Design of a Grid-Connected Off-Board EV Charger Using DQ and Fuzzy Logic Control in Simulink

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ABSTRACT

The increasing adoption of electric vehicles (EVs) in global transportation has led to a demand for efficient and reliable charging systems This project focuses on the development and simulation of an off-board electric vehicle charging system utilizing two advanced control strategies: DQ-based vector control and fuzzy logic control. The complete model is designed in MATLAB/Simulink, incorporating key components such as a three-phase grid interface, DQ transformation blocks, inverter-based power conversion, and a controlled battery charging unit. The DQ controller uses traditional Proportional-Integral (PI) regulators in the synchronous reference frame for precise current and voltage control. On the other hand, the fuzzy logic controller introduces a rule-based, adaptive approach that improves system robustness and dynamic response under varying operating conditions. The proposed control strategies are analyzed based on multiple performance metrics including charging efficiency, total harmonic distortion (THD), transient response, and overall system stability. The simulation results validate the effectiveness of both approaches in maintaining high power quality and reliable EV charging. This work contributes to the development of intelligent, grid-connected off-board chargers for electric vehicles, with the potential to support future demands of smart grid infrastructure and renewable energy integration.

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I. Introduction

The growing international focus on decarbonization and clean energy solutions has propelled fast development in electric vehicle (EV) technologies. Of these advancements, the charging infrastructure is a critical factor in deciding the efficiency, reliability, and usability of EVs. Off-board charging systems, in particular, have become prominent for their capability to facilitate high-power, fast charging, as well as integration with smart grids via bidirectional power flow capabilities [1].

A bi-directional off-board charger not only provides grid energy to the EV battery (G2V – Grid-to-Vehicle) but also facilitates Vehicle-to-Grid (V2G) operations, wherein the energy stored in the battery can be supplied back to the grid during peak hours or grid instability[2].The efficiency of such systems is usually debased by issues of power quality, particularly Total Harmonic Distortion (THD), along with dynamic stability of voltage and current under non-stationary operating conditions.

One of the most common methods applied in three-phase converter systems is the DQ (direct-quadrature) control, which converts the three-phase AC quantities into a rotating reference frame to make active and reactive power control easier [3]. In general, Proportional-Integral (PI) controllers are utilized within the DQ control loops for DC-link voltage regulation and sinusoidal current injection into the grid. Although PI controllers work well in linear systems, their performance can be compromised under non-linear and time-varying conditions [4].

In order to increase robustness and flexibility, this paper investigates another way by combining Fuzzy Logic Control (FLC) with the DQ control method. Fuzzy controllers do not need precise Modelling of systems and are perfectly suited for complex, uncertain, and non-linear systems. Fuzzy controllers have the ability to modify control actions in accordance with linguistic rules that are based on expert experience and provide better performance in real-time situations [5], [6].

This paper is a full modelling and simulation investigation of a bidirectional off-board EV charger with PI-based and Fuzzy Logic-based DQ control approaches. The newly proposed method is experimentally verified using the simulation tool MATLAB/Simulink. Both methods of controls are compared, looking for THD, and voltage/current stability in comparison to each other, which will show the benefits of fuzzy control in dynamic EV charging.

In Section II of this paper, a comprehensive literature survey is presented, highlighting existing control strategies for bidirectional off-board chargers and identifying the gaps addressed by the proposed DQ and fuzzy control schemes. Section III discusses the modelling of individual components, including the AC source, converters (rectifier and inverter), filters, and the battery system. In Section IV LCL and AFE is modelled using its equivalent electrical representation suitable for simulation purposes. Section V explains the implementation of DQ control logic using a PI controller. The decoupling of d-q axis currents, error signal generation, and tuning of the PI controller for regulating voltage and current are described in detail. Section VI presents the proposed fuzzy logic controller-based DQ control strategy. The design process includes the definition of fuzzy rules, membership functions, fuzzification/defuzzification logic, and integration into the control loop for improved dynamic response. Section VII presents the simulation results using MATLAB/Simulink. Performance metrics, output waveforms, validate the effectiveness of the proposed control strategy. Section VIII concludes the paper by summarizing the findings and discussing the advantages of fuzzy logic-based DQ control over traditional PI-based methods.

II. Literature Survey

The rise of electric vehicles (EVs) has intensified the need for reliable and intelligent charging infrastructure. Off-board EV charging systems, where the power electronics are located outside the vehicle, offer advantages such as higher power delivery, reduced onboard vehicle complexity, and better thermal management [1]. These systems are typically governed by global standards like IEC 61851 and ISO 15118, which ensure compatibility, safety, and efficient communication between the charger and vehicle [2].

To manage the power flow between the grid and the EV effectively, advanced control methods are employed. DQ-based vector control is one of the most commonly used techniques in power converters. By transforming three-phase signals into two orthogonal axes (direct and quadrature), DQ control decouples active and reactive power components, enabling precise and independent control [3][4].

In addition to conventional control methods, intelligent techniques like FLC have gained traction. FLC mimics human reasoning and operates effectively without requiring a detailed mathematical model of the system [5]. Its ability to handle system uncertainties and nonlinearities makes it particularly suitable for electric vehicle charging applications. Studies have shown that FLC provides better voltage regulation, smoother current control, and lower total harmonic distortion (THD) under variable load conditions [6].

While DQ control ensures fast response and stability in linear operating conditions, fuzzy logic demonstrates superior adaptability in uncertain and dynamic environments. A comparative study highlights that integrating both control strategies can yield optimal performance achieving both precision and robustness in EV charging systems [8].

Simulation plays a vital role in validating the performance of these control methods. MATLAB/Simulink is widely used for developing and testing control strategies in power electronics. Simulation models have shown the effectiveness of DQ-based and fuzzy logic controllers in achieving efficient and stable EV charging performance under various grid and load conditions [9].

This review reveals that although both DQ-based vector control and fuzzy logic control have been explored individually, limited work has focused on their combined implementation in off-board EV charging systems. The current project aims to bridge this gap by developing a hybrid control system and analyzing its performance through detailed simulations.

III. System Overview

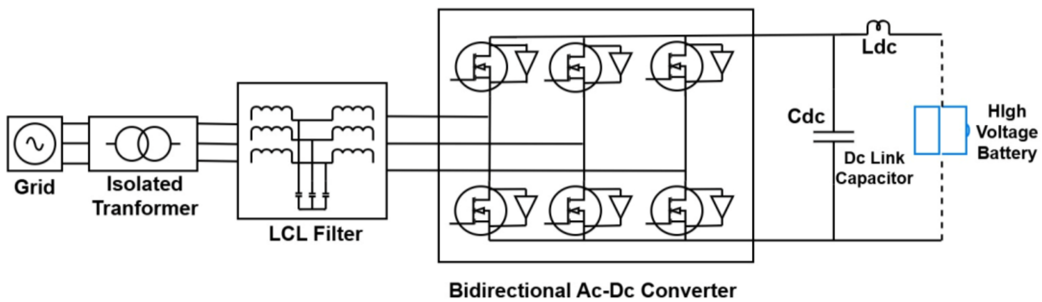

Fig.1 Grid-Connected Bidirectional EV Charging System with AC-DC Converter and LCL Filter

AC SOURCE(Grid): In this system, the grid block acts as a three-phase AC source that facilitates both charging (G2V) and discharging (V2G) operations. The grid block provides power to the EV battery while charging and draws energy from the battery while discharging. The grid should have stable voltage, frequency, and power quality. It also supports smart grid services such as load management and frequency regulation. To ensure the EV system works smoothly and safely with the grid, it’s important to stay in synchronism with the grid’s signals and manage the power flow efficiently.

ISOLATED TRANSFORMER: The isolation transformer in the bidirectional EV charging system ensures safe power transfer from the grid and EV battery through galvanic isolation. It also protects users and electronics from faults like short circuits and ground loops. It transmits AC power to the AFE converter in G2V and distributes power safely to the grid in V2G. The transformer is also handy for voltage matching, improving system efficiency and reducing converter stress. In DC-DC applications at high frequency, small transformers reduce size and improve performance. In Simulink, it allows accurate modeling of isolation, power flow, and fault conditions, making it an essential element of your system's architecture.

LCL FILTER: LCL filter plays a key role in maintaining high-quality power conversion between the EV battery and the grid. Positioned between the grid-side transformer and the AC-DC converter, the LCL filter is designed to suppress high-frequency harmonics generated by the switching operation of the pulse-width modulated (PWM) converter. Without proper filtering, these harmonics can cause electromagnetic interference (EMI), overheating, and degraded power quality.

Compared to an L or LC filter, the LCL filter provides superior harmonic suppression within the desired frequency range, allowing for higher switching frequencies and a more compact design. In Simulink-based modeling, the LCL filter is built using discrete blocks representing inductance and capacitance values, ensuring the simulated converter meets harmonic requirements and maintains a near-unity power factor. Overall, the LCL filter is essential for making the EV charger efficient, grid-compatible, and stable under varying operating conditions.

BIDIRECTIONAL CONVERTER: In the bidirectional EV charging system, the rectifier block is part of the AC-DC converter employed for transforming three-phase AC power from the grid to DC power in G2V operation for battery charging. It uses a six-switch Voltage Source Converter (VSC), typically controlled by PWM, enabling precise and efficient power conversion. Compared to the passive rectifier, this active rectifier enables bidirectional power flow, acting as an inverter in the V2G operation mode of power transfer to the grid. It also ensures DC-link voltage regulation, improves the power factor, and allows for smooth current flow. Regulated through dq-based PI control, the rectifier aids in dynamic control of real and reactive power. It is simulated in Simulink using switching action and integrated with control logic to provide fast response, grid synchronization, and system stability under different loading conditions.

DC LINK CAPACITOR: It helps keep the voltage steady between the battery and motor system. It stores and releases energy quickly during sudden changes like speeding up or slowing down. It also helps smooth out electrical noise caused by fast switching in the converter. This makes the EV's power system run more smoothly and reliably. By reducing voltage ripples, it protects sensitive components and extends their lifespan. It plays a key role during regenerative braking by temporarily holding returning energy. The capacitor acts like a buffer zone, balancing power flow between different stages. Overall, it ensures better efficiency and performance in the EV's electrical drive system.

BATTERY: The battery block, in this system acts as a high-voltage energy storage device, accommodating both charging (G2V) and discharging (V2G) operations. It is usually simulated as a lithium-ion battery due to its high efficiency, high energy density, and long-life cycle. Critical parameters like state of charge (SOC), voltage, and internal resistance are constantly monitored to ensure safe and efficient operation. Real-time SOC estimation is important for controlling charge and discharge limits and is typically performed using algorithms such as Coulomb Counting or advanced filtering methods. In V2G operation, effective battery management is essential to reduce degradation and optimize energy exchange, often involving smart control strategies such as fuzzy logic.

OFF Board Charger Parameters:

Parameter	Values
Total Harmonic Distortion	<5%
Output Voltage (V)	600-800V
Output Current (A)	200-300A
Output Power (KW)	175KW

Table.1 Off Board Charger Design Parameters

IV. Modelling of Components

ACTIVE FRONTEND RECTIFIER: In the proposed bidirectional EV charging system, the Active Front-End (AFE) rectifier is a key power electronic interface for bidirectional energy transfer between the electric grid and the EV battery. The AFE, as compared to the conventional uncontrolled diode rectifier, is built on a controlled Voltage Source Converter (VSC) topology of six IGBT switches that allow rectification during charging (G2V) as well as inversion during discharging (V2G). The switching of the AFE is controlled by a control scheme enforced in the dq reference frame such that active and reactive power can be controlled in a decoupled form.

The AC currents on the grid side are first converted to d-q components by Park transformation. They are subsequently passed through a PI or fuzzy logic controller in order to generate appropriate modulation signals for the PWM block. The primary control objective is to maintain the DC-link voltage at an invariant value, AFE also minimizes harmonic distortion in grid current. It accomplishes this by grid voltage synchronization and the use of an LCL filter located on the AC side.

Simulink realization of the three-phase VSC, dq-transformation blocks, PI or fuzzy controllers, and PWM generation logic constitutes the AFE model. By means of this active interface, charging, discharging, and grid support operations such as frequency regulation and reactive power compensation can be effectively controlled, significantly improving the bidirectional EV system performance.

LCL FILTER:

An **LCL filter** is an essential component used in grid-connected converter systems to mitigate high-frequency harmonics produced by the switching actions of power electronic devices such as rectifiers or inverters. In modern electric vehicle (EV) charging systems and renewable energy applications, maintaining grid power quality is critical, and the LCL filter plays a pivotal role in achieving this. The main function of the LCL filter is to attenuate high-frequency components (switching harmonics) while allowing the fundamental frequency to pass with minimal attenuation. This ensures that the injected current into the grid is sinusoidal and within the allowable harmonic distortion limits.

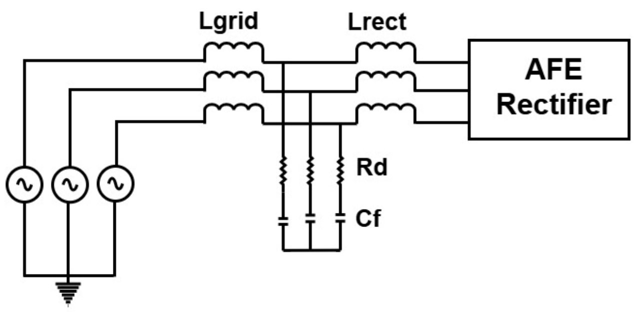

Fig.2 LCL Filter Connected to the Grid and AFE

LCL filter consists of two inductors, one resistor and one capacitor, L_{rect} [μH] is the rectifier side inductor, L_{Grid} [μH] is the grid side inductor, Rd[Ω] is the damping resistance and Cf [μF] is the parallel capacitor between the two inductors. The rectifier side inductor can be calculated as described in Eq. (1). At a switching frequency of 40kHz, the calculation of the filter is performed and increased with twenty percent of the computed value of the inductor to obtain the desired THD.

$$L_{rect} = \frac{V_{dc}}{\eta f_s I_{gridrated} \% ripple} \quad (1)$$

$$I_{gridrated} = \frac{\sqrt{2}P_{load}}{3V_{AC}} \quad (2)$$

For a 2-level converter, the value of η is 4, and for a 3-level converter, the value of η is 8. $I_{gridrated}$ [A] is the rated current at grid side, P_{load} [W] is the load power, V_{DC} [V] is DC link voltage, V_{AC} [V] the phase voltage, and f_S [Hz] is the operating switching frequency. The AC side filter capacitor for three phases can be calculated.

$$C_f = \frac{1\% \frac{P_{rated}}{3}}{\frac{2\pi f_{AC} V_{AC}^2}{3}} \quad (3)$$

where, f_{AC} [Hz] is the grid frequency and P_{rated} [W] the three-phase rated power. The attenuation factor (I_{att}) which indicates the allowable ripple in the grid inductor and switching inductor is represented in Eq. (4). This factor needs to be minimized while maintaining a stable and cost-effective filter. For this design, Iatt is 10 %. The factor "r" is derived by rearranging the above equations and expressed in Eq. (5)

$$I_{att} = \left| \frac{1}{(1 + r(1 - L_{rect}C_f(2\pi f_s)^2)} \right| \% \quad (4)$$

$$r = | \frac{\frac{1}{I_{att}} - 1}{\left(1 - L_{rect}C_f(2\pi f_s)^2\right)} |\% \quad (5)$$

The grid side inductor L_{Grid} is determined by multiplying r with L_{rect} as in Eq.6

$$L_{grid} = rL_{rect} \quad (6)$$

It is also necessary to calculate the resonance frequency Fres [Hz] (Eq. (7)), which should be within a stable region. The stable region of Fres lies between ten times the line frequency and half of the switching frequency. This criteria avoid issues in the upper and lower harmonic spectrums.

$$F_{res} = \frac{1}{2\pi \sqrt{\frac{L_{grid}L_{rect}}{L_{grid}+L_{rect}} C_f}} \quad (7)$$

Finally, the damping resistor Rd can be calculated from the resonance frequency and filter capacitor as in Eq.(8).

$$R_d = \frac{1}{6\pi F_{res} C_f} \quad (8)$$

The DC-link capacitance of the AC/DC converter can be quantified according to the average power Eq.(9),where IDC [A] is the DC current, VDC [V] is the maximum DC link voltage and 1V [V] is the amplitude of allowable DC link voltage ripple, set at 1%.

$$C_{DC} = \frac{I_{DC}V_{DC}}{f_s \Delta V_{1\%} V_{DC}} \quad (9)$$

V. DQ Control LogicWith PI Controller

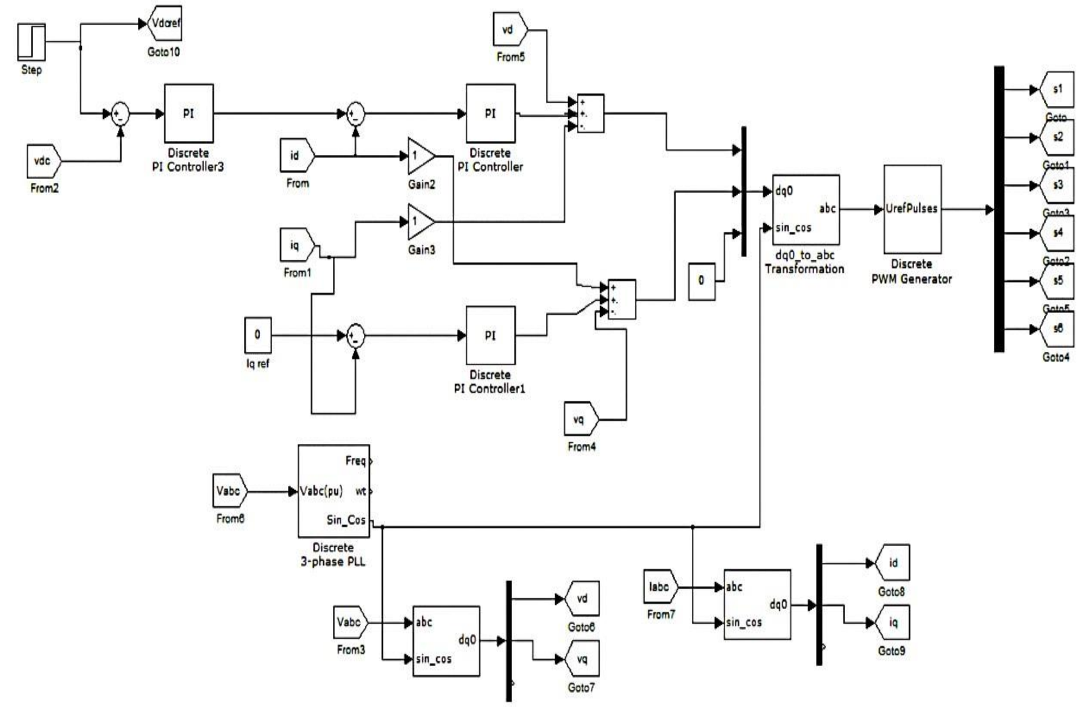

Fig.3 Simulink Model DQ Control Logic with the use of PI Controller

In this system handed, the dq control strategy with PI regulator is important in controlling the power exchange between the battery of the electric vehicle and the grid. System originally converts the three-phase AC current (Iabc) and voltage (Vabc) signals to the rotating dq reference frame through the operation of Park Transformation, which decodes sinusoidal waveforms into two steady DC values direct axis(d) and quadrature axis(q) factors. This makes it easier to control by allowing independent control of active and reactive power. In the control circle, the PI regulator adjusts the measured dq factors to their corresponding reference values by minimizing the error through nonstop adaptations of the control signals that feed into the motor's PWM modulation block. In particular, the d- axis current is typically controlled for regulating DC- link voltage (Vdc) or battery charging current (Idc) to applicable charging or discharging during Grid-to- Vehicle(G2V) and Vehicle- to- Grid(V2G) modes. At the same time, the q- axis current is controlled to ensure power factor correction and grid stability by controlling the reactive power inflow.

The three-phase voltages V_a, V_b, V_c are transformed into DQ coordinates using the following equations:

$$V_d = \frac{2}{3}[V_a * \sin(\omega t) + V_b * \sin(\omega t - 2\pi/3) + V_c * \sin(\omega t + 2\pi/3)] \quad (13)$$

$$V_q = \frac{2}{3}[V_a * \cos(\omega t) + V_b * \cos(\omega t - 2\pi/3) + V_c * \cos(\omega t + 2\pi/3)] \quad (14)$$

$$V_0 = \frac{1}{3}[V_a + V_b + V_c] \quad (15)$$

By controlling V_d and V_q, we can directly influence the active and reactive power delivered to the grid. Specifically V_d controls the active power ,V_q controls the reactive power. To maintain grid stability and improve power quality, V_q is typically regulated to zero, which ensures that no reactive power is exchanged with the grid, thereby achieving unity power factor. To convert control signals back to the physical three-phase system for inverter pulse generation, the inverse transformation is used:

$$V_a = V_d * \sin(\omega t) + V_q * \cos(\omega t) + V_0 \qquad (10)$$

$$V_b = V_d * \sin(\omega t - 2\pi/3) + V_q * \cos(\omega t - 2\pi/3) + V_0 \qquad (11)$$

$$V_c = V_d * \sin(\omega t + 2\pi/3) + V_q * \cos(\omega t + 2\pi/3) + V_0 \qquad (12)$$

This inverse transformation allows the synthesis of sinusoidal PWM signals for the inverter by converting the DC quantitiesV_d and V_q into the respective three-phase time-domain voltages.

The control sense is visible in this Simulink model where Vdc, Vdc_ref, and Idc are tested and fed to the PI regulator, which controls the switching signals (S1 – S6) for the IGBT-supported voltage source inverter. The dq-PI structure is suited for steady-state control and rudimentary dynamic performance. Yet, it's dependent on accurate gain adaptation and is grounded on comparatively direct system gesture, which can circumscribe its disturbance robustness or nonlinearity. However, for clearly defined operating points, the dq-PI system provides a simple and effective solution for real-time EV-grid interfacing. Simulation results generally demonstrate satisfactory performance in sustaining voltage stability and bidirectional power inflow through this system.

VI. DQ Control Logic With Fuzzy Controller

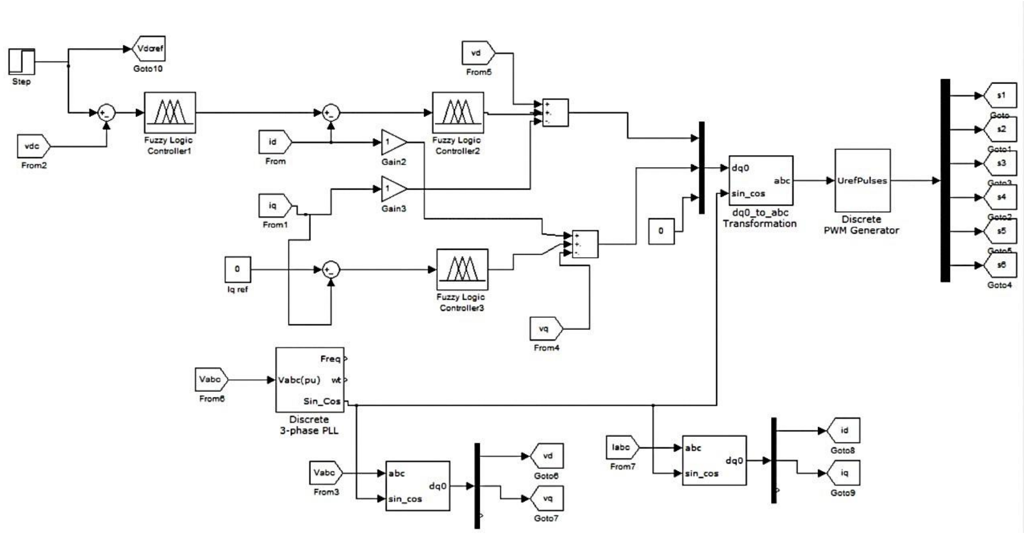

Fig.4: Simulink Model DQ Control Logic with the use of Fuzzy Controller

In this system presented then, the combination of dq- axis control and fuzzy sense improves the dynamic performance and inflexibility of the control strategy of the motor. Although the dq metamorphosis reduces the three- phase AC signals to two orthogonal DC factors (d for active power control and q for reactive power), the fuzzy sense regulator (FLC) replaces or supplements the traditional PI regulator to overcome its failings, including slow response to nonlinearity and poor performance under changing cargo and grid conditions. The fuzzy sense regulator controls the error and error change of signals similar as Vdc, Id, or Command through a set of verbal rules rather than fixed gain values, allowing adaptive control of the voltage source motor (VSC). In the simulation model, fuzzy sense improves the robustness of the dq control by controlling the duty cycle of switching beats more effectively in both Grid- to- Vehicle(G2V) and Vehicle- to- Grid(V2G) modes. This enables the motor to address voltage sags, cargo changes, and harmonics with enhanced stability and lower overshoot.

Also, the fuzzy- dq control strategy renders fine modeling and gain adaptation gratuitous, therefore being well acclimated to intricate and nonlinear systems similar as EV power interfaces. It enhances real- time power inflow regulation, voltage balancing, and grid compliance, particularly during bidirectional transitions. In Simulink, the FLC is enforced as a fuzzy conclusion system which interfaces with dq frame error signals to supply the VSC with modulation references. It has been proven through exploration that fuzzy- grounded control strategies of dq frame systems have better response time, stability, and harmonious reduction compared to conventional PI regulators. therefore, the fuzzy- dq mongrel control is an encouraging system of intelligent, flexible EV- grid integration.

VII. Simulation and Results

The proposed grid- connected bidirectional electric vehicle(EV) charging system was dissembled using MATLAB/ Simulink. The system includes a grid connected an LCL Filter to a bidirectional AC- DC Rectifier, which charges a high- voltage battery. The main focus of the simulation was to dissect and compare the performance of two different control strategies — PI(Commensurable-Integral) control and Fuzzy Logic Control — enforced within the DQ- grounded vector control frame.

Originally, the three- phase voltage and current waveforms(VABC and IABC) were observed. Under both PI and fuzzy control, the waveforms were sinusoidal and well- aligned, attesting proper synchronization with the grid and achieve seamless power factor operation.

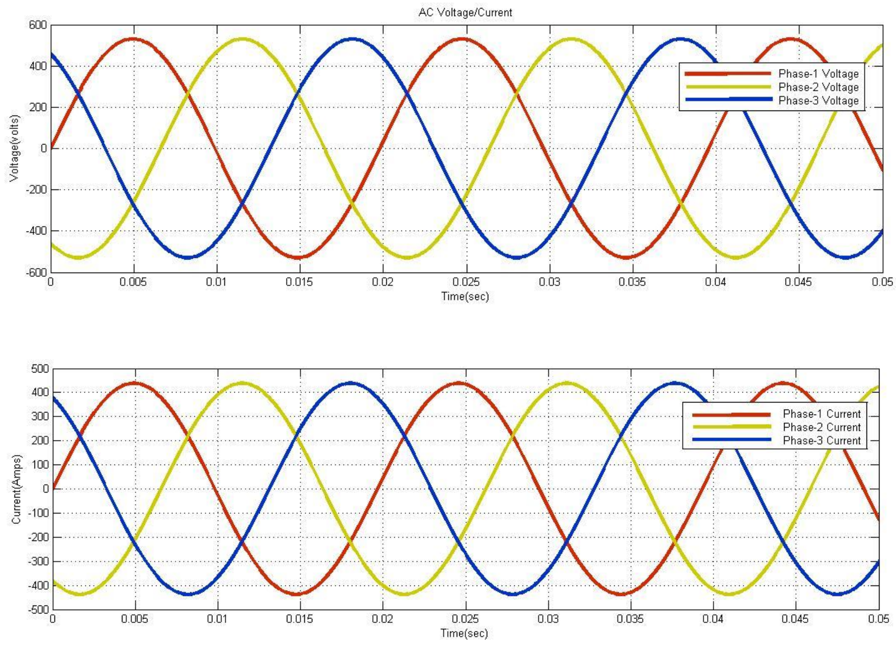

Fig.5: 3-Phase AC Voltage and Current

The DC- link voltage(VDC) and current(IDC) also displayed stable characteristics, indicating that the control algorithms could maintain voltage regulation and current inflow effectively under dynamic operating conditions.From both the voltage and current plots, it is evident that the proposed control system provides reliable and robust performance. The ability to quickly reach steady-state values with minimal overshoot and error highlights the system's strong dynamic performance. Whether the control logic employed is a DQ controller or a fuzzy logic-based controller, the results validate its effectiveness in maintaining desired output characteristics, especially in scenarios involving step changes in reference signals. The system is thus well-suited for applications such as DC microgrids, EV charging, or renewable energy integration where precise voltage and current control is essential.

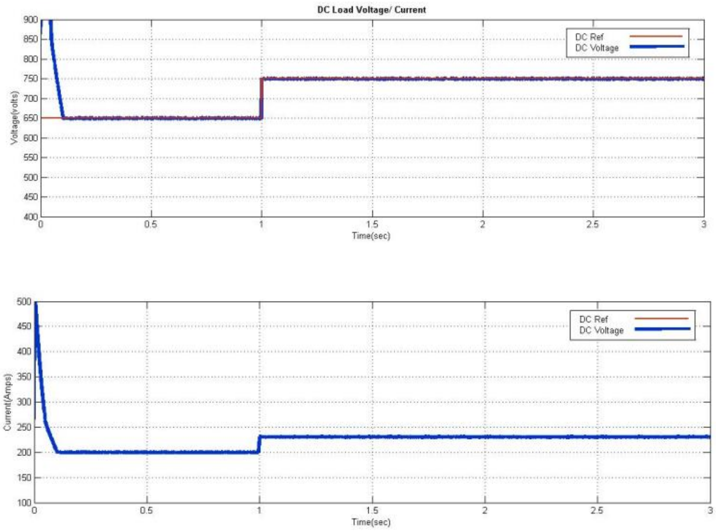

Fig.6: DC Load Voltage and Current Response under Reference Step Change

The harmonic spectrum of the system using a PI controller shows a Total Harmonic Distortion (THD) of 3.47%. While the fundamental frequency is correctly maintained at 50 Hz, several higher-order harmonics are present with significant magnitudes. This level of THD indicates moderate waveform distortion, which may affect overall system efficiency and power quality. Though PI controllers offer good steady-state performance, their ability to suppress harmonics in dynamic conditions is limited.

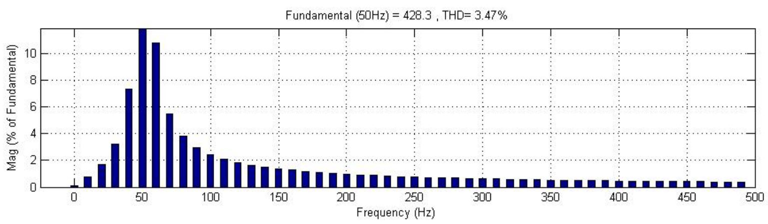

Fig.7: THD of Input AC Current using PI Controller

With the implementation of a fuzzy logic controller, the harmonic spectrum shows a substantial improvement. The THD is significantly reduced to just **0.77%**, and the higher-order harmonic components are almost negligible. The fuzzy controller adapts better to changes and non-linearities in the system, resulting in a much cleaner and more stable output waveform. This indicates superior power quality and overall performance compared to the PI controller.

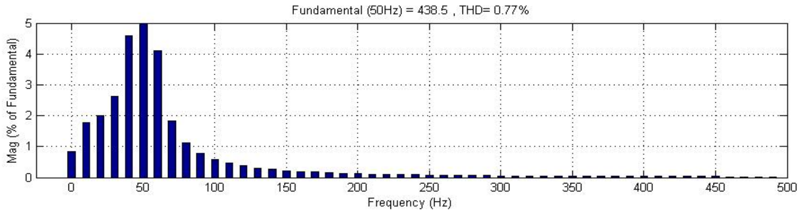

Fig.8: THD of Input AC Current using Fuzzy Logic Controller

In summary, the simulation results demonstrate that while both PI and fuzzy regulators are able of maintaining system stability and performance, the fuzzy sense regulator outperforms the PI regulator in terms of reducing harmonious deformation. This bettered performance, still, comes at the cost of increased regulator complexity, as fuzzy sense requires the design of rule sets and class functions. nonetheless, for operations where high power quality is essential, fuzzy sense provides a largely effective result within the DQ control structure of EV charging system.

VII. Conclusion

In this design, a bidirectional electric vehicle(EV) charging system was developed and dissembled using a grid- connected topology incorporating an insulated motor, LCL sludge, and a bidirectional AC- DC motor. The system was controlled using a DQ- grounded vector control strategy, with two different regulators enforced and compared a Commensurable-Integral(PI) regulator and a Fuzzy Logic Controller(FLC).

The performance of the system was estimated grounded on the Total harmonious deformation(THD) of the grid current. With the PI regulator, the system achieved a THD of 3.3, which is within respectable limits and demonstrates satisfactory performance. still, when the Fuzzy sense Controller was applied under the same DQ control frame, the THD was significantly reduced to 0.77. This easily highlights the superior harmonious reduction capability of the fuzzy sense approach due to its adaptive and nonlinear running of system dynamics.

Overall, the design demonstrates that while PI regulators are simple and effective, the use of fuzzy sense in DQ- grounded control offers bettered power quality and better system performance, making it a promising result for advanced EV charging operations.

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