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Feasibility Study of Efficient and Adaptive Interval Type-2.0 Fuzzy Logic Controller for Hybrid Electric Vehicle Performance Optimization

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ABSTRACT

This research explores the feasibility of employing an efficient and adaptive Type-1 Fuzzy Logic Controller (T-1 FLC) and Interval Type-2.0 Fuzzy Logic Controller (IT-2.0 FLC) to optimize the performance of hybrid electric vehicles (HEVs). The research problem focuses on enhancing the robustness and efficiency of T-1 FLC in HEVs to match the superior performance of IT-2.0 FLC in handling uncertainties and dynamic conditions. Interval Type-2.0 Fuzzy Logic Controllers are a popular option because of their capacity to manage uncertainties inherent in real-world driving conditions. Type-1 Fuzzy Logic Controller-based HEVs have limited ability to handle uncertainties and variations robustly, and they may lack the adaptability required to optimize performance under diverse driving conditions effectively. An electric powertrain permanent magnet synchronous motor (PMSM) and 4 energy storage systems (battery, solar PV, fuel cell, and super-capacitor power structure) are features of an atypical HEV. The PMSM drive, which is the most effective and popular, is utilized in the proposed work. A HEV has been implemented using T-1 and IT-2.0 FLCs for battery and fuel cell storage system along with a solar PV system with an maximum power point tracker (MPPT) controller and a supercapacitor storage system with a PI controller. The efficiency, mileage, and energy consumption of energy of each system are assessed using a combination of plausible driving scenarios and extensive simulations. The IT-2.0 FLC-driven HEV demonstrates outstanding performance by enhancing system Total Harmonic Distortions (THDs), achieving energy savings, optimizing torque output with minimal speed deviation, and extending mileage range. The IT-2.0 FLC outperforms nearly 89.478% in output torque, 95.202% in speed, and nearly 97.26% in battery state of charge preservation. MATLAB/Simulink 2018a was used to implement the entire proposed scheme.
***Index Terms*—**Electrical powertrain, energy storage system, Fuzzy Logic Controller (FLC), hybrid electric vehicle, hybrid energy storage system, Interval Type 2.0-Fuzzy Logic Controller (IT-2.0 FLC)

I. INTRODUCTION

The use of non-renewable resources is usually drastically declining, depending on the nation's energy requirements. The primary objective of utilizing these finite resources is to generate energy for various transportation needs. Electric cars have gained popularity due to their minimal environmental impact, contrasting sharply with the harmful emissions produced by petrol-powered vehicles. Electric vehicles, replacing internal combustion engines gradually, aim to mitigate greenhouse gas emissions. Stringent regulations govern motor drives in Hybrid Energy Storage System (HESS)-based electric vehicles, surpassing those for standard industrial drives. Permanent magnet synchronous motors and induction motors serve as the primary power sources for electric vehicles. The rapid depletion of petroleum-derived goods has spurred the growth of sustainable resources. Wind and solar energy represent prominent categories within the realm of renewable energy sources (RESs). The recent surge in hybrid electric vehicle (HEV) advancement is fueled by growing apprehensions about preserving energy and safeguarding the environment. While mitigating greenhouse gas emissions and lessening reliance on fossil fuels holds promise for these vehicles, improving their efficiency and capability presents a substantial hurdle. It is crucial to adopt sophisticated control systems to bolster the overall performance of HEVs and tackle these concerns adeptly [1-3]. Of the 2, solar photovoltaics (PVs) is more important. After utilizing a number of algorithms to extract the most power possible from solar radiation, a boost converter is employed to raise the voltage level of the solar power. The PV market is attracting more attention from different countries. Furthermore, the automotive

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industry is starting to adopt hydrogen energy more and more. An energy storage system (ESS) and a bidirectional converter (BDC) are used to store the solar PV energy for later use [4]. Storage devices include batteries, fuel cells, and supercapacitors (SCs). A SC, fuel cell, and battery energy storage system (BESS) will be used to improve the efficiency of the intermittent HEVs connected to solar PV systems [5]. The performance of HEVs and the effectiveness of their batteries can be enhanced by using efficient conditioning inverters and chopper circuits. Because non-linear loads are connected to the battery and have higher energy needs when there is less solar energy available, the battery's performance is inefficient. To solve this problem, the SC, a new energy storage technology, was created. As stated, it is important to balance the power generated by solar PV [6, 7]. Batteries are not as energy dense as SCs. The article recommends using SCs to absorb fluctuations caused by high frequencies in solar PV and to smooth out the power that comes from solar-based ESS. The SC won't start charging until the HESS-based system has produced enough extra energy to fully charge all energy storage devices [8-10]. Fuel cells are in charge of making up any remaining energy production shortfall from all utilities. The above and imminent literature review of the research article aims to investigate the influence of electric vehicles on load frequency control within interconnected thermal and hydrothermal power systems utilizing the CF-FOIDF controller [11]. Efficient protection, precise control, and optimized power quality are paramount considerations in HEV systems. Implementing robust strategies in these areas ensures the safety, performance, and reliability of HEVs, thereby enhancing their overall effectiveness and user experience [12-14]. We have employed a range of power electronic (PE) device-based controlling strategies. Various methods, including neural networks, PI controllers, Type-1 Fuzzy Logic Controllers (T-1 FLC), Adaptive Neuro-Fuzzy Inference Systems (ANFIS), and Type-2.0 Fuzzy Logic Controllers (FLC), can control this PE converter. This paper introduces a supervisory control approach for distributed drive electric vehicles. It includes a dynamic controller, handling-stability manager, energy-efficient system, and coordinated torque allocator to synchronize vehicle handling, lateral stability, and energy efficiency performance [15-18]. Interval Type-2.0 Fuzzy Logic Controllers (IT-2.0 FLCs) emerged as an extension to conventional FLCs, providing enhanced adaptability and robustness in handling uncertainties. Nevertheless, despite their benefits, integrating IT-2.0 FLCs into HEVs poses distinct challenges because of the dynamic nature of vehicle operation, fluctuating driving conditions, and complex interactions among the electric motor, internal combustion engine, and ESS. The research gap between T-1 and IT-2.0 FLCs in HEVs lies in understanding their respective abilities to handle uncertainties and variations robustly, computational complexity implications, and adaptability to varying driving conditions. This comparison is motivated by the need to optimize control strategies for improved performance and efficiency in HEVs. Investigating the computational complexity implications and adaptability to diverse driving conditions is crucial in bridging this research gap. Addressing these factors can lead to advancements in controller design and optimization, ultimately enhancing the overall performance of HEVs. Thus, the purpose of this study is to examine the viability of developing an effective and flexible IT-2.0 FLC especially for optimizing HEV performance [19-21]. This study's main goal is to create an IT-2.0 FLC that can split power between its internal combustion and electric components more precisely while also dynamically adapting to shifting driving circumstances and uncertainties. By utilizing IT-2 fuzzy sets, the IT-2.0 FLC will be able to handle a wider range of driving scenarios with more flexibility and a more effective management of uncertainty than traditional IT-2.0 FLCs [22-25]. This article discusses the developments in electric drive technology that is now commercially available for both hybrid and electric passenger cars. Challenges for IT-2.0 FLC in HEVs compared to T-1 FLC include increased computational complexity due to handling uncertainties with higher dimensions. The implementation of IT-2.0 FLC may require more resources and computing power, potentially impacting real-time performance. Its adaptability to varying conditions may also require extensive tuning and calibration, posing challenges in achieving optimal control. Achieving a balance between robustness and computational efficiency is vital when employing IT-2.0 FLCs in HEV systems. This study investigates the impact of vehicle-to-infr astructure (V2I) communication on energy conservation, torque and speed enhancements, and reduced battery degradation for an electric bus under this framework. The need for a comprehensive review of existing T-1 FLC-based HEVs) compared to proposed IT-2.0 FLC-based HEVs incorporating solar, battery, SC, and fuel cell systems is critical. Recent research highlights that while T-1 FLCs offer computational efficiency and ease of implementation, they fall short in handling uncertainties and dynamic variations effectively. Interval Type-2.0 FLCs, by contrast, provide enhanced robustness, stability, and energy optimization, crucial for managing the complex interactions of multiple energy sources. This review is essential to identify performance gaps, evaluate the practical feasibility of IT-2.0 FLCs, and guide future advancements in HEV control strategies, ultimately contributing to more sustainable and efficient transportation solutions. Section I comprises an introduction and a review of techniques previously employed in the literature. Section II presents an energy management strategy and system description. Section III illustrates system modeling. Section IV presents the results and discussion. Section V concludes this work.

II. ENERGY MANAGEMENT STRATEGY WITH SYSTEM'S DESCRIPTION

To optimize overall efficiency, performance, and energy utilization, effectively managing energy for a HEV with multiple energy sources—such as solar PV, SCr, fuel cell, and battery—requires intelligent control of power distribution among these sources. Assuring that each energy source is used as efficiently as possible given its properties and the vehicle's operating circumstances is the aim. Here is a quick synopsis of the approach: solar PV integration is the process of converting solar energy into electrical power using PV panels mounted on the roof or body of the vehicle. The vehicle has the capability to charge through both its SC and battery, or it can solely rely on energy derived from the solar panels. An effective Maximum Power Point Tracking (MPPT) algorithm is implemented to optimize the power output from the solar panels across various sunlight conditions. The use of a SC as a buffer is appropriate because of its quick charge and discharge times, which allow it to store and release energy during sudden acceleration or regenerative braking. To handle sudden power needs, the energy management system uses the SC as a buffer, which lessens strain on the battery and enhances the responsiveness of the car. Battery management is the primary ESS in a HEV is its battery, which supplies power for longer driving distances and when solar energy is scarce. The energy management plan maximizes the battery's lifespan while optimizing its state of charge (SoC) to keep it operating within safe bounds. Other power sources, like solar PV or fuel cells, can be used to recharge batteries when their SoC is low. Fuel cells designed for extended range are dependable and efficient power sources, generating electricity

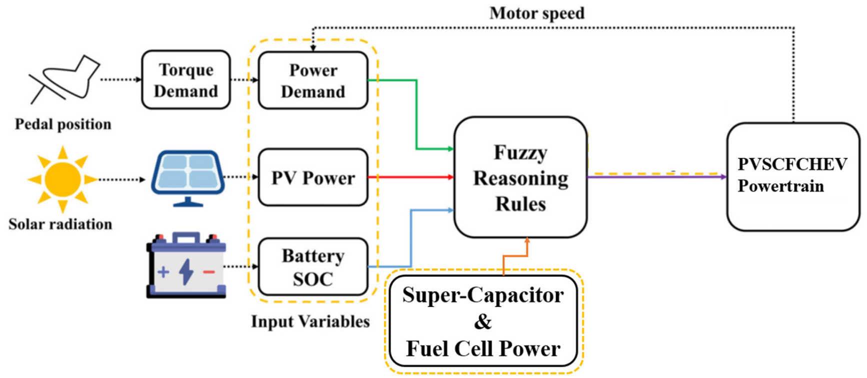

Fig. 1. Energy management strategy based on Fuzzy Logic for hybrid electric vehicle.

through the electrochemical reaction of hydrogen and oxygen. The energy management system extends the vehicle's range without depending only on fossil fuels by using the fuel cell to run the vehicle on electricity even when the battery is low or there is a high demand for power. Advanced control algorithms such as Fuzzy Logic Control (FLC) or Model Predictive Control (MPC) can be utilized to execute the energy management strategy. These algorithms make real-time decisions about how to distribute power among the various sources by taking into account inputs like fuel cell efficiency, solar PV output, power demand, battery SoC, and vehicle speed. The energy management strategy employs real-time adaptation to constantly monitor and adjust to variations in driving conditions, road profiles, and energy availability. It maximizes the distribution of power to meet the requirements of the driver while ensuring that the entire system operates with high efficiency and sustainability. This holistic energy management strategy enhances the performance of the hybrid electric vehicle by effectively regulating the power distribution among the solar PV, SC, fuel cell, and battery. It lowers fuel consumption, decreases emissions, and improves the overall driving experience, all while harnessing renewable energy sources.

The foundation of the Energy Management Strategy (EMS) lies in the IT-2.0 FLC. Despite the highly nonlinear nature of the Photo-voltaic Super-capacitor Fuel Cell Hybrid Electric Vehicle (PVSCFCHEV)

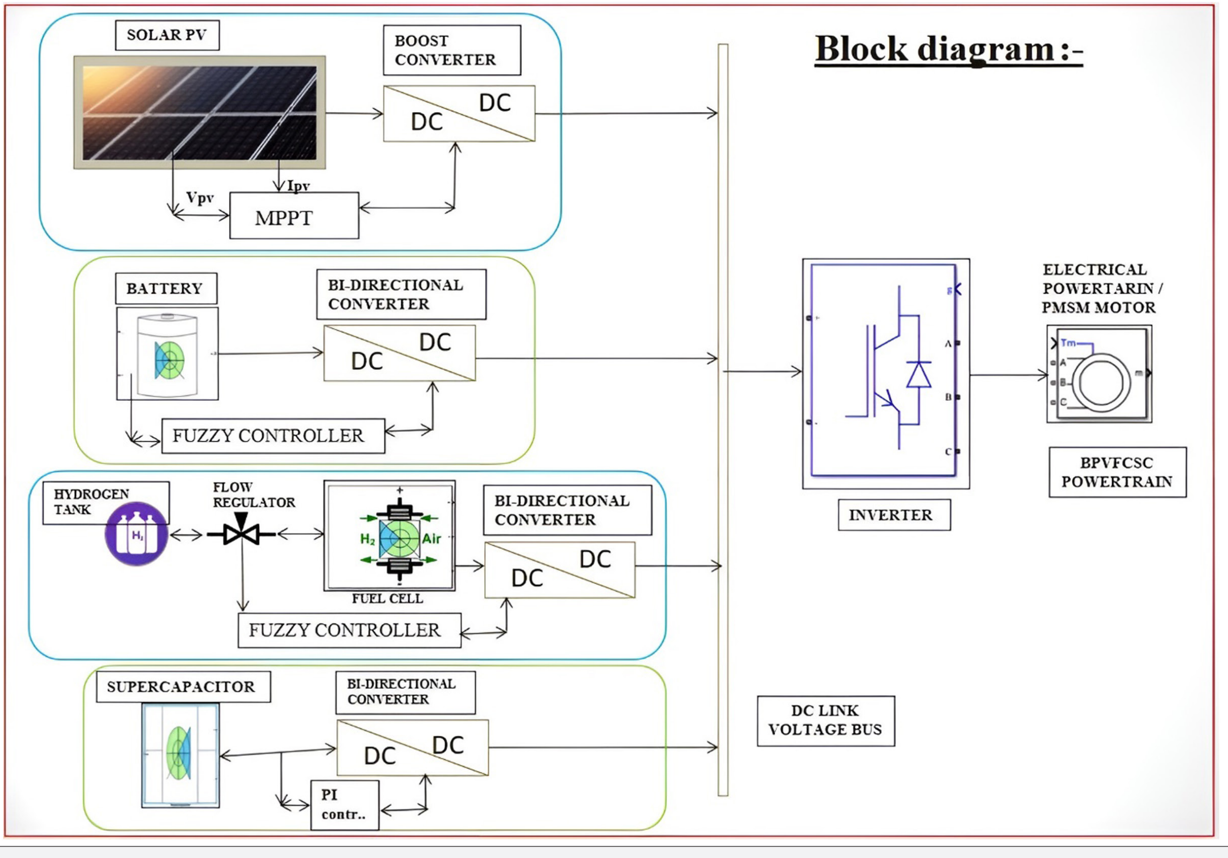

Fig. 2. Block diagram of hybrid electric vehicle system based on Fuzzy Logic Controller/Interval Type-2.0 Fuzzy Logic Controller.

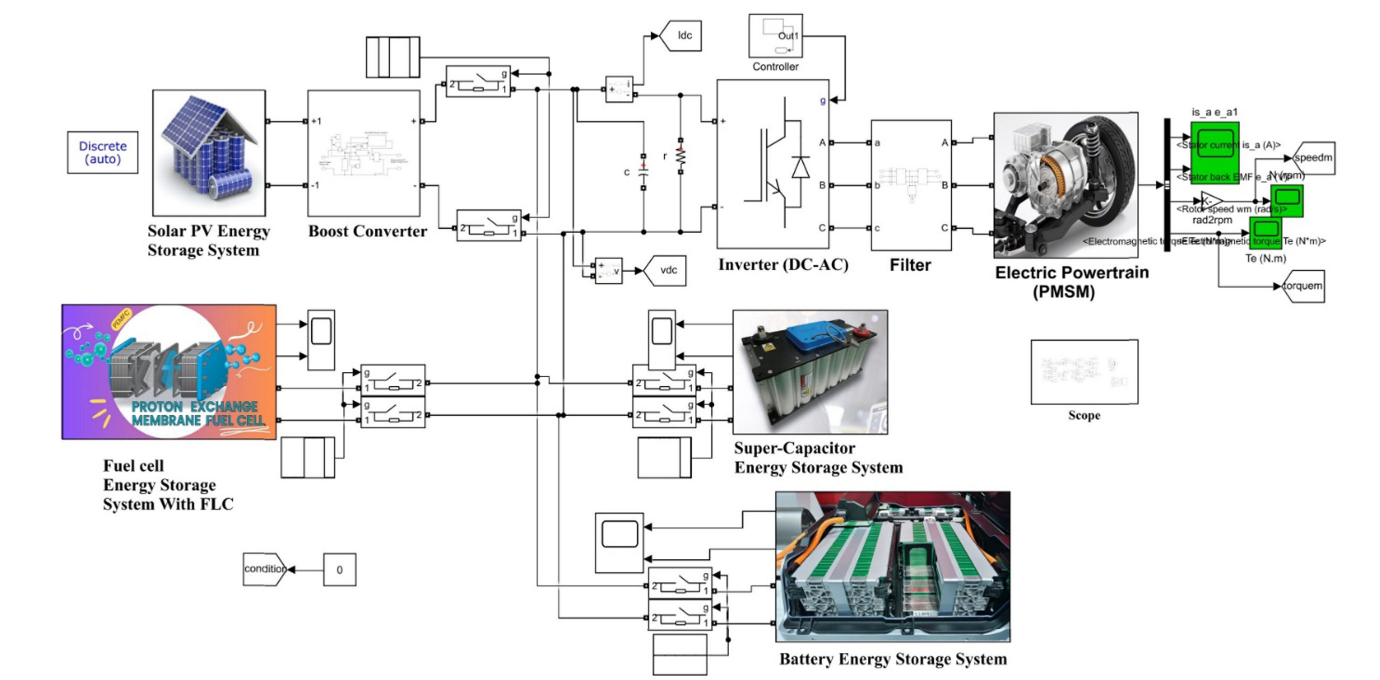

Fig. 3. Simulink model of the hybrid electric vehicle system based on Fuzzy Logic Controllers/Interval Type-2.0 Fuzzy Logic Controllers.

system, the IT-2.0 fuzzy logic approach is preferred over the T-1 FLC due to its adaptability and ability to function effectively without precise mathematical models. Furthermore, IT-2.0 fuzzy logic allows for the integration of expert knowledge into control strategies, facilitating the management of challenging environmental conditions such as the unpredictable and irregular nature of solar energy. Illustrated in Fig. 1, the output parameter for the IT-2.0 FLCis the reference power of the IT-2.0 FC. The input parameters for the IT-2.0 FLC include the demand power of the electric motor, the output power of the PV array, the SoC of the fuel cell, and the SoC of the SC and battery. The positions of the accelerator and brake pedals determine the motor's demand torque, which is then utilized to calculate the motor speed and demand power. Battery, SC, and fuel cell power are prioritized over other energy sources based on availability as the controller's primary control variables, along with solar power.

Figure 2 depicts the block diagram of the proposed PVSCFCHEV, amalgamating all input sources. It employs a T-1 FLC and comprises an electric powertrain (EPT) linked to a HESS. All energy storage devices, including SCs, fuel cells, and batteries, possess instantaneous energy delivery and storage capabilities. The system consists of a solar PV system, a boost converter, a filter, an inverter, and a Permanent Magnet Synchronous Motor (PMSM). Solar power generation serves as the primary energy source for the proposed system. Utilizing a MPPT controller employing the perturbation and observation (P&O) technique optimizes the solar power. The MPPT controller interfaces between the DC link voltage bus and the solar energy system, overseeing the charging process for electric vehicle batteries and ensuring prevention of overcharging. Additionally, it is employed to maximize the PV module's power output in various scenarios.

An ideal condition is considered with a temperature of 250°C and 1000 W/m2 of light. In conjunction with the solar PV system, a battery and a bidirectional DC-to-DC converter (BDC) are connected. Lithium-ion batteries are utilized in the BESSs due to their superior energy density, faster charging capability, and longer charge retention compared to conventional batteries. The BDC is controlled by a Fuzzy Logic Controller (FLC). However, considering the cost and efficiency decline of lithium-ion batteries over time, they necessitate more frequent maintenance. To address this issue, a fuel cell (FC) storage system and a BDC are connected alongside the solar energy and battery energy system. The FC operates based on the principle of electrolysis, converting chemical energy into electrical energy. This chemical energy is produced through a chemical reaction involving oxygen, utilizing various materials. This study employs both the conventional BDC and the hydrogen-based Proton Exchange Membrane Fuel Cell (PEMFC). The BDC is governed by an FLC. Excessive utilization of fuel cells can result in the extraction of hydrogen, posing a significant flammability risk. To mitigate this issue, fuel cell systems are replaced with SC storage systems. These SC systems are then interconnected in parallel with solar energy systems, BESSs, and fuel cell systems, forming a comprehensive PV-HESS system. Initially, solar irradiation is leveraged to optimize the utilization of green energy sources, such as solar PV, and enhance the functionality of the solar PV-HESS system. However, in cases where solar power proves

TABLE I. RULES FOR TYPE-1 FLC

Error/D error	NB	N	Z	P	PB
NB	PB	PB	P	Z	Z
N	P	P	Z	Z	Z
Z	Z	Z	Z	Z	Z
P	Z	Z	N	N	N
PB	N	N	N	NB	NB

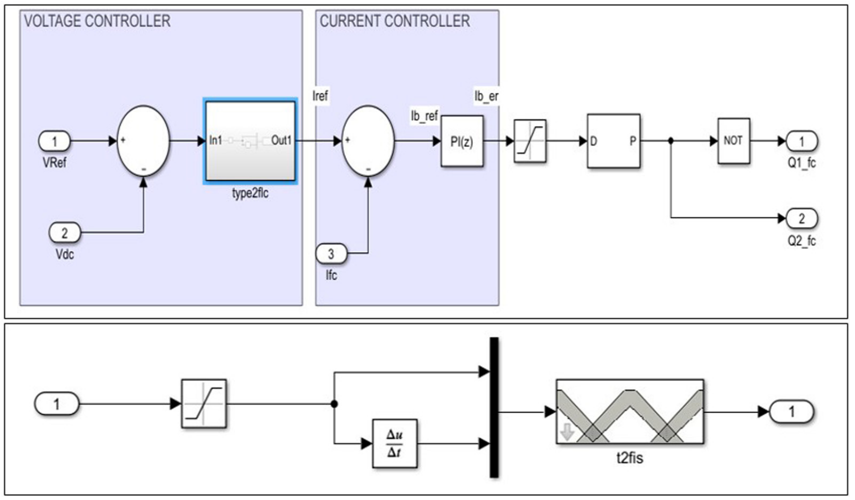

Fig. 4. Simulink model of Interval Type-2.0 Fuzzy Logic Controller

insufficient, the system switches to utilizing the SCs. Should the SoC of the SC degrade, an FLC employed in tandem with the battery to extract power. If none of the other energy sources can provide adequate power for propulsion, the HESS, in conjunction with the T-1 FLC, intelligently draws power from the fuel cell. Additionally, more fuel cells are utilized to restore the battery and SC status. Following passage through an LCL filter, the inverter converts the accumulated DC power from the DC bus into AC power, which is then supplied to the PMSM drive (PVSCFCHEV).

If an IT-2.0 FLC is considered an advanced counterpart to a T-1 FLC, then in an EPT connected Photo-voltaic Hybrid Energy Storage System (PV-HESS) electric vehicle, the T-1 FLC is replaced by an IT-2.0 FLC. The primary distinction between T-1 and IT-2.0 FLC lies in the

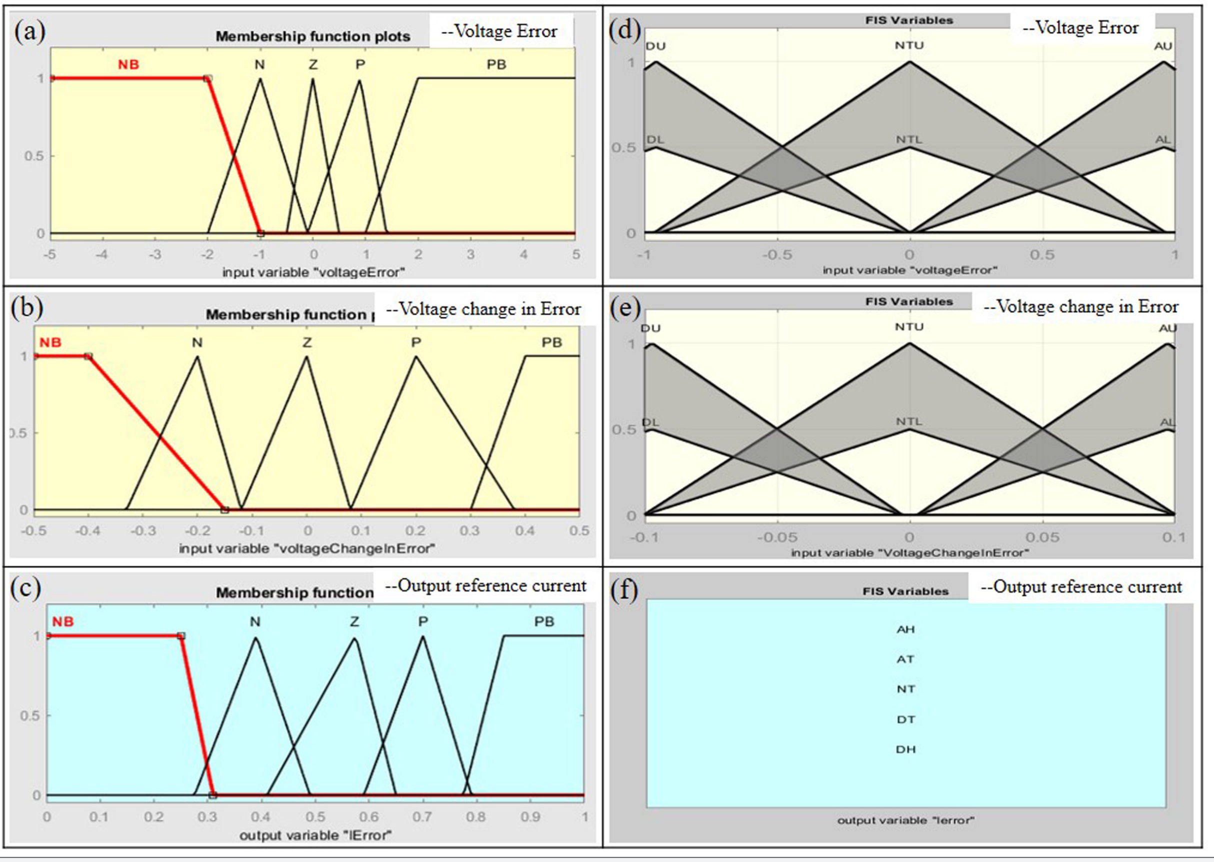

Fig. 5. Membership function plot for Type-1 Fuzzy Logic Controller and Interval Type-2.0 Fuzzy Logic Controller.

TABLE II. RULES FOR INTERVAL TYPE-2.0 FUZZY LOGIC CONTROLLER

E/CE	D	NT	A
D	DH	DT	NT
NT	DT	NT	AT
A	NT	AT	AH

utilization of a type reducer during the defuzzification phase. Apart from the adaptation from T-1 to IT-2.0 FLC controller, all procedures remain identical. Figure 3 illustrates the Simulink model of the proposed PVSCFCHEV based on IT-2.0 FLC.

III. SYSTEM MODELING

In this article, the Sim-Power Systems package is used to create a model of the PVSCFCHEV system in 2018a Matlab/Simulink. In comparison to a T-1 FLC-based HEV, an atypical IT-2.0 FLC-based HEV with an EPT (PMSM motor) and 4 ESSs (battery, solar PV, fuel cell, and SC power structure) likely incurs a higher computational burden. This increased burden stems from the additional complexity involved in managing uncertainties associated with multiple ESSs and their interactions within the vehicle's powertrain. The IT-2.0 FLC must dynamically adapt to varying operating conditions and environmental factors, necessitating more intricate algorithms and computational resources to ensure effective control and optimization of the hybrid vehicle's performance. It builds a physical modeling environment

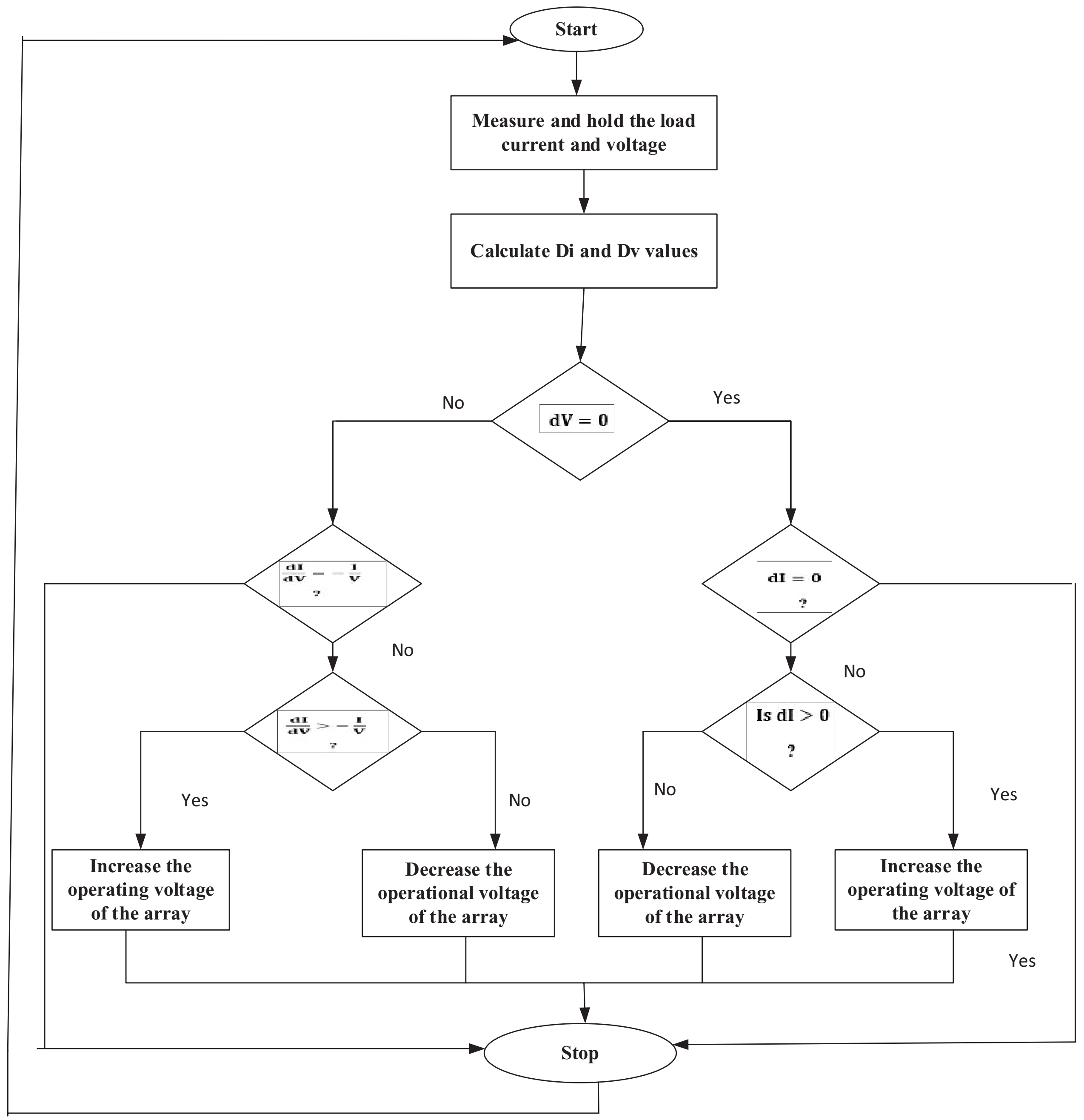

Fig. 6. Flowchart of perturbation and observation maximum power point tracker [27].

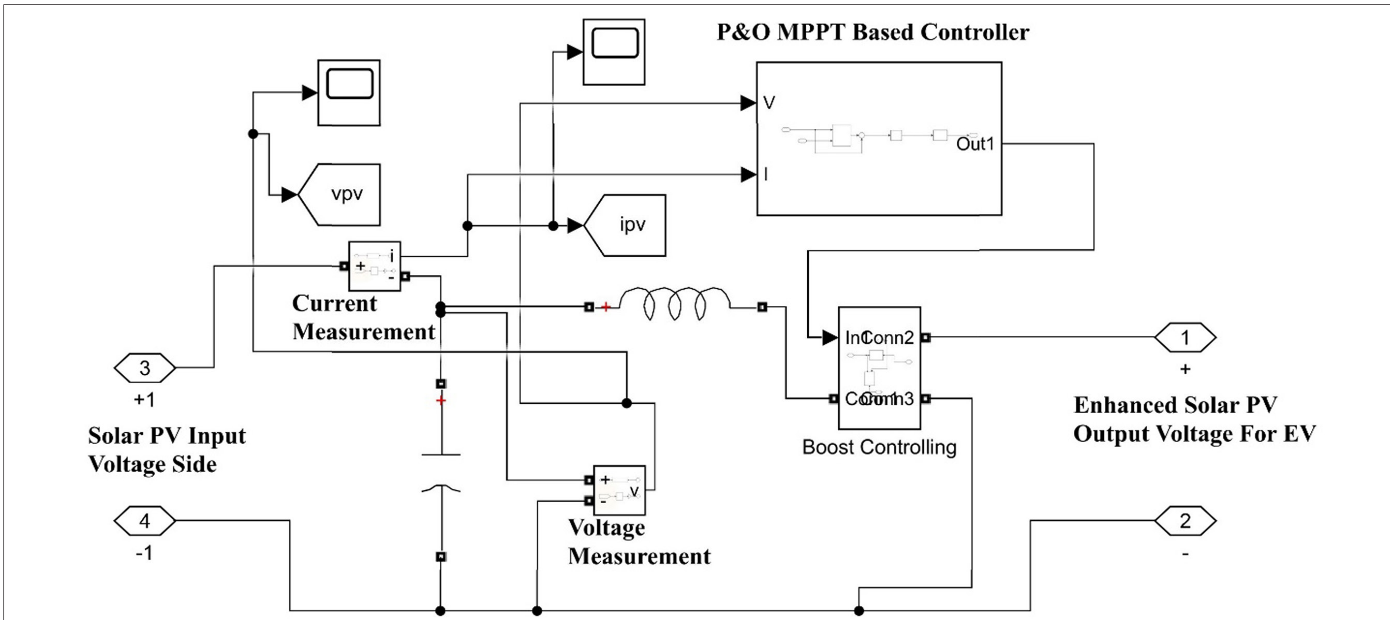

Fig. 7. Boost converter Simulink model for the solar system

with different predefined components connected for the purposes of modeling, simulating, and analyzing electromechanical systems. Utilizing this approach allows for an accurate representation of the system structure through block diagrams and automatic generation of system-level equations. The model of the PVSCFCHEV system in this study consists of 3 primary subsystems: the electrical system, energy management system, and vehicle dynamics system. Figure 3 clearly demonstrates the Simulink model of the HEV system based on FLC/IT-2.0 FLC as designed on the behalf of the proposed block diagram which is mentioned in Fig. 2.

A. Fuzzy Reasoning Law

There are a total of 25 rules (5 × 5 = 25) and Table I conveys information about the rules that are put into practice through the execution of T-1 FLC. The T-1 FLC in this study operates with 2 inputs, voltage error (voltage requirement for the demanded speed and torque) and voltage change in error (changes of voltage for maintaining DC link bus voltage), as depicted in Fig. 5a and 5b, respectively, and outputs reference currents (regulation of power for HEV), as depicted in Fig. 5c. The 2 inputs in this scenario are the actual DC link voltage and the change in DC link voltage.

The defuzzification process for the IT-2.0 FLC uses linear or constant functions for its output membership functions (MFs), while the fuzzy reasoning process employs the Sugeno Inference Method. Defuzzification entails calculating a weighted average of the rule outputs based on their firing strengths. A linear or constant function of the input variables is produced by each rule in the Sugeno-Type

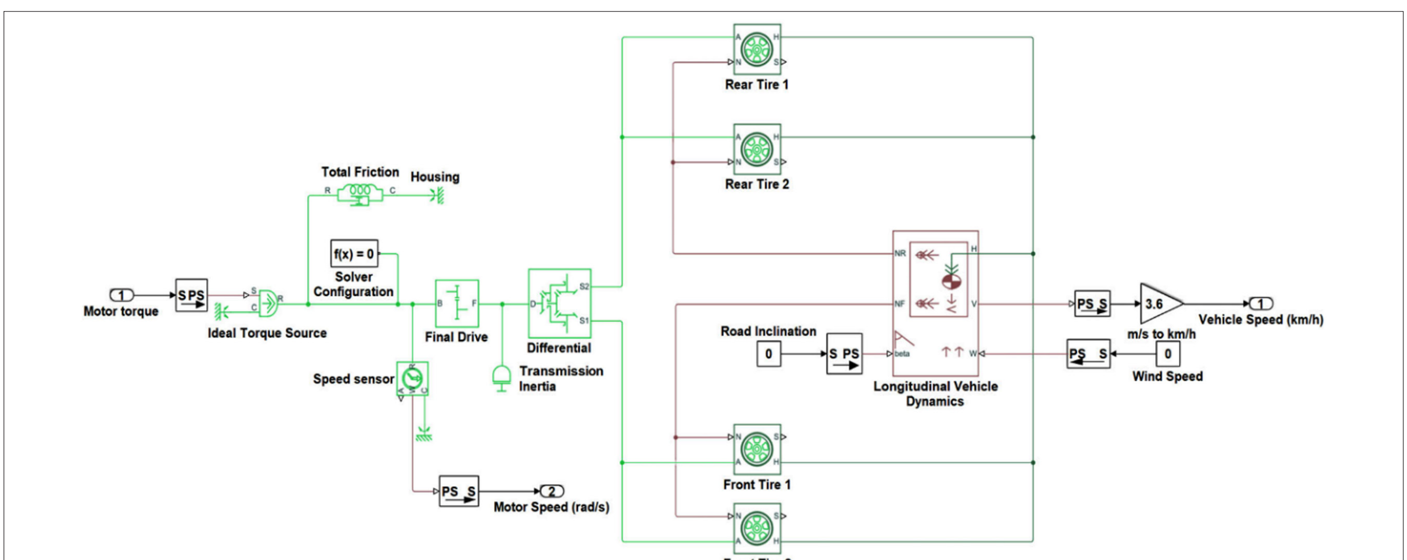

Fig. 8. Block diagram of dynamic system for hybrid electric vehicle.

TABLE III. HYBRID ELECTRIC VEHICLE SPECIFICATION

Parameter	Value with Unit
Total mass	850 kg
Aerodynamic drag coefficient	0.36
Maximum speed	75 km/h
Rolling radius of the tires	0.21 m
Frontal area	2.301 m^2
Gear ratio of the final drive	3.0

IT-2.0 FLC. These functions are produced when the fuzzy rules are evaluated. The degree to which the input values belong to the rule's antecedent fuzzy sets determines the firing strength of each rule for a given input combination.

Error (E) and change in error (CE), the 2 variables, are divided into 3 fuzzy sets. The above Figs. 5d and 5e corresponding to 2 input is same as T-1 FLC, i.e., E as voltage error (voltage requirement for the demanded speed and torque) and CE as voltage change in error (changes of voltage for maintaining DC link bus voltage), show the input MFs. The E and CE MFs are treated as trapezoidal MFs for precision results. In Table II, the IT-2.0 MFs' Rule base is listed. Where A stands for appreciating, NT for neutral, and D for depreciating. The output MFs are depicted in Fig. 5f below, where AT represents a small appreciation, DT represents a large depreciation, DH represents a neutral appreciation, and AH represents a large appreciation [26-28]. Figure 4 represents a Simulink model of IT-2.0 FLC.

B. Controlling Topology

1) Controlling Section of Solar Energy Storage System

The suggested system makes use of solar power generation as its primary energy source, as the PMSM motor necessitates an AC supply. As a result, an inverter is used to transform the solar-generated electricity into an alternating current source. However, the solar PV system only produces small amounts. As a result, the boost converter is connected to the inverter, which is connected to the solar PV system. Also, Fig. 7 depicted a boost converter Simulink model for the solar PV system. Finally, an LC filter connects the inverter to the PMSM motor. In this case, the inverter output harmonics are mitigated by using the LCL filter. In this instance, P&O MPPT topology controls the boost converter, and a PWM generator controls the inverter Fig. 6.

A flowchart [26] with a mathematical model of the P&O technique is shown in Fig. 6 to explain how P&O is implemented. The following is the equation for the solar PV model:

The PV module's current output is:

$$I = N_p * I_{ph} - N_p * I_0 * \left[\exp\left(\frac{v * N_s + I * \frac{R_s}{N_p}}{n * V_t} \right) - 1 \right] - I_{sh} \tag{1}$$

$$V_t = \frac{k * T}{q} \tag{2}$$

$$I_{ph} = \left[I_{sc} + K_i \left(T - 298 \right) \right] * \frac{I_r}{1000} \tag{3}$$

Here, PV current (I_{ph}), short circuit current (I_{sc}), and terminal voltage (V_t), I_r: light intensity (solar irradiation)-(W/m^2) and T: ambient temperature (K).

C. Controlling topology of Bidirectional DC-DC Converter and Filter

The BDC converter is crucial to this implementation work. These days, the primary use of this type of converter is in electric vehicles. For switching between ESSs, it is very helpful. Different control topologies in various ESSs are used to control this BDC. The figures below make this very clear to see. By generating pulses for the BDC, the voltage controller and current also significantly contribute to this task.

The research in this study employed passive filters to reduce high-order harmonics on the output side of the inverter. There are numerous passive filter types, including the L, LC, and LCL filters. The LCL filter has better high-order harmonic attenuation capacity when compared to the L and LC filters. Low value inductor and capacitor values are used in this study's LCL filter to reduce harmonic ripples.

D. Vehicle Dynamics

The way in which the vehicle dynamics system essentially models the mechanical gearbox components of a vehicle is illustrated in Fig. 8. Considering that the purpose of this article is to investigate how the electricity and EMS function to connect this model solely with regenerative braking, both the wind speed and the road inclination are set to zero in this model. The vehicle's specifications are shown in Table III.

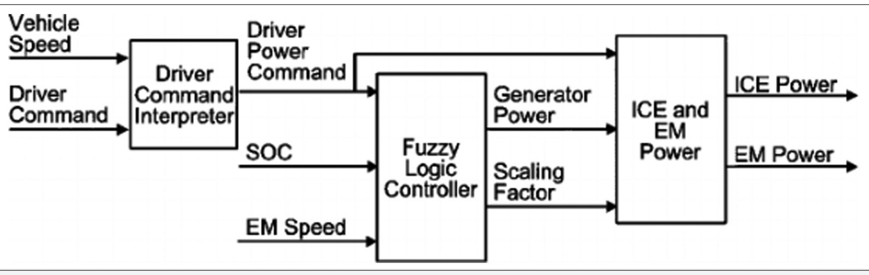

Fig. 9. Improved on block outline of the power regulator [9].

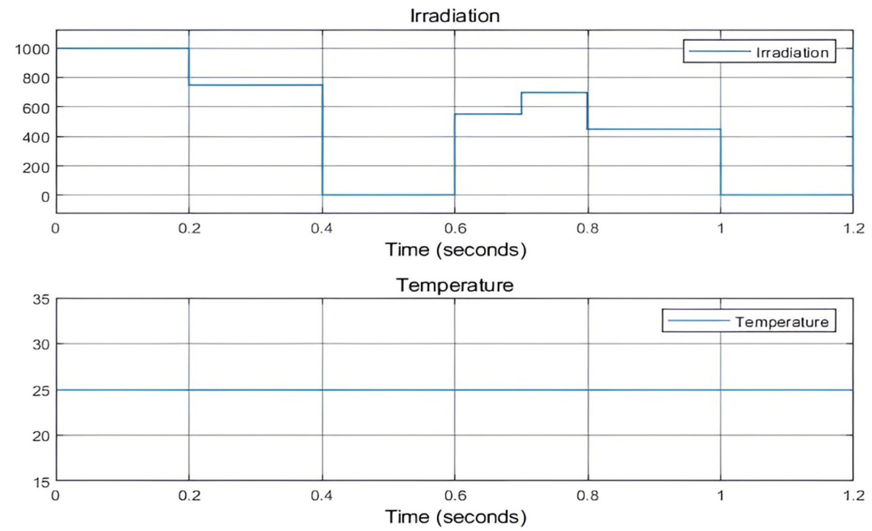

Fig. 10. Solar irradiation (W/m[2]), temperature (°C) in Type-1 and Interval Type-2.0 Fuzzy Logic Controller scenario.

E. Power Split Strategy and Gear Shifting Control

A power split technique is a control calculation utilized in hybrid powertrain frameworks, like HEVs and Plug-in Hybrid Electric Vehicles (PHEVs), to optimize the distribution of force between the internal combustion engine (ICE) and the electric motor(s) based on driving conditions and energy requirements. The primary goal of a power split technique is to achieve the most efficient and optimal operation of the hybrid powertrain. It aims to minimize fuel utilization, decrease discharges, and upgrade generally speaking vehicle performance by wisely dealing with the power stream between the ICE and the electric motor(s) Fig. 9. There are various types of power split techniques, and one of the normal methodologies is the standard based technique, which utilizes a set of predefined rules and limits to determine when to enact the ICE, when to use the electric motor(s), and when to operate both power sources simultaneously. For instance, the ICE might engage during rapid driving or under heavy load conditions, while the electric motor(s) could be used during low-speed city driving or in stop-and-go traffic. Another approach is the Model Predictive Control (MPC) strategy, which utilizes numerical models and real-time optimization algorithms to predict the most efficient power distribution based on current driving conditions and future vehicle behavior. Model Predictive Control persistently changes the power split to adapt to changing road conditions, traffic patterns, and driver behavior. The power split technique plays a crucial role in achieving the benefits of hybrid powertrain systems by combining the advantages of both internal combustion engines and electric motors. This strategy is followed in the process of designing simulation work.

The control of gear shifting in a hybrid electric vehicle (HEV) is a crucial factor in maximizing its performance, fuel efficiency, and overall driving satisfaction. Hybrid electric vehicles, in contrast to traditional internal combustion engine vehicles, incorporate both an electric motor and an internal combustion engine, thereby introducing intricacy to the gear shifting strategy. The control algorithm for gear shifting in a HEV must consider factors such as power demands, battery SoC, vehicle speed, and other relevant variables to guarantee smooth transitions and optimize performance. Below are several crucial factors and strategies to consider when controlling gear shifting in a HEV: efficiency maps, power demand analysis, battery SoC, rule-based strategies, regenerative braking, smooth transitions, simulation and modeling of vehicles, and real-time adaptation are all part of the system. This control strategy is employed in the design of simulation work.

IV. RESULTS AND DISCUSSION

A simulation of the proposed system has been performed using Matlab-2018a software. This section also includes performance data for solar PV-HESS connected to EPT based on T-1 FLC and IT-2 FLC.

Figure 10 shows that the temperature and irradiation values for the T-1 and IT-2.0 FLC-based HEV are the same. It also displays variations in solar irradiance with different values. In this Simulink result scenario, the temperature is kept at 25°C over an assortment of timing durations.

The BDC employs both IT-1 and IT-2.0 FLCs. The Simulink result framework is consistent with the EPT connected HESS based on both

TABLE IV. CHARGING AND DISCHARGING BATTERY PERFORMANCE

(%) Charging of Battery (Batt_SOC) in (0-1) sec		(%) Improvement in Battery SoC through IT-2.0 FLC	(%) Battery Exertion (SoC) In (1-1.2) seconds		(%) Battery Savings through IT-2.0 FLC
Type-1 FLC	IT-2.0 FLC		Type-1 FLC	IT-2.0 FLC	
50-50	50-50.031	31	0.4977	0.00865	97.26

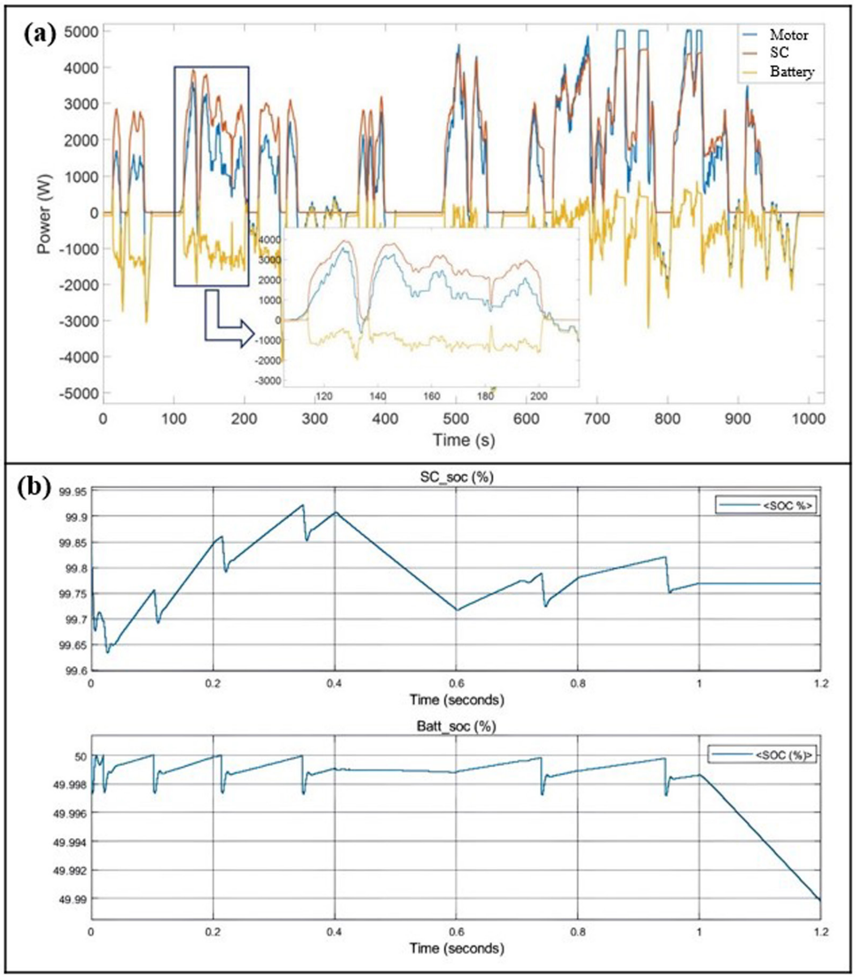

Fig. 11. Simulation results in Type-1 Fuzzy Logic Controller-based hybrid electric vehicle: (a) Power curves for SC and BESS w.r.t. EPT. (b) supercapacitor and battery state of charge (SC_{soc}, $Batt_{soc}$)

T-1 and IT-2.0 FLC. Simulation results for the EPT-connected HESS utilizing T-1 FLC and IT-2.0 FLC are presented in Figs. 11 and 12, demonstrating the performance of the EPT, SC, and battery storage. Figure 11a illustrates the power curves of the system with respect to the SC and battery SoC in a T-1 FLC-based HEV. Initially, the SC generates more power than the demand to restore the battery SoC to a mid-level. Once the battery SoC reaches approximately 50%, the SC ceases to generate excess power and aligns with the demand power, while the BESS supplements the power during acceleration. In a night-time scenario, when the PV array is off, the SC and battery handle the power requirements. The power flow control strategy adjusts the output of all energy sources to match the changing driving power and ensure the availability of buffer power sources. Also, the fuel cell is enough to fulfill the demand of power for he vehicle and charging for SC and BESS systems in the degradation of the remaining 3 sources. Figure 12a illustrates the power curves of the system in relation to the SC and battery SoC in an IT-2.0 FLC-based HEV. The IT-2.0 FLC efficiently manages the energy strategy based on the availability of power from various sources. It prioritizes the PV ESS first; when PV energy is unavailable, it successively switches to the BESS, SC, and finally the fuel cell ESS. This system handles complexity with ease, providing sufficient power through a smart energy management strategy to meet the required torque demand. An IT-2.0 FLC causes a battery charge of 50.031% above the initial 50% SoC, whereas a T-1 FLC does not cause the battery to be charged before that point. The IT-2.0 FLC is responsible for 31% of this increase in battery SoC. The battery energy is consumed in the range of 1 to 1.2 seconds at a rate of 0.4977% and 0.00865%, respectively, for T-1 and IT-2.0 FLC. Interval Type-2.0 FLC has demonstrated a 97.26% reduction in battery energy usage, which clearly shows in Figs. 11b and 12b and all the tabulated data from the waveform is shown in Table IV. It is evident that the IT-2.0 FLC outperforms the T-1 FLC in this case because the controlling strategy causes the waveform of SoC of the battery and SC (SCsoc, Battsoc) to clearly show in the waveform and in the case of IT-2.0 FLC will automatically enhance over those in the case of T-1 FLC. In conclusion, it can be inferred that the hybrid electric vehicle utilizing IT-2.0 FLC operates more efficiently compared to the T-1 FLC-based counterpart, as evidenced by lower energy consumption in both the battery and SC components Fig. 11.

Oscillations in torque and speed using T-1 FLC in HEVs are caused by limited uncertainty handling, static MFs, and inadequate tuning. Interval Type-2.0 FLC suppresses these oscillations by better managing uncertainties, adapting MFs, and providing robust, flexible control. Figure 15 compares the THDs using T-1 FLC and IT-2.0 FLC in an array of parameters. Due to the IT-2.0 FLC's satisfactory

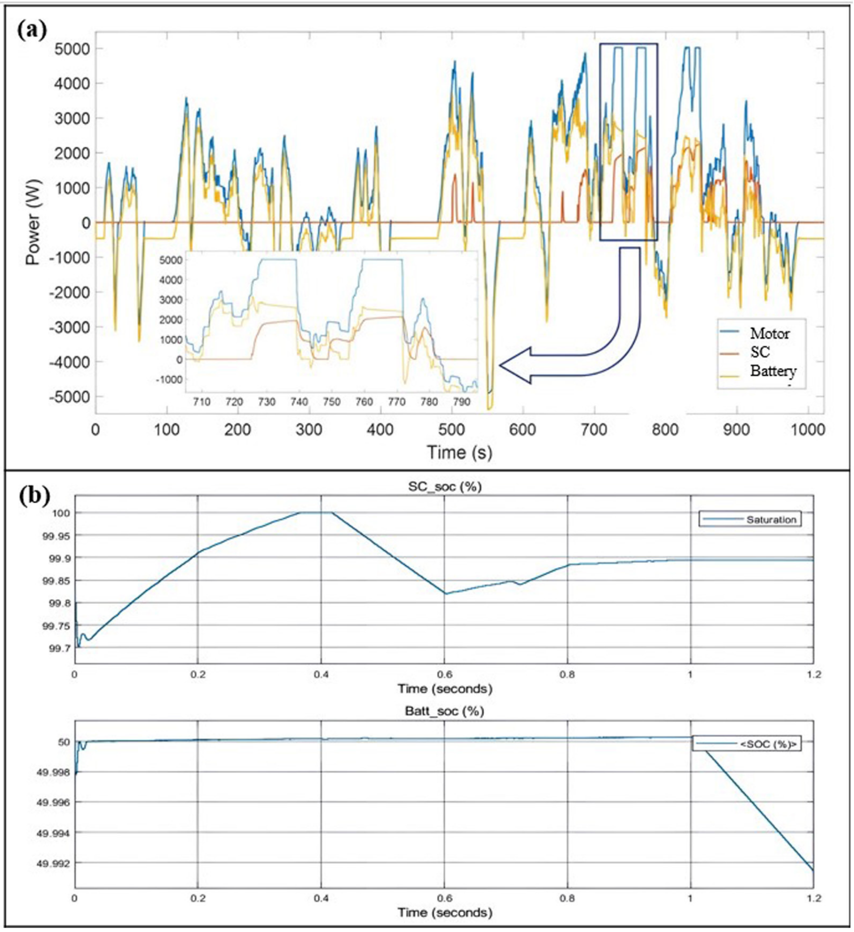

Fig. 12. Simulation results in Interval Type-2.0 Fuzzy Logic Controller-based hybrid electric vehicle: (a) Power curves w.r.t. state of charge and supercapacitor and battery state of charge (SC_{soc}, $Batt_{soc}$)

performance, which is implemented in the HEV's controlling topology, the IT-2.0-based HEV exhibits fewer harmonic distortions than the T-1 FLC-based HEV when we compare the parameters back emf (24.14% to 21.79%), inverter voltage (4.61% to 3.11%), stator current (6.05% to 5.21%), inverter current (6.06% to 2.92%), motor current (8.13% to 6.77%), and motor voltage (6.08% to 4.60%) THDs. It is evident from this that T-1 FLC is not as effective as IT-2.0 FLC. In view of this, we can infer that the IT-2.0 FLC-based HEVs perform admirably. Because there are fewer harmonic distortions and no severe fluctuations when using IT-2.0 FLC in comparison to T-1 FLC, the Fig. 13 clearly demonstrates how IT-2.0 FLC improves the output torque and speed of HEVs. Furthermore, all the tabulated histogram data of speed and torque improvement is shown in Fig. 14. This shows that IT-2.0 FLC topology yields feasible responses when compared to

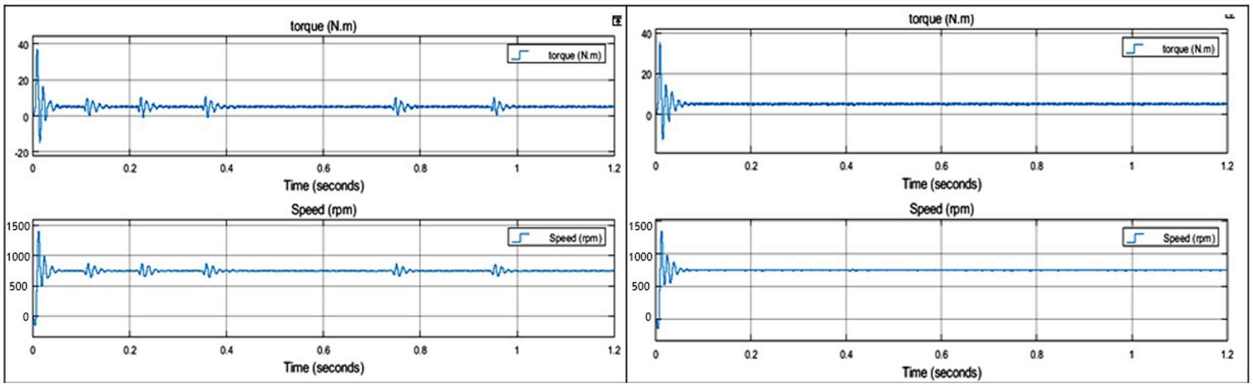

Fig. 13. Simulation results torque (N-m), speed (rpm) (Left-Type-1 Fuzzy Logic Controller hybrid electric vehicle case and right-IT-2.0 Fuzzy Logic Controller hybrid electric vehicle case).

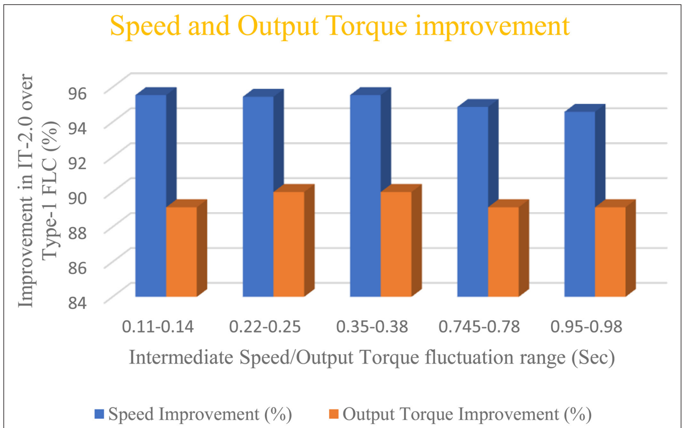

Fig. 14. Speed and Torque Improvement in hybrid electric vehicle due to Interval Type-2.0 Fuzzy Logic Controller (%).

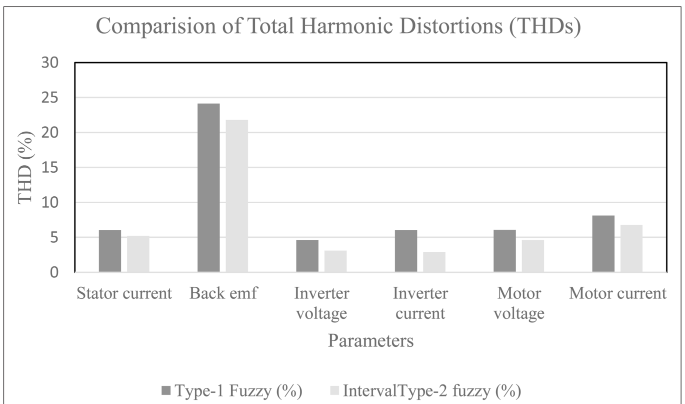

Fig. 15. Comparison of total harmonic distortion

EPT (PVSCFCHEV) connected HESS electric vehicles based on T-1 FLC and IT-2 FLC. Thus, we can conclude that the IT-2.0 FLC-based HEV is working satisfactorily Fig. 12.

In the context of stability analysis, whether conducted in the time or frequency domain, for an EPT (PMSM motor) and 4 ESSs (battery, solar PV, fuel cell, and SC power structure) in an atypical IT-2 FLC-based HEV compared to a T-1 FLC-based counterpart which provides crucial insights. The analysis reveals enhanced stability margins and reduced oscillations in the time domain, indicating improved transient response and system robustness with IT-2.0 FLC. Similarly, in the frequency domain, the IT-2.0 FLC demonstrates better suppression of resonant frequencies and harmonics, contributing to smoother and more stable power distribution among the ESSs. These findings underscore the superiority of IT-2.0 FLC in ensuring stability and reliability in HEVs, offering valuable advancements over conventional T-1 FLC approaches.

V. CONCLUSION

The investigation aimed to compare the performance of IT-2.0 FLCs with traditional T-1 FLCs in HEVs, focusing on increasing mileage, efficiency, and energy savings. The study emphasized the need for robust, uncertainty-tolerant control strategies to enhance HEV performance. Interval Type-2.0 FLCs showed higher efficiency, better mileage, significant energy savings, and greater robustness to uncertainties. They also provided improved transitions, reduced THD for better power quality, and demonstrated versatility and adaptability.

The study validated the performance by comparing T-1 FLC-based Energy Management Strategies (EMSs) connected to HESS in HEVs with those using IT-2.0 FLC. Results showed that IT-2.0 FLC outperformed T-1 FLC significantly, with increases of 89.478% in output torque, 95.202% in speed, and 97.26% in battery SoC preservation. Overall, IT-2.0 FLC-based HEVs demonstrated superior performance in mileage, torque, and power quality, making them more reliable and eco-friendly. The research utilized Matlab/Simulink 2018a for performance assessment and contributes valuable insights for future advancements in HEV control systems.

Availability of Data and Materials: The data that support the findings of this study are available on request from the corresponding author.

Peer-review: Externally peer reviewed.

Author Contributions: Concept – Y.S., Design – Y.S., C.Y.; Supervision – O.S., K.K.B.; Resources – Y. S., A.U.A.; Materials – A.U.A., C.Y.; Data Collection and/or Processing – Y.S., A.U.A.; Analysis and/or Interpretation – O.S., K.K.B.; Literature Search – Y.S., C.Y.; Writing – Y.S., Critical Review – O.S., K.K.B., A.U.A.

Acknowledgement: This research work is taken as a base reference from all given references in this research article and with the help of all these references all datasets that were analyzed or firstly create a model based on T-1 FLC-based HEV with 3 ESS also create an enhanced model based on IT-2.0 FLC HEV with 4 ESS for the comparative study and enhancement of result.

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