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Rover Circuit Protection: A Holistic and Comprehensive Approach

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***Abstract*— Researchers have been working on circuit protection in different ways for decades based on different loads, power, and requirements. Protection measures are particularly crucial for rover circuits due to their high voltage and high current consumption, advanced functionality, system reliability, and component protection needs. While implementing the rescue rover's circuit, we faced problems such as over-current, overheating, low current, short circuits, battery over-discharge, etc. When the Li-ion or Li-po battery in the rover circuit is connected in the wrong polarity, it can cause circuit damage due to its high discharge rating. This paper proposes a comprehensive circuit protection method (CPM) for the entire circuit protection of a rover, which is also applicable to other DC circuits. The proposed comprehensive circuit protection method offers reliable protection against various potential issues, including short circuits, overheating, over-voltage, over-current, low current, low voltage, battery over-discharge, reverse polarity, reverse current, and residual charge issues.**

***Index Terms*— Rover circuit protection, Comprehensive circuit protection, Thermal protection, Short circuit protection, Residual charge protection, Reverse polarity protection**

I. INTRODUCTION

Rovers are used for urban search and rescue, firefighting, nuclear plant operations, mining, construction, planetary exploration, agricultural tasks, etc [1]. The electronic circuit is one of the most important parts of a rover. Alike, the importance of electronic circuit protection of a rover in modern electronics cannot be overstated. Circuit protection is more critical than ever because of the integration of sophisticated electronic devices and the rising demand for higher levels of functionality. We faced many troubles like over-current, over-voltage, short circuits, and overheating in the circuit of our rover, BracU Dichari [Fig.1]; even sometimes, we burned out the whole circuit for some mistakes or protection flaws. This is the direct motivation behind this significant research. Electronic circuits can sustain severe damage if proper protection against the various risks is not provided, and in some situations, this can seriously jeopardize user safety. In our previous project (Bracu Dichari), we also worked on the protection of drone circuits [2]. In previous experiences from these projects, members have seen that the rover stops responding to commands when unexpected anomalies occur. Most anomalies can be related to over-current or unstable voltage due to heavy load. To achieve more reliable operation, we need robust rover circuit protection. And we start working to protect the circuits. The work includes various circuit safety techniques, including short circuits, thermal, over-voltage, and over-current safeguards. Ten effective protections have been put in place to protect the circuit. The importance of each protection strategy is highlighted in the paper, and it is also discussed how circuit protection needs to be taken in a comprehensive way where almost every kind of circuit protection will be available altogether.

Fig. 1. BracU Dichari (Rescue Rover)

II. LITERATURE REVIEW

Researchers are continuing their research to protect circuits. So many methods have been developed to address and protect electronic circuits. To protect the circuit from over-voltage, researchers are applying metal oxide varistors(MOVs) and transient voltage suppressors(TVSs) [3]. An electric circuit Breaker (ECB) also can be used for over-voltage protection as its comparator compare the sensed voltage and compare it with the predetermined voltage value to send it to the micro-controller that controls the MOSFET and the MOSFET controls relay for implementing the decision [4]. For short circuit protection and to reduce the short circuit faults, the collector-emitter voltage monitoring method and collector current monitoring method can be used, but in that case, it takes a lot of time for fault detection. [5]. A temperature detection circuit can be used with a power MOSFET to measure the temperature of the power MOSFET and to control the power MOSFET [6]. But it can only measure the temperature of power MOSFET and can not monitor it digitally. A Reed switch can protect the circuit from short circuits and over-current protection [7]. But in this case, over-current limit is fixed and can not be changed.

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This is why it is not compatible with most of the circuits. A current sensor based on a current protection system is used, where the current sensor sends the data to an MCU, and the MCU sends a signal to a relay to turn off the load [8]. In this system, it can only protect a circuit from over-current. A relay has been used to turn on and off the load, but the relay needs to be better for fast switching. According to another research, an over-current relay can protect a circuit from over-current. But in this regard, the current limit of those relays is fixed, and a user cannot manually determine the current limit. [9]

However, our system uses digital, fast, and precise to protect a circuit. It can instantly protect the circuit from any damage with fast and accurate measurements. Moreover, we have the advantage of controlling the threshold limit of every parameter according to different components and requirements, as thresholds are user-defined. Different circuits may have different operating conditions, furthermore, we can manually set those operating conditions. The threshold control system allows us to use our system in almost all kinds of rover circuits, including other DC circuits. The system can respond quickly and accurately with a low response delay between detection and activation, saving the circuit from severe damage. As many issues can damage the circuit, the protection system must consider all the possible issues and solve them accordingly. The mentioned comprehensive circuit protection method provides ten different shorts of circuit protection solution that almost covers all possible issues that can arise on the rover circuit. Our circuit protection method stands alone in its comprehensive approach, ensuring the highest safety and security.

III. METHODOLOGY

This paper follows the primary research methodology based on experimental results. Firstly identify the problem, find and propose a method to solve it, and then, based on the proposal, make a hardware breadboard model and take data from the experiment to prove the proposal's validity. In the "Design and Implementation" section, we proposed solutions to protect the circuit in five subsections. Then, in the "Experiment and Result" section, the breadboard model and obtained data from the experiments are described.

IV. DESIGN AND IMPLEMENTATION

A. VI Protection

VI protection provides over-voltage, over-current, short circuit, low voltage, low current, and battery over-discharge protection. A current sensor continuously monitors and measures the voltage and current of the circuit and transmits the data to the MCU [Fig.2] . The MCU can be programmed to set a predetermined voltage and current limit. Suppose the voltage or current exceeds this limit (higher or lower). In that case, the MCU sends a signal to the MOSFET switch, and the switch disconnects the battery positive and battery negative both from the circuit (As it is better to disconnect the battery positive and negative both from the circuit rather than just disconnecting the battery positive for safety). This effectively protects the circuit from over-voltage, over-current, short circuit, low voltage, low current, and battery over-discharge, preventing damage to the components and ensuring safe operation.

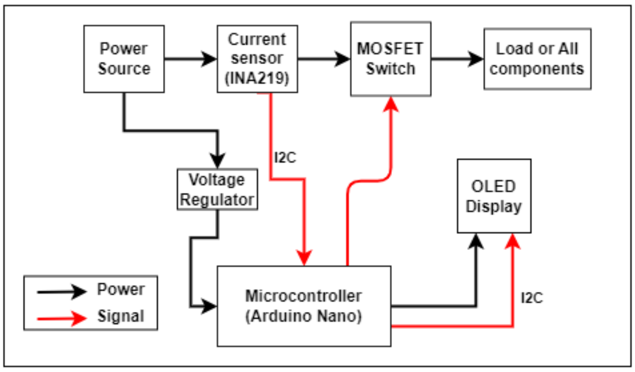

Fig. 2. VI Protection (Circuit Diagram)

MOSFET Switch:
The MOSFET switch is made of 3 MOSFETs. One N-channel and one P-channel MOSFET work together as the first part of the switch; MCU sends an ON-OFF signal to the gate of the N-channel MOSFET and this MOSFET controls the P-channel MOSFET [Fig.3].

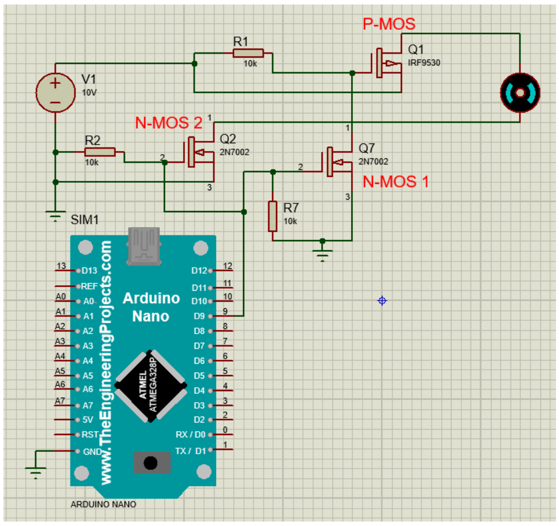

Fig. 3. MOSFET Switch (Simulation circuit)

This P-channel and N-channel MOSFET work together as the first part of the switch, which disconnects the battery positive from the load.Another N-channel MOSFET is connected with the battery negative and load, which disconnects the battery negative from the circuit. The gate of both N channel MOSFET is shorted together and must be controlled by the same digital pin of MCU for ON/OFF the circuit. In the circuit, when disconnecting the power source for safety purposes, we disconnect both the positive and negative terminals of the power source, as it is better to disconnect the battery positive and negative both from the circuit for complete isolation rather than just disconnecting the battery positive for better safety.

B. Thermal Protection

A thermistor is a variable resistor; when the temperature changes, the resistance value of the thermistor gets changed, and comparing this with a fixed-valued resistor, it measures the temperature. Here the thermistors are used to check the temperature of the components (The components that has a chance to overheat). The thermistor sends the temperature value to the MCU. A normal, high, and extremely high temperature is assigned to the firmware before. Suppose any component's temperature crosses the high-temperature limit. In that case, the cooling fan is turned on by the MCU with the MOSFET switch. If any component's temperature crosses the extreme temperature limit, the MOSFET switch (as described before using two N-channel and one P-channel MOSFET) is turned off by the MCU so that the whole power of the circuit gets turned off [Fig.4].

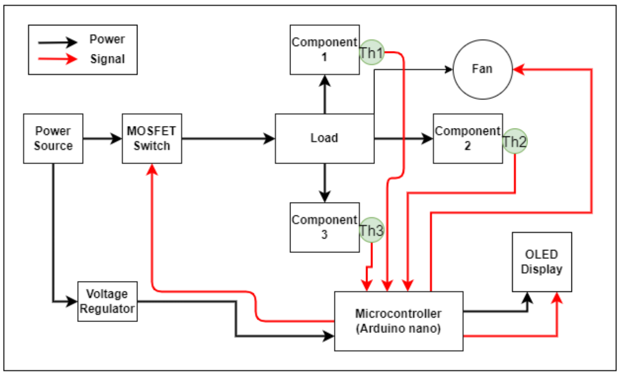

Fig. 4. Thermal Protection(Circuit diagram)

C. Reverse polarity, reverse current and residual charge protection

One N-channel MOSFET and a P-channel MOSFET are used in the circuit as the first part of the switch and this same thing and mechanism is used for the reverse current and reverse polarity protection. MCU sends a signal to an N-channel MOSFET that controls a P-channel MOSFET. This P-channel and N-channel MOSFET work as a switch, but this switch doesn't turn on if the polarity is not in the right way. In the circuit, there is a MOSFET switch at the beginning of the power line [Fig.5], so if someone connects the battery positive-negative in the wrong direction the switch remains closed and the circuit does not burn out. Similarly, another MOSFET switch is connected before every motor or similar component that can give back EMF; to protect the circuit from reverse current. That's how the circuit is being protected from Reverse polarity and reverse current.

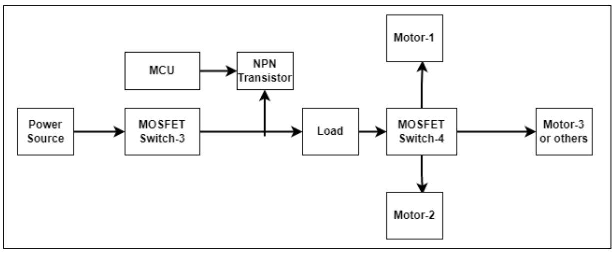

Fig. 5. Reverse polarity, reverse current and residual charge protection

After turning off the circuit, some extra charges are stored in the capacitor or other components; sometimes that residual charge also can damage the circuit. An NPN Transistor is used between the load's positive and negative terminals to solve this issue. The MCU controls the transistor. When the circuit is turned off for any reason, the MCU activates the transistor for 2 seconds; this transistor shorts the load's positive and negative terminal and discharges the stored charge or residue charge. That's how the circuit is protected from residual charge problems.

D. Comprehensive Circuit Protection Method (CPM)

Comprehensive Circuit Protection Method is built by combining all of the above subsystems [Fig.6]. This method proposes 10 types (over-voltage, over-current, low current, low voltage, short circuits, battery over-discharge, reverse polarity, reverse current problems, thermal protection, and residual charge protection) of protection altogether for the whole rover circuit. For executing the method, the current sensor measures the voltage and current value; the thermistor measures the temperature value; MCU processes everything and controls the circuit's power ON-OFF using the MOSFET switch if any parameter crosses the safe limit.

For reverse polarity and reverse current protection, two MOSFET switches are used; one is at the beginning of the power line for reverse polarity protection and another is before motors or components that can give reverse current in the circuit. For residual charge protection, an NPN transistor is used.

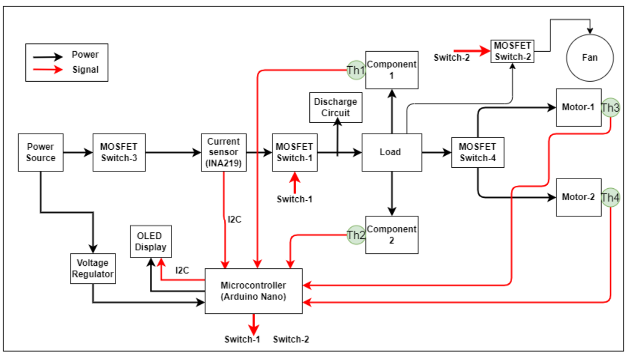

Fig. 6. Comprehensive Circuit Protection Method (Circuit diagram)

V. EXPERIMENT AND RESULT

A. VI Protection

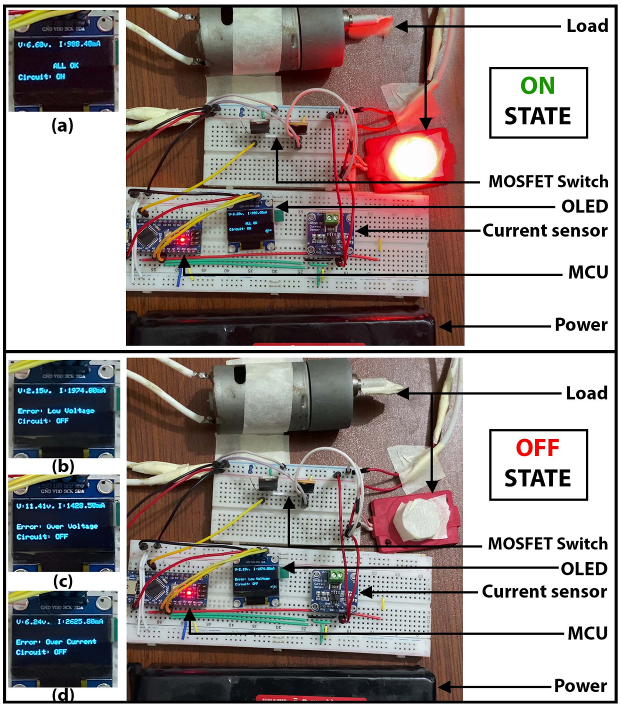

Fig. 7. VI protection (Breadboard Model)

The current sensor (INA219) measures the voltage and current of the circuit continuously, sends the data to MCU (Arduino nano), and prints the value of voltage and current on the OLED display. For the tests here 12v Li-po battery is used as the power source and a 12V DC motor and 12V LED are used as load. A predetermined value for each parameter is set on the firmware (for test purposes in this breadboard model, lower Voltage= 5V; Higher Voltage= 11V; Lower current = 50mA; Higher current= 1500mA.). Users can set any value as threshold value as per their requirement as threshold or limit values are user-defined.
In figure-7(a), all the parameters are normal so the circuit is on (LED on, motor on). In figure-7(b) voltage is lower (2.15V) than the limit so for safety purpose circuit is turned off (LED and Motor off).In figure-7(c) current is normal but the voltage crossed the limit (11.41V) so the circuit is turned off. Similarly, in figure-7(d) the voltage is normal but the current (2625.80mA) cross the limit so the MCU sent the signal to the MOSFET switch gate and turned the circuit off to save it from over current or short circuit. That's how the current sensor helps to shield the circuit.

MOSFET Switch:
Three MOSFETs make up the MOSFET switch (figure-8). As the initial component of the switch, one N-channel and one P-channel MOSFET cooperate; the MCU (Arduino Nano) delivers the ON-OFF signal to the N-channel MOSFET's gate, and this MOSFET controls the P-channel MOSFET. Together, this P-channel and N-channel MOSFET switch separate the battery positive from the load. In order to disconnect the battery negative from the circuit, another N-channel MOSFET is linked to the load negative and the battery negative. The gate of both N-channel MOSFETs is shorted together and controlled by the same digital pin of the MCU. That's how disconnects both the positive and negative terminals of the power source from the circuit to protect it in crucial situations. In figure-8 both the ON and OFF states of the switch have shown and the switch worked properly.

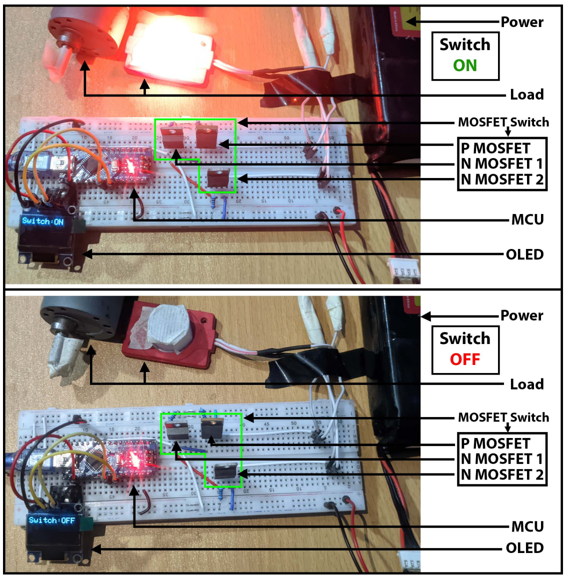

Fig. 8. MOSFET Switch (Breadboard model)

B. Thermal Protection

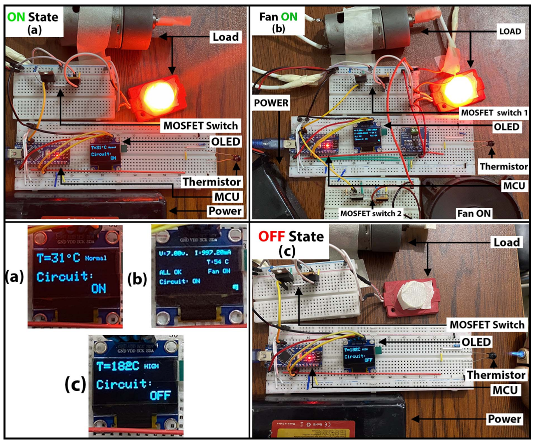

Fig. 9. Thermal Protection (Breadboard Model)

Here a 10k thermistor is used. MCU takes the thermistor value and compares it with a 10k resistor and measures the actual temperature. For test purposes, in firmware, some preconditions are declared. The temperature range below 50°C is set as a normal temperature. If the temperature is greater than 50°C the cooling fan will turn on automatically with the help of the MOSFET switch, then at 65°C it will give a warning message or notification, and after crossing 70°C the circuit will be turned off by the MCU with the

MOSFET switch (As threshold or limit values are user-specified, a user may specify any value as a threshold value to suit their needs and different limit value for different components also). In the breadboard model figure-9(a) the temperature is 31°C, which is below 50°C, which is why the OLED display shows T=31°C normal and the circuit remains on. In figure-9(b) the temperature rises to 54°C which is why the MCU turns on the cooling fan with the MOSFET switch. In figure-9(c) temperature crosses the over-temperature limit(70° C). For this in OLED display, it shows temperature High and the circuit turns off by the MCU with the MOSFET switch. That's how using some thermistors in many points or on components in the circuit, it is possible to recover or resolve the circuit's thermal problem and if the situation goes beyond the tolerance level it turns off the circuit and gives the circuit and component's thermal protection.

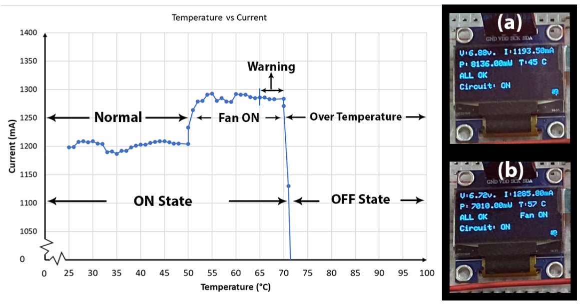

Fig. 10. Thermal Protection (Temperature Vs Current graph data)

Figure-10 is the temperature Vs current graph from our experimental data. From 25°C to 50°C temperature is determined as normal, so (at figure-10(a) 45°C) the circuit is on, and 1193mA current is flowing through the circuit. When the temperature crosses 50°C (at figure-10(b) 57°C), the fan turns on as the cooling system of the circuit and current draw increased to 1285mA. At 65°C circuit sends a warning message or notification. When the temperature crosses the highest limit of 70°C the circuit is turned off and so the current flow through the circuit is 0mA.

C. Reverse polarity, reverse current and residual charge protection

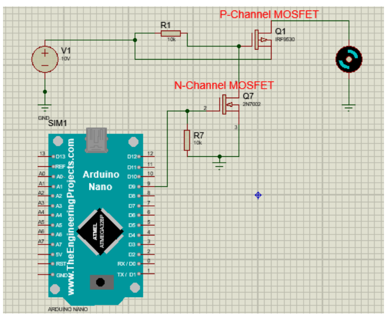

Fig. 11. MOSFET Switch 1st part (only for reverse polarity and reverse current protection)

Figure-11 shows a simulation of an N- and P-channel MOSFET as a switch, An N-channel MOSFET receives the signal from the MCU, and that N-channel controls a P-channel MOSFET. But if the polarity of the voltage source is connected in the wrong way, the switch will not operate and remain closed. That's how the circuit is protected from reverse polarity and reverse current.

D. Comprehensive Circuit Protection Method

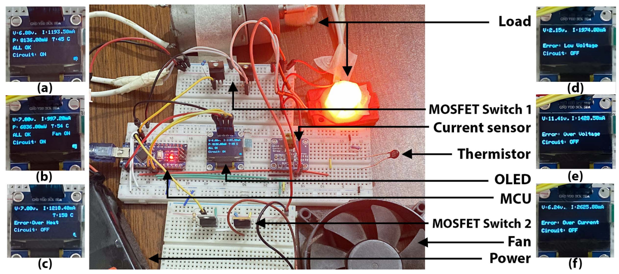

Fig. 12. Comprehensive Circuit Protection Method (Breadboard Model)

In the breadboard model, the current sensor (INA219) is measuring the voltage and current; the thermistor (10K) is measuring the temperature of the component; and the MCU (Arduino Nano) is processing data and ON-OFF fan or the whole circuit if needed to protect the circuit. After creating various situations of the rover circuit problems, the breadboard model of the protection method was tested, and here in figure-12 six of the situations and test results are given. In figure-12(a) all the parameters are perfect and normal, the OLED display is showing the measured values and the circuit is running well. In figure-12(b) everything is fine but the temperature (54°C) is a little higher than the normal temperature so the cooling system (Fan) is turned on. In figure-12(c) the temperature (158°C) crossed the limit of extremely high temperature (70°C set on the code for this test), so the circuit is turned off by the MCU using the MOSFET switch. In figure-12(d) Voltage is so much lower (2.15V) than the predetermined voltage so the circuit is off. Similarly, in figure-12(e) voltage(11.41v) crossed the higher limit of voltage, and the circuit is turned off for safety purposes. Lastly, in figure-12(f) the circuit current (2625.80mA) crossed the safe limit (as a short circuit happened), so the MCU turned off the circuit using the MOSFET switch. Two additional MOSFET switches are utilized for protection against reverse polarity and reverse current; one is placed at the start of the power line for reverse polarity protection, and the other is placed before motors or other circuit components that could produce reverse current. If the positive and negative terminals of the battery are connected in reverse, the circuit is not affected; instead, it gets disconnected because the MOSFET gate does not open. Similarly, if there is any occurrence of back EMF or reverse current from any components, it is unable to cause damage to the circuit as the MOSFET gate does not open. That's how this comprehensive circuit protection method ensures the safety and dependability of the rover circuit. Protect the circuit and components from being damaged in almost every possible way.

Algorithm 1 Comprehensive Circuit Protection Algorithm

Data: $V, I, (T1, T2, T3, ..., TN)$
Result: Circuit OFF; circuit ON; Fan ON
Function *ProtectionAlgorithm*
  if $V <$ *LowerV or* $V >$ *HigherV or* $I <$ *LowerI or* $I >$ *HigherI or* $T1 >$ *EH_Temp1 or* $T2 >$ *EH_Temp2 or* $T3 >$ *EH_Temp3 or ... or* $TN >$ *EH_TempN* **then**
    $0V$ on MOSFET Switch-1 gate $5V$ on NPN Transistor $Delay2second$ $0V$ on NPN Transistor **if** $V <$ *LowerV* **then**
      print "Low voltage or over discharge"
    end
    else if $V >$ *HigherV* **then**
      print "Over voltage"
    end
    else if $I <$ *LowerI* **then**
      print "Low current"
    end
    else if $I >$ *HigherI* **then**
      print "Over current"
    end
    else if $T1 >$ *EH_Temp1* **then**
      print "Component 1 is overheated"
    end
    else if $T2 >$ *EH_Temp2* **then**
      print "Component 2 is overheated"
    end
    else if $T3 >$ *EH_Temp3* **then**
      print "Component 3 is overheated"
    end
    else if ... **then**
      ...
    end
  end
  else if $T1 >$ *H_Temp1 or* $T2 >$ *H_Temp2 or* $T3 >$ *H_Temp3 or ... or* $TN >$ *H_TempN* **then**
    $5V$ on MOSFET Switch-2 print "Turn on fan"
  end
  else
    Trigger the MOSFET Switch-1 print "All OK"
  end

CONCLUSION AND FUTURE WORK

Almost all potential problems that can occur on the rover circuit are solved by our circuit protection approach, which encompasses a comprehensive set of 10 distinct circuit protections, And we were successfully able to provide all of these 10 protection one by one and altogether perfectly in our breadboard model. For the proposed circuit protection, initially, we simulate all the protections system individually and then combine all of them together and make comprehensive and holistic circuit protection in the breadboard model. All the sensors and switches performed flawlessly and we were able to get accurate readings and detect the circuit issues faster and act or respond to these issues faster.

Future directions for improving the system may involve creating algorithms for detecting the issues faster and making the microcontroller respond faster. Predict circuit problems (e.g., short circuit, overheating) by analyzing data, parameter relations (current, voltage, temperature), and patterns. As our rover is a rescue rover and it operates in uneven situations, we want to make a waterproof and fireproof circuit box to shield the circuit from water and fire. In this paper, we just tested the breadboard model; however, we will implement this protection method in our rover circuit.

ACKNOWLEDGMENT

We extend our appreciation to every member of the BracU Dichari team.

NOMENCLATURE

CPM Comprehensive Circuit Protection Method
EMF Electromotive Force
MCU Microcontroller Unit
$MOSFET$ Metal-Oxide-Semiconductor Field-Effect Transistor
$OLED$ Organic Light-emitting Diode
$VIprotection$ Voltage and Current related Protections

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