UWFE Active Pre-charge Proposal

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Introduction

In electrical systems, particularly those involving high-power capacitors and inductive loads such as motor controllers and transformers, the concept of pre-charging is critical for ensuring safe and reliable operation. Pre-charging is a process used to gradually bring the voltage levels of components within a system up to their operating level before the main power is applied. This is done to prevent the inrush of current, which can occur when the system is comprised of a large capacitance.

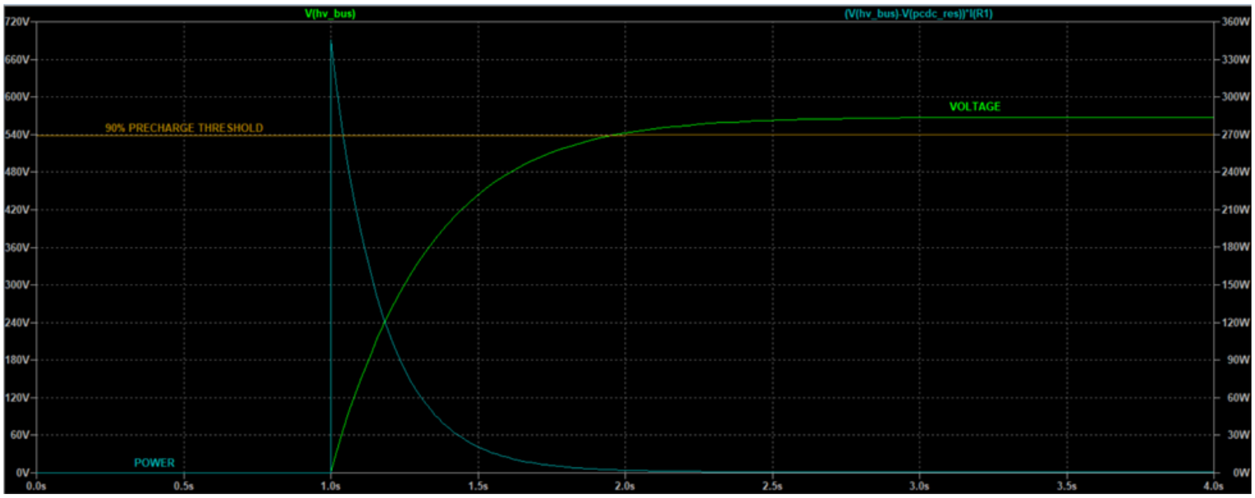
The main purpose of a pre-charge circuit is to limit the initial surge of current that flows into the capacitors or other electrical components when power is first applied. This surge can lead to catastrophic failure in the electrical system and potential arcing. By controlling the inrush current, pre-charge circuits help extend the lifespan of these systems, stabilise voltage levels, and contribute to the overall reliability and efficiency of the electrical system.

Our Current Pre-charge

Our current pre-charge is a simple RC-style passive pre-charge. We use a large 1KΩ resistor, which creates an RC circuit with the high capacitance of our car's tractive system. The circuit works and has been thoroughly validated. Despite this, there are certain aspects that could be greatly improved.

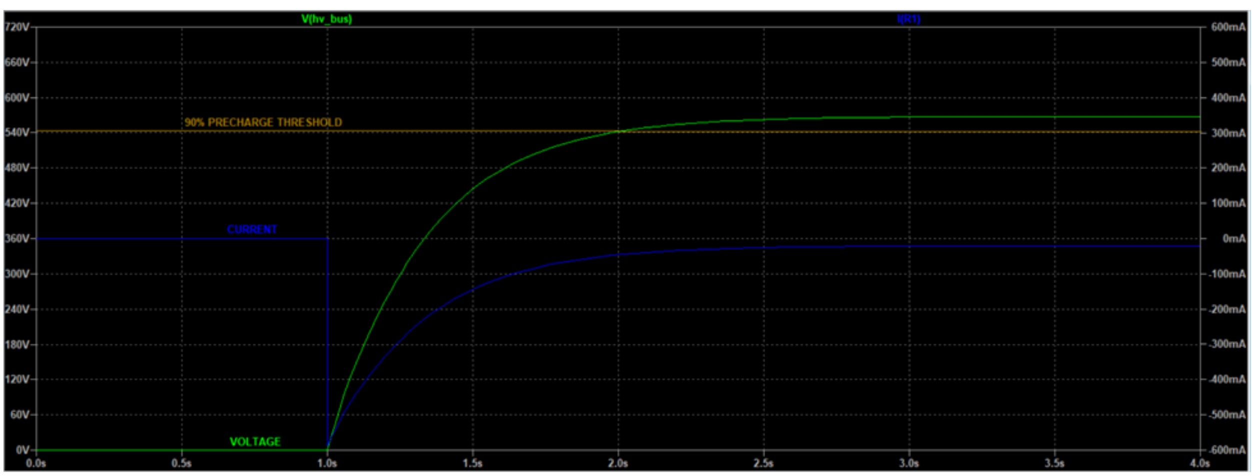
I see three major areas for improvement with our current pre-charge:

1. It is heavy and requires a significant amount of space. The PC/DC resistor (HSC3001K0J) is basically a big metal block. It takes up significant room in our E-box and adds weight to the car.
2. It is inefficient and dissipates power. Our current pre-charge peaks at about 350 watts. Although this is for a short time, it is power that does not need to be wasted. Also, although it is mostly for rules compliance, it requires us to have a proper heat sink.



Power Consumption of Pre-charge Resistor

3. It is relatively slow. It takes about 1 second to reach the required 90% voltage threshold, which itself is not a problem. However, the fact that we use an RC-style precharge means that the inflow current will decrease with time. Maintaining a constant current would greatly reduce this time.

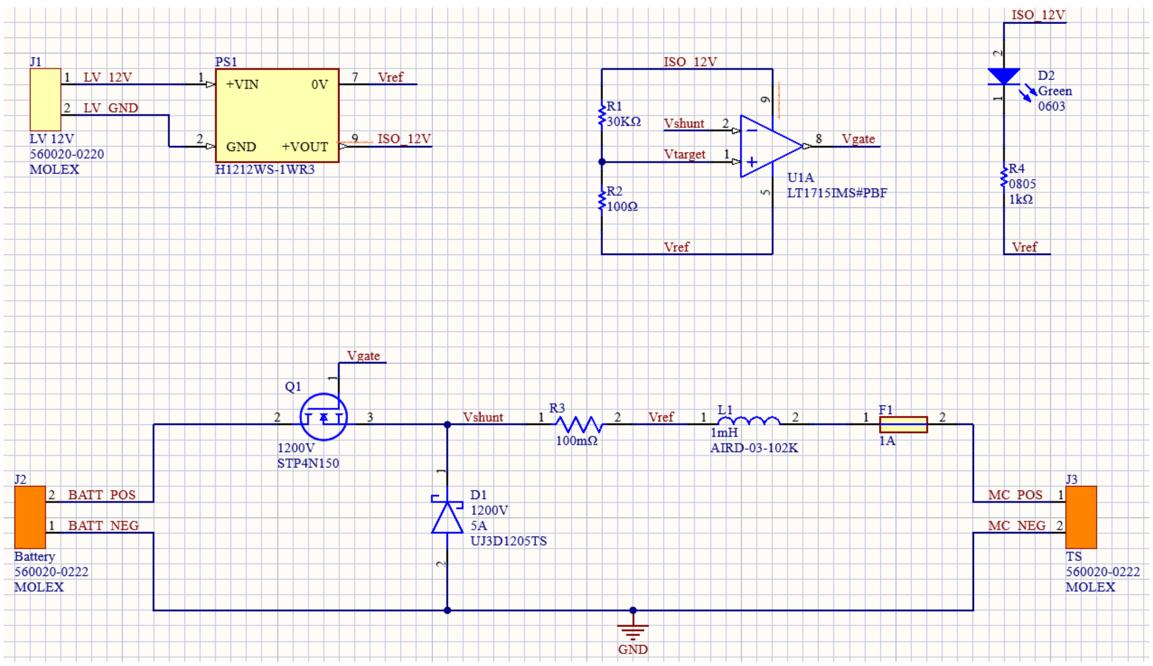


LTspice Simulation of Current Pre-charge

Proposed Solution

I designed a buck-converter-style active precharge circuit that has negligible power loss, maintains a constant (also modifiable) precharge current, can be multiple times faster than our passive RC-style pre-charge, and is rated for any system up to 1200V, providing a roughly 2x safety factor for our 588V peak battery.

Circuit Overview



Pre-charge Circuit Schematic

It is a relatively simple circuit. The bottom portion resembles a standard buck-converter that sources from the battery. It is controlled by a switching MOSFET and uses a 1mH inductor to maintain forward current when the MOSFET is open during switching.

There is an isolated 12V DC rail to power the comparator. This is referenced from the shunt resistor and must be isolated since its voltage changes drastically every time the MOSFET opens or closes. This is powered from an external 12V DC source.

The MOSFET's gate is controlled by a high-speed comparator, which compares the voltage across a 100mΩ shunt resistor (measuring the current, I_{In}, entering the tractive system) to a target voltage specified by a voltage-divider. This allows the circuit to maintain a constant inflow current defined by the following equation,

$$I_{In} = 120 * \frac{R2}{R1 + R2} A$$

The circuit is currently configured for 400mA but can be modified with R1 and R2.

I have also included a 1A fuse for over-current protection should something in the circuit fail.

Pre-charge Speed

Since we have a relatively constant current, the time it takes to precharge will be roughly linear to the voltage of the battery and is given by the following equation:

Precharge Time (seconds) = $C_{TS}V_{Battery}/I_{In}$

where C_{TS} is the approximate capacitance on our tractive system (calculated by adding the capacitance of our motor controller, LV DC-DC and TSAL, obtained through data sheets and experimentation), $V_{Battery}$ is our battery voltage, and I_{In} is the pre-charge current.

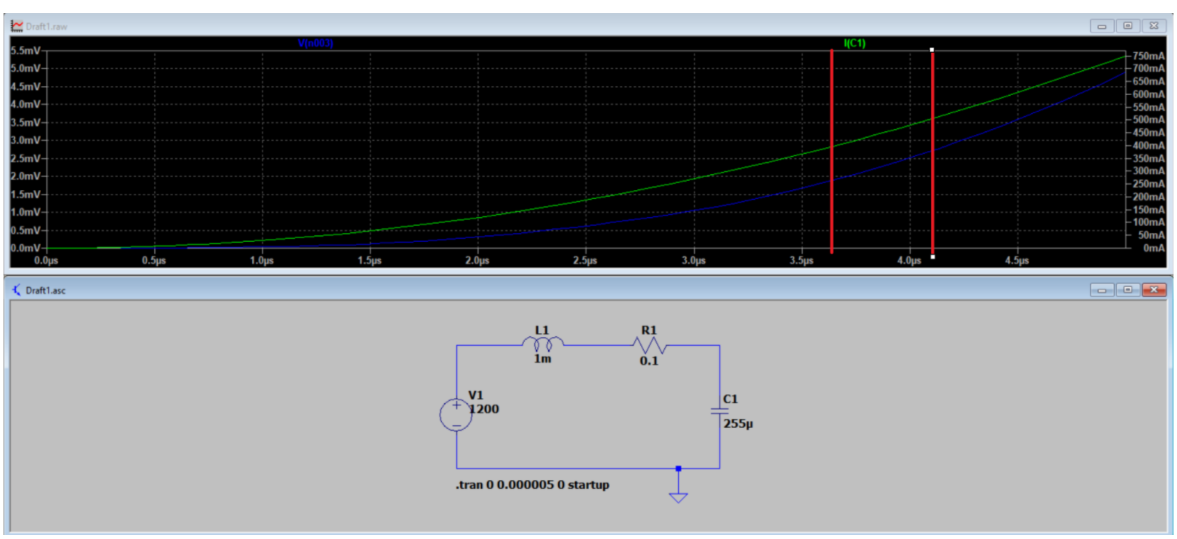
With the assumption that $C_{TS} = 255uF, I_{In} = 400mA$, we get the following theoretical precharge times,

Battery Voltage	Time (ms)
350V (cutoff)	223
504V (nominal)	321
588V (peak)	375

Component Selection

The most important relationship in my circuit is between inductor size and switching speed of my comparator + MOSFET. I need an inductor large enough to regulate the amount that I_{In} is able to deviate from its target while the switching of my comparator + MOSFET is propagating. The max overshoot will occur upon the first MOSFET switch at the beginning of precharge as the voltage difference between $V_{Battery}$ and V_{TS} will be maximized. To simulate this, I used an RLC circuit with $V_{Battery}$ = 1200V (added safety factor), $C_{TS} = 255uF$, $R = 0.1\Omega$, and then tried a few inductor values. I chose my max overshoot to be 100mA (seems reasonable) and ended up deciding on an inductance of 1mH. This gives me a maximum switching period of about 300ns and seems like a reasonable-size inductor to put on a PCB.

Note: any extra resistance introduced to this ideal model will only increase this max period. Thus, it serves as a valid estimate for real-world application.



LTspice Simulation of Transient I_{In} Behaviour (green trace)

I was then able to find a MOSFET and comparator with combined worst-case delays under 120ns.

MOSFET part number: STP4N150
Switching times:

Table 6. Switching times

Symbol	Parameter	Test conditions	Min.	Typ.	Max.	Unit
$t_{d(on)}$	Turn-on delay time	V_{DD} = 750 V, I_D = 2 A,	-	34	-	ns
t_r	Rise time	R_G = 4.7 Ω, V_{GS} = 10 V	-	31	-	ns
$t_{d(off)}$	Turn-off delay time	(see Figure 17. Test circuit for resistive load switching times and	-	47	-	ns
t_f	Fall time	Figure 22. Switching time waveform)	-	45	-	ns

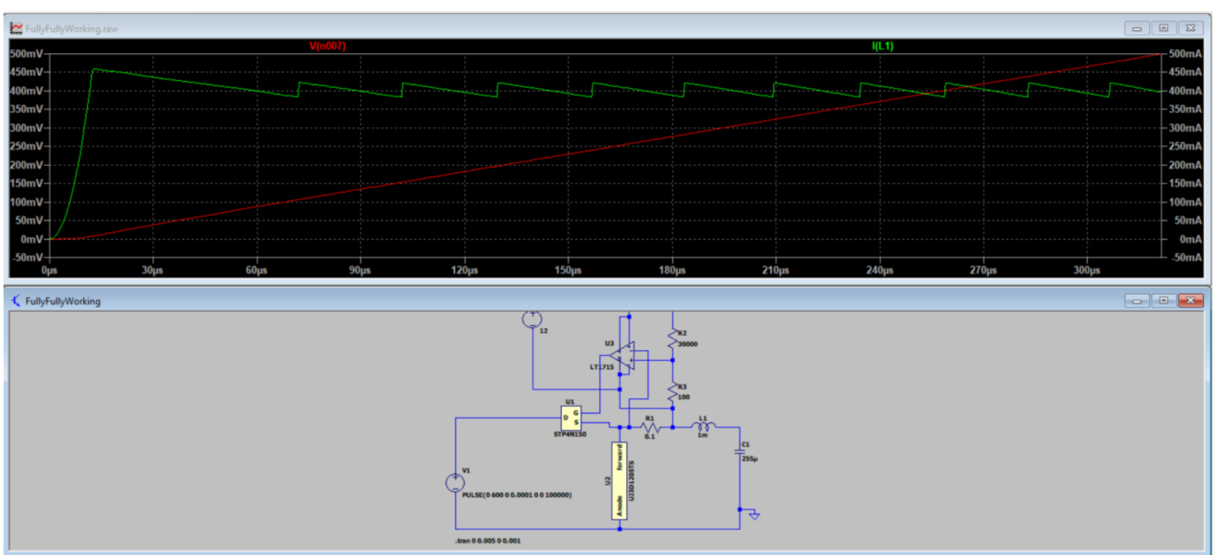
Comparator part number: LT1715
Switching times:

f_{MAX}	Maximum Toggle Frequency	(Note 10)			150		MHz
t_{PD20}	Propagation Delay	$V_{OVERDRIVE}$ = 20mV (Note 11), V_{CC} = 5V, V_{EE} = −5V LT1715C, LT1715I LT1715H	 ● ●	2.8 2.8 2.8	4	6 7 8	ns ns ns
		$V_{OVERDRIVE}$ = 20mV, V_{CC} = 5V, V_{EE} = 0V			4.4		ns
		$V_{OVERDRIVE}$ = 20mV, V_{CC} = 3V, V_{EE} = 0V LT1715C, LT1715I LT1715H	 ● ●	3 3 3	4.8	6.5 7.5 8	ns ns ns
t_{PD5}	Propagation Delay	$V_{OVERDRIVE}$ = 5mV, V_{EE} = 0V (Notes 11, 12)	 ●		6	9 12	ns ns
t_{SKEW}	Propagation Delay Skew	(Note 13) Between t_{PD}^+/t_{PD}^-, V_{EE} = 0V	●		0.5	1.5	ns
Δt_{PD}	Differential Propagation Delay	(Note 14) Between Channels	●		0.3	1	ns
t_r	Output Rise Time	10% to 90%			2		ns
t_f	Output Fall Time	90% to 10%			2		ns

It is also important to note that all components were selected to be operable at 1200V. This provides our 588V (peak) battery with a roughly 2x safety factor, making the circuit more robust.

Simulated Results

Simulating the whole circuit in LTspice on my brick of a computer was very slow, so I was only able to simulate the first few hundred microseconds of the precharge. However, it stabilized very quickly and gave promising results.



LTspice Simulation of Transient I_{In} (green trace) and Tractive System Voltage (red trace)

Conclusion

While it adds complexity compared to our simple RC-style pre-charge circuit, an active pre-charge allows for more control of inflow current, weight reduction in the car, space reduction in the E-box, negligible power loss, and eliminates the need for a documented heat sink. I believe that through rigorous testing and validation of the active pre-charge circuit, this additional risk of added complexity will be greatly diminished and support the transition to using an active pre-charge on the car.

Here's a link to the Altium project:
https://bitbucket.org/waterloohybrid/2024_designs/src/2024_Active_Precharge/