formed according to battery power and state of charge (SOC) limits, which facilitate smooth operations between grid-to-vehicle and vehicle-to-grid operation. The total active weight obtained is then multiplied with the unit templates to obtain reference grid currents. These reference currents direct the production of switching pulses to the voltage source converter (VSC) to produce synchronized and quality current injection into the grid. The SCP-NLMF algorithm is faster to converge, has better harmonic suppression and is more robust than traditional adaptive controllers which further enhances the current quality and system performance in EV charging systems.

5. Simulation Results

The charging system model is created in MATLAB/Simulink, which comprises of utility grid, EV battery, and nonlinear loads. The dynamic nature of the voltage source converter (VSC) and the charging system based on bidirectional converter is considered to comprehend how the entire circuit works. The most important parameters of the system that are monitored include grid voltage (Vg), grid current (Ig), load current (IL), DC-link voltage (Vdc), battery voltage (Vb), battery current (Ib) and battery state of charge (SOC) to measure the performance.

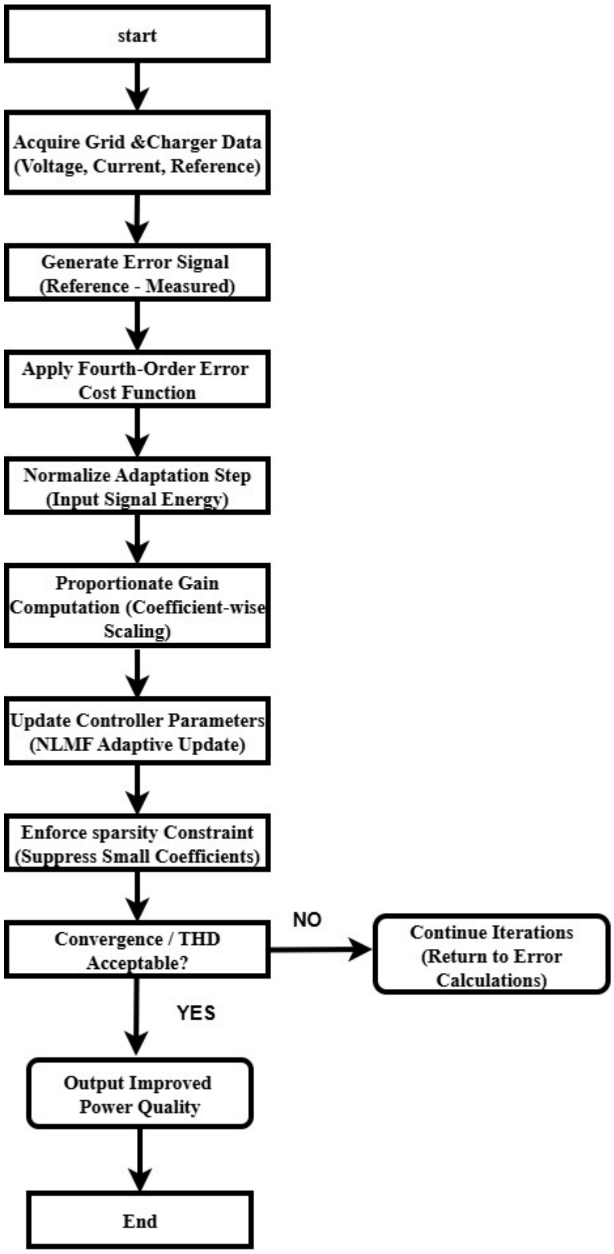

Figure 5 Flow Chart of SCP-NLMF Method

EV battery is a prototype of a high voltage lithium-ion battery pack rated at 400 V which is common in current electric vehicles. It manages the electric power and gives power according to the demand of the car or the requirements of the grid. The Fig 6 presented EV battery system is a high voltage energy storage system that is connected to a power electronic conversion stage, where a 240 V DC input is Stepped up to a 400 V DC output that may be utilized to charge the electric vehicle batteries.

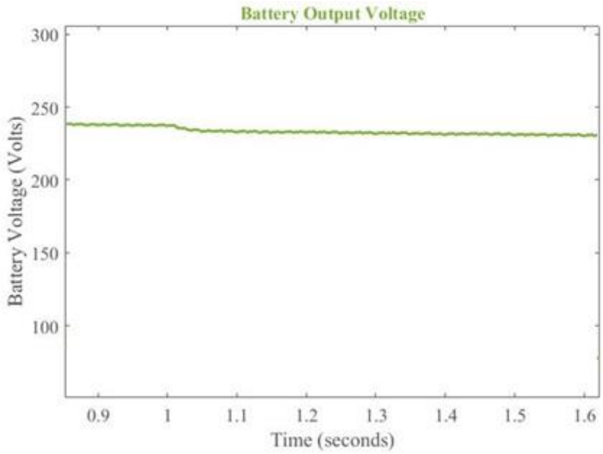

Figure 6 Battery Output Voltage

This voltage enhancement is achieved with the help of a bidirectional DC-DC converter to allow controlled flow of power downstream using the grid to vehicles and controlled flow of power upstream using vehicles to grid. EV battery block model is employed to model the electrical behaviour of a 400 V lithium-ion battery pack, including terminal voltage behaviour, internal dynamics and current limits. The battery voltage (Vb), current (Ib) and state of charge SOC is measured continuously by a special measurement port and this data is important to the system to run it, as well as to take care of system protection. A voltage signal can be used to ensure that the operation is kept within safe limits and charging or discharging can be signified by the current signal. The SOC signal can be used to calculate the available energy, and therefore, smart management of energy can be implemented. In general, the system has the capability to control voltage, make the battery operations safe, and facilitate an easy integration of the EV battery with grid connected or microgrid based DC charging systems. Fig 7 depicts the performance of bidirectional non-isolated DC-DC converter, popular in the electric vehicle charging system and DC microgrids in order to allow two-way power transfer between a low-voltage DC source and a high-voltage DC bus under control. The circuit comprises of a DC input, an energy-store inductor, two actively regulated semiconductor switches such as IGBTs/MOSFETs with antiparallel diodes, and an output. The inductor connected across positive input side is used to store and release energy in switching transitions and therefore smooths the current flow and is necessary to provide voltage conversion. The top switch is operated by the gate signal g2 and the bottom switch that is operated by g1 work in a complementary manner to control the flow of power.

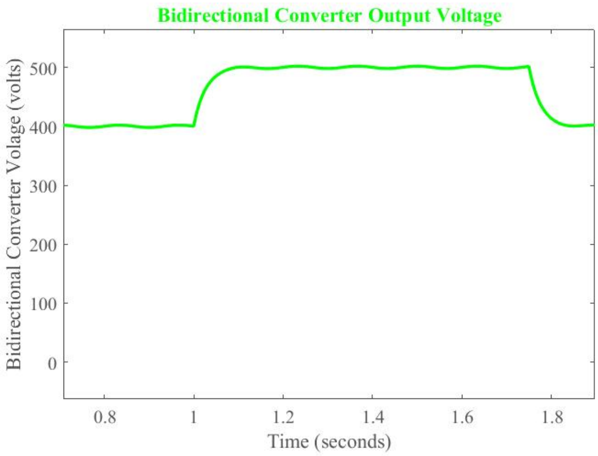

Figure 7 Bidirectional Converter Output Voltage

In boost mode of grid-to-vehicle or source-to-battery operation, the converter is increased to a higher output voltage with the input DC voltage. In this mode, the lower switch is switched to actively charge the inductor with the input supply and the upper switch and diode give a controlled way in which the inductor energy can be passed on to the output capacitor and load to step up the output voltage. However, in buck mode operation, when the vehicle-to-grid or battery-to-source operation is performed, the power is directed into the low voltage side instead of the high voltage side. The upper switch is then modulated to permit the transfer of energy between the output side and the inductor and the lower switch gives a path back to the input and thereby decreases the level of voltage. The antiparallel arrangement of the diodes on the two switches provides safe current commutation and constant conduction in between switching periods. This bidirectional DC-DC

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converter allows to regulate the voltage, control the current, and switch between charging and discharging states without any complications. Its symmetrical design with sufficient gate control signals enables the identical hardware to be used to provide step-up and step-down operation, which makes it very suitable in EV battery interfaces, renewable energy systems, and grid interactive DC networks where bidirectional power flow of flexible and dependable power are required.

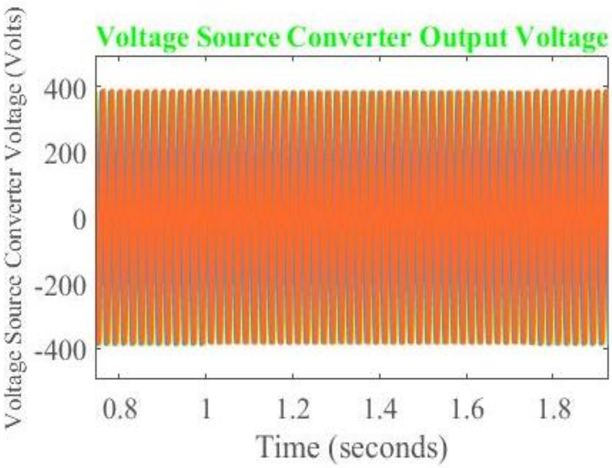

Figure 8 **Voltage Source Converter Output Voltage**

Fig 8 indicates the output of three-phase Voltage Source Converter VSC, an important power electronic interface that is applied in grid connected system, renewable energy integration, and electric vehicle charging system. A DC voltage source across the positive and negative DC rails is provided to the converter marked terminals (+) and (-). This DC connection gives a hard voltage which gets transformed into a regulated three phase AC output. The converter is made up of 6 self commutated semiconductor switches S1 through S6, which are normally IGBTs/ MOSFETs with an antiparallel diode in place to enable the current to flow in both directions. These switches are arranged in three converter legs, each corresponding to one output phase, labeled A, B, and C. The upper switch S1, S3, S5 in each leg has the corresponding phase connected to positive DC bus and the lower switch S2, S4, S6 to negative DC bus. The center of both legs constitutes the phase output terminal. With a proper arrangement of the gating signal to upper and lower switches in a complementary fashion, the converter produces three phase ac voltages of required scale, frequency and phase sequence using the DC input. Pulse width modulation PWM or sophisticated control methods are used to develop the output wave forms and reduce harmonic distortion. The antiparallel diodes on either side of each switch offer freewheeling current paths of the load current through switching transitions, and also enable reactive power exchange between the converter and the ac system. This is the feature that allows the VSC to work in all four quadrants, allowing active and reactive power control. Subsequently, the converter will act either as an inverter or a rectifier accordingly depending on the direction of power flow. Generally, this three stage voltage source converter has a fast dynamic response, accurate power control and high power quality that mandate its complete application in the modern grid-interactive systems like EV charging stations, renewable energy systems, and flexible AC-DC power conversion units.

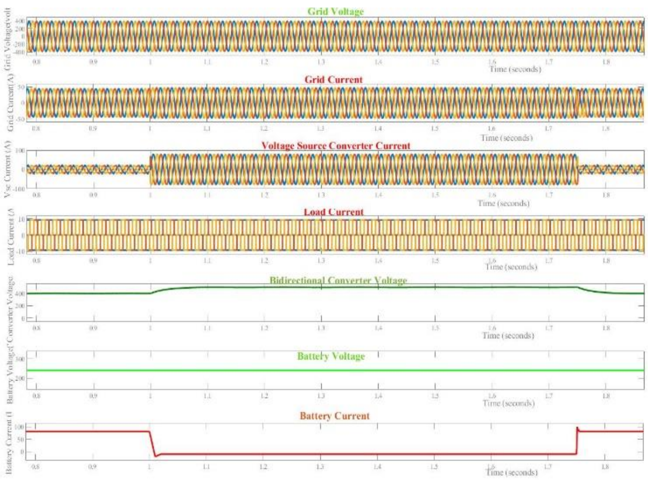

Figure 9 $V_g, I_g, Ivsc, I_L, Vsc, V_b, I_b$

Figure 9 indicates that the behaviour of the system can be evaluated by the output of Grid voltage (Vg), grid current (ig), VSC current (iVSC), load current (iL), DC-link voltage (Vdc), battery voltage (Vb) and battery current (Ib). Also shows the dynamic operation of the charging system between grid-to-electric vehicle (G2EV) and electric vehicle-to-grid (EV2G) modes. The transient of G2EV to EV2G is at 1.75 seconds, during which vg and ig are out of phase with each other, that is, two way flow between the battery and the grid. It further shows the EV2G to G2EV transition at a frequency of one second when the battery and the load both draw electricity at the grid when vg and ig are in phase, battery current becomes negative during a G2EV work indicating that the battery is charging. During these changes in mode the DC link voltage and load current are maintained constant. The vehicle battery initially functions in the charging mode and then suddenly switches to the discharging mode to help the grid and reduce its power consumption need. The polarity of battery current varies depending on the mode of operation as in discharging is positive and in charging negative.

Conclusion

This study presents a multipurpose EV charging system using SCP-NLMF-based control technique. The suggested controller efficiently controls the VSC, resulting in stable grid functioning and appropriate battery charging and discharging characteristics under a range of load circumstances. The developed approach exhibits lower steady state error, Minimized oscillations, and Accelerated dynamic response when compared to traditional Least Mean Square and Normalized Least Mean Square approaches. These findings Establish that the developed charging system provides enhanced durability, efficiency, and compatibility for Well developed grid connected EV charging applications.

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