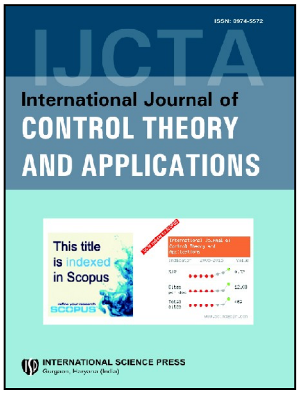

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Modelling and Simulation of a Fuzzy Logic Controller for State of Charge Monitoring and Control Integrated with a Novel Spike Current Method

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Abstract: Limited battery capacity of Electric Vehicles(EV) necessitates the need for controlling the state of charge of batteries and ultra-capacitors used in them. Several methods like Prognostics Health Management, sliding mode Observer, Support vector machine, Relevance Vector Machine, Fuzzy logic control has been developed for the monitoring of State of charge. All these techniques were developed to predict the remaining useful life of a battery but in one way or other these monitoring methods are having an impact on the normal working of the battery connected systems also. SoC of the EV battery can be efficiently maintained during its operation by finding a balance between the utilization of Ultra Capacitor and EV battery during braking and motoring periods. In this paper an novel real time SoC (State of Charge) monitoring topology is modeled and simulated for various real time operating conditions of Electric Vehicles(EV) using a novel SPIKE current measurement method and a Fuzzy Logic Controller(FLC) is designed to control the utilization of battery bank and UC. The controller is modelled and simulated in Maltab/ Simulink environment and the results are found to be very well suited for the operation of EV drive system.

Keywords: State of Charge, Spike Current, Electric Vehicles, Fuzzy Logic Control

I. INTRODUCTION

The Global energy crisis for fossil fuels opened up the opportunities of electric powered domestic and industrial vehicles (EV and IV) in the automotive industry. The fully electric or hybrid model of automotive system in vehicles is widely accepted for the commercial use.The outreach of the electric vehicle market is reliant on driving range, consistency, protection and power management systems[1]. These factors are majorily dependent on the power density of the battery or other energy storage systems installed inside the EV

Improvement in power density and high storage capacity is required for the battery powered vehicles to compete with the conventional fossil fuelled vehicles. The battery system has to be monitored for its state-of-charge (SoC), state-of-health (SoH) and state-of-function (SoF).

Monitoring of the batteries are very important as the continuous usages of battery cells will degrade the performance of the batteries over a period of time. Reliability of the system can only be ensured by continuously monitoring the SoH and SoC. The ability of a cell to accumulate energy, deliver high currents and preserve charge over extended periods, relative to its original or actual capabilities is called as SoH. State of Charge (SoC) of a charged cell will fall with usage as active material on the cell plates gradually deteriorate by events such as, loss of plate active surface area due to recurring dissolution and re-crystallization, loss of electrical contact between metallic grids and active materials [2] [3].

Several metods like Progrnostics Health Management, Sliding mode Observer,Support vector machine , Fuzzy logic has been developed for the monitoring of State of charge. Superior sensing and monitoring technologies are essential to forecast and control battery functionality to identify, and further avoid, potential healt issues.

II. INDIRECT AND DIRECT METHOD OF SOC MONITORING

Measure of State of Charge is mainly done in two methods direct and indirect. Direct methods deals with analysis of chemical, physical properties of the battery.Fig 1 shows the basic working of a Li-Ion Battery Measuring parameters like electrolyte PH and density,cathodic galvanostatic pulses are not practically reliable for systems like Electric Vehicles, Hybrid Vehicles or Industrial Electric Vehicles, since the continous monitoring of the SoC is demanded for ensuring the reliability of the system. The man power, equipment and time required for the above mentioned method is also cumbersome [4] [5] [6].

The above said difficulties of the SoC monitoring can be eliminated by indirect method of monitoring. In this method the variables measured directly from the battery such as current, voltage, and temperature used to provide an accurate estimation of SoC with the help of prefed datas about the energy storage system.

The variables measured for indirect SoC monitoring are not linear with the SoC. Offline and Online methods are the two types of SoC determination techniques in Indirect SoC measurement.In online method, the most common technique of of SoC calculation presently followed is the Coulomb Counting method

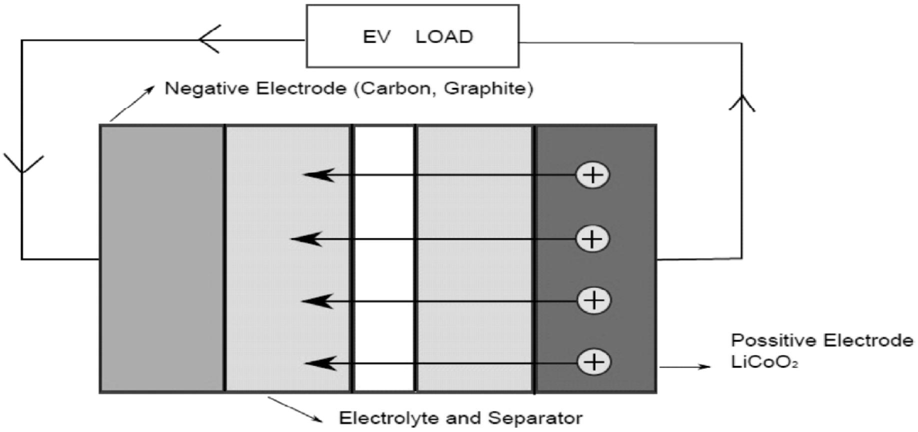

Figure 1: Working of a Li-ion Battery
The equation pertaining to the above said is (1) and (2)

$$\mathrm{SoC} = \mathrm{So}\ C_0 + \frac{1}{C_o}\int_{t_0}^{t} |I|.dt \quad \text{Charge} \tag{1}$$

$$\mathrm{SoC} = \mathrm{So}C_0 - \frac{1}{C_o}\int_{t_0}^{t} |I|.dt \quad \text{Discharge} \tag{2}$$

where Cn is the normal capacity of the battery pack, I is the battery current, So C_0 is the initial SoC and, dt is the time interval.

Koray Kutluay *et al.* offered, a new method for online SOC estimation and monitoring of sealed lead–acid batteries during both discharge, and charge phase, depended on actual battery discharge time versus discharge rate data given in manufacturers' data sheets, and on coulometric measurements. [7][8].

Moreover, the battery available capacity estimation is made routinely at the end of each discharge period by measuring the battery voltage and at the end of each charge phase by measuring the battery current. The technique does not require any open-circuit battery voltage measurement for SOC monitoring.

In this method the used capacity

$$C_u(t) = \int_0^t k(A).A.dt \tag{3}$$

Where A is the discharge current rate , k(A) is the coefficient for discharge rate.The coefficient of discharge is the key factor which has to be found out.

$$k(A_i) = \frac{c^{!}}{A_i t_{di}} \tag{4}$$

$C^{!}$ = Capacity

td_i = necessary time duration to discharge the battery to 1.75V/cell corresponding to A_i given in manufacture data sheet

$k(A_i)$ = Coefficient of A_i

As higher the discharge rate lower the end voltage of the battery. So the available capacity of the battery can be formulated as

$$C = \int_0^{t_{di}} k(A_i).A_i.dt + \int_{t_{di}}^{t_{ev}} k(A_i).A_i.dt \tag{5}$$

$$C = C^{!} + \int_{t_{di}}^{t_{ev}} k(A_i).A_i.dt \tag{6}$$

t_{ev} = necessary time duration to discharge the battery to the end voltage.

There are eight methods of performance estimation of Battery/Cell proposed byKorayKutluay *et.al* i.e.

- Battery capacity estimation
- Monitoring during bulk, over and float charge
- Constant current discharge tests
- Variable load discharge
- Alternate charge discharge test
- Discharge, charge to different paths
- Effects of temperature
- Monitoring of Aged cells

All the SoC measurements adopted now needs an explicit period since the open circuit voltage, constant load current, and coulometric measurements need minimum settling time for its measurements.

III. PROPOSED METHOD OF SOC ESTIMATION IN BATTERY USING SPIKE CURRENT ANALYSIS METHOD

The equivalent circuit of a rechargeable battery is shown in Fig. 2.

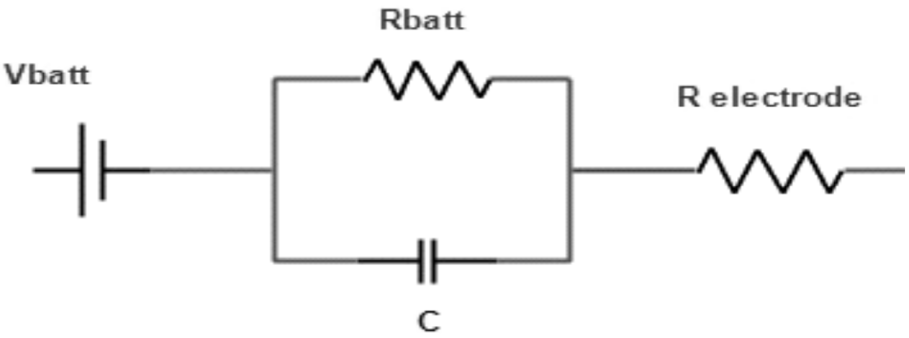

Figure 2: Equivalent Circuit of a Rechargable battery

In Fig 2: Rohm- Electrode Resistance, R batt- Battery Internal Resistance, C= Capacity of the Battery, W batt- Battery Rated Voltage,With the equivalent circuit the voltage of a Nickel Hydride cell is modeled as show in Equation (7):

$$E_{batt} = e_o - K\frac{C}{C-it}.\,it - R.i + Z\exp(-B.it) - K\frac{C}{C-it}.i^{*} \tag{7}$$

Where: E_{batt} -Battery Voltgae(V), e_0 - Battery constant voltage(E), K- Polarization constant (V/(Ah)), Q-Battery Capacity (Ah), it- $\int idt$ – actual battery charge (Ah), A-exponential zone amplitude(V),B-exponential zone time constant inverse $(AH)^{-1}$, R-internal resistance, i- battery current(A), i* -filtered current(A)

Equation (7) shows the voltage equation of a rechargeable dry cell battery. The Technique used in this paper for the SoC determination is a novel Spike charge analysismethod using two capacitor banks. [9] 10] By this method online monitoring of SoC ispossible without disturbing the normal power flow i.e. during the charging or discharging period of batteries, since the determination of SoC in automotive batteries is of critical importance.

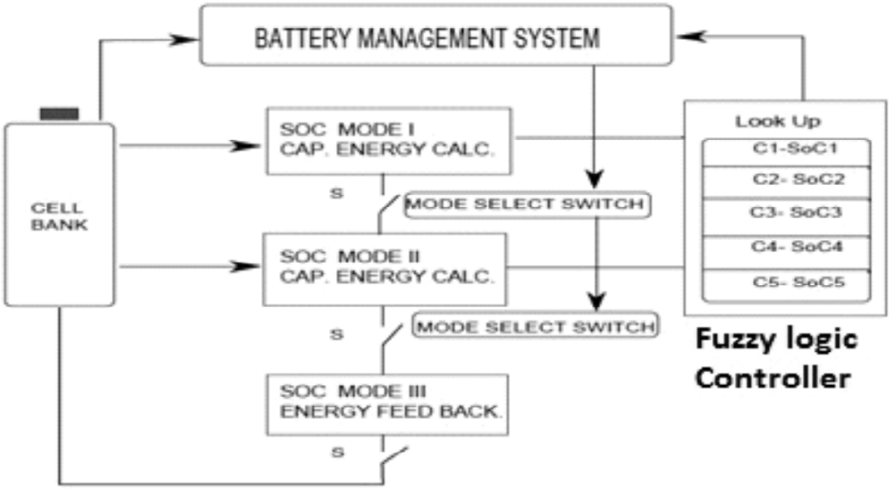

Figure 3: Proposed Schematic Topology for SoC Monitoring

The parameters which monitor the SoC of the battery like nominal voltage, current and different types of loads are modeled using MATLAB/SIMULINK environment. The parameter “it” in (7) determines the actual SoC of the battery connected to load. Variable loads are applied at the battery output to simulate a real time environment.

Fig. 3 shows the working schematic for the SoC monitoring in which the normal battery parameters like battery voltage and working current is always monitored in the Battery Management System (BMS).

Spike Current measuring method of SoC monitoring topology works with the principle of measuring the amount of current injected into the capacitor bank on regular request of SoC. This operation does not disturbs any other processes or power requirement of the devices associated with the Battery.

The variation of injected current over a period of time to the capacitor banks is integrated and the output is compared with a manufacturers experiment data sheet values fed into the lookup table of the fuzzy logic controller. [11] [12]

The operation is divided into three modes for improving the accuracy of SoC estimation and to supply energy back to the Battery after the measurement of SoC.

Mode 1: Cap Bank I

In Mode 1 the battery will be connected to the Capacitor bank 1 through the high speed switch S1.and S 3. During this instant Switches 2, Switch 4 and Switch 5 remain off. The battery normal current will be fed to the capacitor and the current will be fed into the capacitor bank. Now the voltage developed across the capacitor will be equal to the Battery terminal voltage

Mode 2:Cap. Bank II

In Mode 2 the capacitor bank 2 will be used for calculating the SoC, Switch S4 is on and S1, S2, S3, S5 will off. The spike current values will be given to the fuzzy controller for calculating the SoC.

Mode 3: Power Feed Back

It is in this mode the energy stored in the capacitor bank which is used for monitoring the SoC will be fed back to the Battery Since the voltage of two capacitor banks will be equal to the voltage of the Battery recombination of the capacitor are much required to increase the potential. For the simple boost up of voltage two capacitor banks are reconnected in series using two reverse connected switches(IGBT).As the energy is fed back to the battery the operation for SoC measurement ends

(A) Flowchart for SoC Measurement using SPIKE Current method

The flowchart for the spike method type of SoC Measurement is shown in Fig 4. the operation of the system is very unique from all the other types of SoC estimation methods discussed above in the literature. The monitoring of SoC in EV is an ongoing process which doesn’t demand any type of disturbance to the normal working of the system.

The nominal voltage and currents should be within the limits for the SoC operation to take place. The Battery data is processed to feed into the lookup table for the accurate estimation of SoC. After the estimation of SoC the energy is fed back to the battery system for eliminating the losses occurred due to the continuous monitoring [13].

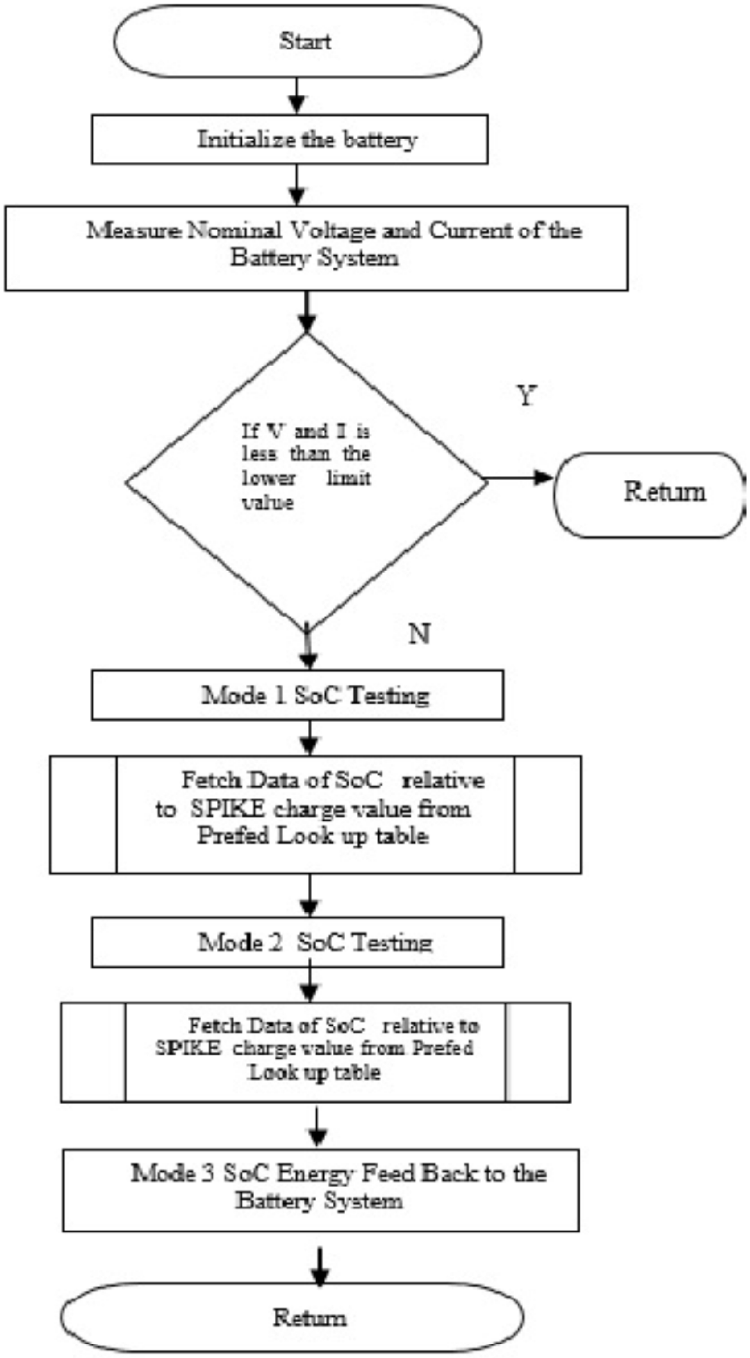

Figure 4: Flowchart for SoC Measurement using Spike current Method

IV. PROPOSED FUZZY LOGIC CONTROLLER FOR SOC CONTROL IN EV BATTERY AND ULTRA CAPACITOR DURING ITS OPERATION

Operational efficiency and the capability of controlling the co-ordinates linearly made Sugeno fuzzy controller appropriate for the SoC control. Sugeno fuzzy controller works with an adaptive technology and it confirms the continuity in output plane. In the modelled fuzzy controller, the input variables are Moment of Inertia, SoC of the Battery, SoC of the Ultra Capacitor and Regenerative Power as shown in Fig. 5.

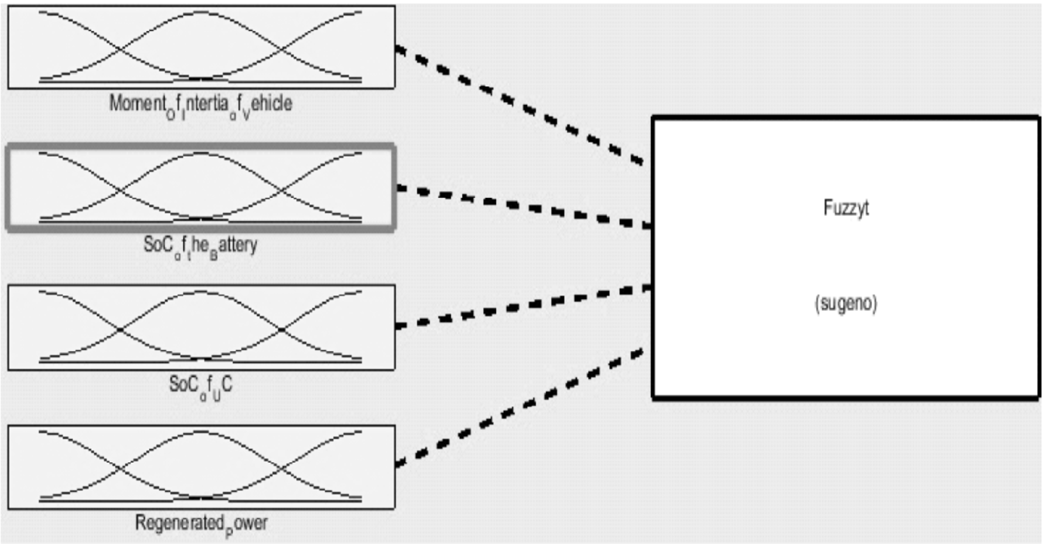

Figure 5: FLC system with input variables sugeno controller and output

Block diagrammatic representation of the proposed fuzzy controller scheme is shown in Fig. 6. The measured variables such as SoC of the battery, SoC of the UC, Regenerated Power during braking operation and Moment of Inertia of the vehicle are fed to the FLC. The FLC will decide the percentage of regenerated power feedback to battery bank or ultra-capacitor [15].

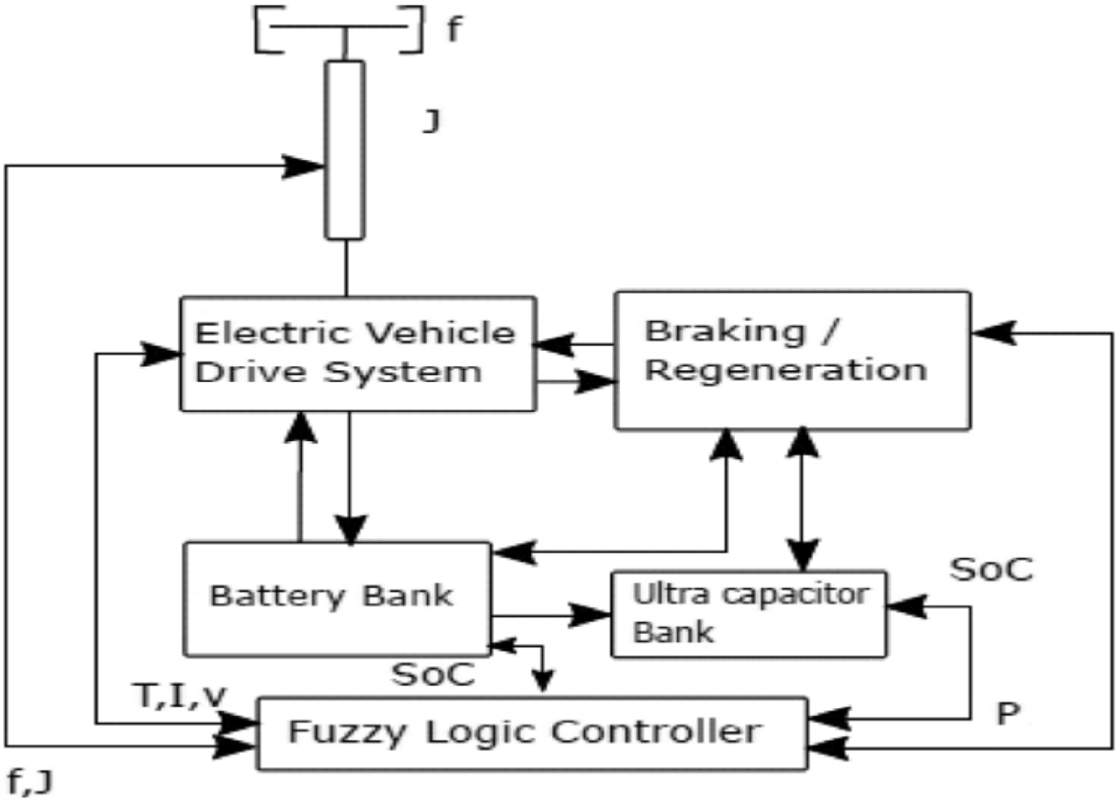

Figure 6: Block schematic of the FLC system

IV. FUZZY RULES DEFINED FOR DRIVE SYSTEM

FLCs accuracy depends on its precise fuzzy rules. According to real time practical experiments and simulation, the rule base for 20 rules is built to relate the four inputs with the output factor. Fuzzy rules are deciding the output factor are as shown below.

1. If (Moment_Of_Intertia_of_Vehicle is high) and (SoC_of_the_Battery is very_low) and (SoC_of_UC is high) and (Regenerated_Power is high) then (output1 is mf5)
2. If (Moment_Of_Intertia_of_Vehicle is high) and (SoC_of_the_Battery is high) and (SoC_of_UC is low) and (Regenerated_Power is high) then (output1 is mf1)
3. If (Moment_Of_Intertia_of_Vehicle is high) and (SoC_of_the_Battery is low) and (SoC_of_UC is low) and (Regenerated_Power is high) then (output1 is mf5)
4. If (Moment_Of_Intertia_of_Vehicle is high) and (SoC_of_the_Battery is med) and (SoC_of_UC is normal) and (Regenerated_Power is high) then (output1 is mf3)
5. If (Moment_Of_Intertia_of_Vehicle is high) and (SoC_of_the_Battery is low) and (SoC_of_UC is very_high) and (Regenerated_Power is high) then (output1 is mf5)
6. If (Moment_Of_Intertia_of_Vehicle is low) and (SoC_of_the_Battery is high) and (SoC_of_UC is normal) and (Regenerated_Power is very_high) then (output1 is mf3)
7. If (Moment_Of_Intertia_of_Vehicle is low) and (SoC_of_the_Battery is low) and (SoC_of_UC is very_high) and (Regenerated_Power is very_high) then (output1 is mf4)
8. If (Moment_Of_Intertia_of_Vehicle is med) and (SoC_of_the_Battery is med) and (SoC_of_UC is normal) and (Regenerated_Power is drooping) then (output1 is mf1)
9. If (Moment_Of_Intertia_of_Vehicle is med) and (SoC_of_the_Battery is low) and (SoC_of_UC is low) and (Regenerated_Power is medium) then (output1 is mf3) (1)
10. If (Moment_Of_Intertia_of_Vehicle is very_high) and (SoC_of_the_Battery is low) and (SoC_of_UC is low) and (Regenerated_Power is medium) then (output1 is mf3)
11. If (Moment_Of_Intertia_of_Vehicle is very_high) and (SoC_of_the_Battery is high) and (SoC_of_UC is very_high) and (Regenerated_Power is drooping) then (output1 is mf2)
12. If (Moment_Of_Intertia_of_Vehicle is med) and (SoC_of_the_Battery is low) and (SoC_of_UC is normal) and (Regenerated_Power is medium) then (output1 is mf3)
13. If (Moment_Of_Intertia_of_Vehicle is very_high) and (SoC_of_the_Battery is low) and (SoC_of_UC is normal) and (Regenerated_Power is medium) then (output1 is mf4)
14. If (Moment_Of_Intertia_of_Vehicle is high) and (SoC_of_the_Battery is high) and (SoC_of_UC is high) and (Regenerated_Power is high) then (output1 is mf3)
15. If (Moment_Of_Intertia_of_Vehicle is med) and (SoC_of_the_Battery is low) and (SoC_of_UC is normal) and (Regenerated_Power is medium) then (output1 is mf4)
16. If (Moment_Of_Intertia_of_Vehicle is high) and (SoC_of_the_Battery is med) and (SoC_of_UC is very_high) and (Regenerated_Power is very_high) then (output1 is mf3)
17. If (Moment_Of_Intertia_of_Vehicle is low) and (SoC_of_the_Battery is low) and (SoC_of_UC is normal) and (Regenerated_Power is drooping) then (output1 is mf4)
18. If (Moment_Of_Intertia_of_Vehicle is med) and (SoC_of_the_Battery is very_low) and (SoC_of_UC is very_high) and (Regenerated_Power is very_high) then (output1 is mf5)

19. If (Moment_Of_Intertia_of_Vehicle is med) and (SoC_of_the_Battery is low) and (SoC_of_UC is very_high) and (Regenerated_Power is very_high) then (output1 is mf5)
20. If (Moment_Of_Intertia_of_Vehicle is med) and (SoC_of_the_Battery is high) and (SoC_of_UC is normal) and (Regenerated_Power is drooping) then (output1 is mf4)

Linguistic variables used are High, Very High, Normal, Medium and Low. The output membership function vary from 0 to 1 in a linear range i.e., mf1=0, mf2=0.25, mf3=0.5, mf4=0.75 and mf5=1. The output membership function denote the ratio of energy feed back to battery bank or ultra capacitor. For e.g., if the output membership function is mf4 which is 0.75 the amount of power feed to battery will be 75 percent of the regenerated power and the rest 25 percentage will be feed to the ultra capacitor bank[16]. Such a control strategy can utilize the energy available during different instances of the vehicle operation effectively, which in turn can stabilize the SoC of the battery for longer operation [17] [18].

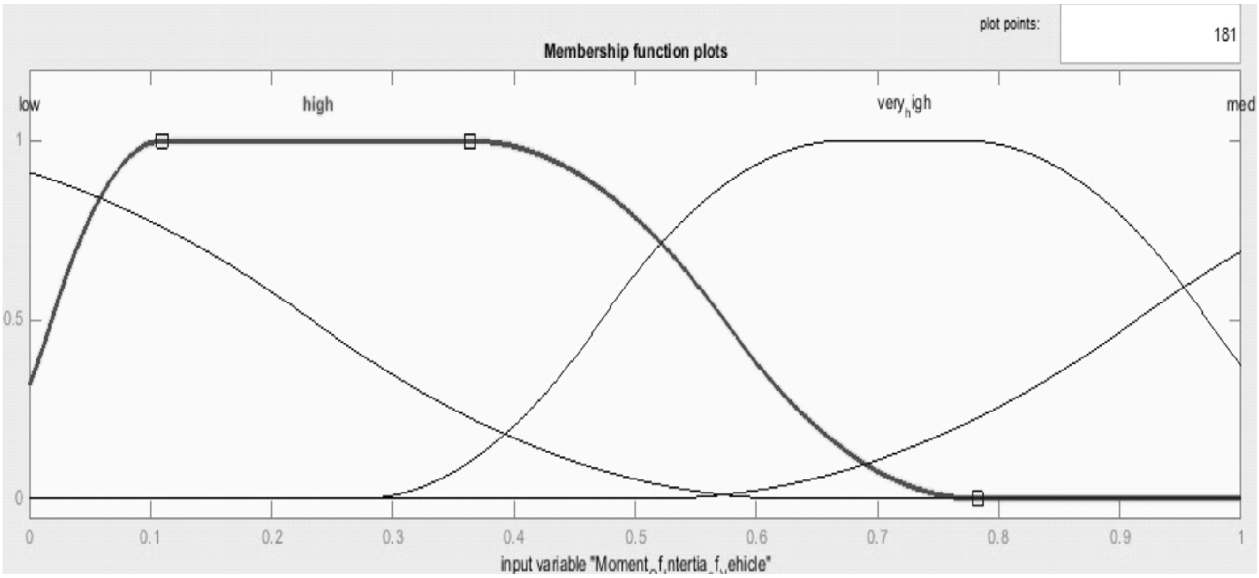

Figure 7: Membership function of the input variable- Moment of Inertia

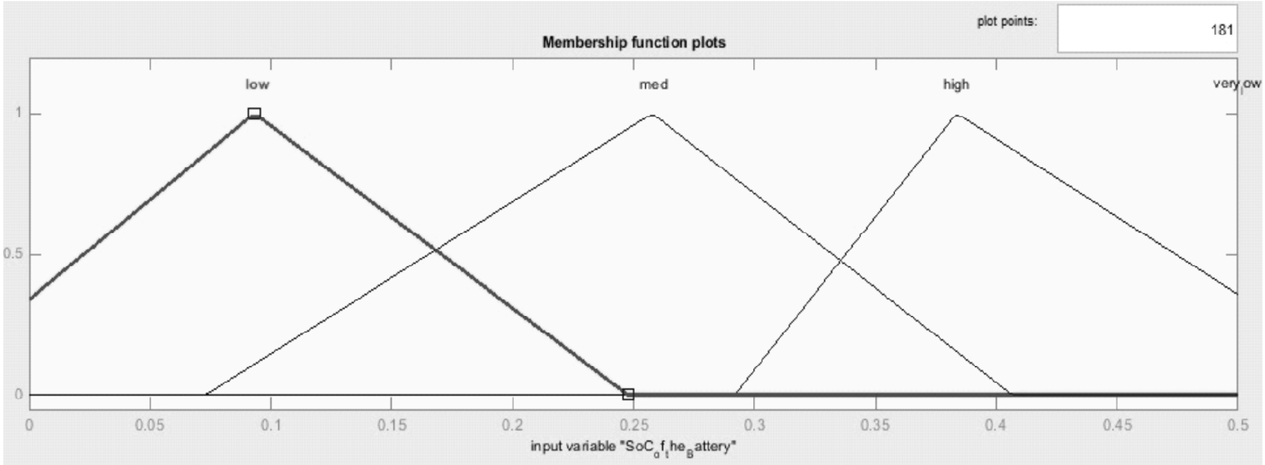

Figure 8: Membership function of the input variable -SoC of the battery

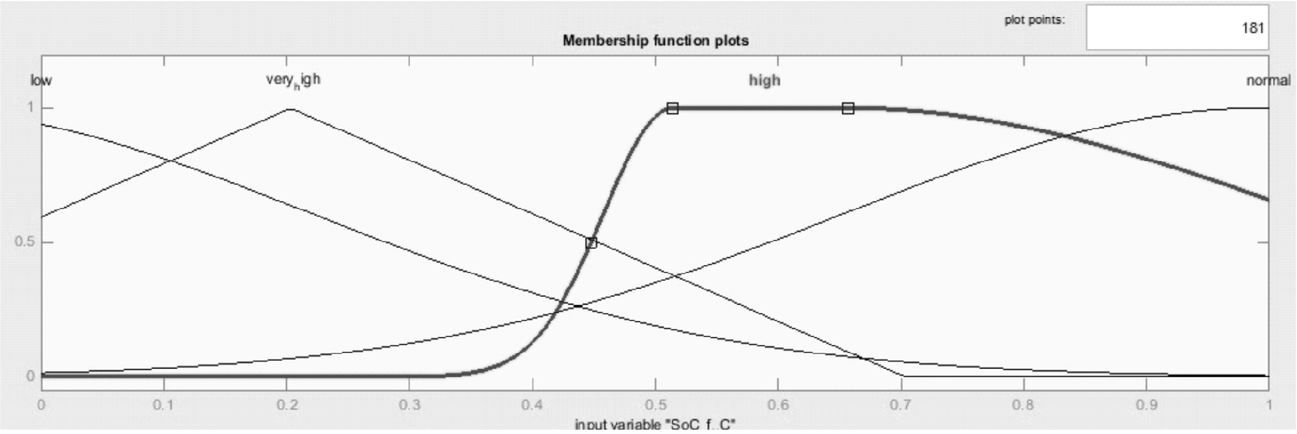

Figure 9: Membership function of the input variable -SoC of the UC

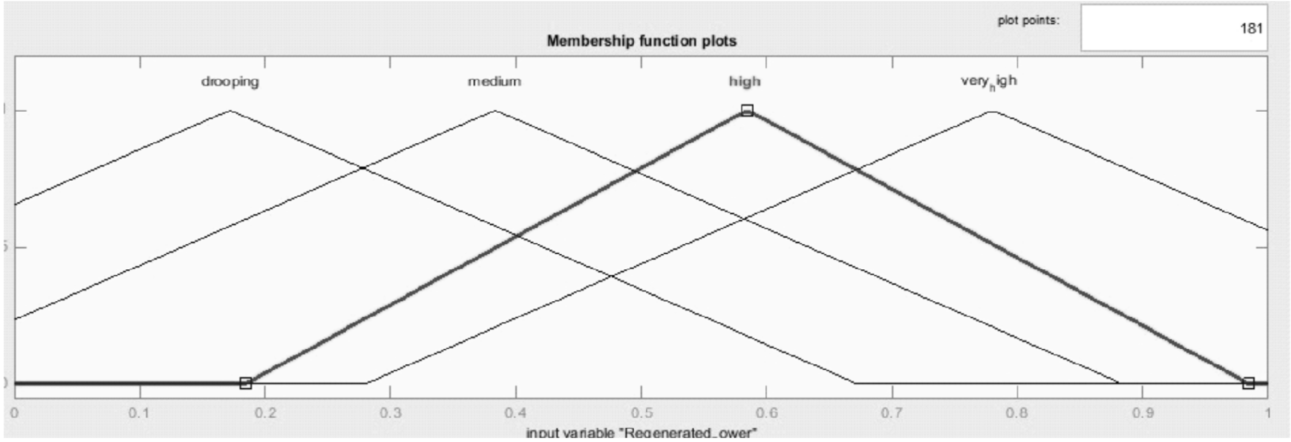

Figure 10: Membership function of the input variable-Regenerated Power

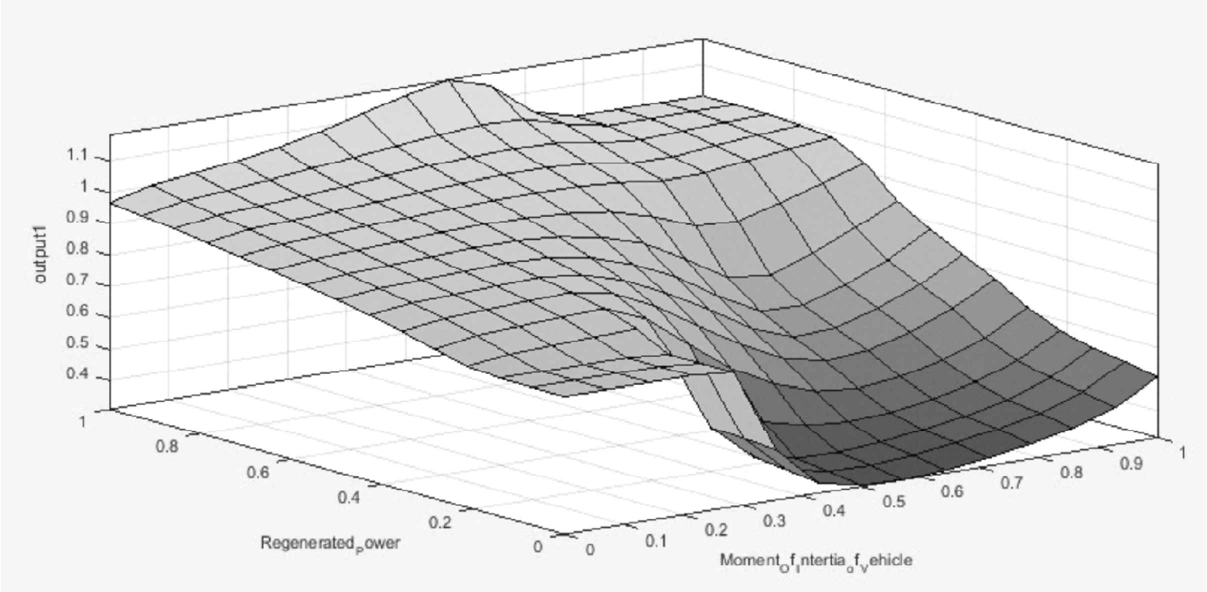

Figure 11: Relationship between output factor, regenerated power and moment of inertia of the vehicle

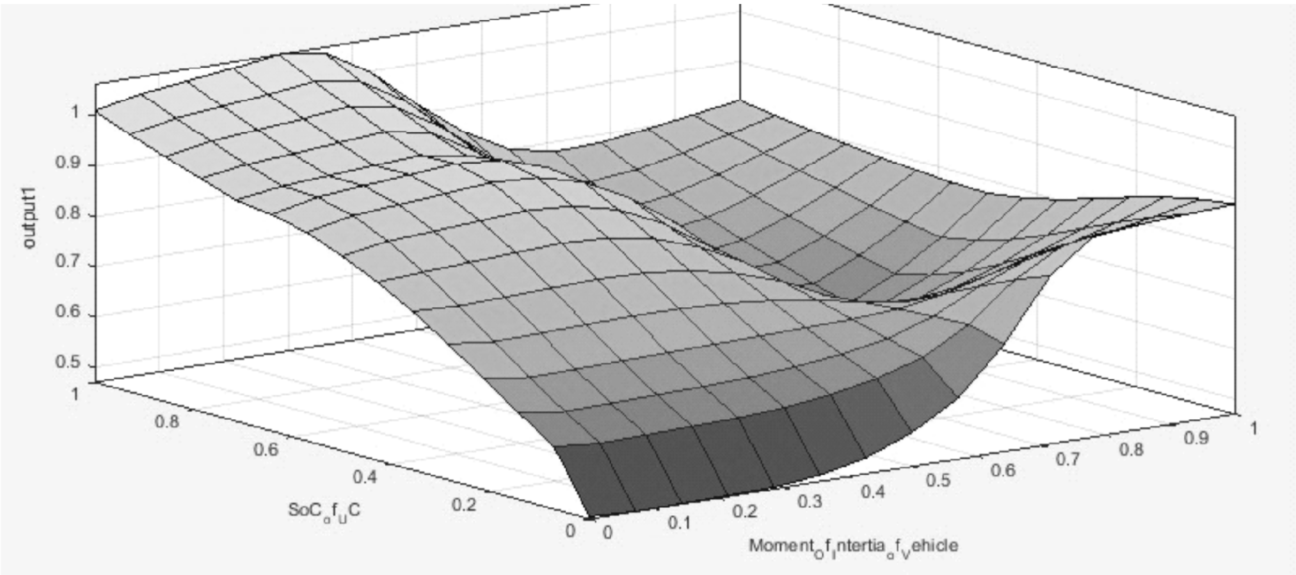

Figure 12: Relationship between output factor, SoC of UC, moment of inertia of the vehicle

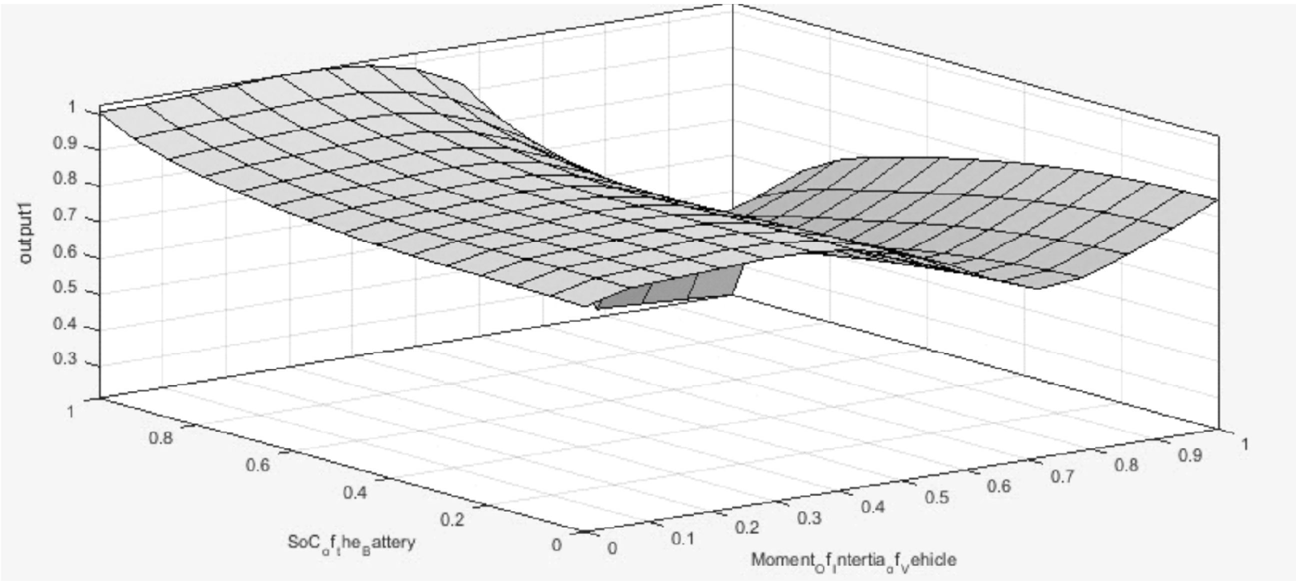

Figure 13: Relationship between output factor, SoC of battery, moment of inertia of the vehicle

The membership function of the input variables are carefully designed based on the practical real time datas. The input membership functions are shown in Fig. 7, Fig. 8, Fig. 9, Fig. 10 and the response surface of the output factor is shown from Fig. 11, Fig. 12, Fig. 13 The output surface shows theconvergence of the output factor towards optimum values [19] [20].

VI. CONCLUSION

The paper is divided into two sections, first part presents a novel approach towards the prediction of SoC in Electric Vehicles, Hybrid Electric Vehicles and Industrial Electric Vehicles. The online monitoring of SoC developed in earlier researches had direct impact on the normal operation of the corresponding system.The novel approach towards SoC monitoring is called Spike method. In this method the current injected into the capacitor bank is processed and compared with the pre-fed data in the lookup tables of FLC. The outputs are simulated for different operating conditions in practice, including different charge–discharge rates and strategies, variable load conditions, different ambient temperatures, aged cells, different initial SOCs, and remaining capacities of sealed lead–acid batteries [21] [22]. The second part elucidates a FLC controller for controlling the regenerative power feed back to the battery and ultra capacitor. The output surface viewer of FLC confirms the convergence of output factor to optimum ratios of power feed back.

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