Artificial Neural Network-Driven Energy Management and Control Strategy for Microgrid

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***Abstract*— The rapid integration of renewable energy sources (RESs), such as photovoltaic (PV) systems, introduces severe power intermittency and uncertainty into modern microgrids. Maintaining the stability of the DC-link voltage is a critical challenge under these fluctuating generation and variable load conditions. While traditional Proportional-Integral-Derivative (PID) controllers are widely used, they struggle to manage the complex, nonlinear interactions between distributed energy resources, energy storage systems, and dynamic loads. This paper proposes an Artificial Neural Network (ANN)-driven Energy Management and Control Strategy designed to enhance DC-link voltage stability and optimize power flow. The proposed system integrates a PV system, a Hybrid Energy Storage System (HESS) consisting of a Battery Energy Storage System (BESS) and a supercapacitor, and residential/commercial loads. The data-driven ANN controller is deployed to regulate the DC-bus voltage, coordinate power sharing, reduce battery stress by diverting high-frequency transients to the supercapacitor, and maximize renewable penetration. Simulation results demonstrate that the ANN-based approach provides a faster dynamic response.**

Keywords*— *Artificial Neural Networks (ANN), DC-link voltage stability, Microgrid, Battery Energy Storage System (BESS), Supercapacitor.

Keywords—Microgrid, Fuzzy logic, Energy management, Hybrid storage, Supercapacitor

I. Introduction

The yearly growth in electric energy consumption, pollution, and fossil fuel depletion have forced the globe to switch to decentralized production. The advancement of power electronics has led to the growing use of renewable energy, resulting in the creation of microgrid (MG) [1]. MGs are controlled small networks with dispersed generation, loads, and energy storage. MGs may be DC, AC, or hybrid [2]. Given the DC nature of renewable sources (RS) like solar panels and most loads like TVs, LED bulbs, etc., and its simpler construction, improved efficiency, and dependability, the DC microgrid has gained attention [3]. MGs need storage systems to balance production and consumption since RS rely on the environment [4]. Supercapacitor (SC) have high power density and low energy density, unlike batteries. To create hybrid energy storage systems (HESS), two or more energy storage systems must be combined [5]. This combination's availability and inexpensive cost make it popular. HESS reduces the initial cost of a single energy storage . HESS control algorithms divide power into low-frequency and high-frequency components and regulate DC link voltage. Reduce battery current stress, enhance battery life, decrease charging and discharging rates, and maintain safe battery and SC.

Numerous control systems, including as neural networks, fuzzy logic, rule-based control, and model predictive control, have been published for battery and SC power and energy management [22-30]. Adding a SC to a battery storage system in a wind-based hybrid remote area power system [22] may not assure the dynamic charge/discharge rate limit and SoC within operating limitations. A dynamic energy management technique for PV and HESS-based DC microgrids was developed in [23]. The power management method for HESS-based uninterrupted power supply systems reduces battery stress utilizing SC [27]. [28] showed that HESS reduces battery costs and enhances system efficiency. A study [29] offered two energy management strategies for electric vehicles using heuristics and an artificial neural network (ANN). A rule-based control strategy was presented in [30] to integrate a battery ESS with solar and wind systems. However, these approaches have limitations, such as requiring huge data storage and intense computing. A model predictive controller (MPC) for hybrid power sources was presented in [31] and [32]. One shortcoming of this strategy is that it requires more mathematical calculation due to its traditional MPC foundation.

In [19], fuzzy logic and filter-based approaches are used. The filter cutoff frequency depends on battery charge and load current. This strategy improves hybrid energy storage system control in a DC microgrid with pulsed power loads [20]. A rate limiter replaces the low-pass filter to decompose the average and transient current components of the hybrid energy storage system to guarantee optimal battery depletion.

The proposed method limits battery and fuel cell charge and discharge current gradients and maintains DC bus voltage. In reference [27], the predictive model controller uses a battery and supercapacitor for energy storage. Main characteristics of the implemented controller are safe supercapacitor and battery charge levels. The conventional predictive model controller affects the system computationally and cannot modify the DC bus voltage.

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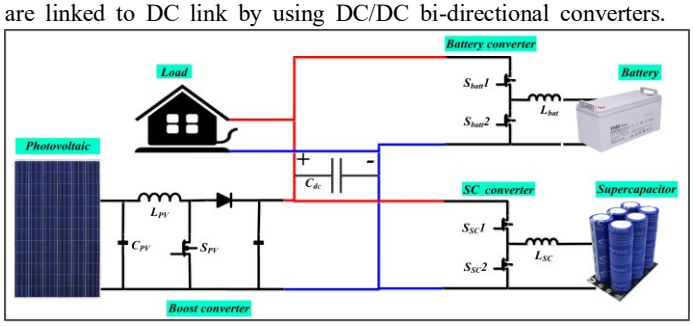
The DC bus voltage cannot be employed consistently in the real-time DC microgrid, despite this simpler method. A DC microgrid with a hybrid energy storage system is controlled by a novel Energy Management Strategy (EMS) based on a cuckoo search algorithm and neural network (CCSNN) in [29].

Prior research concentrated only on power-sharing across storage systems and optimizing energy extraction from renewable sources, while overlooking the regulation of DC voltage. Consequently, this study presents the design of Fuzzy logic to regulate the DC link voltage, enhancing stability under varying situations, whether in production or load, and achieving a rapid reaction.

II. Ease of Use System Configration

The structure of DC microgrid is shown in Fig. 1. PV source is linked to the DC link via DC/DC boost converter, and the HESS (battery/SC) are linked to DC link by using DC/DC bi-directional converters.



Modeling pf PV sources

Different mathematical models of PV were developed to introduce their characteristics and behaviour caused by the physical construction of PV cells. In this work PV model comes from [35],. PV voltage-current characteristics may be summarized as follows equation:

$$I_{pv} = I_{ph} - I_0\left[exp\left(\frac{q(V_{pv}+R_S\cdot I_{pv})}{AN_SKT_j}\right)-1\right]-\frac{V_{pv}+R_S\cdot I_{pv}}{R_{sh}} \quad (1)$$

MPPT approach must be used to manage PV source in order to obtain the maximum power generated from PV panels [36],[37].

Modeling of HESS

The voltage of battery, V_{batt} may be expressed as follows when modeling a Li-ion battery[43]:

$$V_{batt} = E_0 - A_b e^{-(B.it)}\frac{Q}{Q-it} I_{bat} - R_b i + A_b e^{-(B.I_{bat})} - K\frac{Q}{Q-I_{bat}} i{I_{bat}}^* \quad (9)$$

Where R_b and B represent the exponential zone amplitude (V), and the exponential zone time constant inverse (Ah^{-1}), R_b is the battery internal resistance of (Ω), Q is the battery capacity (Ah), ${I_{bat}}^*$ is the filtered battery current (A), I_{bat} is the actual battery charge (Ah), and E_0 is the constant battery voltage (V).

The following is a description of the Battery State of Charge SOC_{bat} model developed[44].

$$SOC_{batt} = 100\left(1+\frac{\int I_{bat}dt}{Q}\right) \quad (10)$$

The charge-discharge cycle of the battery is determined by the amount of power that is accessible, the requirement. The state-of-charge limits of the battery are used to establish the energy limitations of the battery[45]:

$$SOC_{bat_MIN} \le SOC_{bat}(t) \le SOC_{bat_MAX} \quad (11)$$

The SC voltage $V_{SC}$the capacitance C_{SC} determine the Superc energy E_{SC}[47]:

$$E_{SC} = \frac{C_{SC}V_{SC}^2}{2} \quad (12)$$

As a result, the stored energy will vary in accordance with changes in the capacitor voltage, and the SOC_{SC} may be calculated as follows:

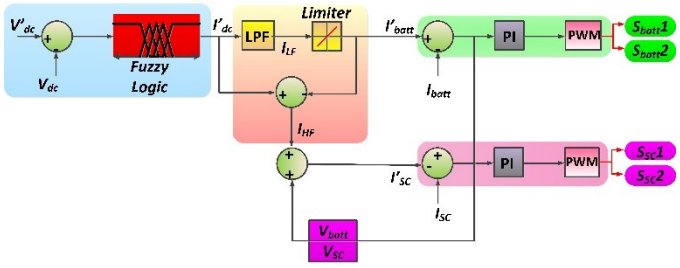
$$SOC_{SC} = \frac{\frac{C_{SC}V_{SC}^2}{2}}{\frac{C_{SC}V_{SCRATED}^2}{2}}\times 100\% \quad (13)$$

III. Energy mangment And Fuzzy Logic

Principle

The primary aim of the suggested control technique is to sustain a designated reference DC bus voltage, notwithstanding uncertainties or disruptions. This is accomplished by reducing the discrepancy between the observed DC bus voltage and its intended reference value. A cascaded/dual-loop control methodology is presented and examined to achieve this, as seen in Figs. 9 and 16. The suggested control technique comprises two PI control loops: one for the battery and another for the supercapacitor.

The outer control loop, based on the principles of Fuzzy Logic Control, seeks to maintain the DC bus voltage (Vo) at its target reference value (Vref) and provide the requisite total reference current (IT). The inner control loop seeks to adjust the currents of the battery and supercapacitor (IBatt and ISC) to their designated reference values (IBatt ref and ISC ref). The inner control loop employs the PIbat and PIsc controllers to provide control signals (duty cycles DBatt and DSC) for the power converters of the battery and supercapacitor, respectively. These controllers provide the accurate regulation of currents to their designated reference values, facilitating effective management of energy transfer among the components of the hybrid energy storage system.



The fundamental idea of the implemented control method is that the supercapacitor manages the high-frequency power component, and the battery addresses the average power component. In the control technique shown in Fig. 9, the total current IT is partitioned into low and high frequency components with a low pass filter (fLPF). The low-frequency component (ILFC) is obtained from IT, as seen in the following equation:

ILFC = fLPF(IT) (15)

The method fLPF() pertains to the used low-pass filter. A rate limiter (fRL) is introduced to restrict the charge/discharge rates of the battery current, as seen in Fig. 9. The rate limiter's output serves as the reference current signal for the battery converter: IBatt reference equals fRL(ILFC) (16)

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Fuzzy logic

The Fuzzy logic control employs fuzzy logics to determine judgements and regulate the controller's output. The key

elements of an MPPT controller based on fuzzy logic are fuzzification, defuzzification, rule-base, and inference[13].

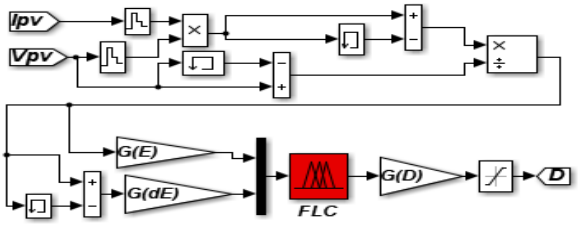


Fig. 1. *Subsystem simulation of the fuzzy MPPT algorithm*

This method is based on two input parameters: the error E and an adjustment in error ΔE, and one output parameter D (duty ratio variation) [17]. The value of D may be retrieved from a rule base table, such as Table II.

TABLE I. FUZZY RULE BASE TABLE

E / dE	NG	NM	EZ	PM	PG
NG	NG	NG	NM	NM	EZ
NM	NG	NM	NM	EZ	PM
EZ	NM	NM	EZ	PM	PM
PM	NM	EZ	PM	PM	PG
PG	EZ	PM	PM	PG	PG

Fuzzy logic control typically involves three phases: fuzzification, rule basis table search, and defuzzification. During the process of fuzzification, numerical parameters are transformed into linguistic variables using a membership function that is comparable in nature. For this particular scenario, a total of five fuzzy membership functions are employed: NB (indicate negative big), NS (indicate negative small), ZE (indicate zero), PS (indicate positive small), and PB (indicate positive big). In addition, the toolbox offers the Surface Viewer to the designer. This viewer displays a three-dimensional graph that illustrates the mapping from the FLC's two inputs to the output, as seen in the figures below.

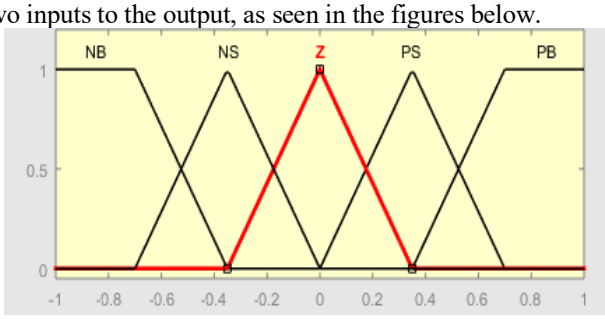


Fig. 2. Fuzzy logic membership functions for Input "E "

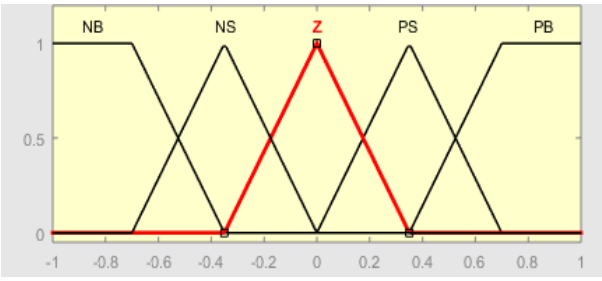


Fig. 3. Fuzzy logic membership functions for Output "D "

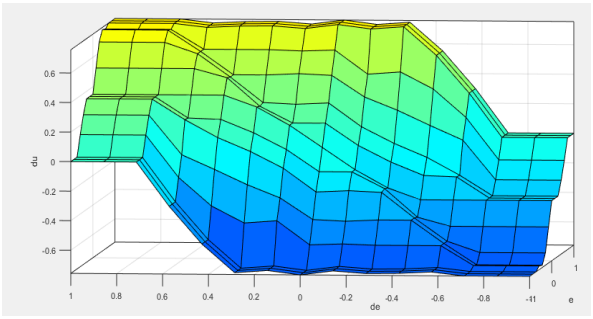


Fig. 4. Surface mode fuzzy controller rules surface

The fuzzy logic control shown in figure 10 consists of four distinct operational blocks is as follows: Fuzzification, Interference process, knowledge base, and Defuzzification.

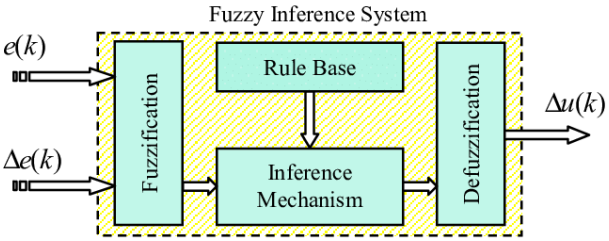


Fig. 5. functional diagram of fuzzy logic control

During the fuzzification process, the crisp input variables E_k and dE_k are transformed into fuzzy variables, with their degree of confidence determined by the associated membership functions. The membership functions are triangular and trapezoidal in design, and there are two inputs and single output. The linguistic designations of the suggested controller are as follows: Positive Big (PB), Negative Small (NS), Positive Small (PS), Positive Medium (PM), Zero (ZE), Negative Medium (NM), and Negative Big (NB). All of the input and output membership functions include these five language elements.

The knowledge base encompasses the establishment of rules, expressed as IF-THEN general structures, that regulate the interaction between variables that are input and output. The inference engine uses the input fuzzy sets to make choices by applying the IF-THEN rules stored in the knowledge base. The Mamdani's method is used for the inference engine.
The inference engine generates the output for the set of fuzzy variables. This step encompasses many techniques used to generate the fuzzy set value for the output fuzzy parameter ΔT.
The defuzzification mechanism used in this case is the centroid or centre of gravity, which is utilised to compute the ultimate fuzzy value. In this case, the precise value of the output variable ΔT is considered to represent the geometric centre for the output fuzzy parameter. [18] Provide the discretized domain of conversation.

$$z_0 = \frac{\sum_{i=1}^{n} z_i \cdot \mu_{res}(z_i)}{\sum_{i=1}^{n} \mu_{res}(z_i)} \quad (3)$$

The typical inputs for a (MPPT) fuzzy logic control consist of an error E, which represents the gaps between the desired and actual values, and a change in error ΔE, which represents the rate at which the error is changing. The user has the autonomy to choose the method by which to calculate E and ΔE. Given that the derivative of P with respect to V is equal zero at the (MPP), [12] employs an estimate.

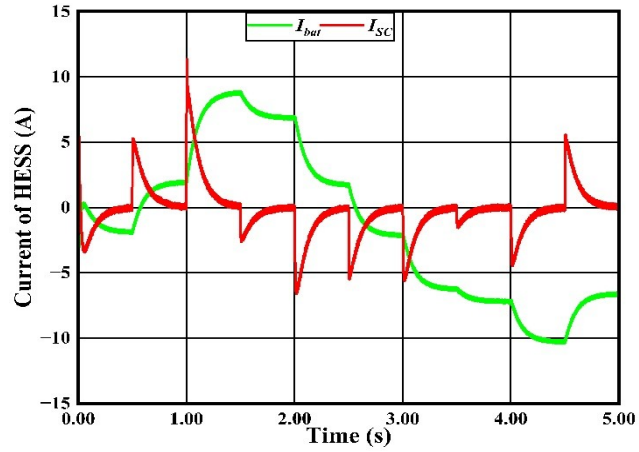
$$E_k = \frac{P_k - P_{k-1}}{V_k - V_{k-1}} \quad (4)$$

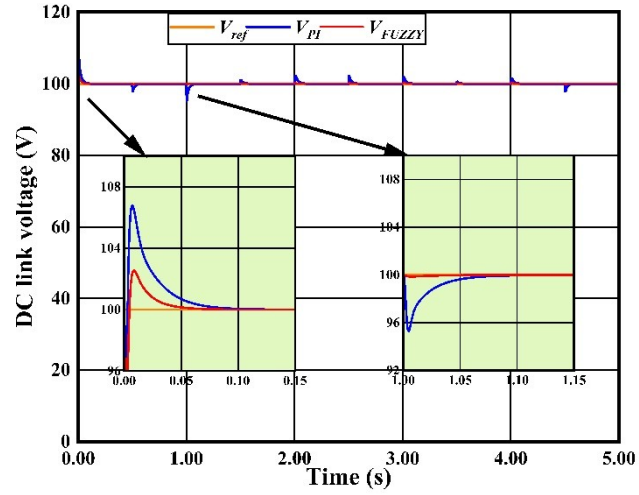
$$dE_k = E_k - E_{k-1} \quad (5)$$

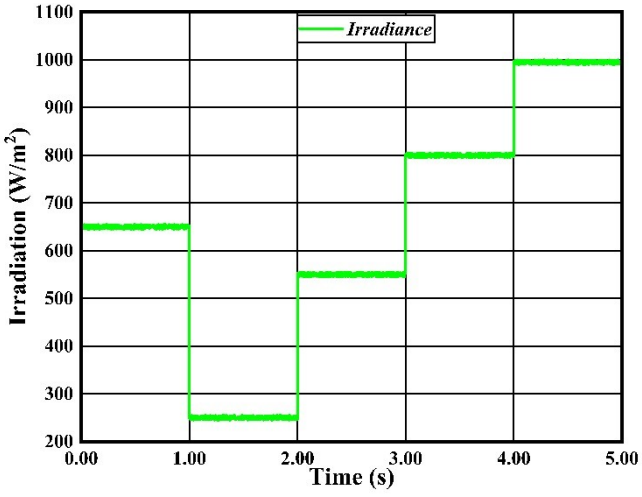
After calculating and converting E and dE into linguistic variables, the fuzzy logic control output , usually represented as a variation in duty ratio dD of the power converter, may be obtained by referring to a rule basis table like Table II.

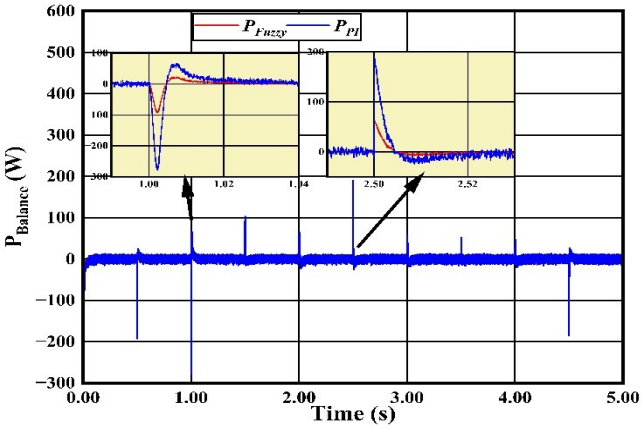
The linguistic variables named ΔD for comparable maxing of E and ΔE are determined by the specific power converter being utilised and the user's expertise. For instance, if the operating point is significantly to the left of the maximum power point (MPP), indicated by E being PB and ΔE being ZE, then there is a desire to significantly increase the duty ratio, denoted by dD being PB, in order to reach the MPP

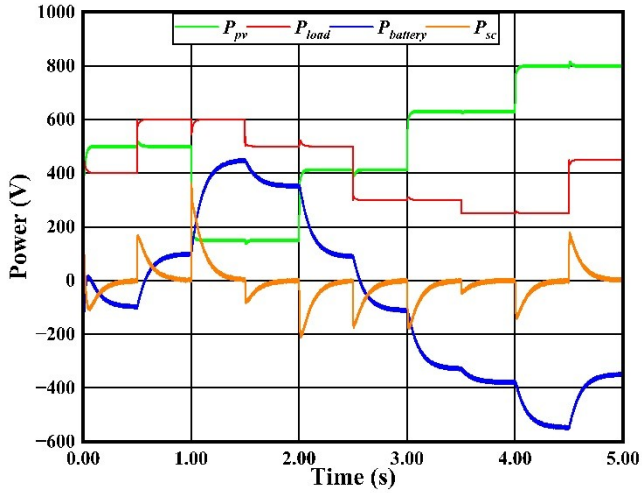
IV. Result And DISSECTION

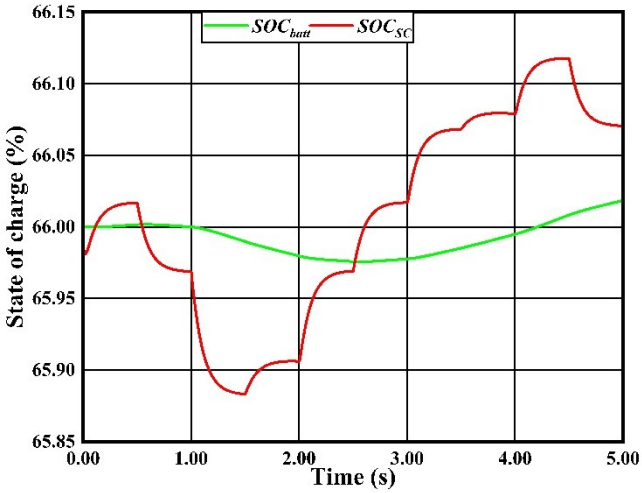












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