Monitoring Temperature of IGBT with Embedded NTC Thermistor

Vijit Dubey
Electrical and Computer Engineering
Texas A&M University
College Station, Texas, USA
vijit4072@tamu.edu

***Abstract*— Induction heating machines use IGBT to switch near LC tank's resonant frequency. IGBT gets hot over time due to switching losses. The IGBT heat sink plate is connected to a chill plate, which is usually water cooled. Due to using impure cooling water or putting low water pressure through the chill plate there is a decline in heat exchange, resulting in IGBT getting too hot. This paper discusses, using NTC thermistor embedded on the IGBT heat sink plate to monitor the temperature. The circuit board can monitor upto 9 IGBTs and display an alarm notification on PLC-HMI.**

***Index Terms*— IGBT temperature, switching losses, NTC thermistor, induction heating, voltage divider, Opto-coupler, timer circuit, noise filtering.**

I. Introduction

Induction heating is the process of heating an electrically conducting object by electromagnetic induction due to eddy currents. An induction heater consists of an electromagnet and an electronic oscillator that passes high frequency through the electromagnet [1]. Due to high frequency eddy currents, the metal gets hot. Ferromagnetic and ferromagnetic materials like iron, heat may also be generated by hysteresis. The frequency of current passing through is inversely proportional to the depth of penetration of heating. Frequency is usually 5-30 KHz for thick materials, 100-400 KHz for small workpieces and 480 KHz and above for microscopic pieces. For switching purposes, either an IGBT (insulated-gate bipolar transistor) or a MOSFET (metal–oxide–semiconductor field-effect transistor) is used. IGBT is used for high power applications (greater than 5KW) and MOSFET is used for low power applications (less than 500W). Interpower Induction Inc. usually makes machine for small work pieces, at 100-400 KHz for 5KW to 5000KW applications.

IGBT have an NTC (negative temperature coefficient) thermistor embedded to their heat sink plate. FF900R12IP4 is used in few models of induction machine at Interpower Induction Inc. [2] Figure 1 shows the picture of the IGBT and Figure 2 shows the circuit diagram of the IGBT. Here pin 6, 7 represent the terminals of NTC thermistor.

Figure 1: IGBT FF900R12IP4

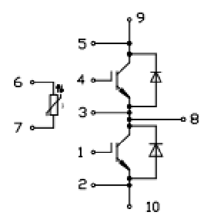

Figure 2: IGBT FF900R12IP4 circuit diagram

NTC-Thermistor

This IGBT comes with a thermistor measuring the base plate's temperature to ease the design of accurate temperature measurement [3]. It is isolated from rest of the module using an isolation gel. The majority of the heat in the chip flows directly through the baseplate towards the NTC's position [3]. Since the heat flow is not instantaneous, NTC only represents temperature in static points of operation. The transient phenomena like heat generated due to short circuit conditions cannot be monitored as the detected correlating time constants are far too small. NTC resistance is exponentially proportional to the temperature [2]. Figure 3 shows the graph between resistance and temperature as per the information provided by the manufacturer. The NTC has an accuracy of $\pm$0.1°C. The power rating of the thermistor in FF900R12IP4 is 20mW. Hence, the monitoring circuit has to be designed at low power.

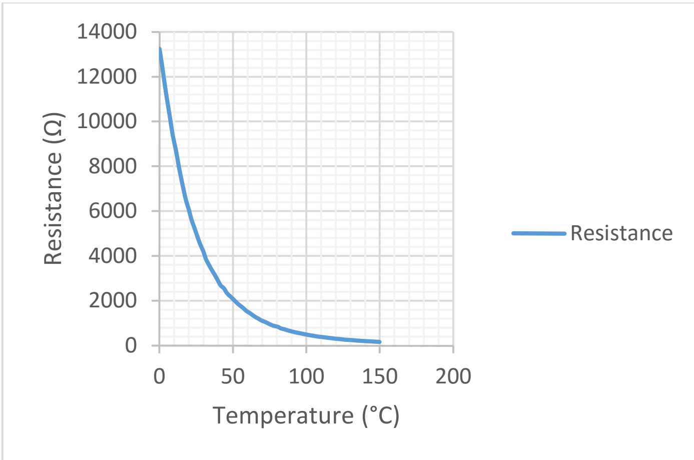

Figure 3: Rated Resistance vs Temperature

Temperature measurement circuit with NTC

The basic approach is based on a voltage divider, where voltage across each element changes with change in resistance. Since NTC is non-linear, using it in parallel with another resistance in a voltage divider will make the Voltage vs Temperature graph linear. Also, keeping the resistance of R1 high and R2 relatively smaller will make the voltage response more sensitive. After calculations, R1 was decided to be 200KΩ (1/4 W) and R2 as 3.3KΩ (1/4 W). As per the datasheet [2], the NTC resistance can go to the extremes of 13.5KΩ at 0°C to 126Ω at 150°C. Hence, the parameters will vary between the values in Table 1. The parameters are calculated for 0°C and 150°C respectively. Voltage across R2 is used to estimate the temperature the NTC is responding to.

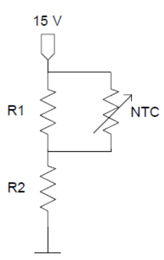

Figure 4: Voltage divider circuit

TABLE I
PARAMETERS IN VOLTAGE DIVIDER CIRCUIT AT 0°C AND 150°C

	Temperature 0°C	Temperature 150°C
Voltage input (V)	15.00	15.00
NTC resistance (Ω)	13257.00	126.00
R1 (Ω)	200000.00	200000.00
Effective parallel resistance (Ω)	12432.89	125.92
R2 (Ω)	3300.00	3300.00
Total effective resistance (Ω)	15732.89	3425.92
Overall current (mA)	0.95	4.38
Voltage across R2 (V)	3.15	14.45
Voltage across NTC (V)	11.85	0.55
Current through NTC (mA)	0.89	4.38
Power dissipated by NTC (mW)	10.60	2.41

II. Calculations

Discretizing the curve on the datasheet and trying to fit it into an equation gave the Resistance vs Temperature as below. Here, R_{ntc} refers to NTC resistance and T refers to temperature in Celsius.

$$R_{ntc} = 219.6985 + (13164.9523 * e^{-0.039784*T})$$

Solving for calculating voltage across R2 with respect to change in R_{ntc} was observed to be as below.

$$V_{R2} = \frac{49170}{0.9877 * R_{ntc} + 3300}$$

Merging both of the equations above the voltage across R2 with respect to temperature was observed to be as below.

$$V_{R2} = \frac{49170}{3516.996 + 13003.02 * e^{-0.039754*T}}$$

Now, a specific temperature would give a specific voltage output. This voltage signal can be measure by a PLC-HMI to give an output temperature to the user. Figure 5 shows the expected curve after calculations of Voltage across R2 vs temperature sensed by NTC.

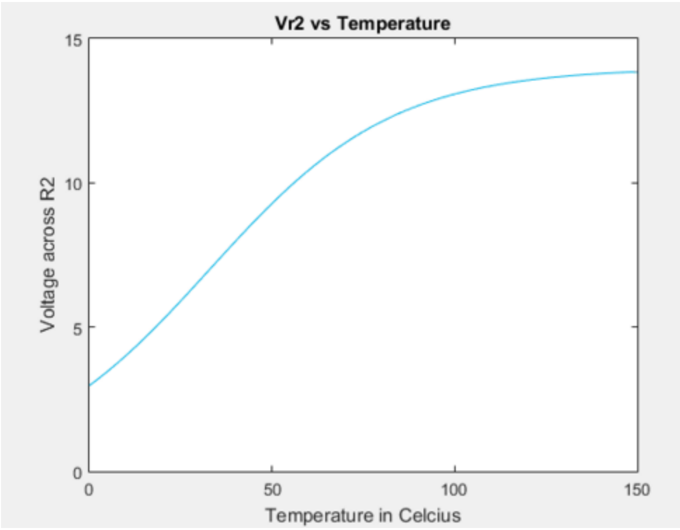

Figure 5: Calculated plot of expected voltage across R2 at different IGBT temperatures

While testing the circuit with a machine, it was observed that the NTC gets a lot of noise from the IGBT module. The IGBT switches at a frequency near resonance of the LC tank. Hence, to filter out the noise, a 220uF (35V) capacitor was added across R1 and a 0.1uF capacitor was added across R2. Using oscilloscope it was observed that after adding the capacitors the signal was noise free even at full load. The new voltage divider had a basic idea as shown in figure 6.

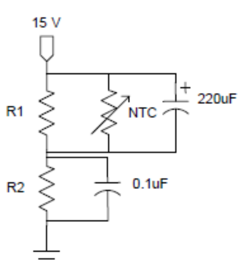

Figure 6: Modified voltage bridge circuit for removing noise coming from NTC resistor

A Unitronics PLC is used in the machines made by Interpower Induction Inc. Figure 7 shows the Input-output module of Unitronics. Most of the input ports were used for other functions in the machine. So using an input for each IGBT thermistor would not be feasible. It was decided to make a timer circuit, which would switch between IGBTs and refresh temperature after some time. This way one analog input and one digital input are needed for monitoring any number of IGBTs. The selection can be done using opto-couplers.

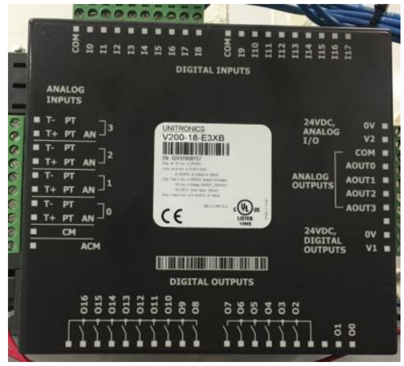

Figure 7: Unitronics Input-Output module

Switching circuit

A timer circuit was made using a NE555 IC in astable circuit mode. The high time was set to 1.006 seconds and low time to 503.118 milliseconds [4]. This was done using a 220uF capacitor and two 3.3KΩ resistors. The IC produced a square wave with time period of 1.509 seconds. The circuit diagram is shown in schematic in page 3a. The output signal of NE555 was used as a clock signal of decade counter. CD4047BE IC was used as a decade counter. Decade counter counts each time it receives a rising edge to its clock signal (pin 14) [5]. Once the reset input (pin 15) gets high, it starts counting from the beginning. Hence, each output is connected to selector pins. Jumping a pin with reset bus will select that count as reset. If pin 4 is jumped with reset then it will reset the moment IC counts to 3. Hence, it will keep switching between 1 and 2. The output from pin of the decade counter goes into anode of optocoupler. In the circuit designed PS2501-4 is used [6]. While decade counter switches, current would flow through the corresponding GaAs diode hence enabling the corresponding NPN silicon phototransistor. Figure 6 shows the PS2501-4 IC circuit diagram. If current flows from 1 to 2 it would gate the NPN photo transistor and let current flow from 16 to 15. This would let us switch between different IGBT thermistors. The output of NE555 (pin 3) goes as digital input to the PLC and voltage across R2 goes as analog input to the PLC. Both grounds are common and are kept in reference to the circuit.

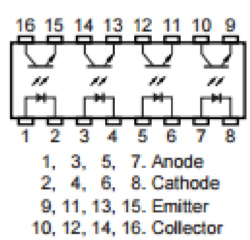

Figure 8: PS2501-4 circuit diagram

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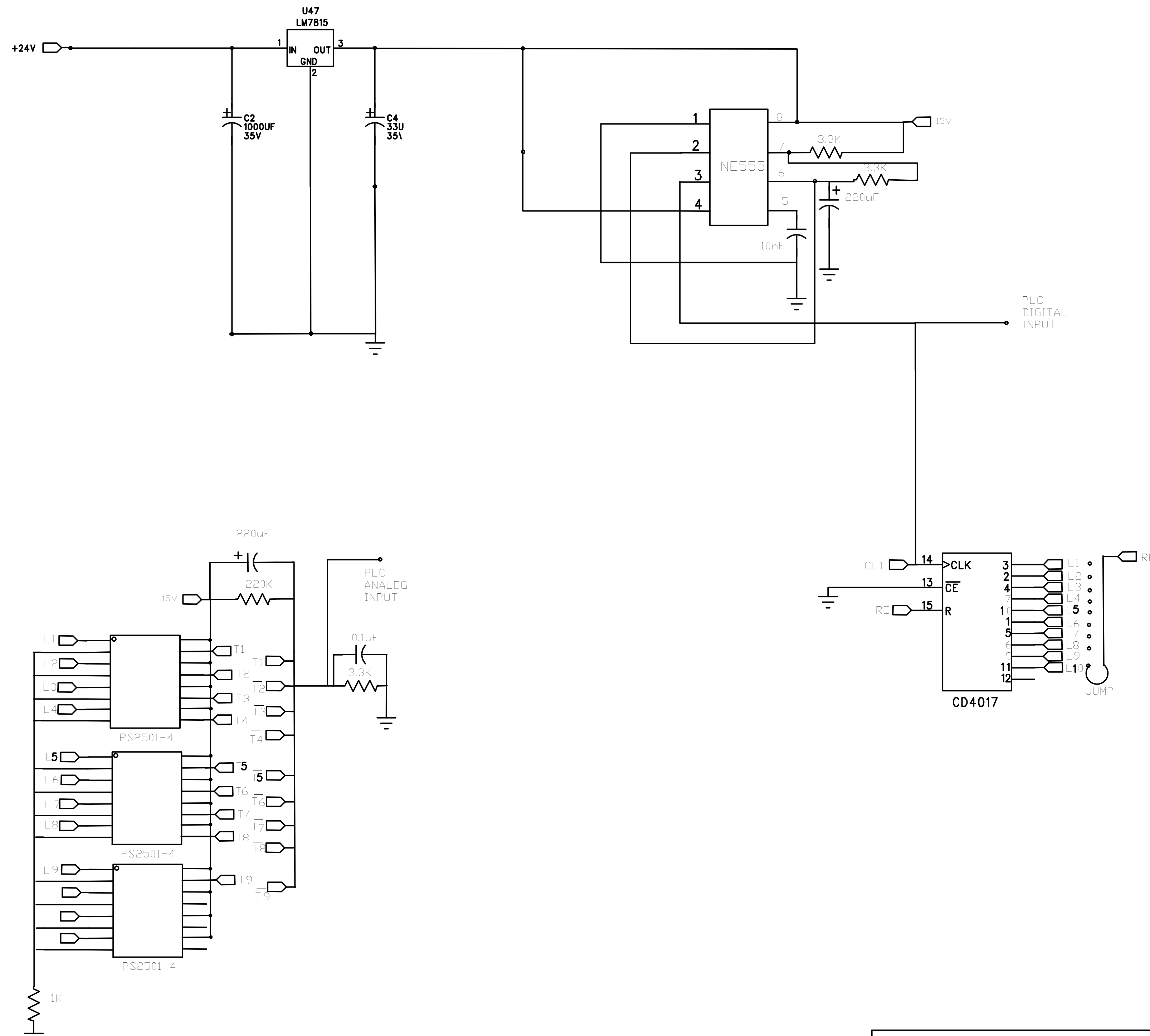

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Making a PCB

After testing the circuit on a breadboard, a printed circuit board was designed using Eagle CAD. The board was assigned company part number LM5025. The output from the Eagle looked as in figure 9. The Gerber of the different layers of board were exported and sent for printing to K&F Electronics. Figure 10 and 11 show the board received after printing.

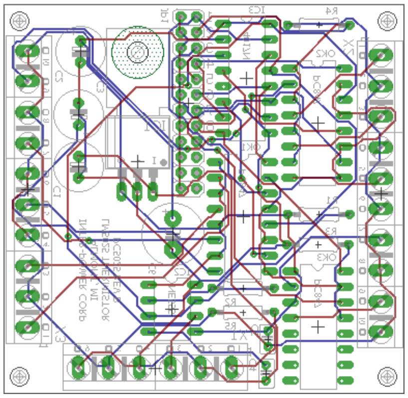

Figure 9: Circuit board designed in Eagle CAD

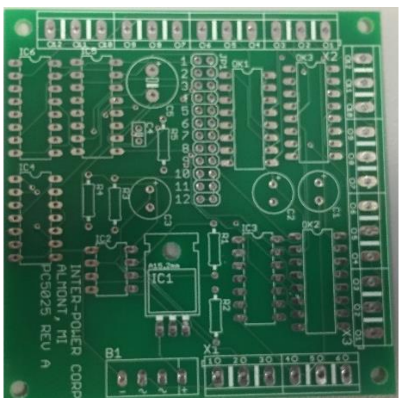

Figure 10: PCB received from K&F Electronics

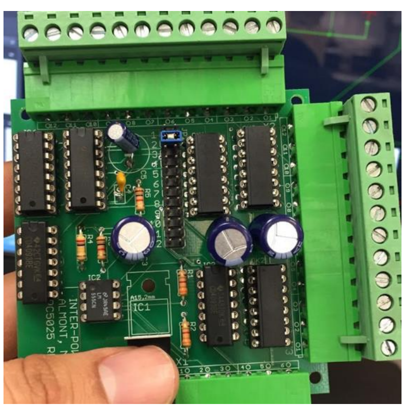

Figure 11: Assembled testing PCB

III. Testing the Board and Results

The setup after soldering board was tested with an Interpower machine. The machine had 2 IGBTs. Hence, the NTC thermistors were connected to corresponding to 1 and 2. The jumper was put to the pin next to marker pointing 2 so that it switches between two thermistors. Output from pin three of NE555 was sent to digital input 5 and voltage across R2 was sent to analog input 0 of Unitronics I/O module.

The board went through two tests. In first test, the machine was run at different % load levels and the voltage output read through the PLC was used to trace the resistance of the NTC. Then using a multimeter the resistance of the NTC was recorded. The deviation was found to be under 200Ω. In the second test, the IGBT heat sink plate was manually heated using a power resistor, fed using an autotransformer, shown in figure 12. A thermo-compound is added between the heat sink plate and the power resistor dissipation plate for uniform heating. The difference in reading between the calculations and the practical result was not huge. Figure 13 and Table 2 discuss various parameters.

TABLE II

COMPARISON BETWEEN THEORETICAL AND PRACTICAL VALUES

Vplc	Resistance calculated by PLC (Ω)	Resistance observed manually (Ω)	Temp as per PLC (°F)	Temp actual (°F)	Difference in temperature (°F)
5.3	6052	6590	68.83	66.2	-2.63
5.6	5548	5860	72.91	70.34	-2.57
6	4956	5200	78.2	76.1	-2.1
6.3	4561	4880	82.19	79.16	-3.03
6.7	4089	4290	87.39	85.1	-2.29
7	3771	3900	91.28	91.4	0.12
7.3	3478	3631	95	93.2	-1.8
7.6	3209	3276	99.06	98.96	-0.1
8	2882	2956	104.31	104.3	-0.01
8.3	2657	2735	108.31	108.3	0.01
8.6	2447	2555	112.4	112.1	-0.3
8.9	2252	2328	116.5	116.6	0.1
9.2	2070	2100	120.8	120.7	-0.06
9.5	1899	1920	125.15	125.2	0.09
9.9	1687	1719	131.25	131.4	0.11
10	1637	1645	132.82	133	0.16

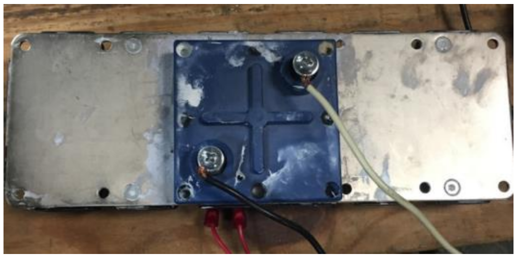

Figure 12: IGBT heat sink manually heated using a power resistor.

Unitronics PLC does not have the feature to input non-linear equations in logic. Hence, by using 200KΩ in parallel to NTC and both of them in series to 3.3KΩ, makes the voltage across R2 to behave almost linearly as NTC resistance changes from 60°F to 130°F. After curve fitting, the approximate linear relationship between the voltage across R2 and temperature (°F) of IGBT was found to be following.

$$T = 13.47532 * V_{R2} - 2.95217$$

This equation gives values accurate up to 3°F. The equation gives more accurate values as the temperature increases. Getting accuracy at higher temperatures is of higher priority than at lower temperatures.

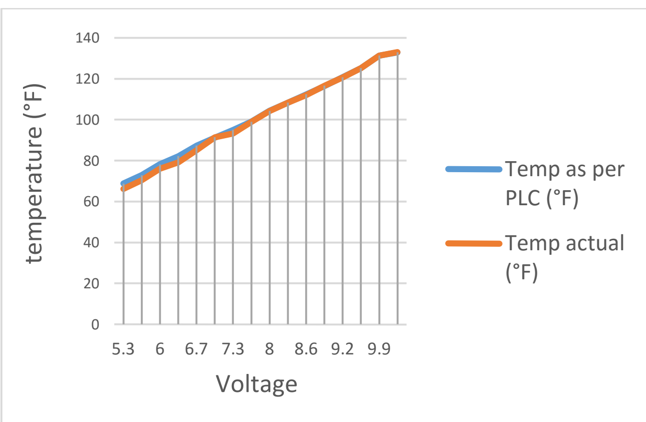

Figure 13: Plot showing variation between temperatures read by PLC vs temperature calculated theoretically by calculations

PLC has been programmed to select the number of IGBTs the circuit board is monitoring. User has to jump the same number on the board that is selected on the HMI. The circuit goes though the same sequence each time. So, each IGBT has to be classified with a number so that information of correct IGBT is shown on the screen. Figure14 shows HMI screen which monitors 3 IGBTs. The logic was set to show "Not Monitored" status at or below -0.2°F, "Okay" status between -0.2°F and 78°F and "Too Hot" status above 78°F. IGBT 1 and 2 are at 80°F and are showing a status of "too hot". IGBT 3 is at 0°F and is showing a status of "not monitored".

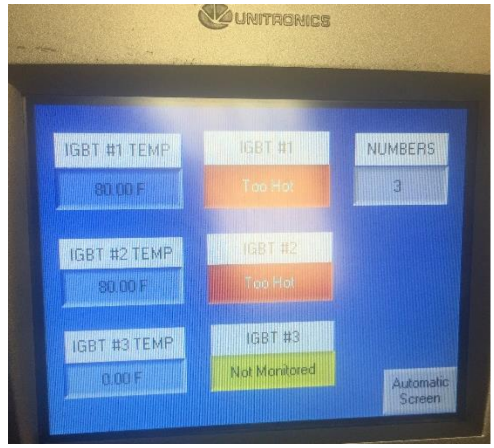

Figure 14: HMI screen showing status of 3 IGBTs.

IV. Conclusion

This paper discussed a new circuit designed to monitor temperature of up to 9 IGBTs using a thermistor embedded to the heat sink plate. The PCB was put to an existing induction heating machine and was tested at full load. The circuit gave one digital and one analog feedback to the PLC-HMI. After testing, the accuracy was found up to 3°F. The board can be used in such induction machines in the future.

References

[1] V. Rudnev, Handbook of induction heating. New York: Marcel Dekker, 2003.
[2] FF900R12IP4 Datasheet, Infineon Technologies, 2015.
[3] Using the NTC, Infineon Technologies, 2015.
[4] LM555 Timer, 1st ed. Texas Instruments, 2015.
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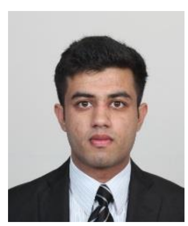
[6] Photocoupler, California Eastern Laboratories, 2015.



Vijit Dubey was born in Hamirpur, Himachal Pradesh, India in 1991. He received his B.E. degree in Electrical Engineering from Punjab Engineering College (PEC). He is currently pursuing his M.E. in Electrical Engineering from Texas A&M University. His research interests are in switching power supplies.