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Fuzzy Logic Based Embedded Diagnostics for the Components of EV

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ABSTRACT: The technological developments are gaining high scope in the field of electrical vehicle (EV)automation. The challenges in EV automation include analysis and development of methods to improve the performance of EV subject to normal and abnormal conditions. This paper focuses on developing an embedded solution for condition monitoring which would be a useful prognosis that increases the lifetime of the EV components like the electric motors, control unit etc. The outcome of this paper is identification of the healthy and faulty conditions in the EV components using Fuzzy logic-based rules parameterization.

KEYWORDS: Electric Vehicle, Fuzzy Logic, Fault detection

I.INTRODUCTION

Safety is the most significant issue in industrial applications that involves human interaction. Any type of failure or malfunction of the components of the Electric Vehicle (EV) may result in a fatal accident. Therefore, implementing a prognosis technique for detection of such faults is necessary to improve safety and reliability of the overall system.In general, EVs have simpler structures, lower noises, higher stabilities, and most importantly, environmental protection. But EVs are still under relatively weak circumstance. A single failure of EVs' core components may result in very costly breakdown, or even life safety threat [1]. So, it becomes a necessity to prognose the faults in an early state. EVs are generally considered to be consisting of the different components. Each of this component forms a coordination among themselves to make an EV work as shown in the fig 1. The details of these components are discussed in section II along with their faults. Section III deals with the fuzzy logic while results are presented in detail in section IV.

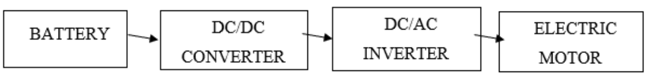

Fig 1 Block Diagram of EV

II.ELECTRIC VEHICLE

A.Components of EV

Battery:fed electric drives are commonly being used for electric vehicles applications due to various advantages, such as: nearly zero emission, guaranteed load levelling and good transient operation. In general Lithium-ion battery is being used in majority of the vehicles.

DC/DC Converter: Different voltage levels are required by the various electronic components in an EV. This is the most basic requirement for DC/DC converter[2].The DC-DC converter is required to perform mainly two functions: first to match the battery voltage to the motor rated voltage and second to control the power flow under steady-state and transient conditions, so that the drive performance is as per the requirement. In this thesis work, a buck-boost converter is employed which connects the battery to the motor. The model used is shown in fig 2.

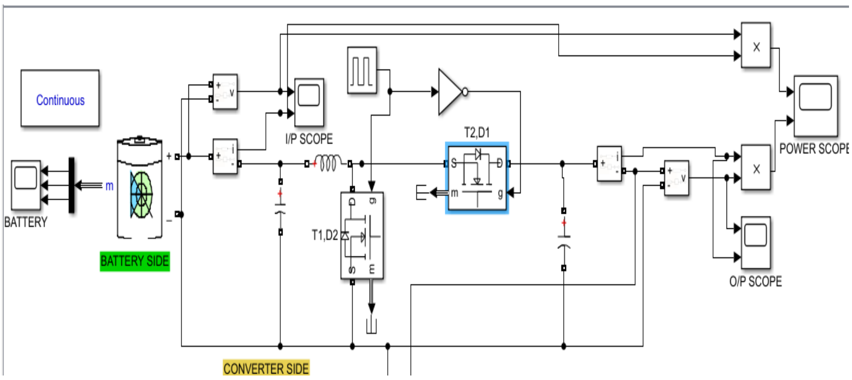

Fig 2 DC/DC Converter

DC/AC Inverter: Nowadays, brushless dc motor is widely used in electric vehicles because of their efficiency, better speed versus torque characteristics, higher speed range and noiseless operation. The motor has three phases and commutation is performed electronically. To run the motor a three-phase inverter is necessary. Sensing rotor position is very important to generate proper switching sequences for the three-phase inverter. To do so, three hall sensors are provided with the BLDC motor for three phases of the motor.

The inverter circuit used in the model is three phase 6 pulse Voltage Source inverter (VSI) as shown in fig 3. The switches used are MOSFET. MOSFETs are used instead of IGBT as they have no tail current when turned off. MOSFETs, in particular, combine several desirable characteristics, such as high breakdown voltage, low on-resistance and fast switching speed, with their inherent advantages of high-temperature capability, high-power density and high efficiency.

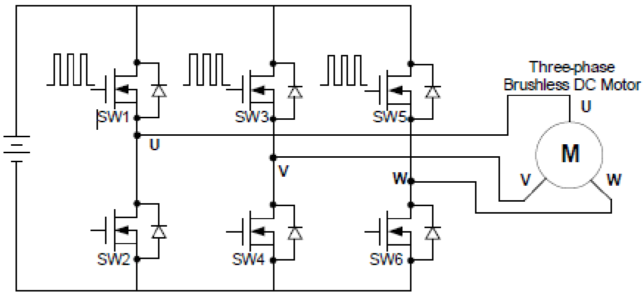

Fig 3 Three phase 6 pulse VSI

Electric Motor: Electric vehicle was converted mainly from the existence of an internal combustion vehicle by replacing the internal combustion engine and fuel tank with an electric drive motor and a battery unit while retaining all other components. Of the available motors, Brushless DC motor is mainly employed as it its able to respond faster and at higher operating speeds and simpler to control in regard to speed control and reversing.

Sensors: EV has a million of in-built sensors for efficient working. The one we have dealt with in the model is the pedal force sensor. The sensor is based upon capacitive sensing technology and is thin, rugged, and provides high reliability in rough environments.The advantages of the capacitive sensor principle are simplicity, high response speed and resolution (0.04), compact sensor outlines, and insensitivity to dirt and condensation.

B. Faults in Electronic Control Unit

Since the primary focus of this paper is to identify the various faults in the components of EV using Fuzzy logic, this sub-section deals with the common type of faults that predominantly occurs in EV components.

Although Li-ion batteries are known as long-service devices, their lives depend greatly on environmental condition and operation mode.

Faults of Li-ion batteries [3] usually come from

- ageing process
- abuse operation.

In case of DC/DC converter, common faults that occur includes [4]

- open circuit
- short circuit

Faults on inverter side of an Electric Vehicle have great impact on system stability. Faults considered are [5],[6]:

- Faults due to malfunctions of valves and controllers
  (i) Arc backs (or back fire)
  (ii) Arc through (Fire through)
  (iii) Misfire
  (iv) Quenching or current extinction
- Open circuit failures in inverters
- Short circuit failures

Major Faults of BLDC Motors are broken rotor bar, static & dynamic air gap irregularities, dynamic eccentricity, winding short, bearing & gearbox failure. In general, they can be classified as

- stator faults
- rotor faults
- bearing faults.

In sensors, faults occur due to

- Ageing
- Faulty connections of cables

This paper deals with faults in the Electronic Control Unit and sensor part of the EV. The next section deals with the fuzzy logic, their rules and membership functions.

In [4] and [9] we find converter and inverter fault diagnoses has been addressed separately, while this paper not only provides simultaneous addressing of Fuzzy rules for both converter and inverter faults to device a decision but also sensor fault prognosis for EV.

III.FUZZY LOGIC

The Fuzzy Logic is employed to determine the type of fault. Fuzzy logic makes use of the Fuzzy Inference Process to provide the crisp output. In order to determine the condition of the components of EV, we design fuzzy rules based on the input and output variables. MATLab Fuzzy Toolbox has been used to perform the following simulations. Here the input variables to the Fuzzy logic are, Load of the motor which is considered in terms of Acceleration / Brake (ie higher the load lesser the acceleration of motor and vice versa), Speed of the motor and Line voltage of the inverter. The output variable is the Fault Type. Dividing Acceleration/Brake into 8 sets: VH(Very High), H(High),M(Medium), VL(Very Low), L(Low), Slow, Medium and Critical. Dividing Speed into 4 sets: VerLow, Low, Medium and High. Dividing Line voltage into 4 sets : Neg (Negative), Under, Perfect and High Dividing Fault Type into 10 sets : Normal, F1(Fault type 1), F2(Fault type 2), F3(Fault type 3), F4(Fault type 4), F5(Fault type 5), F6(Fault type 6), F7(Fault type 7), F8(Fault type 8), F9(Fault type 9).
The linguistic variables are defined using triangular membership (fig 4) function as shown in fig 5.

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$$\mu_A(x) = \begin{cases} 0, & x \le a \\ \frac{x-a}{m-a}, & a < x \le m \\ \frac{b-x}{b-m}, & m < x < b \\ 0, & x \ge b \end{cases}$$

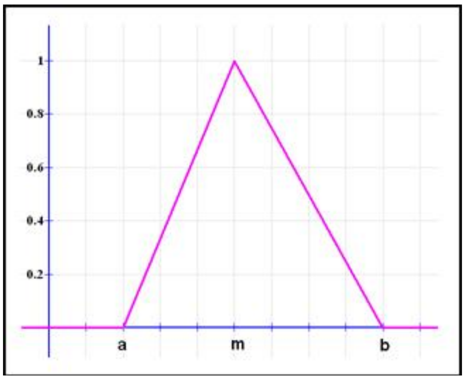

Fig 4 Triangular Membership Function

Using the same formula of that of the triangular membership function, the other input variables and the output variable is defined.

The next step is to define the rule set. To do this the model was made to run in different scenarios as discussed in section IV .

1 If (Acc/Brake is VL) and (Speed is veryLow) and (LineVoltage is neg) then (FaultType is F2)
2. If (Acc/Brake is H) and (Speed is veryLow) and (LineVoltage is under) then (FaultType is F9)
3. If (Acc/Brake is Medium) and (Speed is low) and (LineVoltage is under) then (FaultType is F4)
4. If (Acc/Brake is VH) and (Speed is Med) and (LineVoltage is perfect) then (FaultType is Normal)

In a similar manner, the entire rule set was framed.

$$Uacc/brake \begin{cases} Uvh \begin{cases} (x+10)/10 & -10 < x \le 0 \\ (5-x)/5 & 0 < x < 5 \end{cases} \\ Uh \begin{cases} (x-3.5)/3.5 & 3.5 < x \le 7 \\ (11-x)/5 & 7 < x < 11 \end{cases} \\ Um \begin{cases} (x-10)/3 & 10 < x \le 13 \\ (16-x)/3 & 13 < x < 16 \end{cases} \\ Ul \begin{cases} (x-15)/5 & 15 < x \le 20 \\ (26-x)/6 & 20 < x < 26 \end{cases} \\ Uvl \begin{cases} (x-25)/6 & 25 < x \le 31 \\ (35-x)/4 & 31 < x < 35 \end{cases} \\ Uslow \begin{cases} (x-33)/6 & 33 < x \le 39 \\ (42-x)/3 & 39 < x < 42 \end{cases} \\ Umedium \begin{cases} (x-41)/3 & 41 < x \le 44 \\ (46-x)/2 & 44 < x < 46 \end{cases} \\ Ucritical \begin{cases} (x-44)/11 & 44 < x \le 55 \\ (65-x)/10 & 55 < x < 65 \\ 0 & x \ge 65 \end{cases} \end{cases}$$

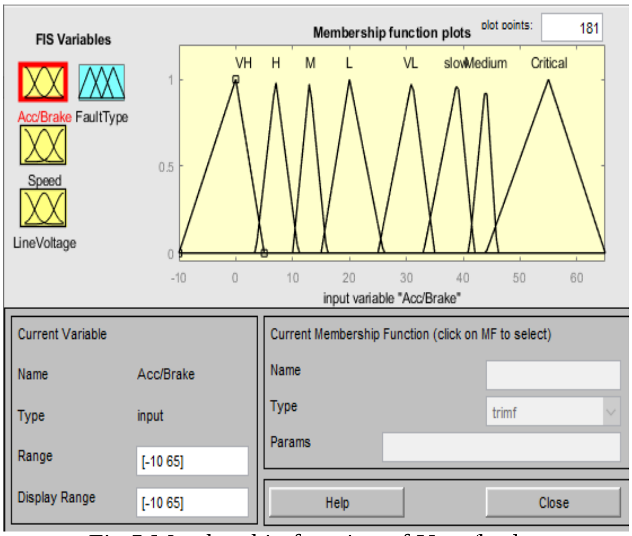

Fig 5 Membership function of Uacc/brake

Now defuzzification was carried on by means of centroid method.

$$x* = \frac{\int \mu A\tilde{}(x).xdx}{\int \mu A\tilde{}(x).dx}$$

Where,

x∗ is the defuzzified output,

μA˜(x) is the area of the Sub-region andx is the center of area of that sub region.

Before proceeding to add this fuzzy logic controller to the main model we verify it with a test case. Let us consider the crisp inputs to be 23Nm, 51.5rpm and 58.3v. This is converted as fuzzified input by the formula

$$Utriangular = \max\left\{\min\left(\frac{[x-a]}{[m-a]}, \frac{[b-x]}{[b-m]}\right), 0\right\}$$

Where, a, m and b are the points as shown in fig 4

The converted fuzzified inputs are given to the rule base created. The Implification method adopted is MIN method(logical AND) and Aggregation is by MAX(logical OR). Once we get the aggregated output, deffuzification by centroid method occurs as per the above formula and crisp output is obtained. Here,the acc/brake is under L, speed is in both verylow and low while line voltage is in neg membership function. By the method of defuzzification we find the crisp output to be 2.15 that falls under F2 type of fault.

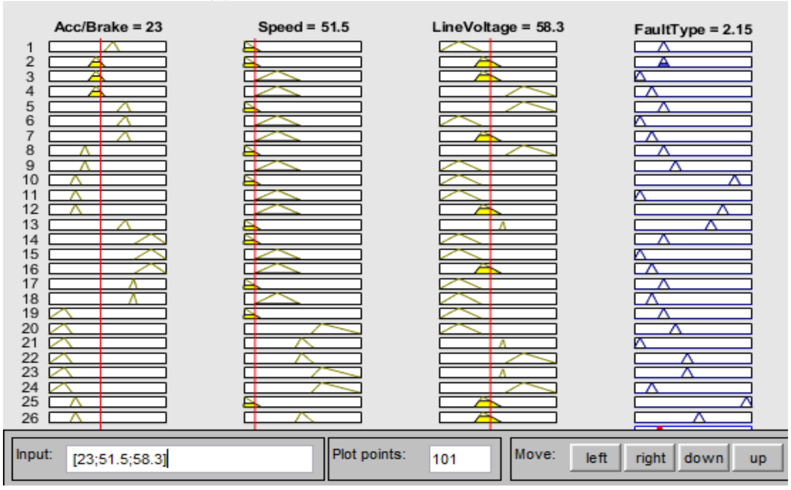

Fig 6 F2 fault type verification

Now we proceed by adding the Fuzzy Logic Controller to the EV model designed in Simulink MATLab 2018a as discussed in the following section.

IV. RESULTS

The Fuzzy rules which have been discussed above is now inserted to the models to identify the working condition of the various components of EV. If there occurs any type of fault, then it is identified based on the output of fuzzy as shown in the display. From the range of the output the type of fault can be detected as shown in table 1 below.

In all the scope results presented in this section, the X axis is time in seconds and the y axes are input torque to the motor in Nm, speed of motor in rpm and line voltage of the inverter in Volts respectively.

Range	Fault type
0-1	Normal
1-2	**F1**--Converter-Boost Mode Fault
2-3	**F2**--Converter-Buck Mode Fault
3-4	**F3**--Sensor-Aging
4-5	**F4**--Sensor-Delay
5-6	**F5**--Inverter-Misfire
6-7	**F6**--Inverter-Open Ckt
7-8	**F7**--Inverter-ShortCkt-1P
8-9	**F8**--Inverter-ShortCkt-2P
9-10	**F9**--Inverter-ShortCkt-3P

Table 1 Fault Type Identification

The Simulink model for the normal working condition of the electric vehicle is shown in fig 7.

When the EV moves, it's actually the torque that does the moving. More torque means more force we have to accelerate the car, since torque is force x distance (Newton-Meters).Accordingly, in this model the BLDC motor used has 4 inputs(A,B and C are the three-phase supply and T_m is the input torque to motor) where, T_m is given the brake/ acceleration force pattern.

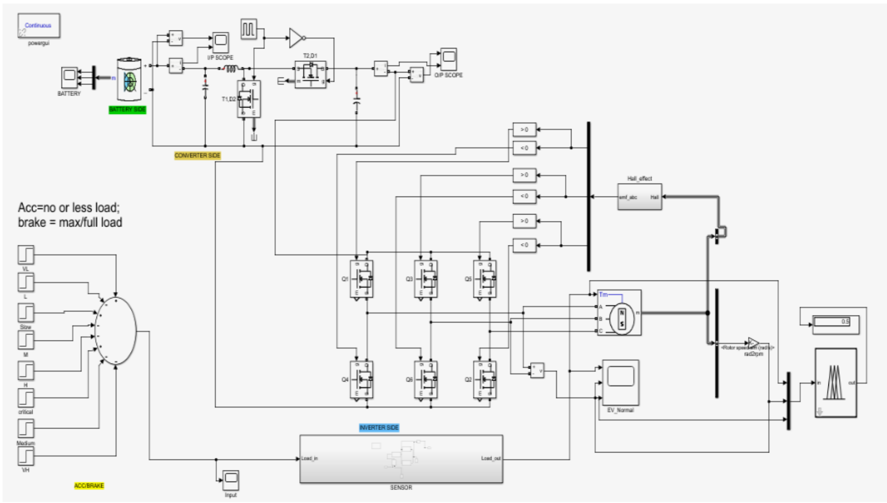

Fig 7 Simulink model of EV (under normal condition)

The scope (fig 8) depicts the load to the motor in terms of torque (Nm), speed of the motor (in rpm) and line voltage of the inverter (in volts). In all these plots X axis is time in seconds.

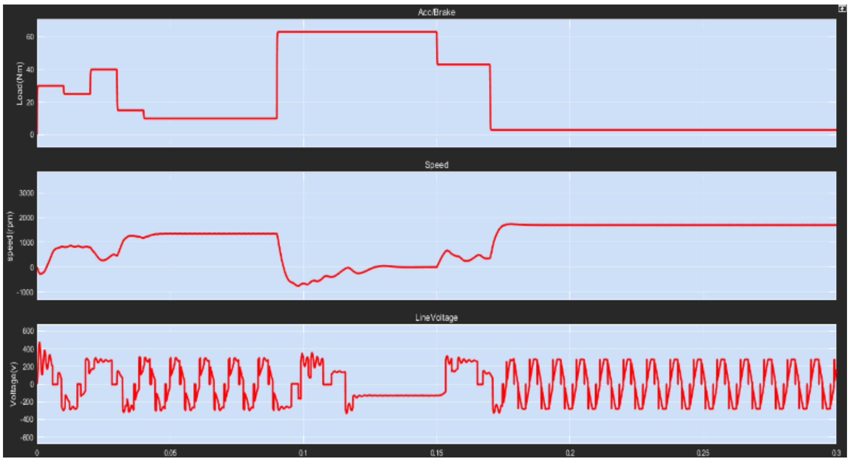

Fig 8 Scope- Normal working condition

Once the model is made to run, we find the fuzzy decision is 0.5 (fig 9) indicating that there is no fault in the model and all components of EV are in normal working condition.

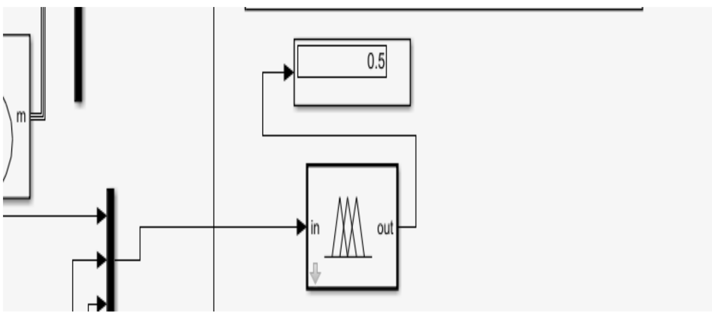

Fig 9 Display- Normal working condition

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In this case of normal condition, we find speed of the motor as 1700rpm and line voltage of inverter between -300 to 300v.
Let us consider that a fault has been introduced in the converter section of fig 7.
Here, D2 is made open circuit and T1 is in normal mode while T2 and D1 are in off state. Very high voltage spike is observed across T1 and the OC diode in this condition. These high voltage spikes could damage the power switching components in the converter. [4]
Now we find the speed of the motor as 3342 rpm exceeding the nominal speed. This is shown in scope below. Here X axis is time in seconds.

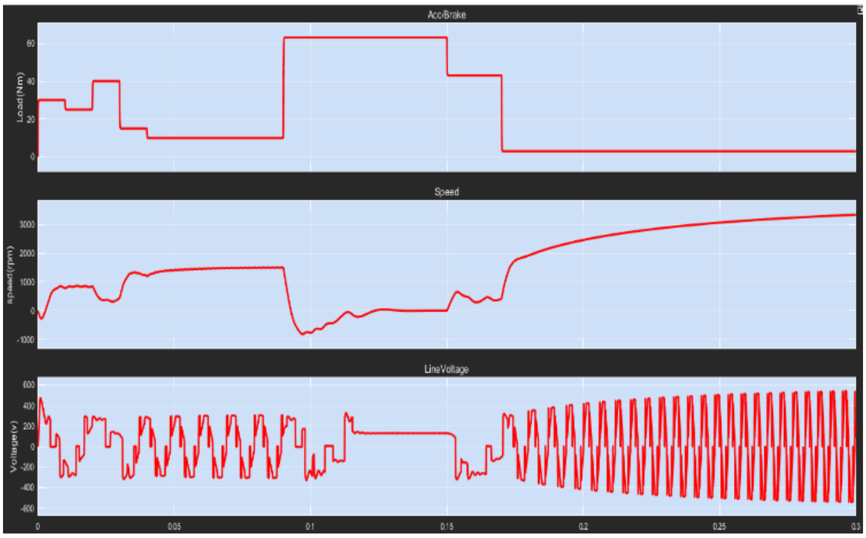

Fig 10 Scope- boost mode fault

As per the Fuzzy rules we see that the Fuzzy output is 1.5 depicting boost mode fault as per table 1.When fault is introduced during the buck mode operation of the converter [4], we find that the motor stalls.The fuzzy output is shown in fig 12 which corresponds to buck mode failure of the EV.

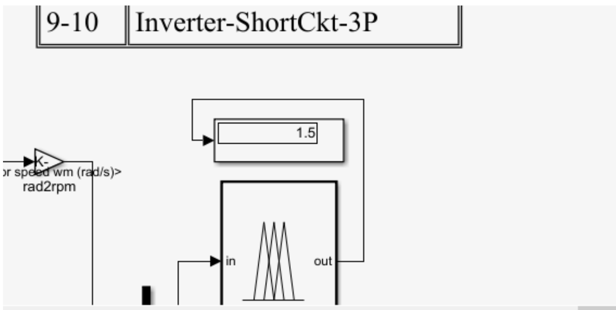

Fig 11 Display- boost mode fault

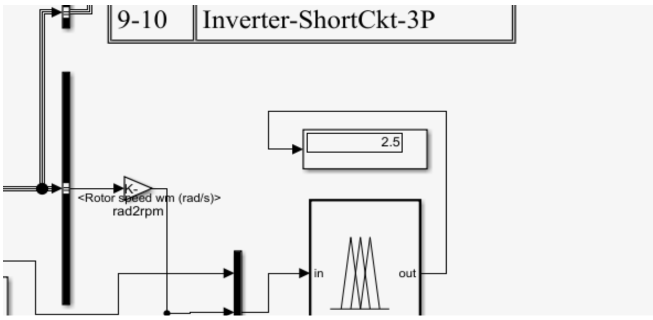

Fig 12 Display- buck mode fault

If the pedal force sensor fails, the following fault symptoms may occur:
- Vehicle does not respond if the accelerator pedal is pressed
- EV doesn't accelerate over a specific limit.
- Vehicle hesitates to move when the gas pedal is pressed.
- Vehicle jerks upon depressing the pedal

Causes for failure maybe due to the following reasons:
- Ageing of the sensor.
- Damaged cables or connections on the accelerator pedal sensor
- Faulty electronic evaluation unit in the sensor.

Accordingly, faults are introduced in the sensor module of the Simulink model shown in fig 7. Here, the pedal-force sensor is modelled based on capacitance transduction and is placed next to the accelerator / brake of the Electric Vehicle modelled. Due to ageing, improper functioning of the sensor may lead to false output. This ageing factor is modelled as an exponentially decaying function over time. As shown in plot 2 of fig 14, due to this fault the load to the motor is not being sensed accurately and this leads to improper speed of motor.

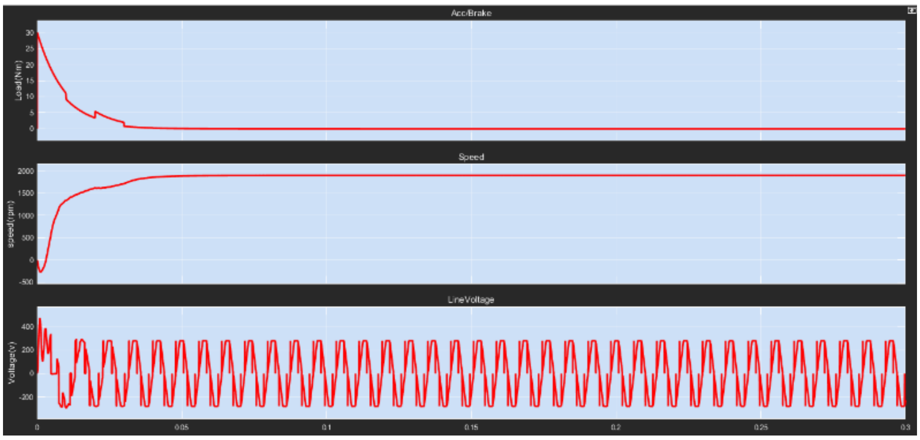

Fig 13 Scope- Sensor Aging fault

The fuzzy output is 3.55 that lies in the range for sensor-ageing fault.Similar to this, due to delay in reading the input which can be due to the reasons mentioned above, we get improper output. This is modelled as delay fault and the motor speed along with line voltage of inverter was monitored. In this case, the sensor is modelled to work after a delay of 0.15s.The below fig shows the fuzzy output 4.5 for delay fault

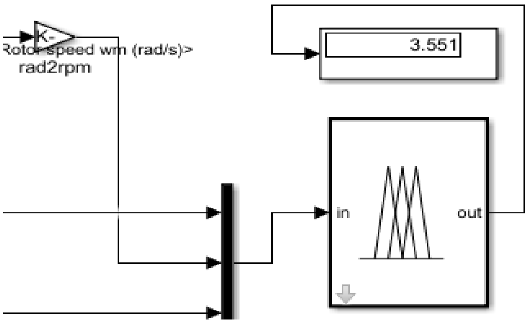

Fig 14 Display- Sensor Aging fault

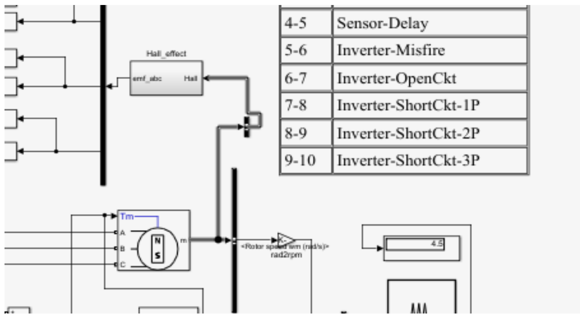

Fig 15 Display-Sensor delay fault

The remaining five faults have been introduced in the inverter section. As discussed in [5] and [6] there could be misfire, open circuit and short circuit of the switches in the inverter section. Fault module has been designed and is attached to the six switches of the inverter.

Due to misfire of switches 1 and 3, we find the variation in line voltage abruptly [5] and thereby the speed of the motor getting affected as shown in fig 16

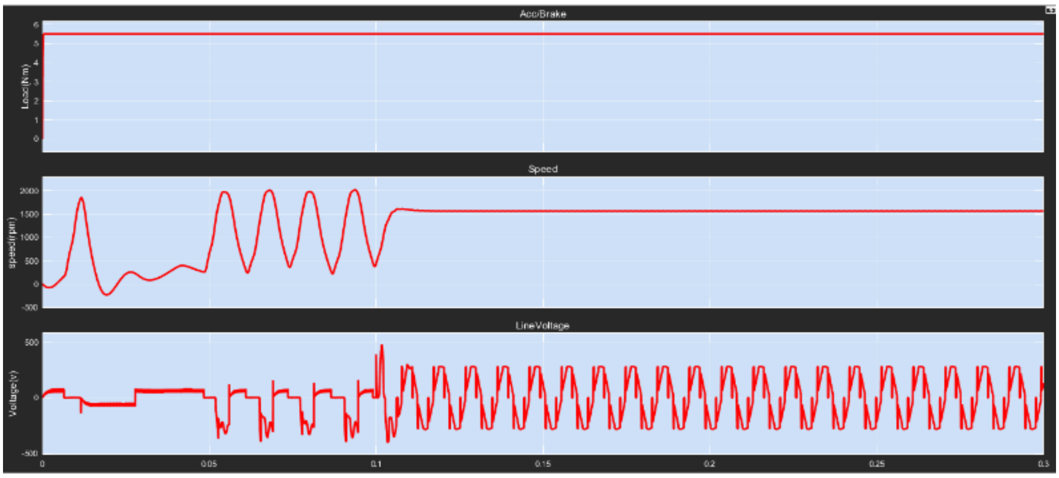

Fig 16 Scope- Misfire

The fuzzy rules find this change in line voltage and accordingly displays the output of 5.5 which lies in the range of 5-6 as shown below in fig 17.The next type of fault is open circuit of inverter switches [7]. Here switch 1 is made open circuit after 0.1s leading to change in line voltage and in speed of motor. The motor's speed toggles due to un availability of Phase A which leads to the fuzzy output shown below

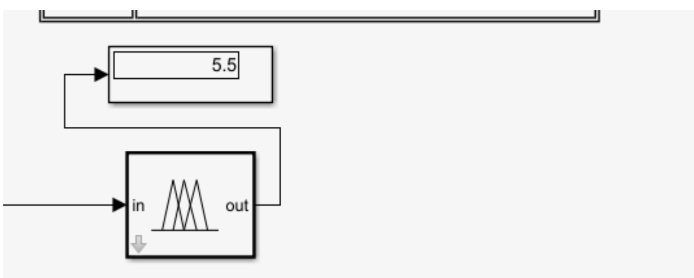

Fig 17 Display- Misfire

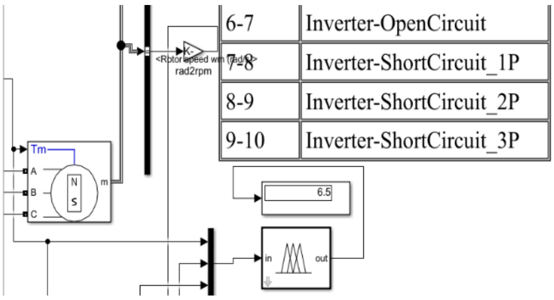

Fig 18 Display- Open Circuit Fault

When inverter switches are made short circuit, it leads to dangerous outcomes as detailed in [6]. The display units for all three types of short circuit faults are shown below.When Phase C is alone made short circuit line voltage is between -150 to 150v. The fuzzy output lies in the range as shown below in fig 19. Due to 2 phase short circuit, both phase C and B are short leading to dangerous toggling of motor. The line voltage has also dipped accordingly. The fuzzy decision is shown below in fig 20.

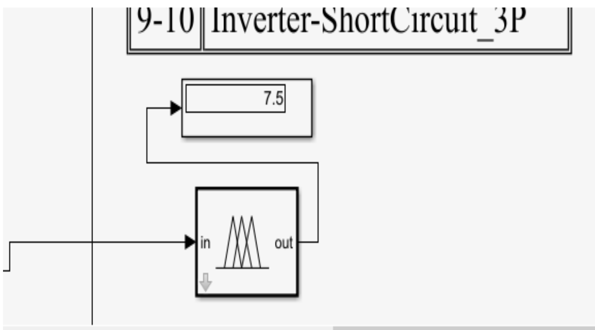

Fig 19 Display- Short Circuit Fault 1 Phase

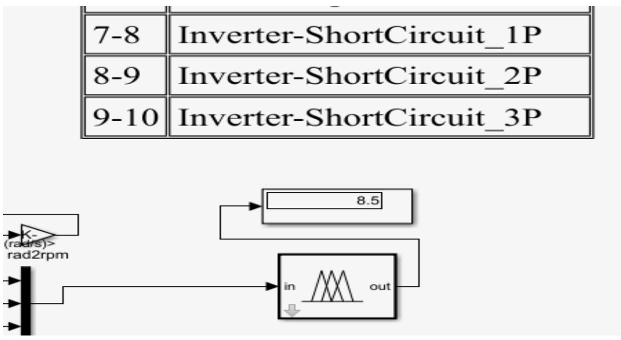

Fig 20 Display- Short Circuit Fault 2 Phase

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When all 3 phases of the motor power supply are short, the motor stalls completely and so do the line voltage. The fuzzy output is also as per the rules. This shown in fig 21 and fig 22 respectively.

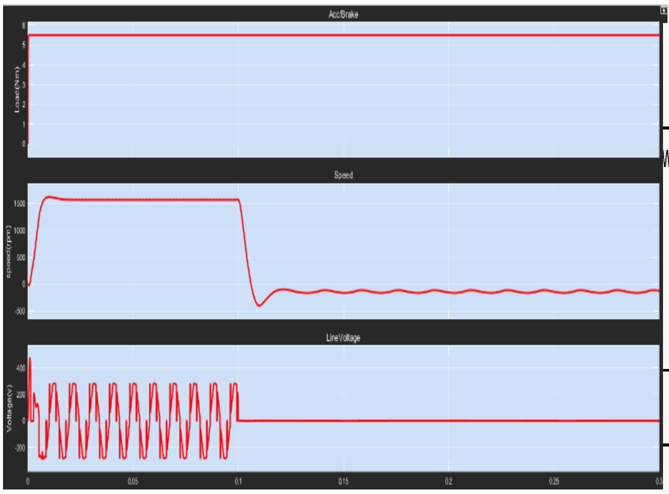

Fig 21 Scope- Short Circuit Fault 3 Phase

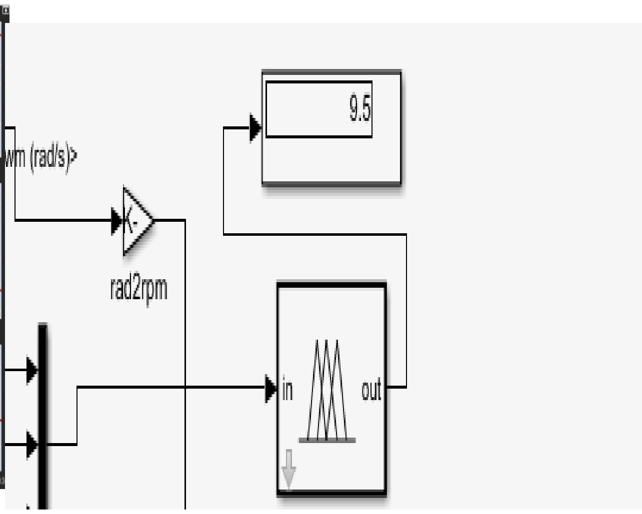

Fig 22 Display- Short Circuit Fault 3 Phase

V. CONCLUSION

This paper presents modelling, design and fault diagnosis of the ECU components of EV using MATLab Simulink. The different types of faults have been introduced in the major components of EV like converter, inverter and in the pedal-force sensor parts using Simulink. These faults are now easily prognosed by means of Fuzzy Logic. The output of the fuzzy logic is a numeric digit that determines the type of fault according to its range. The results contribute new prognosis facility using Fuzzy Logic. The output paves new embedded solution for pre-determining the type of fault in EV. The future work, in progress includes modelling and analysis of fault in other components of EV like motor, battery etc. In conclusion, the Fuzzy logic inference when implemented for condition monitoring the abnormal characteristics or faults occurring if any, would be diagnosed easily in case of an EV.

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BIOGRAPHY

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Dr. P. Vanaja Ranjan, professor DEEE, in College of Engineering Guindy, Anna University with 27 years of teaching experience. She initiated the establishment of the Embedded System Technologies, South India for the first time. Her areas of interest include, Fault diagnosis based on signal processing and embedded system technology