Interval Type-2 Fuzzy Logic Controlled Shunt Converter Coupled Novel High-Quality Charging Scheme for Electric Vehicles

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Interval Type-II Fuzzy Logic Controlled Shunt Converter Coupled Novel High-Quality Charging Scheme for Electric Vehicles

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Abstract — The deployment of electric vehicle charging stations degrades the quality of power in the distribution grid. This paper proposed an interval type2 fuzzy logic controlled shunt converter coupled novel high-quality charging scheme for electric vehicles. This system includes three-phase bidirectional front-end AC-DC pulse width modulation converter, back-end DC-DC PWM converter and three-phase three-wire distribution static compensator. The bidirectional converters help to perform both grid to vehicle and vehicle to grid mode of operations. The combination of DC-link voltage with decoupled current control technique is exploited for AC-DC converter. A multi-step constant current control technique is proposed for the DC-DC converter to charge and discharge the battery. A fuzzy logic controller based instantaneous reactive power theory control method is proposed for shunt converter. The performance of type1, interval type2 and real coded genetic algorithm optimized fuzzy logic controllers are evaluated by the shunt converter DC-link voltage and the total harmonic distortion of the source current. Lithium-ion batteries are utilized as an energy storage device for electric vehicles in the proposed system. The entire system is modelled and evaluated in the MATLAB/SIMULINK environment. An interval type2 and RGA optimized fuzzy logic controller affords the better performance during V2G and G2V operations, respectively.

Index terms — Battery charger, Electric vehicles, Fuzzy logic controller, Power quality, Total harmonic distortion.

I. INTRODUCTION

Recent years, the numbers of electric vehicles charging stations (EVCS) are rapidly increasing to adopt the electric vehicles (EVs) by replacing the internal combustion engines due to the fossil fuel scarcity and environmental pollution. According to the international energy agency report of a global electric vehicle outlook 2018, the number of charging stations in 2010 and 2017 is 4,054 and 4,30,151, respectively [1]. The different power electronic converters are utilized to implement the EVCS. So, it brings more challenges to the distribution system such as voltage instability, harmonics, neutral current, power loss, etc.

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The researchers investigated the various issues on the distribution system with different charger topologies and power levels. The multiple battery charger topologies, charging power levels for plug-in electric and hybrid vehicles are reviewed in [2]. Technical challenges, impacts, prospects and international standards regarding charging methods, grid integrations, power quality problems, safety limitations, communication networks and equipment maintenance are discussed in [3]. The non-linearity of power electronic converters presents in the EVCS produces more harmonics in the distribution system. The harmonics are investigated with various charger topologies such as single-phase uncontrolled rectifier, bidirectional controlled rectifier, three-phase uncontrolled rectifier, thyristorized controlled rectifier and bidirectional controlled rectifier. A three-phase uncontrolled rectifier-based charger produces 30% total harmonic distortion (THD) in source current and it is identified in [4]. A three-phase bidirectional converter-based charger produced 8.1% and 9.4% THD during grid to vehicle (G2V) and vehicle to grid (V2G) operations and it is given in [5]. An observed current THD of six pulse and 12-pulse thyristor bridge rectifier-based chargers [6] are at 70% and 15% respectively. Since all kind of EV chargers producing the THD more than the acceptable limits of 5% as per the IEEE 519-1992 standard. The exceeded THD does significant harm to the distribution grid like overheating of conductors, increase power loss, distribution transformer life degradation [7], etc. Hence, the harmonic mitigation technology is must require for the EVCS. On the other hand, a modified Luo converter [8] and bridgeless Cuk converter [9] based EV charger is designed for power quality improvement. The reactive power control through coordinated EV charging is discussed in [10].

To mitigate the harmonics in the distribution system, a shunt converter also called as distribution static compensator (DSTATCOM) is more preferred. Because it affords a better performance compared with passive filters and shunt active filters. Passive filters are offered well only for constant types of loads. An operating principle, various configurations, design procedures and control methods for DSTATCOM is studied in [11]. In [12], a DSTATCOM is used in the distribution power generating system to improve power quality. The performance of DSTATCOM entirely depends on the reference current generating method and a DC-link voltage regulation controller.

An instantaneous reactive power theory (IRPT), synchronous reference frame theory and ADALINE based control methods are compared in [13]. Other methods such as current decomposition, symmetrical component, icosφ, and neural network theories are presented in [11]. Among these methods, the IRPT method is more efficient and flexible in designing a...
controller for DSTATCOM [14]. The various controllers have been reported for DSTATCOM DC-link voltage regulation to improve its performance. The conventional proportional-integral (PI) and least mean square based adaptive neuro fuzzy logic controllers are designed in [15], [16]. The real coded genetic algorithm (RGA) optimized PI controller and adaptive neuro-fuzzy inference system-based controllers are employed for three phase four wire DSTATCOM in [17]. Chebyshev functional expansion based neural network controller is designed for shunt compensation in [18]. A generalized neural network-based control algorithm is developed in [19] for DSTATCOM in the distribution system, and its performance is compared with artificial neural network-based controllers such as ADALINE, multi-layer perceptor and radial basis function neural network.

On the other hand, a fuzzy logic system (FLS) has been exploited to design the controllers. A traditional or type1 (T1) FLS is more efficient for less sophisticated systems. In contrast, an interval type2 (IT2) FLS provides better results for more complex system due to its additional freedom in the degree of membership by the footprint of uncertainty (FOU) in their fuzzy sets (FSs) [20]. An IT2 FLS concept, theories, design procedures, controls and applications are studied in [21], [22]. In [23], examined the steady-state analysis of IT2 fuzzy logic controller (FLC) and presented that it is more robust and affords smoother control surface in comparison with their T1 counterparts.

Moreover, many kinds of literature used IT2 FLC for drives and power system applications. An IT2 FLC is employed for permanent magnet synchronous machines with modified reference frame theory in [24]. In [25], IT2 FLC is implemented for doubly fed induction generator-based wind energy system. Also, it is employed for parallel delta robot in [26]. An RGA optimized FLC is successfully designed for dynamic voltage restorer in [27]. All existing work related to the DSTATCOM considers the diode bridge rectifier with the resistive and inductive component as a nonlinear load. The proposed system considers the EVCS is a nonlinear load.

This work mainly focused on to design the IT2 FLC controlled shunt converter coupled charging scheme for electric vehicles. Besides, a multi-step constant current charging method is proposed for EV battery charging. Moreover, a T1 FLC and RGA optimized T1 FLC are designed for shunt converter to examine the performance of the IT2 FLC. Further, this paper is systematized as follows. Section II describes the proposed high-quality electric vehicle charging scheme. The control strategy for the proposed system is presented in section III. An obtained result and their discussions are focused in section IV. Finally, in section V drawn the main conclusion of this work.

II. HIGH QUALITY ELECTRIC VEHICLE CHARGING SCHEME

The block diagram of the typical EVCS is presented in Fig. 1. It is constituted by the AC-DC and DC-DC converters [3]. A single/three-phase uncontrolled or controlled rectifiers can be employed for AC-DC conversion. A buck converter is more preferred for DC-DC conversion from a higher voltage to the battery charging voltage.

![Fig. 1. A structure of typical EVCS](image1)

The block diagram and a schematic diagram of the high-quality EVCS is depicted in Figs. 2 and 3, respectively.

![Fig. 2. Block diagram of the high quality EVCS](image2)

In this system, a bidirectional AC-DC and DC-DC converters are utilized to make a grid to vehicle (G2V) and vehicle to grid (V2G) operations. The shunt converter is connected at the point of common coupling to mitigate the source current harmonics during G2V and V2G operations. An insulated gate bipolar transistor is used in the converters.

![Fig. 3. Schematic diagram of the high quality EVCS](image3)

A. Bidirectional AC-DC Converter Design

The bidirectional three-phase AC-DC converter is connected to the distribution grid through the filter inductance. The DC output voltage of this converter is expressed as (1) [7]

\[ V_{dc} = \frac{2\sqrt{2} V_{LL} L}{\sqrt{3} m} \]  

Where, \( V_{LL} \) - Line voltage (V), \( m \) - Modulation index

The value of the DC-link capacitor is selected as per the equation (2) [28]

\[ C = \frac{P_{dc}}{V_{dc} \times 4\pi f \times \Delta V_{dc}} \]

Where, \( P_{dc} \) - Maximum DC power (W), \( f \) - Supply frequency (Hz), \( \Delta V_{dc} \) - Ripple voltage (V)

B. Bidirectional DC-DC Converter Design

The bidirectional DC-DC converter connected between the AC-DC converter and the EV battery pack. It is designed to
operate in a buck mode during charging of the battery and in boost mode during discharging of the battery. So, the battery side filter inductor has to design for both buck and boost modes of operation.

The following expressions [28] are used to find the inductor value in buck (3) and boost (4) modes.

\[ L_b = \frac{D(V_{dc} - V_b)}{f_s B_L} \]  
\[ L_b = \frac{D V_b}{f_s B_L} \]  

Where, \( L_b \) - Battery side filter inductor (H), \( V_{dc} \) - DC- link voltage (V), \( V_b \) - Battery voltage (V), \( f_s \) - Switching frequency (Hz), \( \Delta I_c \) - Ripple current (A).

The output filter capacitor \( (C_b) \) of the DC-DC converter for battery charging is calculated by using (5)

\[ C_b = \frac{\Delta V_L}{f_s B_L} \]  

Where, \( \Delta V_L \) - Output ripple voltage (V)

C. Modelling of Lithium-ion Battery

Most of the EV manufacturers use the lithium-ion battery for plug-in hybrid EV and battery EV due to its higher specific energy and energy density and other potential benefits [29]. The dynamic model of the battery for charging and discharging is designed by (6), (7) [30].

\[ V_{NI} = V_0 - R_i i - K \frac{q}{q + 0.1} + i - S - K \frac{q}{q - q} q + A e^{-B q} \]  
\[ V_{NI} = V_0 - R_i i - K \frac{q}{q - q} - K \frac{q}{q - q} - q + A e^{-B q} \]  

Where, \( V_{NI} \) - Nonlinear voltage (V), \( V_0 \) - Constant voltage (V), \( R_i \) - Battery internal resistance (\( \Omega \)), \( K \) - Polarization constant (Ah\(^{-1}\)), \( i \) - Low frequency current dynamics (A), \( S \) - Battery current (A), \( q \) - Extracted capacity (Ah), \( Q \) - Maximum battery capacity (Ah), A - Exponential voltage (V), B - Exponential capacity (Ah\(^{-1}\)).

The state of charge (SOC) of the lithium-ion battery is obtained by using (8)

\[ SOC = (1 - \frac{1}{Q} \int_0^t i(t) dt) \times 100 \]  

The fully charged battery SOC is 100% and empty battery SOC is 0%.

D. Shunt Converter Design

The shunt converter with efficient control method and controller is most preferably used to mitigate the source current harmonics in the distribution system. It consists of a voltage source converter, energy storage capacitor and interfacing inductor. The minimum output voltage of the VSC across the capacitor is calculated by using (1) with the consideration of the modulation index as one. The energy storage capacitor \( (C_{dc}) \) and interfacing inductor \( (L_i) \) is designed by using the following expressions (9), (10) [7].

\[ \frac{1}{2} C_{dc} (V_{dcl}^2 - V_{dcl}^2) = k_i 3 V a l t \]  
\[ L_i = \frac{\sqrt{2} V_{dcl}}{12 \alpha f d c \ v} \]  

Where, \( V_{dcl} \) - Selected reference voltage (V), \( V_{dcl} \) - Minimum required DC-link voltage (V), \( V \) - Phase voltage (V), \( I \) - Phase current (A), \( t \) - Time to recover the DC bus voltage (s), \( a \) - Overloading factor, \( k_i \) - Energy variation during dynamics.

III. CONTROL STRATEGIES FOR PROPOSED HIGH QUALITY EVCS

A. Electric Vehicle Charger Control Strategy

The EV charger consists of the bidirectional AC-DC and DC-DC converters. A DC-link voltage with current control method is designed for a three-phase bidirectional AC-DC converter. The control strategy of the AC-DC converter is depicted in Fig. 4. This method consists of outer voltage and an inner current loop to provide a fast-transient response and high static performance.

![AC-DC converter control strategy](image)

**Fig. 4. AC-DC converter control strategy**

The Clarke and Park transformations are used to transform the ordinary ‘abc’ variables into rotating reference frame variables ‘dq0’. Hence, inverse Clarke and Park transformations are used to convert ‘dq0’ variables into ‘abc’ variables [31].

Next, the control strategy for the bidirectional DC-DC converter is designed based on battery charging methods. Different charging methods are available, such as constant voltage (CV), constant current (CC), constant power (CP), constant current constant voltage (CCCV), trickle current charge and pulse charge method [3], [30]. Among these methods, CCCV is a commonly used approach for charging EV lithium-ion battery. In this mode, initially, the battery is charged by constant current, and once the battery SOC has reached 80%, it is switched to CV mode to charge the remaining 20% of the battery. The CV method requires longer time, which is about three times compared to CC method. The CCCV method produce more transient while switching from CC to CV mode. The CC charging method rapidly increase the battery voltage, and it is possible to exceed the battery voltage limit.

In this work, a multi-step constant current (MSCC) control technique is proposed to generate the reference current for the DC-DC converter. The block diagram of the proposed MSCC control strategy is depicted in Fig. 5. In this method, a reference current is produced based on the SOC (battery voltage) and charging/discharging (Ch/Dch) mode selection signal. Operating performance of the proposed MSCC control strategy is illustrated in Fig. 6.

![Proposed MSCC control strategy for DC-DC converter](image)

**Fig. 5. Proposed MSCC control strategy for DC-DC converter**

SOC MATHEMATLAB function \( b^* \) CS PI PWM Ch/Dch mode selection DC-DC converter
At charging mode (Ch/Dch=HIGH), the charging reference current has been set at 33.5 A, if the SOC is less than 80%. If the SOC is crossed 80%, then the reference current will be reduced to 23.5 A. Again, the reference current will be reduced to 13.5 A, once if the SOC is greater than or equal to 90%. Furthermore, if the SOC is stretched 100%, the reference current is set at zero, and the protection switch (Ps) will isolate the EV battery pack. So, it protects against overcharging of the battery. During the discharging mode (Ch/Dch=LOW), if the SOC range lies between 20%-100% then the reference current is set as -33.5 A. If the SOC is below 20%, then the reference current will be zero and isolation process will be started. It affords protection against the deep discharging. The protection switch is operated by the control signal (CS). The protection switch is in the closed position when the CS is high. In contrast, the switch is in the open position when the CS is low. The proposed MSCC method reduces the charging time of the battery, produce less transient during current reduction compared to switching from CC to CV mode, and keeps the battery voltage within the limited value by reduce the charging current.

B. Shunt Converter Control Strategy

In this work, an IRPT based various Takagi Sugeno model FLCs such as T1, IT2 and RGAFLC are proposed for shunt converter in high-quality EVCS. The structure of the proposed control strategy is depicted in Fig. 7.

![Fig. 7. Schematic diagram of the proposed control strategy for shunt converter](image)

An IT2 FLC is similar to the T1 FLC except for the replacement of defuzzification by an output processing unit. That block contains a type reducer and defuzzifier. An IT2 FSs are used in the rule base of IT2 FLC. Hence, it produces the IT2 FS output. So, a type reduction method is employed to convert the IT2 FS into T1 FS before defuzzification. Fig. 8 shows the schematic diagram of the IT2 FLC. The fuzzification, fuzzy inference engine, knowledge base and defuzzification are similar for both T1 and IT2 FLC. Additionally, a type reducer is involved only in IT2 FLC. In RGA T1 FLC is designed by remapped the T1 FLC MFs with optimized value.

![Fig. 8. Schematic diagram of IT2 FLC](image)

- **Fuzzification**

  It is the process to map the crisp sets to the FSs by using the different types of membership functions (MFs). In this work, a Shunt converter DC-link voltage error (E) and change in error (CE) are the inputs and power loss (Ploss) is the output. The input data are mapped with seven triangular MFs. The mapped FSs have been defined as PL – Positive Large, PM – Positive Medium, PS – Positive Small, ZE – Zero, NS – Negative Small, NM – Negative Medium, NL – Negative Large. Figs. 9 to 11 shows the mapped FSs of T1, IT2 and RGAFLC respectively. The minimum and maximum values of the universe of discourse for all inputs and outputs are chosen as +1 to −1.

![Fig. 9. Mapped MFs of T1 FLC (a) Error (b) Change in error](image)

- **Rule Base**

  The FLC rules are stored in the rule base. The rules are same for all type of FLCs, but antecedents and consequents are different for T1 and IT2 FLCs. IF-THEN rules are framed as:

  IF ‘E’ is NL and ‘CE’ is NL THEN ‘O’ = aE+bCE+c

  Where NL represent the MF of inputs E and CE. a, b, c are the Takagi Sugeno fuzzy inference system model parameters. In similar way, 49 rules are framed for all the MFs as presented in Table I and set the equal weights for all rules.

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>FUZZY LOGIC RULES</th>
</tr>
</thead>
<tbody>
<tr>
<td>CE/CE</td>
<td>NL</td>
</tr>
<tr>
<td>NL</td>
<td>NL</td>
</tr>
<tr>
<td>NM</td>
<td>NL</td>
</tr>
<tr>
<td>NS</td>
<td>NL</td>
</tr>
<tr>
<td>ZE</td>
<td>NL</td>
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<td>PS</td>
<td>NM</td>
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<tr>
<td>PM</td>
<td>NS</td>
</tr>
<tr>
<td>PL</td>
<td>ZE</td>
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• Fuzzy inference engine

It applies the fuzzy reasoning mechanism to produce the consequences by combining all the fired rules. Meet operation is used to connect multiple antecedents in the rules, and the rules are united by the join operation. The product t-norms technique is employed in the join and meet operations. The mathematical representation of meet and join operation is explained in [18].

The surface view of the FLCs is presented in Fig. 12.

Fig. 12. Surface view of FLC (a) T1 FLC (b) IT2 FLC (c) RGA T1 FLC

• Type Reduction

Direct conversion of IT2 consequents to crisp set is more complicated. Due to the computational limitations, the type reducer is used to obtain the T1 FS from the IT2 FSs. There are many kinds of type reduction methods available. The popular methods are center-of-sets, centroid, height and modified height. The center-of-sets method is employed in this work. This method produces the left ($O_l$) and right ($O_r$) most point of the type reduced set. These points are obtained by using the Karnik-Mendal algorithm [17].

• Defuzzification

The FSs are converted into the crisp sets in the defuzzification process. The output crisp value is obtained by calculate the average of the type reduced set left and right most points. It expressed as (11)

$$O = \frac{O_l + O_r}{2}$$  \hspace{1cm} (11)

• RGA optimization method

In general, the researchers designed the MFs based on the human knowledge and experience of the system. So, it may produce an inefficient result. Over the last decades, the optimization algorithm plays a vital role to design the control parameters for various applications.

In this work, an RGA optimization is used to optimize the T1 FLC MFs. The real value parameters are used in the genetic operation is called RGA. The steps involved in the RGA is presented in Fig. 13. The working principle, comparison of binary coded genetic algorithm and RGA, various steps in RGA such as tournament selection, simulated binary crossover (SBX) and polynomial mutation are studied in [32]-[34]. The RGA optimized the fuzzy MFs based on the minimization of integral square of the source current THD.

IV. RESULTS AND DISCUSSION

An overall system is modelled and simulated in the MATLAB/SIMULINK environment. The simulation parameters are given in Table II. The performance of the shunt converter coupled charging scheme is studied for T1, IT2 and RGA optimized fuzzy logic controllers. All the controller performances have been investigated under G2V and V2G operations.

TABLE II

<table>
<thead>
<tr>
<th>SIMULATION PARAMETERS</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid supply voltage ($V_{Li}$)</td>
<td>415 V (ph-ph)</td>
</tr>
<tr>
<td>Supply frequency ($f$)</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Filter inductor ($L_f$)</td>
<td>5 mH</td>
</tr>
<tr>
<td>DC-link capacitor ($C_f$)</td>
<td>3300 µF</td>
</tr>
<tr>
<td>DC-link voltage ($V_d$)</td>
<td>750 V</td>
</tr>
<tr>
<td>Battery side inductor ($L_b$)</td>
<td>4 mH</td>
</tr>
<tr>
<td>Battery side capacitor ($C_b$)</td>
<td>50 µF</td>
</tr>
<tr>
<td>Converter switching frequency ($f_c$)</td>
<td>10 kHz</td>
</tr>
<tr>
<td>Battery nominal voltage ($V_s$)</td>
<td>360 V</td>
</tr>
<tr>
<td>Battery capacity ($Q$)</td>
<td>66.2 Ah</td>
</tr>
<tr>
<td>Shunt converter DC-link voltage ($V_{sh}$)</td>
<td>700 V</td>
</tr>
<tr>
<td>Shunt converter DC-link capacitor ($C_{sh}$)</td>
<td>3300 µF</td>
</tr>
<tr>
<td>Interfacing inductor ($L_i$)</td>
<td>0.5 mH</td>
</tr>
</tbody>
</table>

The modelled system is simulated up to 4 s. First 2 s, it is operated in G2V mode and another 2 s, it is performed in V2G mode. The response time of the overall system is observed as 5 µs. The various parameters such as source voltage, load current, compensator current, source current, battery voltage, battery current, battery SOC, power factor, DC-link voltages, THD, real and reactive power are observed with T1, IT2 and RGA optimized FLCs. The THD is measured up to 50th harmonics of 10 cycles under G2V and V2G mode for all cases.

A. Control of Shunt Converter by T1 FLC

The performance characteristics of T1 FLC during G2V operation are shown in Fig. 14.
The performance characteristics of the proposed shunt converter coupled charging scheme with T1 FLC during G2V operation are illustrated in Fig. 14. In this operating mode, 33.5 A current is supplied to the battery through a DC-DC converter. So, the battery SOC starts to increase from 32% because the initial SOC of the battery has been set at 32%.

The battery voltage is also increasing towards fully charged voltage. The power factor has been maintained above 0.97 and the shunt and AC-DC converter DC-link voltage is maintained at a predefined value of 700 V and 750 V, respectively. The measured THD of the source current and load current are 4.37% and 10.35%, respectively. Hence, the THD is reduced by 57.78% and the corresponding harmonic spectrum has been presented in Fig. 15.

Fig. 15. Harmonic spectrum during G2V (a) Source current (b) Load current

Fig. 16 shows the performance characteristics of the proposed charging scheme with T1 FLC during V2G operation. Here, the EV battery provides the power to the grid. So, the battery current is -33.5 A, and the SOC is decreasing from its maximum value. The battery voltage is falling towards the fully discharged voltage. The power factor is maintained above 0.96, and the shunt and AC-DC converter DC-link voltage are kept at a constant value of 700 V and 750 V respectively. The measured THD of the source current and load current are 4.59% and 9.96%, respectively. Hence, the THD is reduced by 53.91%, and the corresponding harmonic spectrum has been shown in Fig. 17.

Fig. 16. Performance characteristics of T1 FLC during V2G operation

Fig. 17. Harmonic spectrum during V2G (a) Source current (b) Load current

B. Control of Shunt Converter by IT2 FLC

The performance of the proposed shunt converter coupled charging scheme with IT2 FLC during G2V operation are depicted in Fig. 18. In this mode, the battery absorbs the power from the grid through AC-DC and DC-DC converters. So, battery voltage and SOC are increasing and the power factor has been maintained above 0.97. The measured THD of the source current and load current are 4.38% and 10.31%, respectively. Hence, the THD is reduced by 57.5%, and the corresponding harmonic spectrum has been presented in Fig. 19.

Fig. 20 shows the performance characteristics of the proposed charging scheme with IT2 FLC during V2G operation. Here, the battery voltage and SOC are decreasing, but the shunt and AC-DC converters DC-link voltage are maintained at a predefined value of 700 V and 750 V, respectively. The measured THD of the source current and load current are 4.50% and 10.19%, respectively. Hence, the THD is reduced by 55.78%, and the corresponding harmonic spectrum has been shown in Fig. 21.

Fig. 21. Harmonic spectrum during V2G (a) Source current (b) Load current
C. Control of Shunt Converter by RGA Optimized T1 FLC

The performance responses of the shunt converter coupled charging scheme with RGA optimized T1 FLC during G2V are illustrated in Fig. 22. In this mode, the battery is charging so the battery voltage and SOC are increasing. The measured THD of the source current and load current are 4.33% and 10.35%, respectively. Hence, the THD is reduced by 58.16%, and the corresponding harmonic spectrum has been presented in Fig. 23.

The proposed shunt converter coupled charging scheme performance is compared with the existing charging scheme. All the shunt converter controllers performed well than the existing systems and kept the source current THD within the allowable limits of 5% as per the IEEE-519 standard. With the obtained results, based on the source current THD, it is clearly identified that the RGA optimized T1 FLC performed well during G2V operation. In contrast, the IT2 FLC performed well during V2G operation, and it is shown in Table III. The transient response during G2V to V2G conversion is shown in Fig. 26.

Moreover, the performance of T1, IT2 and RGA FLCs in shunt converter DC-link voltage regulation is compared at the initial of G2V and V2G operations. The variation of the shunt converter DC-link voltage based on the controller is given in Fig. 27. Also, the controller performance has been evaluated based on the rise time, settling time, peak time and overshoot during the initialization of G2V and V2G operations.
The system responses are presented in Table IV. The settling time, peak time and overshoot are less with IT2 FLC as compared to T1 and RGA T1 FLCS in both G2V and V2G modes. The rise time is low with RGA T1 FLCS as compared to T1 and IT2 FLCS in both G2V and V2G modes. With all the investigated results and analysis, it is clear that IT2 FLC displays robust performance as compared with the other two controllers.

V. CONCLUSION

In this work, a shunt converter coupled novel high-quality charging scheme is designed for electric vehicle applications. The proposed system has been validated through simulation carried out in the MATLAB/SIMULINK environment. When the shunt converter with effective and efficient control technology is integrated into the conventional charging scheme which reduced the THD of the grid current less than 5%, which is the IEEE-519 standard limit of the THD. Moreover, a T1 FLC, IT2 FLC and RGA T1 FLC have been designed to improve the shunt converter performance by effectively regulating the shunt converter DC-link voltage. Eventually, the proposed system performs well with IT2 FLC and the response is faster than other controllers. An obtained result has shown the satisfactory operation of the system. The hardware implementation of the proposed system has been considered as the future work. Moreover, IT2 FLC will be designed for renewable energy powered EVCS to handle the non-linearity/uncertainty of renewable energy sources effectively.

The system responses are presented in Table IV. The settling time, peak time and overshoot are less with IT2 FLC as compared to T1 and RGA T1 FLCS in both G2V and V2G modes. The rise time is low with RGA T1 FLCS as compared to T1 and IT2 FLCS in both G2V and V2G modes. With all the investigated results and analysis, it is clear that IT2 FLC displays robust performance as compared with the other two controllers.

V. CONCLUSION

In this work, a shunt converter coupled novel high-quality charging scheme is designed for electric vehicle applications. The proposed system has been validated through simulation carried out in the MATLAB/SIMULINK environment. When the shunt converter with effective and efficient control technology is integrated into the conventional charging scheme which reduced the THD of the grid current less than 5%, which is the IEEE-519 standard limit of the THD. Moreover, a T1 FLC, IT2 FLC and RGA T1 FLC have been designed to improve the shunt converter performance by effectively regulating the shunt converter DC-link voltage. Eventually, the proposed system performs well with IT2 FLC and the response is faster than other controllers. An obtained result has shown the satisfactory operation of the system. The hardware implementation of the proposed system has been considered as the future work. Moreover, IT2 FLC will be designed for renewable energy powered EVCS to handle the non-linearity/uncertainty of renewable energy sources effectively.

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