Type-2 of Fuzzy Logic Control Optimization in Interleaved Bidirectional Converters for Battery Performance

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This research paper presents an innovative approach to battery performance and power management through the development and realization of an interleaved bidirectional DC-DC converter, enhanced by Type-2 Fuzzy Logic Controllers (T2FLC). The primary focus of this study is on improving the efficiency and reliability of power transfer between numerous energy storing strategies within T2FLC, including batteries and supercapacitors, thereby optimizing the overall vehicle performance and extending the driving range. The Interleaved bidirectional system architecture leverages the advantages of interleaved converters to reduce current ripple, which in turn minimizes heat generation and improves the longevity of the energy storage components. The bidirectional nature of the converter facilitates efficient energy management between the storage devices and the electric drive system, supporting both charging and discharging processes. This is particularly beneficial in regenerative braking scenarios, where the recovered energy can be effectively redistributed. A significant part of this control is the integration of Type-2 Fuzzy Logic Controllers, which offer robust performance under uncertain and highly dynamic operating conditions, common in EV applications. The Type-2 FLCs are designed to adaptively manage the power flow, enhancing the system's response to sudden changes in driving conditions or energy demand. Simulation results exhibit that the suggested system significantly outperforms conventional power management strategies, particularly in terms of energy efficiency and dynamic response. Furthermore, the implementation of Type-2 FLCs has shown to provide superior handling of uncertainties and nonlinearities in the system, validating the proposed approach as a viable solution for next-generation electric vehicle power management systems. This study lays the groundwork for future research in the field, with potential applications extending beyond automotive to other domains requiring efficient and reliable energy managing solutions.

Keywords: Interleaved Bidirectional DC–DC Converters, Type-2 Fuzzy Logic Controllers, Electric Vehicle Power Management, Energy Storage Optimization.

1. Introduction

Electric power sources worldwide, serving a wide range of industries, agriculture, and civilian or military applications, exhibit diversity in terms of their intended functions, equipment, and the types of systems they provide. Autonomous power generation systems, often harnessed from solar and wind energy, are frequently employed to support a variety of devices, infrastructure, and systems, fulfilling needs such as heating and lighting across various sectors. A common feature among the majority of these systems is their utilization of super-capacitors, accumulators (batteries), or various energy storage solutions to ensure consistent and reliable operation under various conditions and demands[1].

In recent times, clean energy sources, including technologies like solar photovoltaics and wind turbines, have seen extensive use in the creation of renewable power generation systems. Nonetheless, the variability in power generation caused by weather changes and occasional high demands for output power renders Renewable Energy Sources (RES) unsuitable for standalone operation as the sole power source. The typical approach to tackle this issue involves utilizing energy storage devices alongside the RES to mitigate their variability, thereby achieving a consistent and seamless power supply to the load[2].

Because of the factors mentioned earlier and the increasing demand for systems capable of bidirectional energy transfer between two DC buses, Bidirectional DC-DC Converters (BDCs) have garnered heightened interest. Beyond their conventional use in energy storage and DC motor control, BDCs have emerged as a promising choice for numerous applications, including portable devices, spacecraft power systems, Uninterruptible Power Supplies (UPS), electric vehicles, fuel cells, and renewable energy systems[3],[4].

DC-DC converters are sophisticated electronic devices that convert direct current (DC) from one voltage level to another. They are crucial in various applications, including renewable energy systems. These converters enable the precise control of power flow, which is essential for efficiently managing the charging and discharging processes of batteries [5], thus ensuring optimal performance, extending battery life, and improving the overall energy efficiency of the system.

The increasing adoption of small-scale hybrid photovoltaic (PV)-battery systems in recent times has the potential to enhance energy management and enhance the reliability of residential loads. In the past, low voltage (LV) battery systems, particularly the lead-acid type, were prevalent because of their affordability. Nevertheless, their weight and size have remained prominent issues [6].

Batteries, including lithium-type batteries, are now being explored for their potential applications in energy storage systems and the automotive industry [7]. These batteries have the advantage of reducing cable size, temperature, and losses over long transmission distances. In a hybrid PV-battery system, a Battery Energy Storage System (BESS) can either supply or absorb power using a buck and boost DC/DC converter, serving both on-grid and off-grid operations. The interleaved topology has proven to be the most advantageous, offering benefits such as high efficiency, improved thermal performance, reduction of current ripple, mitigating electromagnetic interference, and achieving a higher conversion ratio compared to traditional converters [8]. Type-1 fuzzy logic controllers (T1FLCs) have found widespread success across diverse applications, relying on human expertise to determine membership functions and fuzzy rules. However, real-time applications invariably contend with uncertainties stemming from available data. This study introduces a type-2 fuzzy logic control (T2FLC), incorporating components such as the fuzzifier, rule base, fuzzy inference engine, and output processor featuring type reduction and defuzzifier. By utilizing type-2 fuzzy sets for antecedent and/or consequent membership functions, the T2FLC can effectively manage rule uncertainties, particularly in scenarios of extreme uncertainty or when engineers struggle to precisely ascertain membership grades. Moreover, the proposed T2FLC is implemented in the control of a buck DC-DC converter. Experimental findings demonstrate the robustness of the proposed T2FLC against variations in input voltage and load resistance during converter control [9].

2. System Description

An interleaved bidirectional DC-DC converter[10], a sophisticated mechanism designed for efficient power management by transforming DC voltage levels to suit various needs, enabling power flow in both directions between a DC source and a battery. This innovative converter employs multiple units operating in a coordinated, slightly out-of-phase manner, known as interleaving, which enhances power delivery, minimizes ripples, and boosts efficiency for charging. Essential components include a DC source, such as a solar panel array or another DC power supply, serving as the primary input, and a rechargeable battery that stores energy for later use. The system is meticulously manipulated by a Type-2 Fuzzy Logic Controller, utilizing advanced fuzzy logic to adeptly handle uncertainties and imprecision in decision-making, thereby optimizing the converter's performance. This controller oversees the entire process, from monitoring system parameters like voltage levels and battery state to generating precise control signals that dictate whether the converter charges the battery by adjusting the power from the DC source or supplies power back to the DC source by drawing on the battery's reserves. This setup not only ensures efficient energy management but also significantly enhances the system's adaptability and response to varying operational demands. Fig. 1 describes the suggested system's block diagram.

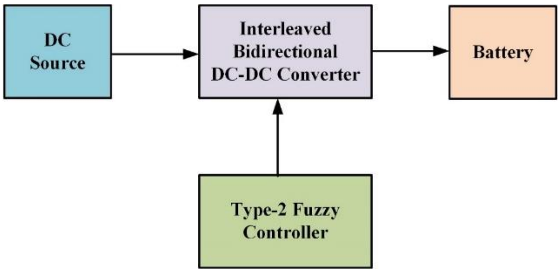

Fig.1 Block diagram of Interleaved Buck converter with Type 2 fuzzy control

3. Interleaved Bidirectional DC-DC Converter

Figure 2 illustrates a dual-phase topology, where V_1 and V_2 denote the battery and the DC voltage source, respectively. Additionally, the currents passing through V_1 and V2 are labeled as I1 and I2, and the corresponding powers are calculated as $P_1 = V_1 \times I_1$ and $P_2 = V_2 \times I_2$. The converter is set to operate in boost mode to facilitate energy transfer from the DC source to the battery. Conversely, it switches to buck mode to enable the DC source to Discharge the battery. The operation in forced continuous conduction mode (FCCM) is ensured as the active switches within the same leg, specifically S1 with S3 and S2 with S4, are triggered in a complementary fashion, preventing the operation in discontinuous conduction mode (DCM). This ensures that, despite potential changes in the direction of the inductor current, it does not drop to zero during any part of the switching cycle. For simplicity, only the boost mode operation ($D > 0.5$) is depicted, alongside the primary theoretical waveforms, in Figure 3.

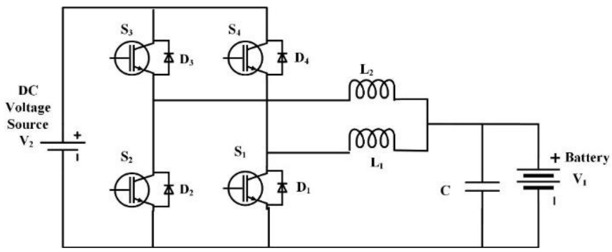

Fig.2 Circuit Diagram of Interleaved Bidirectional DC-DC converter

In the qualitative analysis of the converter, it is assumed that PWM controls the active switches within each leg in a complementary manner, and the power stage components are considered ideal. During the first stage $[t_0, t_1]$, S_1 and S_2 are activated at t_0, while S_3 and S_4 are deactivated, leading to the reverse biasing of their corresponding antiparallel diodes, D_3 and D_4. The linear increase in the currents across inductors L_1 and L_2 is attributed to the energy provided by V_1. Given the identical characteristics of the inductors, the current I_1 is evenly distributed between them. The capacitor C plays a crucial role in energizing V_2, and this phase concludes with the deactivation of S_2 and activation of S_4.In the subsequent stage $[t_1, t_2]$, S_1 and S_4 remain active from t_1, with S_2 and S_3 being inactive. The currents through L_1 and L_2 maintain equality on average[11]. The energy from L_2 is directed towards the load, while I_1 is split, part flowing through S_4 and D_4, and the rest through S_1. This phase ends as

S_2 is activated and S_4 is deactivated. The third stage [t_2, t_3] mirrors the first phase in its operations. The fourth phase [t_3, t_4], however, resembles the second stage but with S_2 and D_3 activated at t_3 in place of S_1 and D_4. During this time, the current through L_2 sees a linear increase, and the energy from L_1 is directed to the load, concluding with the activation of S_1 and deactivation of S_3.

Through the principle of volt-second balance, the static gain of the regulator is calculable, indicating the efficiency and effectiveness of energy transfer within the system.

$$\frac{V_2}{V_1} = \frac{I_1}{I_2} = \frac{1}{1-D} \quad (1)$$

The duty cycle, denoted by D, directly influences the static gain, as outlined in expression (1), which matches the static gain observed in a traditional boost converter operating under continuous conduction mode (CCM), applicable when D exceeds 0.5. Given the equal distribution of current across phases, the calculation of the filter inductances is enabled, ensuring accuracy and efficiency in the system's operation.

$$L_1 = L_2 = \frac{D(1-D)V_2}{f_s \Delta I_L} \quad (2)$$

where I_L is the current ripple across inductors L_1 and L_2, and f_s is the switching frequency. The formula yields the filter capacitance:

$$C = \frac{DI_2}{2f_s \Delta V_c} \quad (3)$$

where the voltage disturbance across capacitor C is denoted by ΔV_C. The filter capacitor's average running current is:

$$I_{C(rms)} = \sqrt{I_2^2 + 2(1-D)\left[\frac{\Delta I_L^2}{12} + I_{L(avg)}^2 - 2I_{L(avg)}I_2\right]} \quad (4)$$

where the mean inductor current is denoted by $I_{L(avg)}$. (5) and (6) provide the average and root mean square (rms) currents via S_1 and S_2, respectively.

$$I_{S1,S2(avg)} = \frac{1}{T_s}\int_0^{DT_s}\left[\left(\frac{I_{Lmax}-I_{Lmin}}{DT_s}\right)t + I_{Lmin}\right]dt \cong D_{Lavg} \quad (5)$$

$$I_{S1,S2(avg)} = \frac{1}{T_s}\int_0^{DT_s}\left[\left(\frac{I_{Lmax}-I_{Lmin}}{DT_s}\right)t + I_{Lmin}\right]dt \cong \sqrt{DI_{Lavg}} \quad (6)$$

where $I_{L(min)}$, $I_{L(max)}$, and T_S are the switching period, the lowest and highest levels of the inductance current, respectively. (7) and (8) provide the average and root mean square (rms) currents via S_3 and S_4, respectively.

$$I_{S3,S4(avg)} = \frac{1}{T_s}\int_{DT_s}^{T_s}\left[\left(\frac{I_{Lmin}-I_{Lmax}}{(1-D)T_s}\right)(t-DT_s) + I_{Lmax}\right]dt \cong (1-D)I_{Lavg} \quad (7)$$

$$I_{S3,S4(avg)} = \frac{1}{T_s}\int_{DT_s}^{T_s}\left[\left(\frac{I_{Lmin}-I_{Lmax}}{(1-D)T_s}\right)(t-DT_s) + I_{Lmax}\right]dt \cong \sqrt{1-D}I_{Lavg} \quad (8)$$

The switches' maximum voltages across them are:

$$V_{S1max} = V_{s2max} = V_{s3max} = V_{s4max} = V_2 \qquad (9)$$

Diodes D_3 and D_4's average and rms currents are determined by (10) and (11), accordingly.

$$I_{D3,D4(avg)} = \frac{1}{T_s}\int_{DT_s}^{T_s}\left[\left(\frac{I_{Lmin}-I_{Lmax}}{(1-D)T_s}\right)(t-DT_s)+I_{Lmax}\right]dt \cong (1-D)I_{Lavg} \qquad (10)$$

$$I_{D3,D4(rms)} = \frac{1}{T_s}\int_{DT_s}^{T_s}\left[\left(\frac{I_{Lmin}-I_{Lmax}}{(1-D)T_s}\right)(t-DT_s)+I_{Lmax}\right]dt \cong \sqrt{1-D}I_{Lavg} \qquad (11)$$

It may be said that the formulas (10) and (11), derived for switches S3 and S4, are the same. Diodes D_1 and D_2 may be analyzed using the same method in relation to switches S_1 and S_2, accordingly. The diodes' highest voltages across them are

$$V_{D1max} = V_{D2max} = V_{D3max} = V_{D4max} = -V_2 \quad (12)$$

The converter may provide bidirectional power flow while operating in either boosting or buck mode, as was previously indicated. This behavior is dependent on which switches are operated. The qualitative and quantitative research indicates that the behavior of the circuit is similar to a conventional boost topology. Because the formulas defining the current and voltage loads on the components are comparable, only one operating zone has to be analyzed if the bidirectional interleaved converter is intended to run with Duty cycle is greater than 0.5 and less than 0.5.

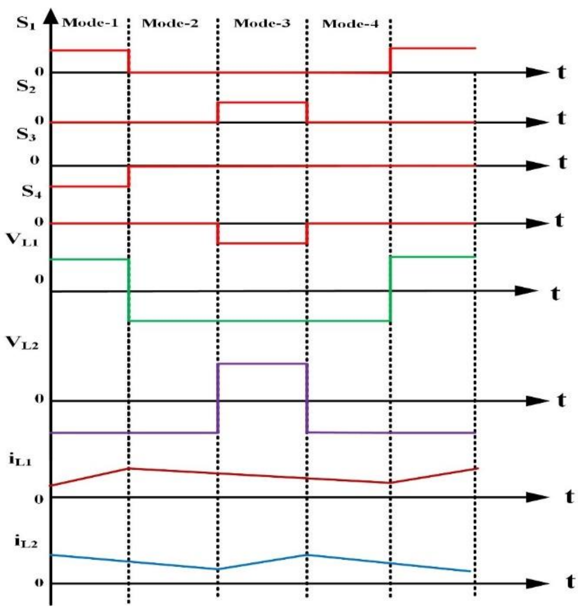

Fig.3 Switching mode waveforms for different modes of IL Converter

4. Fuzzy 2 type controller

An overview of the type-2 fuzzy logic method is covered in short in this segment. The father of fuzzy, Professor Lotfi A. Zadeh , developed the idea of type 2 fuzzy sets as an expansion of the notion of well-recognized conventional fuzzy groups, type-1 fuzzy sets.

T2FLSs often exhibit ambiguous membership grade features. The following is an explanation of type 2 fuzzy sense: The type 2 fuzzy logic groups use the Footprint of Uncertainty (FOU) as a domain in their membership function. It is constrained by 2 type-1 fuzzy logic (FL) membership utilities, namely Upper Membership Function (UMF) and Lower Membership function (LMF) . It is feasible to directly predict and manage uncertainties thanks to the extra degree of flexibility offered by the Footprint of Uncertainty. Figure 5 describes a associative function of type-2 fuzzy logic .

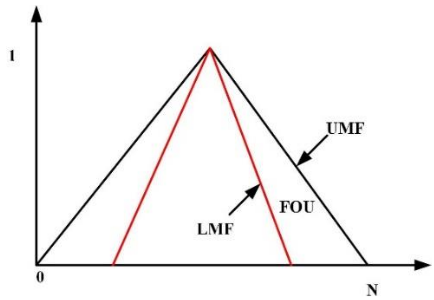

Figure 4. Membership Function of type-2 Fuzzy logic

Two type-1 fuzzy logic membership functions, namely UMF and LMF, which are limited by the FOU, were used to conduct operations on the type-2 fuzzy logic, producing the firing strength. The type-1 and type-2 fuzzy logic regulators (FLCs) have a similar basic construction. This study uses an type-2 fuzzy logic control, often known as the Mamdani technique or the Max-Min approach. The primary components of IT2FLC were the fuzzer, knowledge base, reasoning engine, and output process. The output process was the one area where the type-1 and the type-2 FLC structures differed. The primary components of the output processor in IT2FLC were the type reducing agent and defuzzifier. From the type-reducer, they produced a type-1 fuzzy group output, and from the defuzzifier, they produced a sharp number. In situations where it was impossible to pinpoint the precise membership grades—such as when a regulation was unclear—IT2FLC may be employed. Figure 4 describes the basic construction of an type-2 FLC.

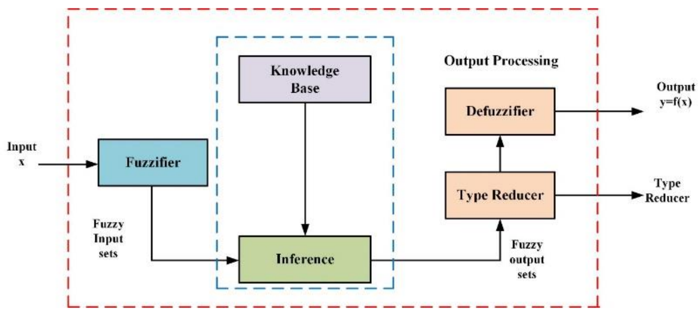

Fig.5 Type 2 Fuzzy logic structure

It may be represented as follows based on Fig. 5.

Fuzzifier: This transformed actual values as inputs into fuzzy membership function values.

Inference system: To yield a fuzzy end product, the type-2 FLC utilized the fuzzy reasoning process.

Defuzzifier/type reducer: The reducer type's job was to convert the type-2 fuzzy set to type-1 fuzzy set, while the defuzzifier changed the fuzzy output for certain values. When using the centroid approach to defuzzify an type-2 fuzzy logic regulator , the Karnik-Mendel Algorithm, as developed by Karnik and Mendel, is used.

Knowledge base: This component included a collection of membership functions referred to as the database and a set of fuzzy rules known as the basic rules.

The Karnik Mendel Algorithm's design stages for the type-2 fuzzy logic regulator approach of defuzzification are as results: A. The following procedures can help you find the CL value:

1. Using Equation (13), initialize the value of θi.

$$\theta_i = \frac{1}{2}\left[\underline{\mu}_A(x_i) + \overline{\mu}_A(x_i)\right], i = 1,2,3, \dots N \quad (13)$$

2. Determine the value of c' by using Equation (14),

$$C' = c(\theta_1, \theta_2, \dots, \theta_N) = \frac{\sum_{i=1}^{N} x_i\theta_i}{\sum_{i=1}^{N} \theta_i} \quad (14)$$

3. To meet the constraint, get the K value as follows.

$$x_k \le c' \le x_{k+1} \quad (15)$$

4. Utilizing Equation (16), determine the value of c''.

$$c'' = \frac{\sum_{i=1}^{N} x_i\overline{\mu}_A(x_i) + \sum_{i=k+1}^{N} x_i\underline{\mu}_A(x_i)}{\sum_{i=1}^{N} \overline{\mu}_A(x_i) + \sum_{i=k+1}^{N} \underline{\mu}_A(x_i)} \quad (16)$$

5. Step 2 will be followed if c''=c'; otherwise, set c' = cl'' and quit.

B. The following procedures may be used to determine the value of cr: 1. Using Equation (17), initialize the value of θi.

$$\theta_i = \frac{1}{2}\left[\underline{\mu}_A(x_i) + \overline{\mu}_A(x_i)\right], i = 1,2,3 \dots N \quad (17)$$

2. Utilizing Equation (18), get the value of c'.

$$C' = c(\theta_1, \theta_2, \dots, \theta_N) = \frac{\sum_{i=1}^{N} x_i\theta_i}{\sum_{i=1}^{N} \theta_i} \quad (18)$$

3. To satisfy the constraint, get the K value as follows:

$$x_k \le c' \le x_{k+1} \quad (19)$$

4. Determine the value of c'' by using Equation (20).

$$c'' = \frac{\sum_{i=1}^{N} x_i\overline{\mu}_A(x_i) + \sum_{i=k+1}^{N} x_i\underline{\mu}_A(x_i)}{\sum_{i=1}^{N} \overline{\mu}_A(x_i) + \sum_{i=k+1}^{N} \underline{\mu}_A(x_i)} \quad (20)$$

5. Stop if c'' = c'; if not, set c'=cr'' and get to step 2 [12]. Once the values of cl and cs have been determined, the centroid values may be computed. The following equation is used to

calculate the centroid values[13]:

$$Centroid = (c_1 + c_r)/2 \quad (21)$$

$(c_l+c_r)/2$ is the centroid (24) N is the maximum number of iterations that the centroid calculation procedure will undergo, despite being an iterative process.

5. Simulation Results & Discussions

The simulation of Interleaved Bidirectional DC–DC Converters with Type-2 Fuzzy Controller is simulated in MATLAB/SIMULINK

Table 1. Parameters used in Simulation

Sl.no	Parameters	Values
Battery Details		
1	Type	Lithium-Ion
2	Voltage (V)	300
3	Measured Capacity (Ah)	200
4	State of Charge (%)	50
5	Response time (s)	1
Interleaved Converter Details		
6	Inductance (mH)	1
7	Capacitance (μF)	195
8	DC Voltage Source (V)	400
9	Switching Frequency (kHz)	20

Table-1 outlines the parameters used in a simulation involving a Lithium-Ion battery and an interleaved converter, key components in power management systems for applications such as electric vehicles. The battery is specified with a nominal voltage of 300 volts and a rated capacity of 200 ampere-hours, starting with an initial state of charge at 50%, and has a quick response time of 1 second to power demands. The interleaved converter, designed to efficiently manage power between the battery and the system, features an inductance of 1 millihenry and a capacitance of 195 microfarads, with a 400-volt DC voltage source supplied to it. It operates at a switching frequency of 20 kilohertz, which affects the converter's execution in terms of efficiency and the quality of the power conversion process. Together, these parameters define the operational characteristics and performance expectations of the simulation, providing insights into the system's behavior under the specified conditions.

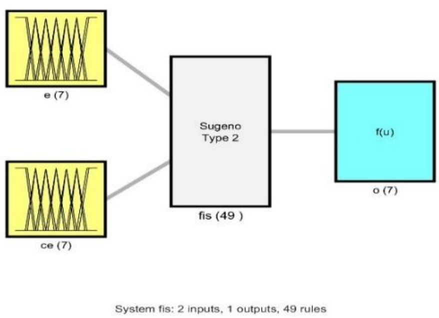

Fig.6 Formation of Type 2 Fuzzy model in MATLAB

The formation of the Type 2 fuzzy model in simulation is represented in the Fig. 6

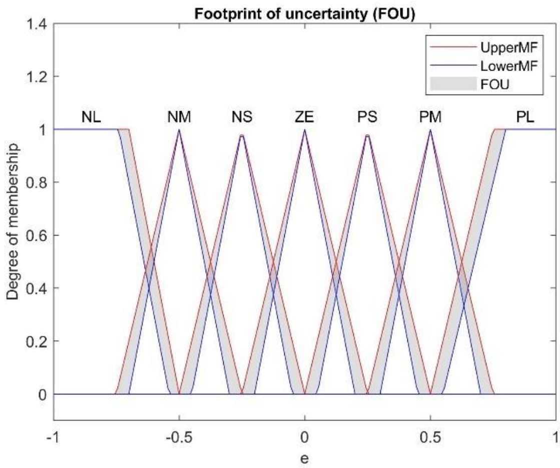

Fig.7 Error in Type 2 Fuzzy logic formation

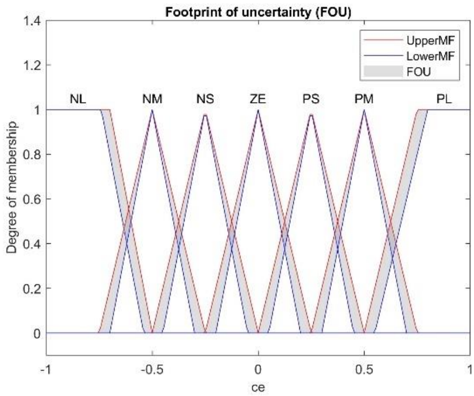

Fig.8 Change in Error in Type 2 Fuzzy logic formation

Fig.7 & 8 exhibits the Type 2 Fuzzy logic structures error and change in error respectively. In the graphical representation of a Type-2 Fuzzy Logic Control (FLC), the footprint of indecision reflects the uncertainty associated with input variable quantity, such as error and change in error. Typically, the x-axis of the graph represents these input variables, with error and its rate of alteration being common choices. The y-axis, on the other hand, depicts the degree of membership, indicating the extent to which a given input value belongs to a particular fuzzy set. In a Type-2 FLC, uncertainty is depicted by a broader footprint, encompassing a range of possible values for the input variables. This broader footprint accounts for the additional uncertainty inherent in Type-2 Fuzzy Logic due to the presence of secondary memberships, which capture uncertainty about the uncertainty itself. As a result, the footprint of indecision in the Type-2 FLC graph appears wider compared to its Type-1 counterpart, illustrating the controller's ability to handle and model uncertainties more comprehensively, leading to more robust and adaptable control decisions. The rule base is represented in the Fig.9.

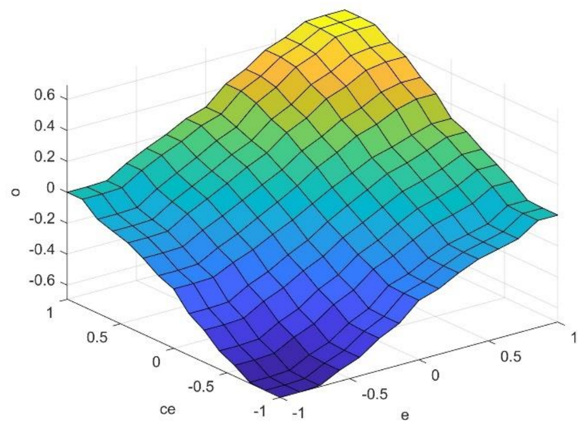

Fig.9 Rule base of Type 2 Fuzzy logic control

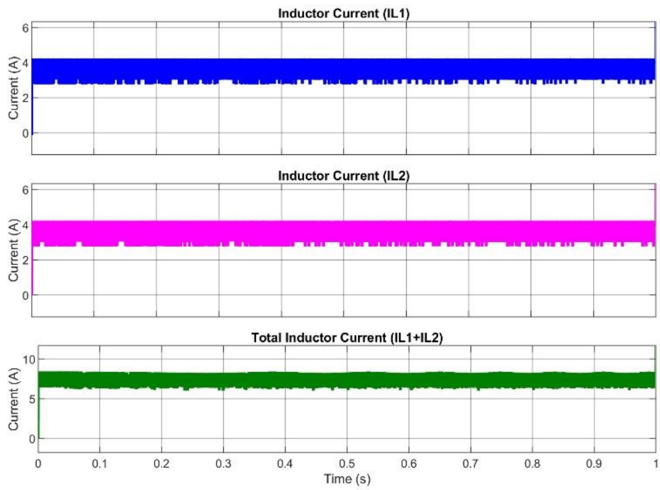

Fig.10 Inductor Currents of Interleaved Bidirectional Converter

The Inductor Currents of Interleaved Bidirectional Converter is shown in the Fig.10. here the inductor current is represented as I_{L1} and I_{L2}, the addition of the two current will give the total current of the converter. Fig.10 shows the Battery SOC, Voltage and Current during the operation of Type 2 fuzzy controlled converter. Here the battery will starts to charge, the SOC of the battery increases , as the current is represented in negative the battery is said to be in charging mode. Thus the Type 2 controller with Interleaved bidirectional converter provide optimum power management in the battery storage system.

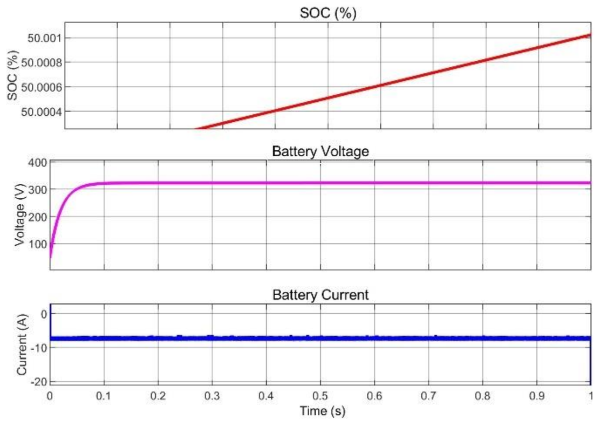

Fig.11 Battery SOC Voltage & Current during Charging

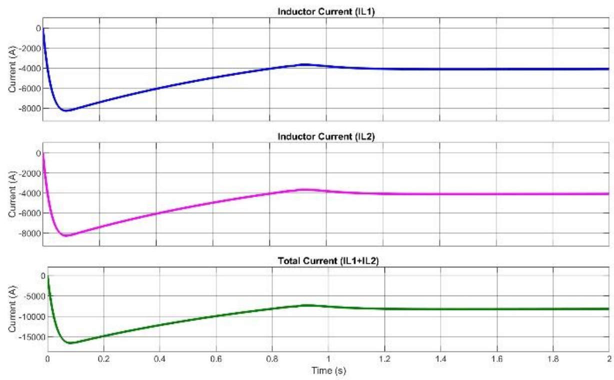

Fig.12 Inductor Currents of Interleaved Bidirectional Converter during Discharging

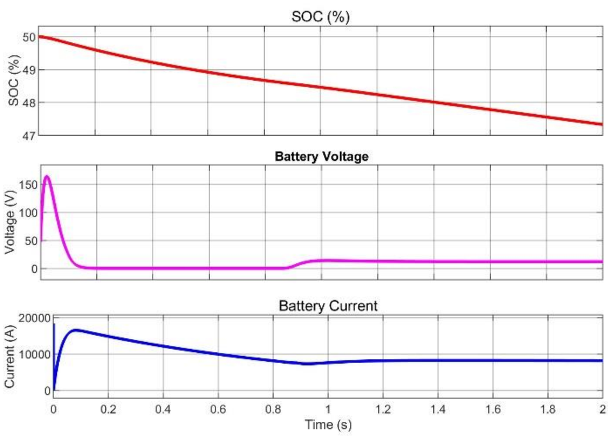

Fig.13 Battery SOC Voltage & Current during Discharging

The Inductor Current of the Bidirectional regulator during Discharging is shown in Fig.12. here it its inferred that that the inductor currents are negative. Where the Fig.13 represents the Battery SOC Voltage & Current during Discharging, Here the SOC of the battery decreases from 50% which is indicated clearly. Thus the Type 2 controller with Interleaved bidirectional converter provides both charging & Discharging in the battery storage system.

6. Conclusion

In conclusion, this study effectively illustrates the effectiveness of a battery storage power management technique utilizing an interleaved bidirectional Converter controlled by Type-2 Fuzzy Logic Controllers (FLC). This innovative system tackles key issues in battery energy management, particularly in efficiently and reliably transferring power among multiple energy storage devices. By harnessing the advantages of interleaved converters, such as reduced current ripple and minimized thermal stress, the system not only enhances battery efficiency and performance but also prolongs the lifespan of energy storage components. The bidirectional nature of the converter ensures optimal energy utilization, facilitating efficient charging and discharging processes, as well as the effective redistribution of energy captured through regenerative braking.The incorporation of Type-2 FLCs represents a significant advancement in power flow management within the system, offering improved adaptability and robustness in fluctuating and uncertain operating conditions. This is especially relevant considering the increasing importance of renewable energy as a voltage source and the need to store energy in batteries effectively. The empirical results from simulations confirm the superiority of the proposed power management system over conventional methods, demonstrating significant enhancements in energy efficiency and dynamic response. This research highlights the potential of combining advanced control technologies like Type-2 fuzzy logic with innovative power conversion techniques to transform battery storage power management. The findings not only validate the proposed approach as a practical solution for improving battery storage system performance but also pave the way for further exploration into broader applications requiring sophisticated and dependable energy management strategies.

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