Think City Precharge Circuit Behavior Modification

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Introduction

We have not been able to pinpoint the cause of the precharge resistors overheating, but without expending considerable resources to further research the problem and then devise a solution, we can still prevent the problem from occurring by controlling its enabling conditions. It is most conservative to assume that the failure mode is effectively a direct short between the positive and negative battery cables. If we reprogram the BMS contactor closing sequence to prevent the precharge resistor from overheating in this scenario, then we can eliminate the MLEC failure problem that has left Think owners stranded, frustrated, without a car for days at a time, and will eventually leave them with a significant repair bill. (If rebuilt MLECs continue to fail (become unrepairable) and the replacement MLEC supply runs out, it will eventually render the cars completely unrepairable.) Resolution of this problem will require assistance from Enerdel to modify the programmed behavior of the contactor closing sequence according to the recommendations in this proposal.

Proper operation of the precharge resistor circuit

The function of the precharge resistor is to limit current flow from the battery to a large capacitor external to the battery. In the case of the Think, that capacitor is 1,000 µF and is located inside the Power Conversion Unit (PCU). A capacitor is an electrical component that stores electric charge, and in an instantaneous circuit analysis can be thought of as a voltage source. A fully discharged capacitor acts like a 0V source for the first instant that it is connected to a circuit. If the battery were to be connected directly to the discharged capacitor, the only resistance to current flow would be the very low resistance of the cables. Using Ohm's Law, any voltage (let alone 400V) divided by a very small resistance will equate to an extremely high current. This high current would damage the cables and the battery internally. The precharge resistor limits the current flow, allowing the capacitor voltage to safely approach the voltage of the battery until it is close enough that the main contactors can close without arcing, connecting the battery directly to the capacitor (and other power electronics) and bypassing the precharge resistor. After the main contactors close the precharge contactor opens to completely remove the resistor from the circuit.

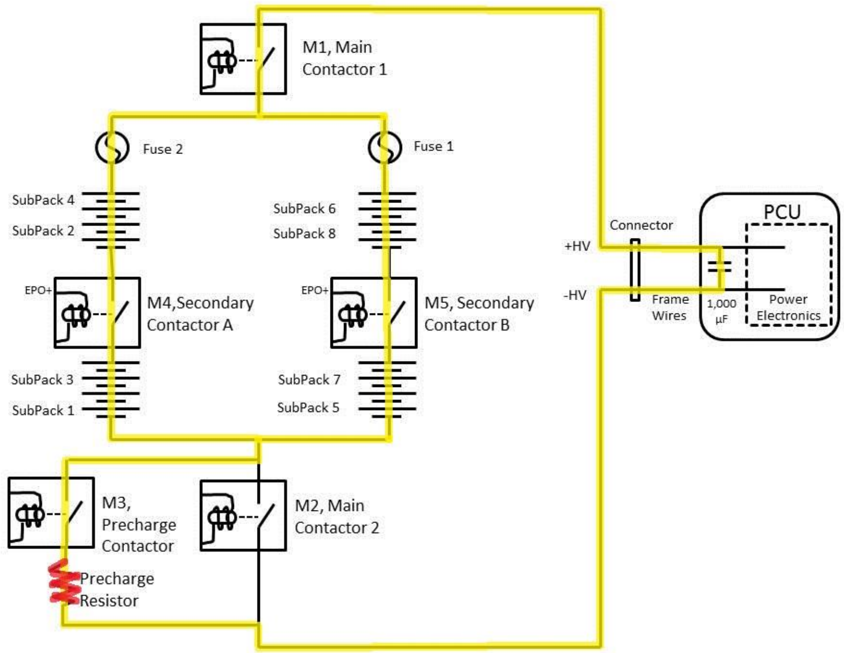

Figure 1. Simplified schematic illustrating current flowpath during precharge.

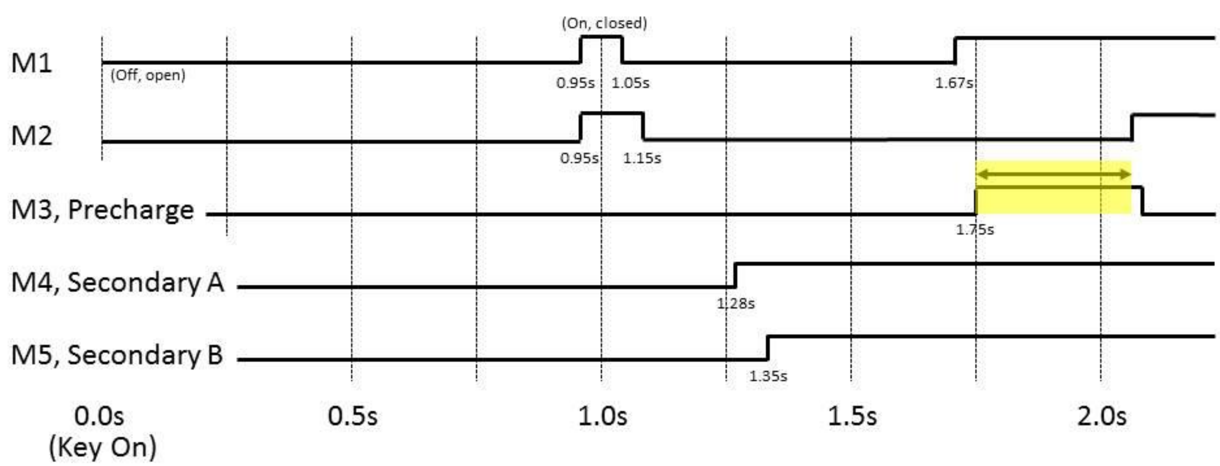

Figure 2. Contactor closing sequence illustrating the period during which the precharge resistor is energized during normal start-up operation. (Times are approximate)

The voltage across the precharge resistor in this resistive-capacitive circuit is given by the following equation:

$$v(t) = v_0 e^{-\frac{t}{RC}}$$

The BMS is programmed to close contactor M2, bypassing current around the precharge resistor, when the capacitor voltage reaches 95% of battery voltage. To calculate the time required for the PCU capacitor voltage to rise to 95% of battery voltage (voltage drop across the resistor is 5% of initial voltage):

$$\frac{v(t)}{v_0} = 0.05 = e^{-\frac{t}{RC}}$$

$$\ln 0.05 = -\frac{t}{RC}$$

$$t = -(\ln 0.05)RC$$

$$R = 47\Omega \qquad C = 1000\mu F$$

Based on this calculation, the capacitor should be charged to 95% of battery voltage in 0.141 seconds.

The current through the resistor is simply obtained by dividing the voltage by the constant resistance, and the power dissipated in the resistor is simply the product of the voltage and current, simplified in the following equation:

$$w(t) = \frac{v_0^2}{R} e^{-\frac{2t}{RC}}$$

Integrating this equation over the time that the resistor is energized results in the total energy absorbed by the resistor:

$$H(t) = \int_0^t w(t)\,\partial t = \frac{v_0^2 C}{2}\left(1 - e^{-\frac{2t}{RC}}\right)$$

If the circuit operates as designed, the resistor will only be energized for 0.141 seconds resulting in 80 Joules of energy released as heat. (This is 99.7% of the maximum energy that would heat the resistor regardless of how long it was energized as long as no current is allowed to bypass the capacitor.) The single impulse energy rating of 700 Joules for the precharge resistor is easily sufficient to handle this 80 Joule event.

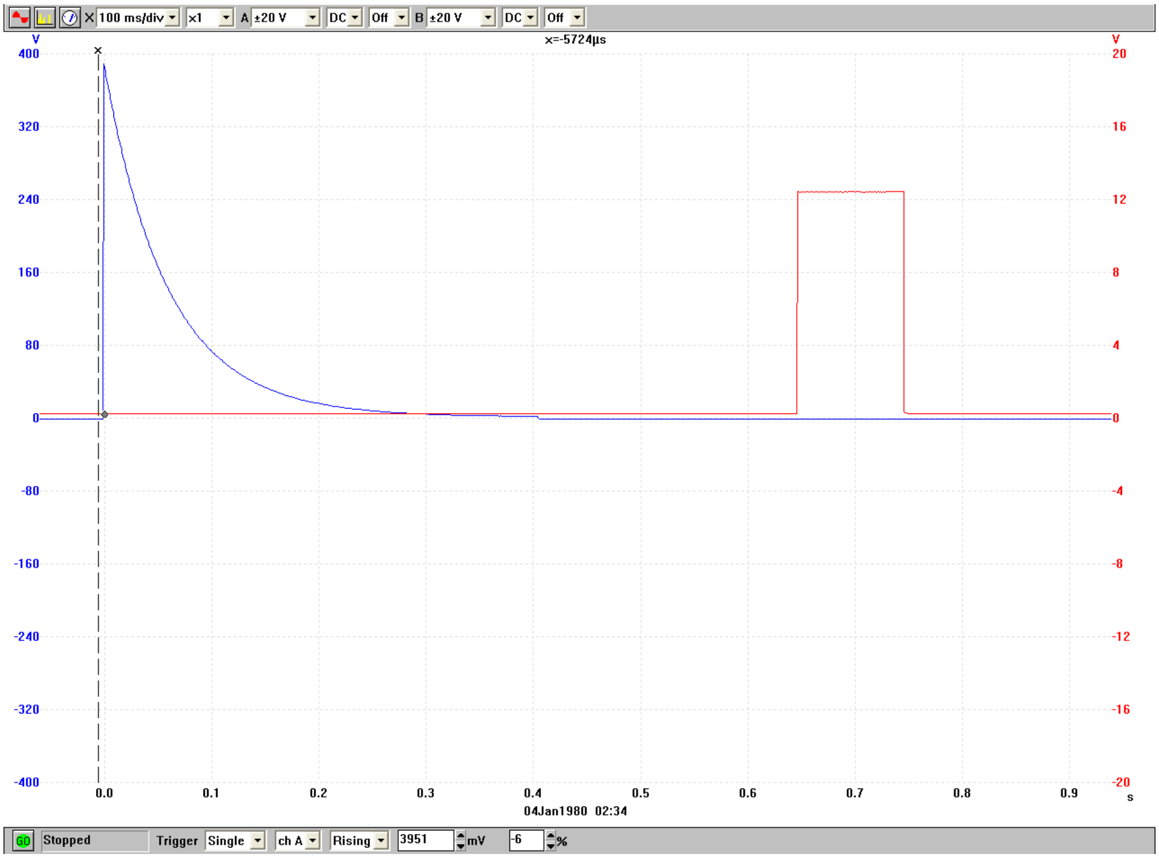

Figure 3. Oscilliscope trace of a voltage across the precharge resistor (blue) during a typical start-up. (The red square pulse is an unrelated heater request signal.)

In Figure 3 the voltage pattern follows a predictable shape, spiking to nearly 400V and exponentially decaying toward 0V. There is insufficient detail to determine precisely when the voltage drops below the 5% threshold (about 19V in this case), but it looks as if it occurs well after the predicted 0.141 seconds, probably closer to 0.2 seconds, and definitely before 0.3 seconds.

A comparison of the empirical observation of the precharge sequence illustrated in Figure 3 to the description of how the circuit should behave raises some interesting questions:

Why does the capacitor seem to charge more slowly than predicted? (It's not all that far off; I suspect that there are additional capacitors in the PCU, maybe within the charger and DC/DC converter that increase the capacitance value.) Why is the precharge resistor energized for 0.4 seconds when it has clearly reached the 95% threshold by 0.3 seconds? How does the BMS determine when the capacitor is charged to 95%? Is there an analog circuit that compares the voltage of the capacitor and the battery? Or is there an analog-to-digital conversion and logic processing that must take place before contactor M2 is closed?

Precharge circuit operation during a casualty

The equations above describe the proper operation of the precharge circuit, but the precharge resistor must withstand the worst-case scenario of a short circuit across the capacitor. (We know that current must be bypassing the capacitor, whether by inadvertent loading by the power electronics, short circuiting due to moisture, or any number of unknown factors.) In this case the equations are much simpler; instead of a resistive capacitive circuit we just have a resistive circuit. The voltage across the resistor is constant; it is equal to battery voltage. The power dissipated in the resistor is simply the product of the current and the voltage. The energy that heats the resistor is simply the product of the power and the time that the resistor is energized.

In this casualty scenario, we can solve for the time that would be required to exceed the resistor's single impulse energy rating of 700 Joules:

$$H(t) = 700\,J = \frac{v_0^2}{R}t$$

It would only take 0.206 seconds for the resistor to overheat. Empirical observation of the contactors shows that the precharge resistor is normally energized for about 0.4 seconds. The BMS will leave the precharge contactor closed for 1 full second if the 95% threshold is not reached, then open the precharge contactor for 2 seconds, and then close it again for another full 1 second in an attempt to charge the capacitor to 95%. This amounts to 2 full seconds of the resistor being energized—enough to release nearly ten times the energy rating of the resistor.

The maximum average power rating for the resistor is 3.5 Watts, so if the resistor has just generated 700 Joules of heat it will have to wait 200 seconds (700 J/3.5W), before it can safely be energized to that degree again. The BMS must prohibit all attempts to close contactors before the precharge resistor has had a chance to dissipate its heat to the surroundings.

The behavior of the precharge circuit clearly needs to be modified. Without having a more precise understanding of the exact mechanisms and limitations of the BMS voltage sensing and computing abilities, I cannot recommend a specific protocol. The only factors that can be changed in this system are the contactor timing and an increase in the resistance value of the precharge resistor. (No other factors, including the energy rating of the resistor, should be modified.) The only reason I can imagine for increasing the resistance value is if BMS processing time is causing a significant delay in energizing contactors. The new contactor closing sequence must not energize the precharge resistor for any time greater than 0.2 seconds without some verification that the capacitor is being charged. Without the BMS sensing a reasonable increase in capacitor voltage, the precharge contactor should not be closed for more than 0.2 seconds for every 200 seconds of de-energized time.

Conclusion

The Enerdel battery is properly designed and programmed to perform within its design specifications, but the design of the contactor closing sequence should be changed to prevent battery failure due to causes outside of its control (external to the battery assembly). The present design of the battery will prevent it from coming online and set a malfunction code if it detects an abnormality in the circuit external to the battery. This serves the purpose of protecting the Lithium-ion battery cells, but still renders the battery totally inoperative until an expensive circuit board is replaced. A more robust design would ensure that the entire battery assembly would be protected from damage to the external circuit.

I believe that this change is absolutely necessary for Think drivers' safety and satisfaction and for the purposes of controlling warranty costs (and eventually owner costs when the warranties expire). (It may also become a matter of MLEC inventory as well.) It might also be prudent for Enerdel batteries in other applications to include this casualty design consideration.