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Simulation and Optimization of an Automotive Surge Stopper Circuit

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SUMMARY

This report focuses on the design and simulation of a surge stopper circuit, used in automotive electronics in order to protect against high power voltage transients that originate from a vehicle's 12V battery supply.

The circuit was designed with two particular automotive electronics standards in mind: ISO7637 and Ford's EMC compatibility standards. The transient waveforms and their parameters were presented, as well as system level requirements of the surge stopper dictated by the target circuit the surge stopper is protecting. Automotive specific requirements such as AEC-Q100 component qualifications were also presented.

The surge stopper circuit was subdivided into two main elements: a surge stopper used to prevent high voltage, high power transients from reaching the target circuit, and a power path switch, to allows for the target circuit to be supplied by an auxiliary battery. Both elements were introduced with a design where only discrete and passive components were used. In the case of the Surge stopper element, an alternative design using only resistors and TVS diodes was presented. For the power path switch, a diode OR circuit was presented. The flaws in these passive-discrete circuits were described, and the dedicated IC circuits were then introduced and their design described.

Once the details of their design were presented, the simulation setup was introduced. Performed in LTSpice, the specific details of the tests were presented, as well as the challenges faced when creating the simulation environment.

The simulation results verified that the surge stopper circuit design successfully protected the target circuit. However the results also illustrated that a few of the discrete components used in the design had too low of a power dissipation rating, and will have to be re-sourced. Future steps include physically prototyping the design in order to test it in real circuits, as well as researching and testing ways to reduce the system's overall cost.

1. INTRODUCTION

Circuits used in modern day automobiles are complex and are often powered by the vehicle's 12V battery pack. As the battery pack is also used to power other high power elements (eg. alternator, starter motor, and lights and windshield wiper), there are significant transients being produced, some of which may be large enough to permanently damage logic-level IC's. Effective protection of these circuits is often used in order to minimize the effects of these high power, high voltage transients. This report focuses on the design and simulation of a surge stopper circuit that performs this task, as well as the ability to switch power from a primary battery to an auxiliary voltage source. It is separated into five sections: Requirements, System Design, Circuit Design and Component Selection, Simulation, and Conclusion and Recommendations.

Requirements describe the circuit requirements defined by the external system it is connected to, as well as automotive specific standards the circuit must meet. System Design outlines the high level layout and design of the protection circuit. Circuit Design and Component Selection describes the detailed circuit design and schematic, as well as the initial selection of the various components. Simulation describes the process and setup of the simulation of the circuit

1.1. SCOPE

In order to ensure sufficient confidentiality is preserved with the project and to increase brevity, the scope of report ignores elements and systems outside of the surge stopper circuit. These will be presented as pre-existing system requirements that must be followed. This also helps to simplify the focus of the report. This report focuses on only the circuit design and components of a surge stopper circuit, and not its layout on the board or the rationale behind selecting the transients to protect against.

2. REQUIREMENTS

2.1. SYSTEM AND PROJECT REQUIREMENTS

2.1.1. TARGET CIRCUIT REQUIREMENTS

The following table describes the requirements of the “target circuit” the surge stopper is protecting. The target circuit itself is composed of two different loads: logic loads and power loads. Logic loads are classified as components of the target circuit that are used for processing or communication purposes, such as microcontrollers, bus transceivers, memory elements. Etc. Power loads are classified as components of the target circuit that are used for driving actuators, lights, or other high power loads.

Table 1: Target Circuit Requirements

#	Requirement	Value
1	Minimum logic load voltage range	**Content withheld for confidentiality reasons**
2	Maximum logic load voltage range	
3	Minimum power load voltage range	
4	Maximum power load voltage range	
5	Max logic loads current draw	
6	Max power loads current draw	
7	If battery voltage < min logic load voltage, switch to auxiliary power supply.	
8	Minimize amount of time target circuit powered by auxiliary power supply.	
9	Auxiliary power supply voltage	
10	Auxiliary power supply max current	

2.1.2. Purchasing Requirements

All components used in automotive grade circuits must meet particular standards defined by the Automotive Electronics Council. These standards are denoted with a numerical suffix, and signify that the components meet a particular level of quality and are capable of tolerating the harsh environment of a vehicle. There are three classes of the AEC standard that must be followed[1]:

AEC-Q100: This class illustrates automotive grade multi-pin integrated circuits such as processors, memory, bus transceivers and load drivers.
AEC-Q101: This class illustrates automotive grade discrete components such as diodes, mosfets and op-amps.
AEC-Q200: This class illustrates automotive grade passive components such as resistors, capacitors and inductors.

For the surge stopper circuit, all components used in the circuit were required to be AEC qualified. They also had to be purchasable in small quantities in order to accommodate prototyping and testing. Footprint compatible non-automotive variants of the components were considered acceptable alternatives, if the automotive variant was not available.

2.2. Environmental Requirements

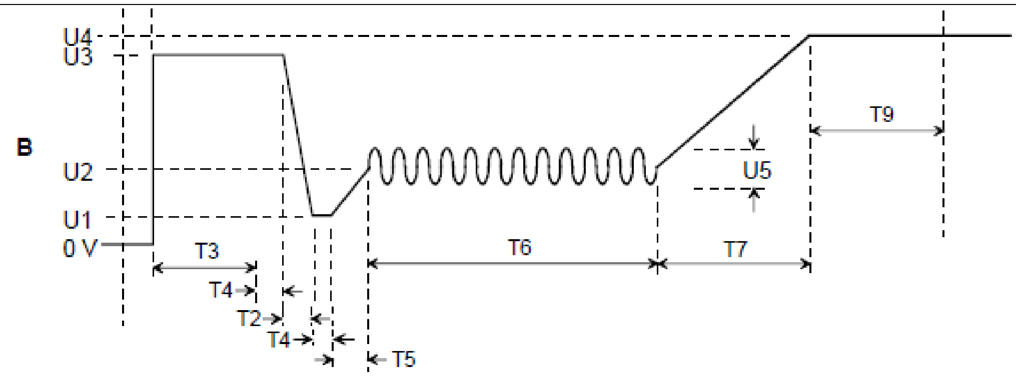
As the board the surge stopper circuit sits is being designed to fit in a production vehicle, it is imperative that the components are capable of surviving high vibration, as well as large temperature extremes. In order to accomplish this
No specific standards were found regarding vibration limits for components

2.3. Transient Handling Standards

Previous efforts had discovered two automotive transient standards that the surge stopper circuit should be capable of protecting against: Ford's Electromagnetic Compatibility Section (Ford EMC), and ISO7637. Certain transient pulses from both of the standards were selected to protect against. The following sections describe each pulse and their characteristics

2.3.1. Ford EMC

Four different pulses from the Ford EMC standard were to be tested: CI 230-B, CI 270, CI-220-G2 and CI-260-C[3].



Key

T1 = 100 msec
T2 = 5 msec
T3 = 185 msec
T4 =15 msec
T5 = 50 msec
T6 = 10 sec
T7 = 500 msec

T8 = 11 sec
T9 = 325 msec
U1 = 5 V
U2 = 9 V
U3 = 12.5 V
U4 = 13.5 V
U5 = 2 Vp-p @ 4 Hz

Figure 1: CI 230-B pulse (source: Ford EMC standard)

Figure 1 shows the voltage profile of test pulse CI 230-B, also known as the Cranking condition. It is modelled to represent the worst case voltage of a vehicle's 12V battery during a cold start of the car[3]. In this condition a large amount of power is used by the vehicle in order to spin the engine's alternator and to fire the sparkplugs, which causes the voltage of the battery to drop to 5V for as long as 15msec.

Requirement	
Amplitude (V)	Duration
-14 (-0.7, +0)	≥ 60 sec
19 (+0.95, -0)	≥ 60 min
24 (+1.2, -0)	≥ 60 sec (1)

Figure 2: CI 270 Voltages (source: Ford EMC standard)

Figure 2 shows that CI 270 does not have a particular waveform, and consists of purely DC voltage. It is meant to represent overvoltage due to conditions such as a jump start from a truck (which uses a 24V battery instead of 12V) or the accidental installation of the battery with its negative and positive terminals flipped[3].

Pulse G2 Parameters

U_p	13.5 V
U_s	30 V
U_s^*	21.5 (-1/+0) V
t_r	10 (-5 /+0) ms
t_d	150 mS +/-20%
R_i	0.5 Ohms

All voltage values are with respect to 0 volts unless otherwise specified.

Voltage values listed are across a 0.5 ohm resistive load (see *section 16.3*).

a: Unsuppressed pulse

b: Suppressed pulse

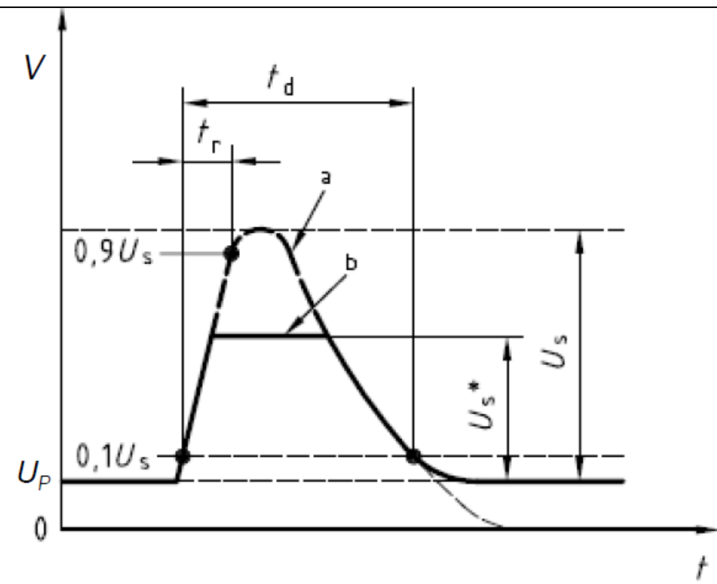
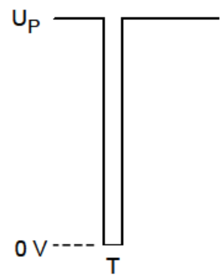


Figure 3: CI 220-G2 pulse (source: Ford EMC standard)

Figure 3 illustrates the parameters and waveform shape of the CI 220-G2 pulse, also known as a Suppressed Load Dump. A load dump transient is generated when the car battery accidentally disconnects from the alternator while charging[6]. Because of the inductive nature of the still spinning alternator windings, a large voltage spike appears across the alternator terminals, and consequently across any loads connected to it[6]. To help dissipate the energy of this transient, most modern vehicles contain a Central Load Dump Protection system, which suppresses the load dump voltage (pulse b in figure 3). The surge stopper circuit design described in this report was required to protect against this suppressed load dump, and not the unsuppressed voltage.



Key:

	Power from Vehicle Battery			Regulated Power from another Module		
U_P	13.5 VDC			Nominal Supply Voltage (e.g. 5 Vdc, 3 Vdc)		
T [(1)]	100 us	300 us	500 us	100 us	300 us	500 us

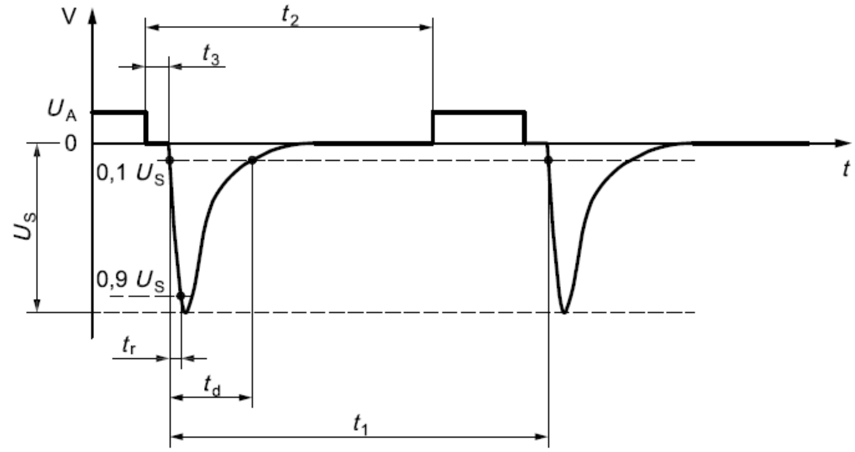
(1) Waveform transition times are approximately 10 us

Figure 4: CI 260-C pulse (source: Ford EMC standard)

Figure 4 shows the test pulse from CI 260-C, also known as a Single Voltage Dropout. A single voltage dropout was defined in the standard as a momentary loss of battery voltage, which could happen over the lifetime of the vehicle. The Surge stopper circuit was required to prevent the dropout from reaching the target circuit.

2.3.2. ISO7637-2

Five pulses from ISO7637-2 were tested: pulse 1, 2a, 3a and 3b.



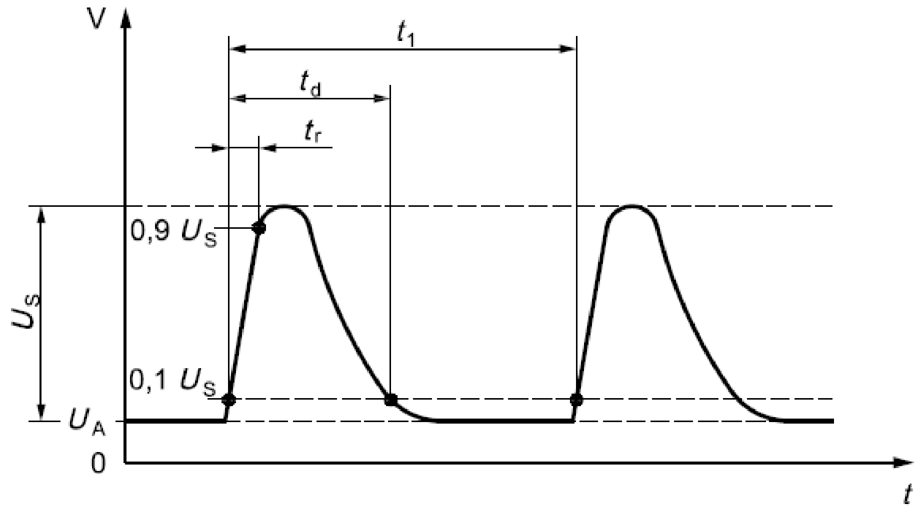
Parameters	Nominal 12 V system	Nominal 24 V system
U_s	–75 V to –150 V	–300 V to –600 V
R_i	10 Ω	50 Ω
t_d	2 ms	1 ms
t_r	$(1\,^{0}_{-0,5})$ µs	$(3\,^{0}_{-1,5})$ µs
t_1 [a]	⩾0,5 s	
t_2	200 ms	
t_3 [b]	<100 µs	

[a] t_1 shall be chosen such that it is the minimum time for the DUT to be correctly initialized before the application of the next pulse and shall be ⩾0,5 s.

[b] t_3 is the smallest possible time necessary between the disconnection of the supply source and the application of the pulse.

Figure 5: ISO7637-2 Test Pulse 1 (source: ISO7637-2 standard)

Figure 5 shows the shape and parameters of test pulse 1, which represents the transient formed when an inductive load parallel to the target circuit is suddenly disconnected[4].

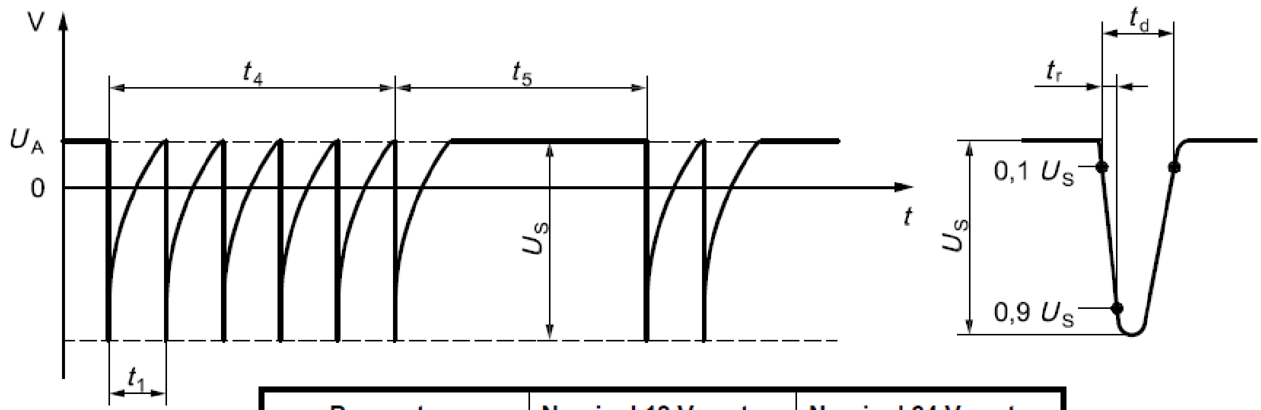


Parameters	Nominal 12 V and 24 V system
U_s	+37 V to +112 V
R_i	2 Ω
t_d	0,05 ms
t_r	$(1\ {}^{0}_{-0,5})$ µs
t_1[a]	0,2 s to 5 s

[a] The repetition time t_1 can be short depending on the switching. The use of a short repetition time reduces the test time.

Figure 6: ISO7637-2 pulse 2a (source: ISO7637-2 standard)

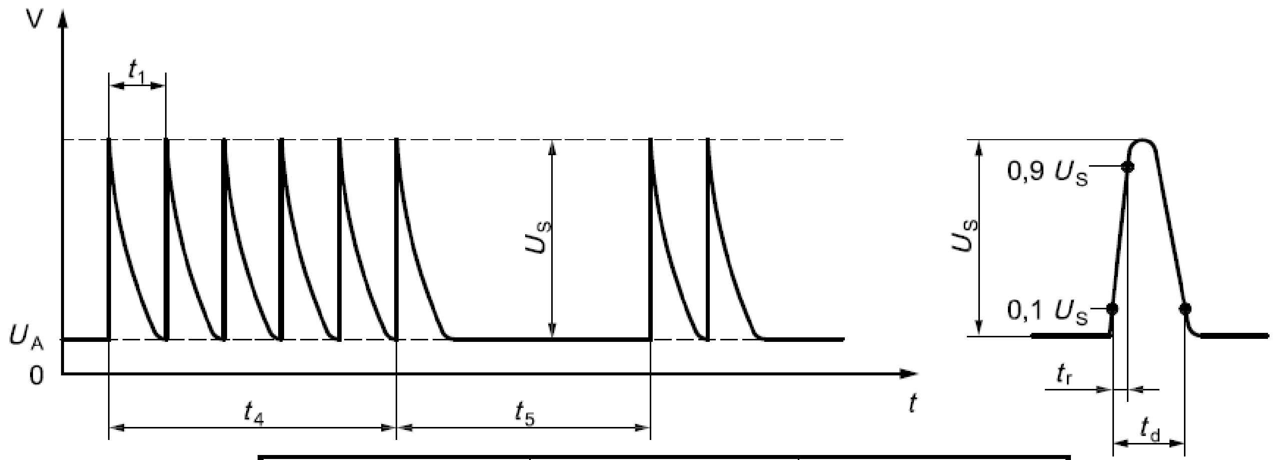
Figure 6 shows the voltage waveform and parameters for pulse 2a, which represent inductive voltage spikes caused by DC motors acting as generators[4]. Test pulse 2b was not listed as a requirement because the voltage amplitude of the transient is below the car battery's nominal voltage of 13.5V.



Parameters	Nominal 12 V system	Nominal 24 V system
U_s	–112 V to –220 V	–150 V to –300 V
R_i	50 Ω	
t_d	150 ns ± 45 ns	
t_r	5 ns ± 1,5 ns	
t_1	100 µs	
t_4	10 ms	
t_5	90 ms	

Figure 7: ISO7637-2 pulse 3a (source: ISO7637-2 standard)

Figure 7 illustrates the pulse 3a and figure 8 illustrates the pulse 3b, both of which represent transients due to switching of elements attached to a vehicle's car battery[4].

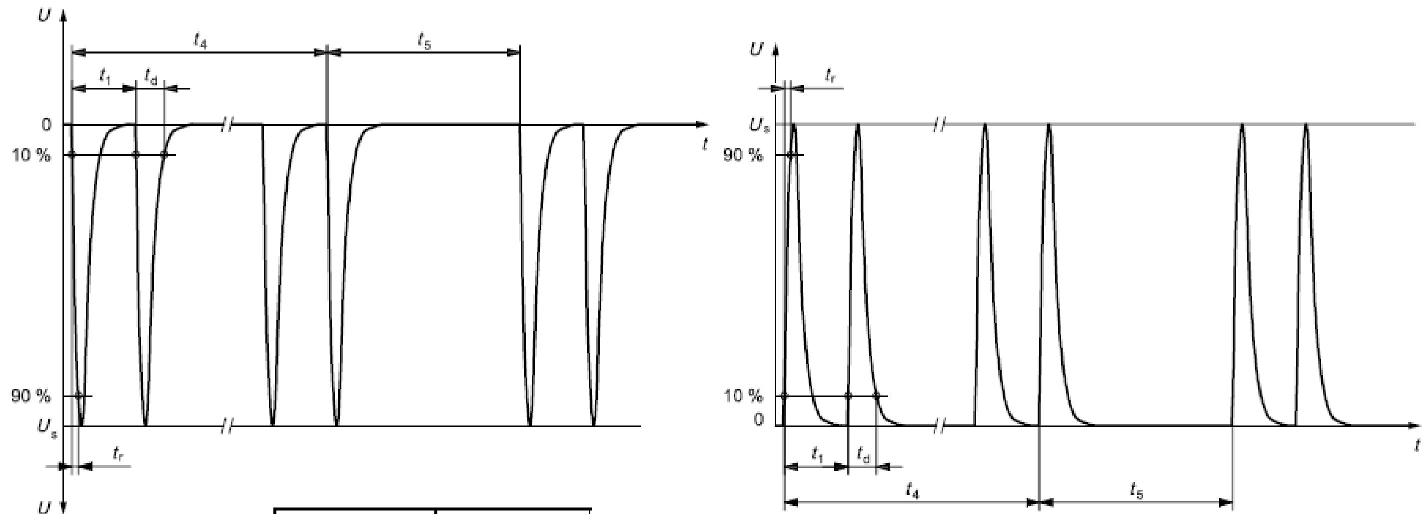


Parameters	Nominal 12 V system	Nominal 24 V system
U_s	+75 V to +150 V	+150 V to +300 V
R_i	50 Ω	
t_d	150 ns ± 45 ns	
t_r	5 ns ± 1,5 ns	
t_1	100 µs	
t_4	10 ms	
t_5	90 ms	

Figure 8: ISO7637-2 pulse 3b (source: ISO7637-2 standard)

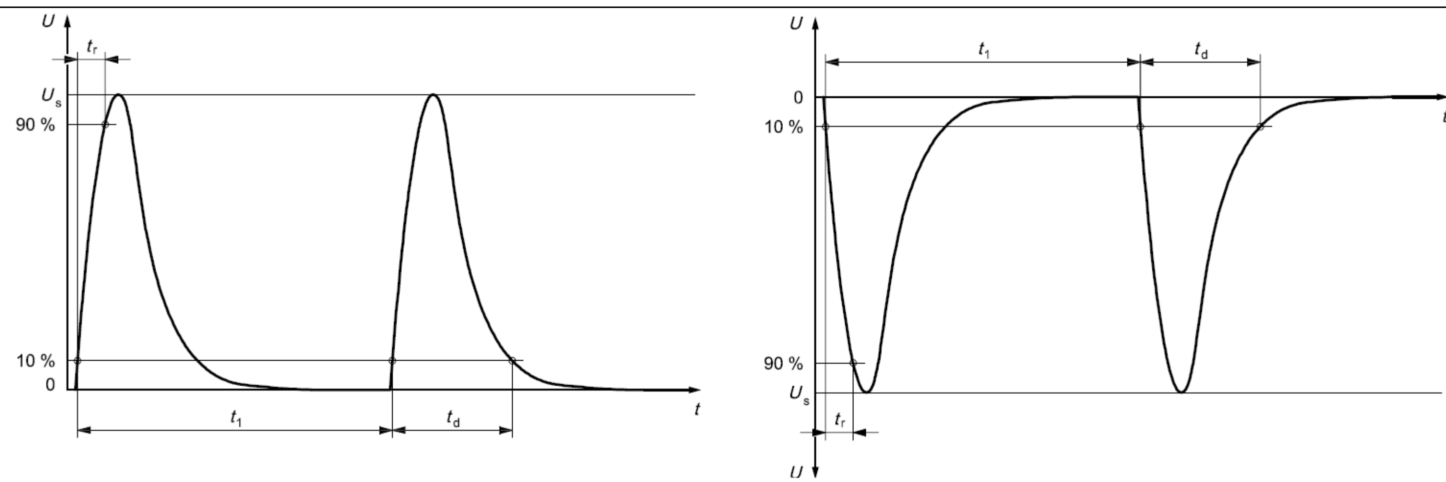
2.3.3. ISO7637-3

The surge stopper circuit was required to protect against 4 test pulses defined by the ISO7637-3 standard: fast pulse a, fast pulse b, slow pulse + and slow pulse -. All pulses were designed to represent transients due to switching loads or inductive loads powered by the 12V battery[5]. Figures 9 and 10 show the waveform and parameters of the four test pulses outlined by the standard.



Parameters	12 V system
U_s in V	-60V, 40V
t_r in ns	5
t_d in µs	0,1
t_1 in µs	100
t_4 in ms	10
t_5 in ms	90
R_i in Ω	50

Figure 9: ISO7637-3 fast pulse a and b (source: ISO7637-3 standard)



Parameters	
U_s	+45V, -45V
t_r	⩽1 µs
t_d	0,05 ms
t_1	0,5 s to 5 s
R_i	2 Ω

Figure 10: ISO7637-3 slow pulse + and - (source: ISO7637-3 standard)

3. SYSTEM DESIGN

The following block diagram graphically illustrates the requirements of the surge stopper circuit as well as the overall layout of the circuit.

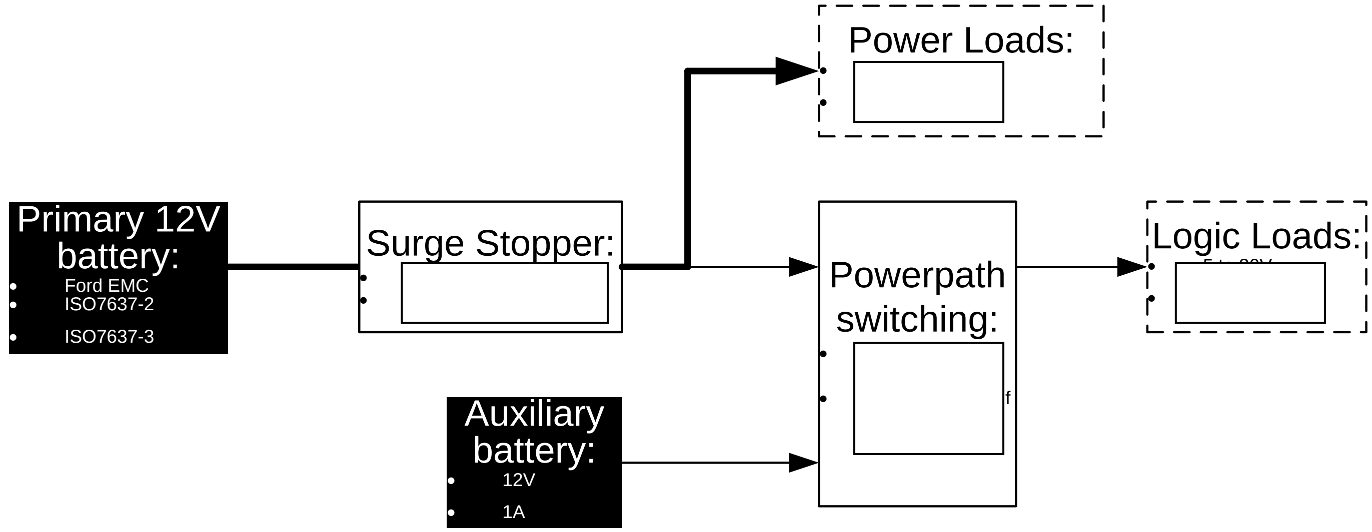


Figure 11: Circuit Block diagram

As visible in figure 11, the vehicle's primary 12V battery is connected to the target circuit through the surge stopper and the powerpath switcher. Initially it was hoped that the power loads could be placed after the powerpath switching components in order to facilitate continued power after battery disconnection, however this was impractical because the auxiliary battery would not be capable of providing enough current for both the power and logic loads. The only drawback to this layout is that the power loads may not be protected from extended voltage dropout of the primary battery. Reviewing the requirements from 2.1.1 however illustrates that there is no minimum voltage level for the power loads.

4. CIRCUIT DESIGN AND COMPONENT SELECTION

4.1. SURGE STOPPING

Two different options existed in order to perform the surge stopping functionality of the circuit: suppression using only discrete and passive components, or suppression using a dedicated surge stopper IC.

4.1.1. DISCRETE AND PASSIVE COMPONENT APPROACH

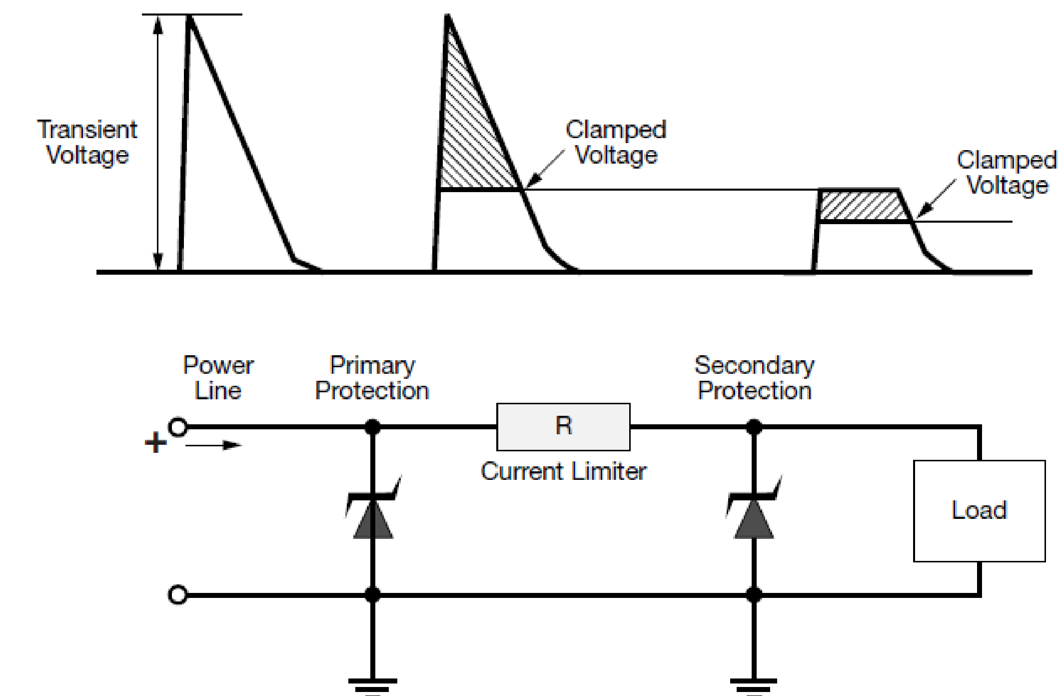


Figure 12: Current and Voltage suppression using TVS diodes (source: Vishay App note)

The principle behind the first option of using discrete and passive components can be seen in figure 12. The high transient voltage is clamped to a more reasonable amplitude using a dedicated high power TVS diode[7]. When handling high power transients such as the load dump (outlined by Ford's EMC CI 230), a single TVS diode may not be capable of handling the power dissipation. As a result two TVS diodes with two different standoff voltages are often placed in shunt with the load, in order to further reduce the voltage. A current limiting resistor is placed in series with the load in order to reduce the amount of power the secondary TVS will have to dissipate[7].

The following table lists the advantages and disadvantages of the discrete and passive method:

Table 2: Evaluation of surge stopping using passive and discrete components

Advantage	Disadvantage
-simple. Uses only TVS diodes and resistors	-unable to limit current. Max current through current limiting resistor depends upon primary battery voltage (ohm law)
Low cost and easy to source automotive grade components	-too high of a resistor value produces a voltage divider effect on the load.
	-does not protect against cases of reverse current flow (eg. Target circuit has large capacitance and is at 14V, primary battery is at 12V)
	-TVS diodes may not evenly absorb equal amounts of power, leading to primary protection (figure 12) taking too much power.
	Not robust

4.1.2. DEDICATED SURGE STOPPER IC

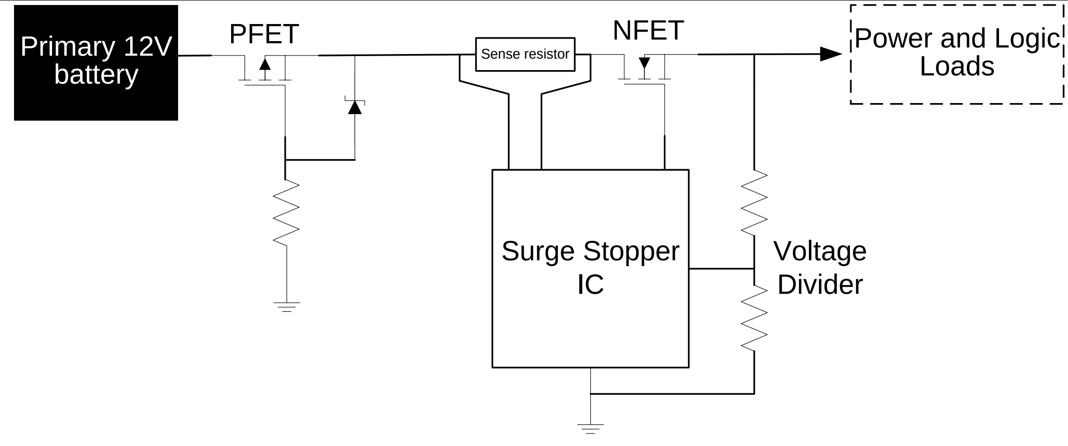


Figure 13: Surge Stopper IC generic circuit

The operation of a dedicated surge stopper IC focuses around the control of an N type pass transistor. Activating the transistor allows current to pass through to the power and logic loads. An overcurrent condition is detected by monitoring the voltage drop over a sense resistor, and an overvoltage condition is detected by monitoring the voltage of the primary battery through a voltage divider (figure 13). An overvoltage and overcurrent issue is resolved by altering the gate voltage of the pass transistor to place it into a linear operation or triode mode. This converts the drain source pins into a potentiometer, dissipating the excess energy of the transient as heat[8].

The chief advantage of using the dedicated surge stopper is its ability to completely cut off current flow in order to protect the target circuit. This is useful in situations where the power loads fail to a short circuit condition, and draw greater than 16.5A. The surge stopper will be capable of cutting current to the loads, preventing overheating or failure of downstream components in the target circuit. The P type mosfet is useful because it prevents the target circuit from seeing a negative voltage, which can occur if the battery is accidentally connected backwards.

Because of the lower capabilities and greater uncertainty with the discrete-passive component approach, the dedicated IC approach was selected. Preliminary research and communication with more experienced company engineers led to the selection of the **Content withheld for confidentiality reasons**. The **Content withheld for confidentiality reasons** had been used on a previous company project and hence had a proven track record.

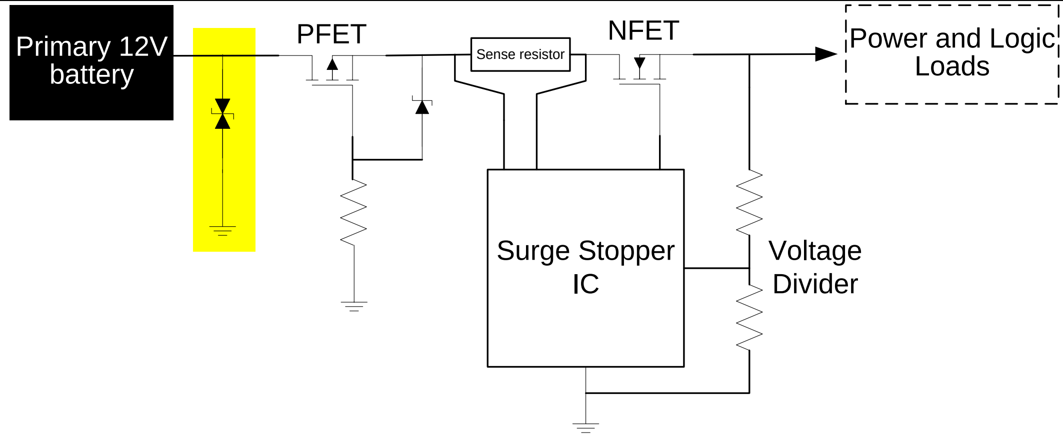


Figure 14: Surge stopper circuit with bidirectional TVS diode clamp

Further investigation into **Content withheld for confidentiality reasons** however led to a potential flaw.

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As seen in figure 14, a pair of TVS diodes placed end to end in order to limit the negative and positive transient voltages to values within the surge stopper ratings.

It should be noted that during the circuit design phase a similar surge stopper IC

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4.2. POWERPATH SWITCH

The need for a powerpath switch was determined after finding that transients could cause the voltage of the target circuit to fall below 5V, such as the pulses of CI 260 from Ford's EMC. The placement of a powerpath switch would ensure that the target circuit would have at least a 5V power supply at all times. Two options existed for the powerpath switch: a diode OR circuit or a dedicated powerpath IC.

4.2.1. DIODE OR CIRCUIT

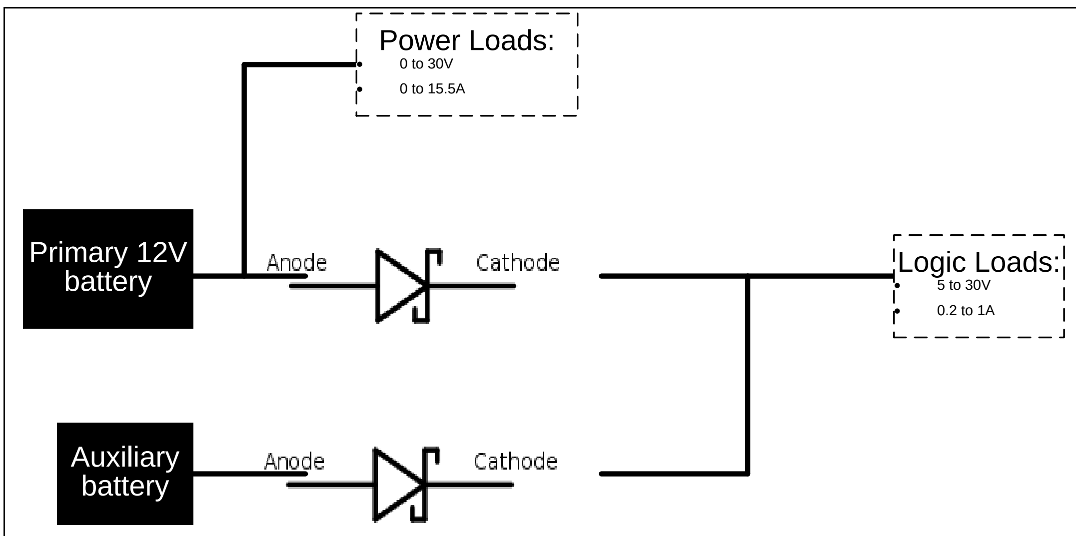

Figure 15: Diode OR circuit configuration

Figure 15 shows the detail circuit configuration of the diode OR circuit and its potential application in the surge stopper circuit. The use of diodes prevents current flowing backwards from the primary battery (whose nominal voltage is 13.5V) into the Auxiliary battery, whose nominal voltage is 12V. The diode configuration also ensures that the logic loads (who were defined in 2.1.1 as needing at least 5V at all times) remain powered.

The following table outlines the advantages and disadvantages of the diode OR approach:

Advantage	Disadvantage
Simple, cheap to purchase and build	Forward voltage drop of ~0.4V means a maximum constant power loss of 1A * 0.4V = 400mW of power over the schottky diode.
Schottky Diodes readily come in familes that can easily pass at least 1A without damage.	No tunable switching voltage thresholds. Diode OR configuration means battery with highest voltage always provides all power. As a result temporary transients such as cranking condition (Ford EMC CI 230-B) would cause the primary battery voltage to fall below the auxiliary battery voltage. This means the target circuit could end up being powered by the auxiliary supply for up to 10 seconds. This violates the system requirement of minimizing the time the target circuit is powered by the auxiliary battery.
A much smaller PCB footprint than if using a dedicated powerpath switcher IC	If both batteries at same voltage, then power is drawn from both sources equally. This would violate the system requirement of minimizing the amount of time the target circuit is powered by the auxiliary battery.

Because of power loss over the schottky diodes and the high probability of the auxiliary battery supplying power when it should not, the diode OR circuit was not used as a powerpath switch. Instead a dedicated powerpath switching IC was used, with the understanding that this will result in greater board space and a higher cost.

4.2.2. DEDICATED POWERPATH IC

A dedicated powerpath IC performs a similar task to the diode OR circuit, but has more configuration options and controls the flow of current through the use of external mosfets rather than diodes. The specific powerpath IC selected was also **Content withheld for confidentiality reasons**. The following figure illustrates the application circuit the design was based upon.

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Figure 16:

From Figure 16, it can be seen that the

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Using this application circuit and relationship, an appropriate circuit was able to be designed.

4.3. DETAILED CIRCUIT DESIGN

4.3.1. SURGE STOPPER

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Figure 17: Surge Stopper Circuit Schematic with labelled sections

Figure 17 illustrates the final schematic of the surge stopper, as simulated in LTSpice.

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4.3.2. Power Path Switch

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Figure 18: Power Path Switch Circuit Schematic with labelled sections

Figure 18 shows the detailed schematic of the Power Path Switch circuit, as well as its major components.

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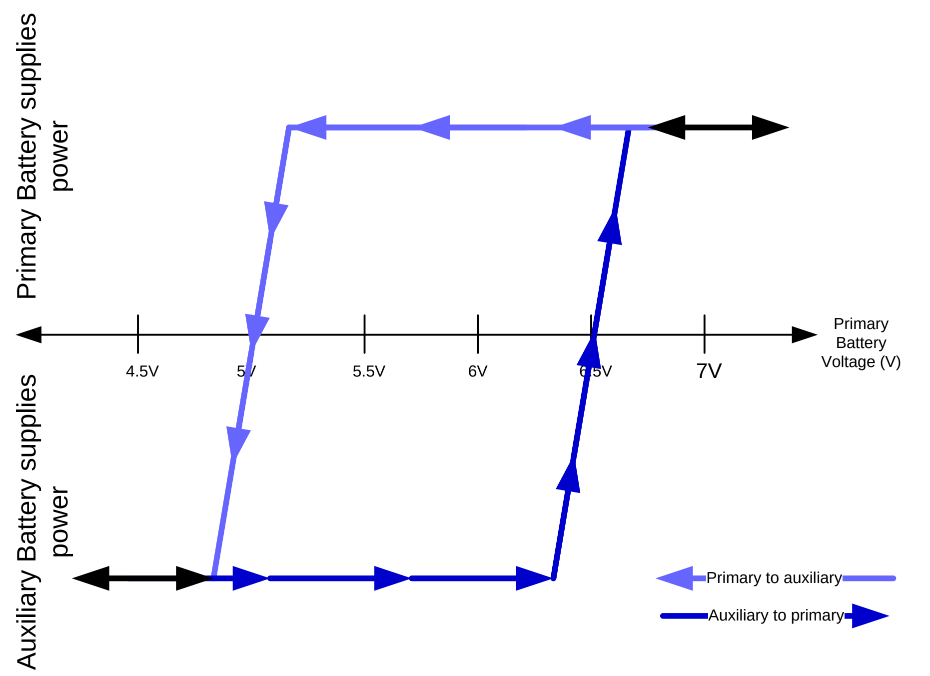

Figure 19: Power Path Switching Hysteresis curve

Inputs V1, V2 and VS monitor each battery's voltage, pulling G1/G2 high in order to prevent reverse current flow (eg. In condition when VS measures 13.5V, but V1 measures 12V).

Transients that are voltage dropouts (such as CI 260-C) would cause the auxiliary battery to provide power for extended periods of time. In order to minimize the amount of time the logic loads are powered by the auxiliary battery, a bank of several large bulk capacitors (C5 to C8) were added. The pass mosfets M2,M4, M5 and M6 were chosen because of their previous use in the surge stopper circuit, as well as their high power ratings and low RDSon rating.

5. SIMULATION

In order to verify the functionality of the surge stopper circuit, the system and the transients it was protecting against were modelled in LTSpice. This section outlines the setup details of the tests, as well as the challenges faced when attempting to accurately model the circuit, and the results of the simulation.

5.1. SIMULATION SETUP

5.1.1. ASSERTIONS AND ASSUMPTIONS

A number of assertions and assumptions were made in order to more accurately model the transients and to visualize their effect on the surge stopper circuit.
The first was the load resistance. Being a non-ideal voltage source, the Ford EMC and ISO7637 standards presented a series resistance as one of the parameters of the pulse. In order to ensure that the surge stopper circuit saw the full voltage waveform of each transient, the logic load resistance had to be set at a high enough value to not load the source. For simulation purposes, the load resistance was set to ensure it was 40 times higher than the source resistance, ensuring a high enough input impedance.

5.1.2. PULSE CREATION

A number of factors were taken into consideration when modelling the transient waveforms in LTSpice.

To save time and reduce effort, pulses of the same category were tested by only choosing the most severe of them. For example all ISO7637 transients had voltage amplitudes consisting of a range. To test the system, the voltages chosen to be modelled were always at the highest range.

For all non-repetitive exponential pulses such as the load dump (Ford EMC CI 220-G2), the linear rise and exponential fall in voltage was not capable of being modeled due to tool limitations. As a result they were conservatively modelled as an exponential rise and exponential fall in voltage. Conservative modelling also applied for repetitive exponential pulses such as ISO7637-2 3A and 3B, which could also not be accurately modelled due to tool limitations. As a result these repetitive pulses were conservatively modelled as sawtooth waves instead, which have a power level greater than exponential pulses.

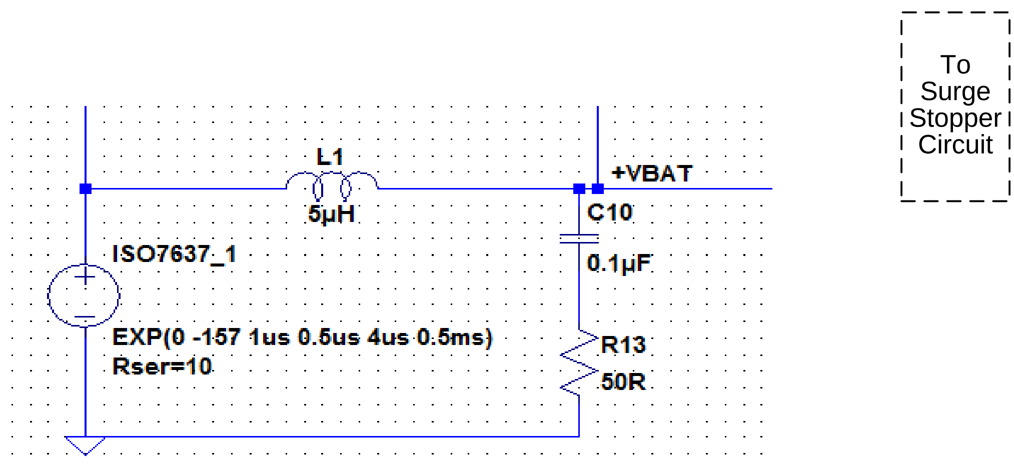

Figure 20: Artificial Network

The final factor taken into consideration with the generation of the transient pulses was the addition of an artificial RLC network, shown in Figure 20. The ISO7637-2 document describes this artificial network as a way of simulating the wiring harnesses in an automobile[4]. The existence of this artificial network allows for more conservative testing, as the inductor will cause inductive spikes and produces more extreme transients.

5.2. CHALLENGES ENCOUNTERED

A number of challenges were encountered when setting up the simulation . The following table lists the problems encountered and the solutions used to address them:

Table 3: Challenges encountered while simulating surge stopper circuit

Challenge	Solution
Spice model for particular 75V TVS diodes originally sourced could not be found or requested in time for report creation.	Compromise made, with a different model with a lower voltage cutoff (60V instead of 75V)
Rise and fall time constants for exponential transients did not visually match their calculated value	Rise and fall time constants modified until length of rise and fall visually matched to parameters described in the standard.
Originally simulation set with perfect source to make more conservative, however problems with TVS diodes not clamping	Series resistance added to voltage source.
TVS diode breakdown voltage affects power dissipation and is dependent upon current flowing through the system. Simply choosing TVS diode based upon breakdown voltage was not sufficient.	TVS diode reverse voltage chosen by available spice model and by trial and error with simulation results.
Test pulses that began at zero volts had to have low source resistance, in order to ensure large bypass capacitor of 330uF charged up quickly	
Inductor due to external wiring harness	

network caused brief inductive spikes which occassionally caused timestep issues	
Overvoltage setpoint at 27V, but non-idealities/test setup caused voltage to reach 27.5V in load dump condition.	Overvoltage setpoint changed to 26V to accommodate this.

5.3. SIMULATION RESULTS AND ANALYSIS

Simulation results and Analysis were focused on two components: voltages seen by power load/logic load, and power consumption of TVS diodes and past mosfets of surge stopper.

Voltages were measured at three different points: At the waveform generator, at the net connected to the power loads (+VBAT_12V0 in figure 17 and 18), and at the logic load after the power path switch.

Power dissipation was measured at three different points as well: across the TVS diodes placed before the surge stopper (D3 or D2 in figure 17 and 18, depending on which one is clamping during the test), and across the pass mosfets M1 and M3.

Power dissipation was judged across the TVS diodes was judged by comparing the dissipation with the rating listed in the diode's datasheet (see figure 21). Power dissipation across the mosfets were judged according to the max power dissipation rating at 25 degrees ambient temperature. For the P type mosfet used (part number FQB22P10TM_F085) the maximum power dissipation was listed at 125W[2]. For the N type mosfet used (part number SQM85N15), the max power dissipation was listed at 375W[10].

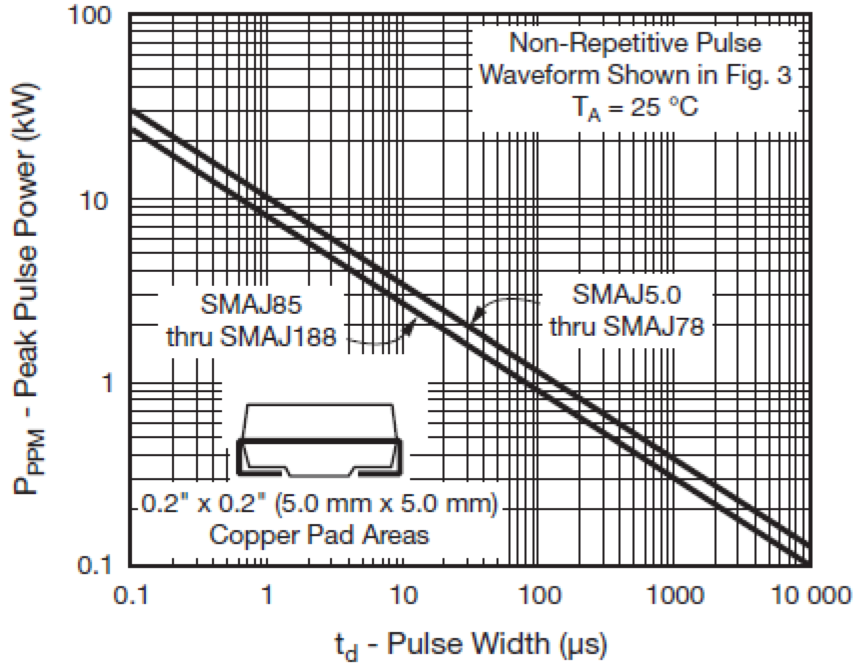

Figure 21: Power dissipation rating of SMAJ series TVS diodes (source: Vishay datasheet)

5.3.1. Ford EMC CI 230-B (Cranking Condition)

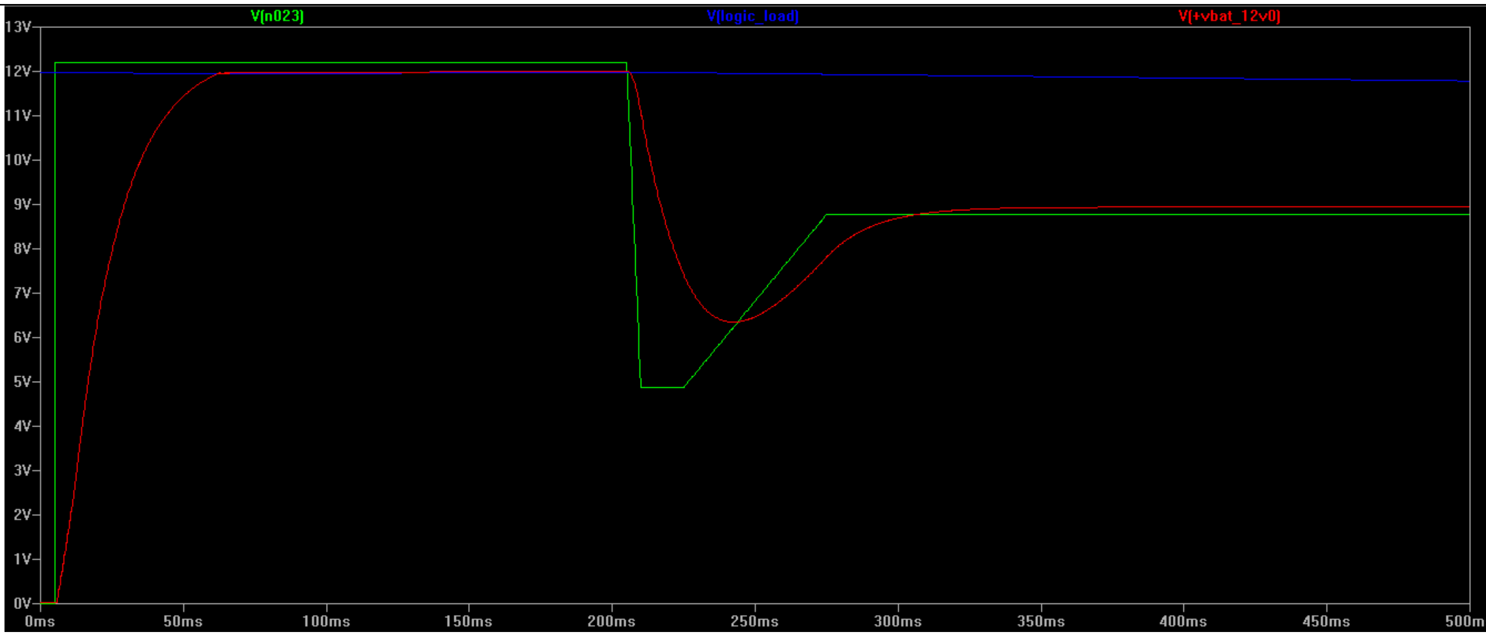

Figure 22: Ford EMC CI 230-B Voltage Plot

From Figure 22 one could observe the effect of the cranking condition transient CI 230 B (yellow on graph) on the power load voltage (Red on graph) and logic load voltage (blue on graph).

The unique exponential curves of the power load voltage is attributed to the large bulk capacitance placed on the same net (see 4.3.1). The near steady value of the logic load is also attributed to the large bulk capacitance located on the same net (see figure 19).

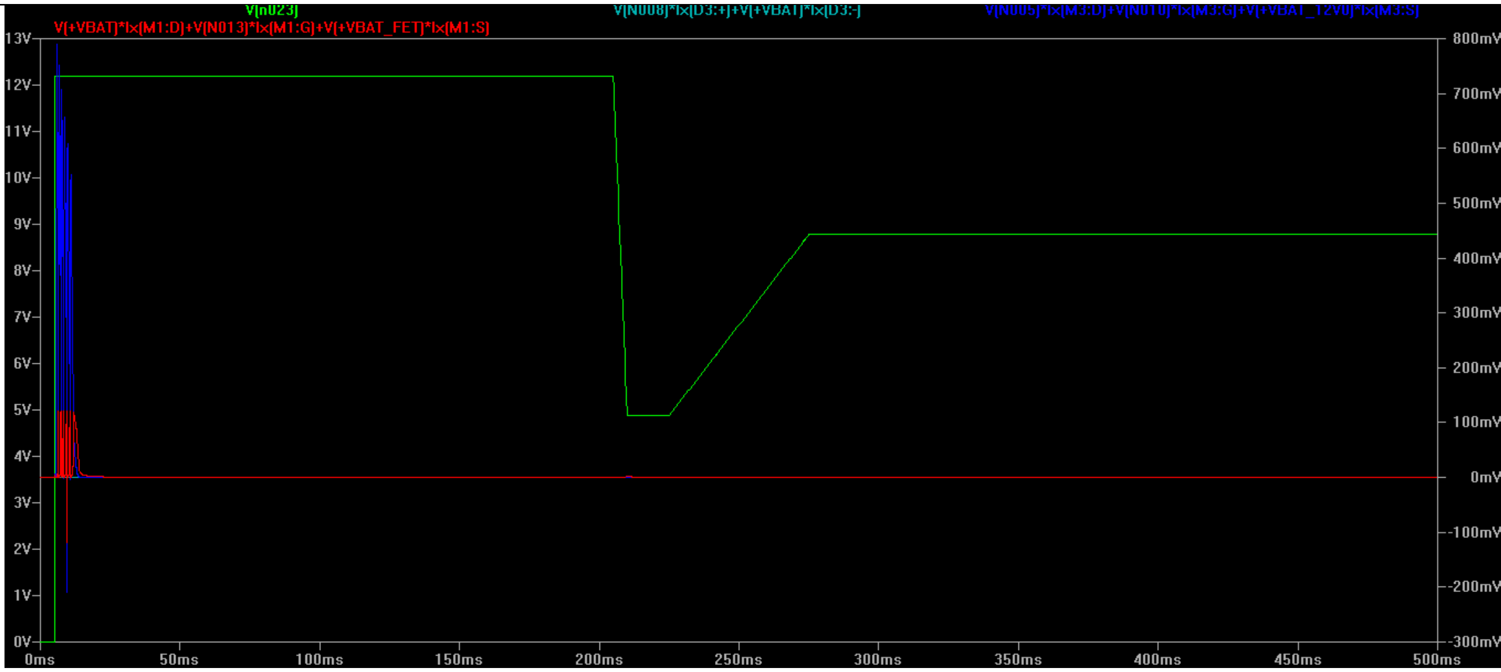

Figure 23: Ford EMC CI 230-B Power Consumption Plot

From Figure 23 one could observe the effect of the cranking condition transient CI 230 B (yellow on graph) on the power dissipation of the N type pass mosfet (Blue on graph, M3 in schematic), P type pass mosfet (Red on graph, M1 in schematic) and TVS diodes (teal on graph, D3 in schematic).

All power values of the graph are under the limits of each component, therefore they will all be capable of handling this transient without any issue.

5.3.2. Ford EMC CI 270 (Over/Under Voltage)

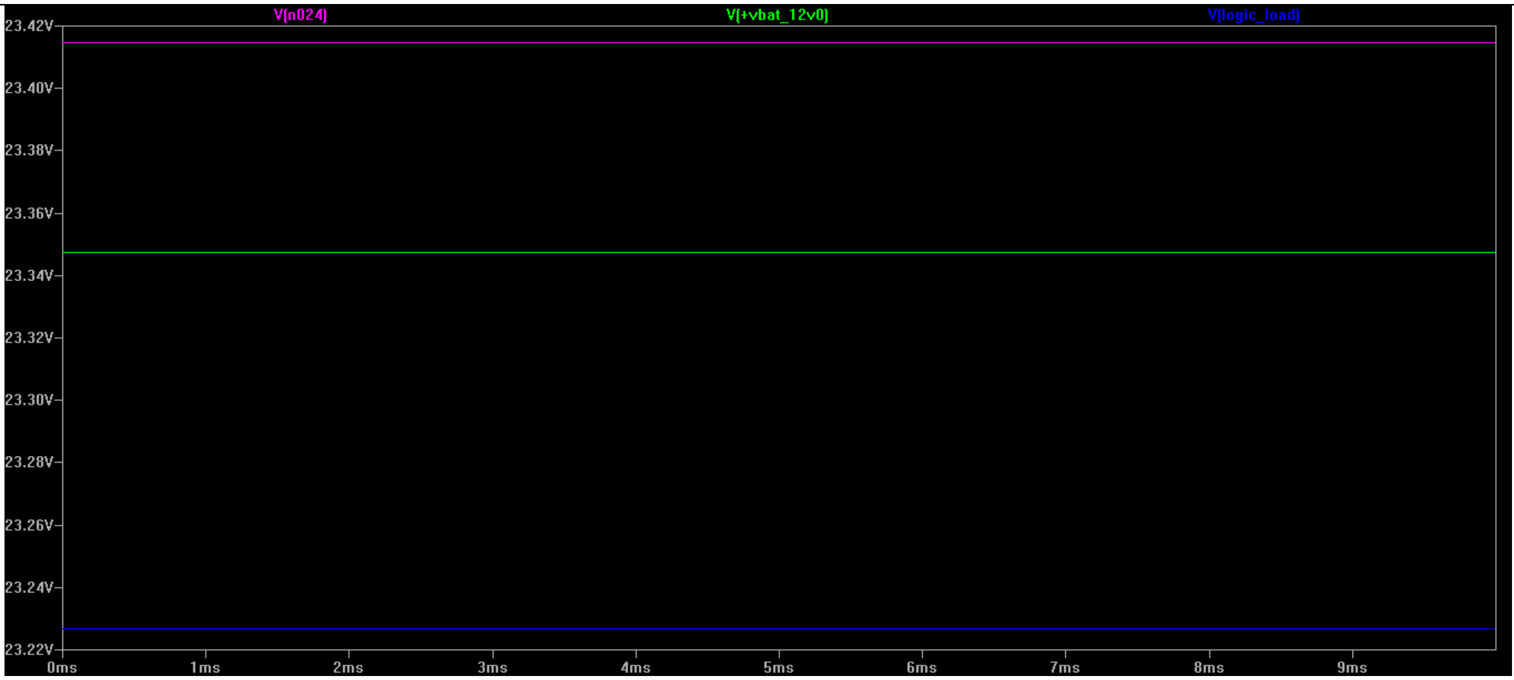

Figure 24: Ford EMC CI 270 24V voltage plot

From Figure 24 one could observe the effect of 24V overvoltage condition CI 270 (pink on graph) on the power load voltage (yellow on graph) and logic load voltage (blue on graph). No transient exists and the power dissipation is minimal because the voltage amplitude is within the listed operating range of the target circuit.

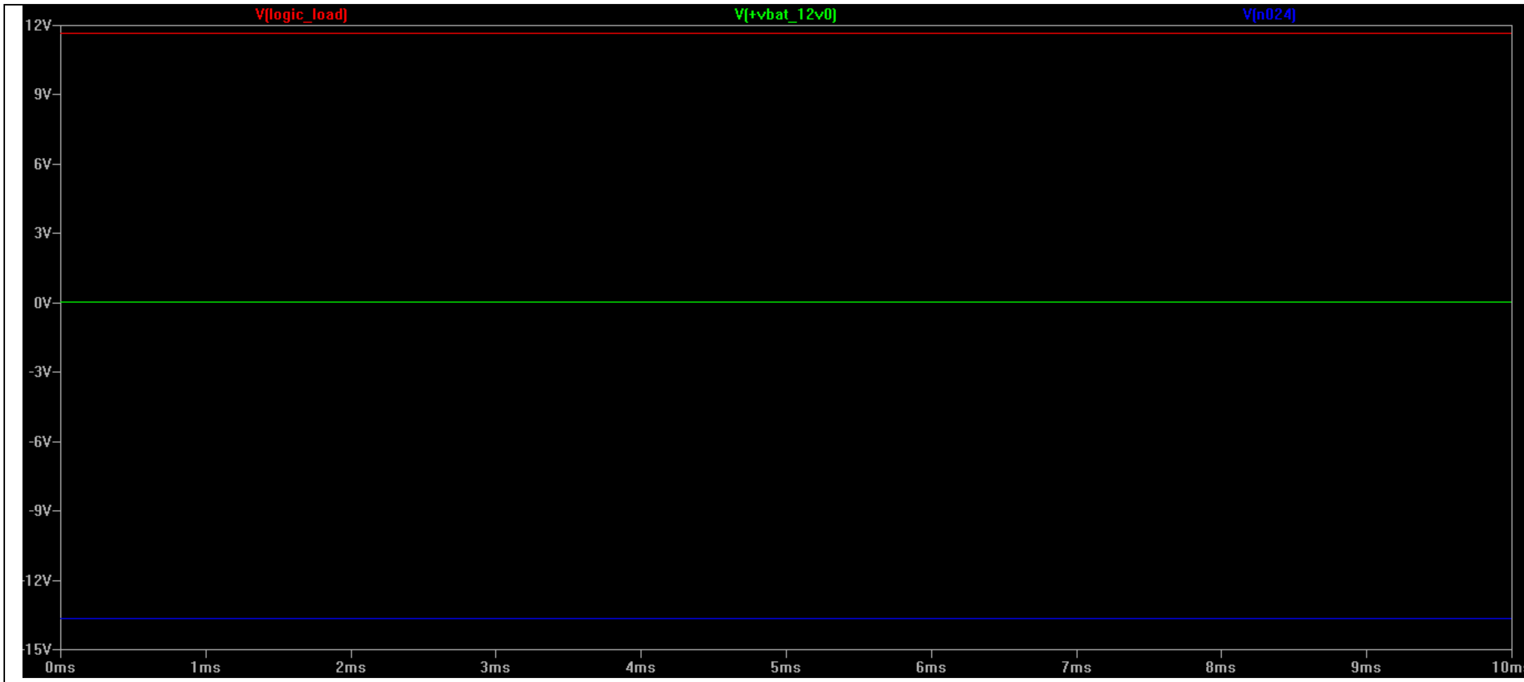

Figure 25: Ford EMC CI 270 -14V voltage plot

From Figure 25 one could observe the effect of the -14V reverse voltage transient CI 270 (blue on graph) on the power load voltage (green on graph) and logic load voltage (red on graph). This simulation result shows the operation of the Power Path switch and the P type pass mosfet. The P type pass mosfet detects the negative voltage and turns off, preventing the power load from seeing a negative voltage (which could damage the IC's it powers). The powerpath switch detects the low (0V) value of the primary battery, and switches the source of power to the auxiliary battery (V4 in figure 19).

5.3.3. FORD EMC CI 220-G2 (LOAD DUMP)

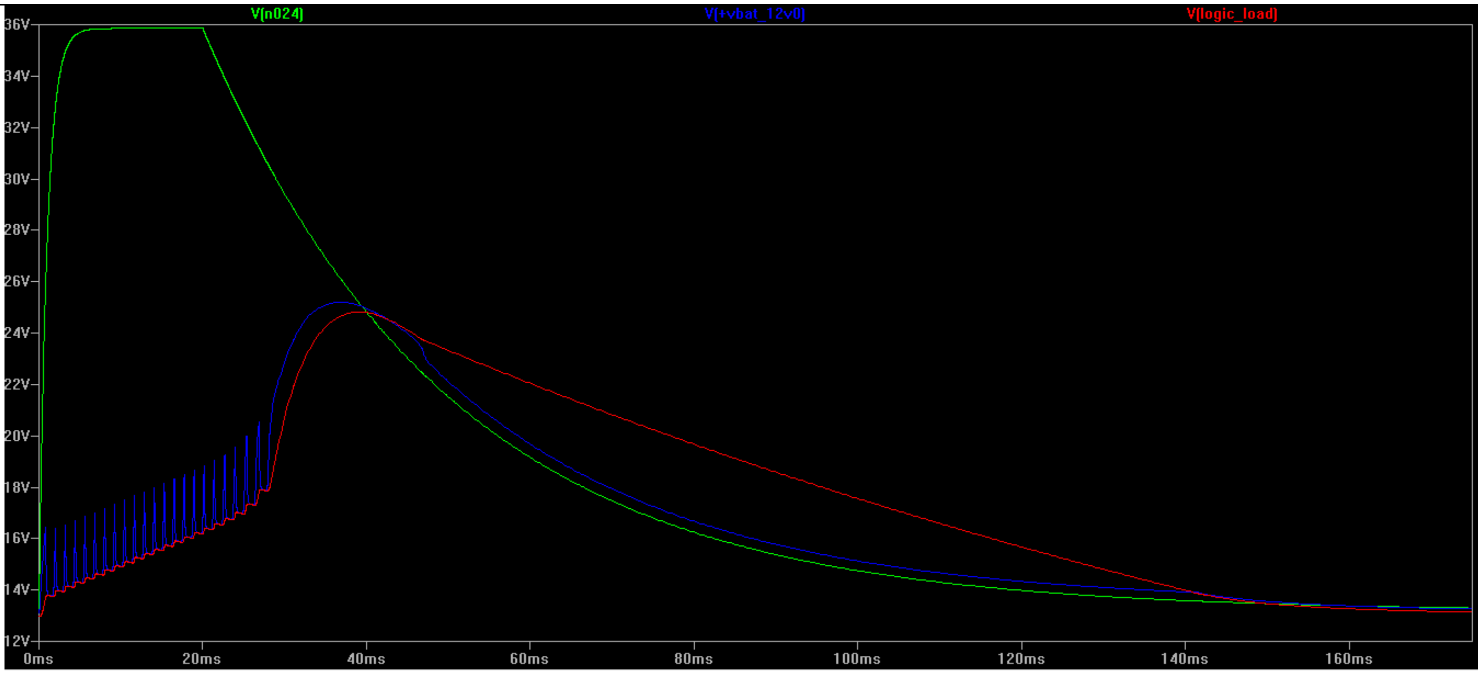

Figure 26: Ford EMC CI 220-G2 b voltage plot

From Figure 26 one could observe the effect of the load dump condition transient CI 220-G2 (green on graph) on the power load voltage (blue on graph) and logic load voltage (red on graph). The voltage spikes present on the power load voltage are due to the constant switching of the N type pass mosfet (M3 on schematic). These voltage spikes are heavily clamped by the downstream capacitors past the power path switch, which explains the more smooth waveform.

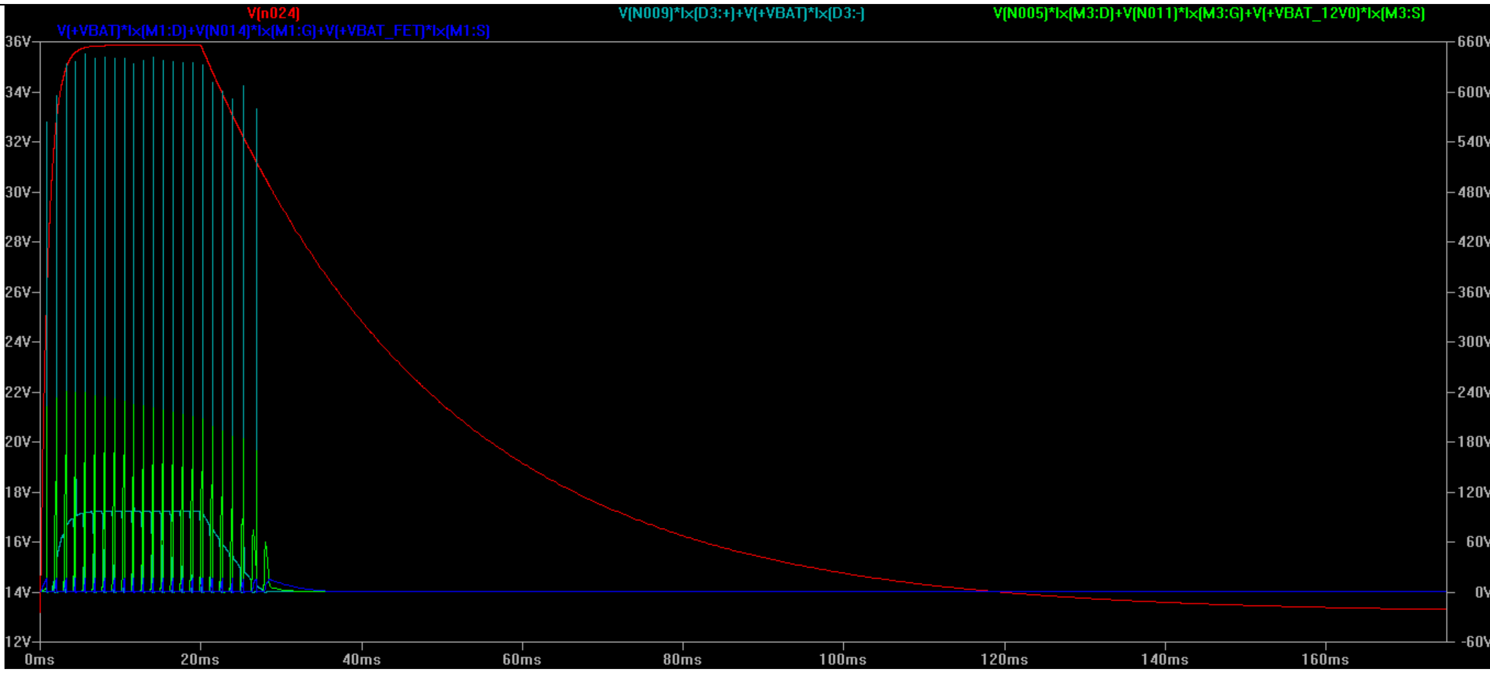

Figure 27: Ford EMC CI 220-G2 b power consumption plot

From Figure 23 one could observe the effect of the load dump transient CI 220 G2 b (red on graph) on the power dissipation of the N type pass mosfet (green on graph, M3 in schematic), P type pass mosfet (blue on graph, M1 in schematic) and TVS diodes (light blue on graph, D3 in schematic).

By visual inspection, the pulse width of the load dump curve is approximately 40ms long. When using this pulse width on the TVS diode peak power dissipation graph (figure 21) one notices that the listed pulse width only reachs 10ms. Extrapolation of the graph shows that the TVS diodes would not be capable of dissipating that much power without damage. Their limit according to the graph is under 100W, but their expected power dissipation according to the simulation peaks at over 600W. Future designs of this circuit would require a more robust TVS diode family.

Visual inspection of the graph in figure 27 also informs us that the max power dissipation seen by the N type pass mosfet is approximately 220W, which is within its maximum power dissipation range.

5.3.4. ISO7637-2 PULSE 1

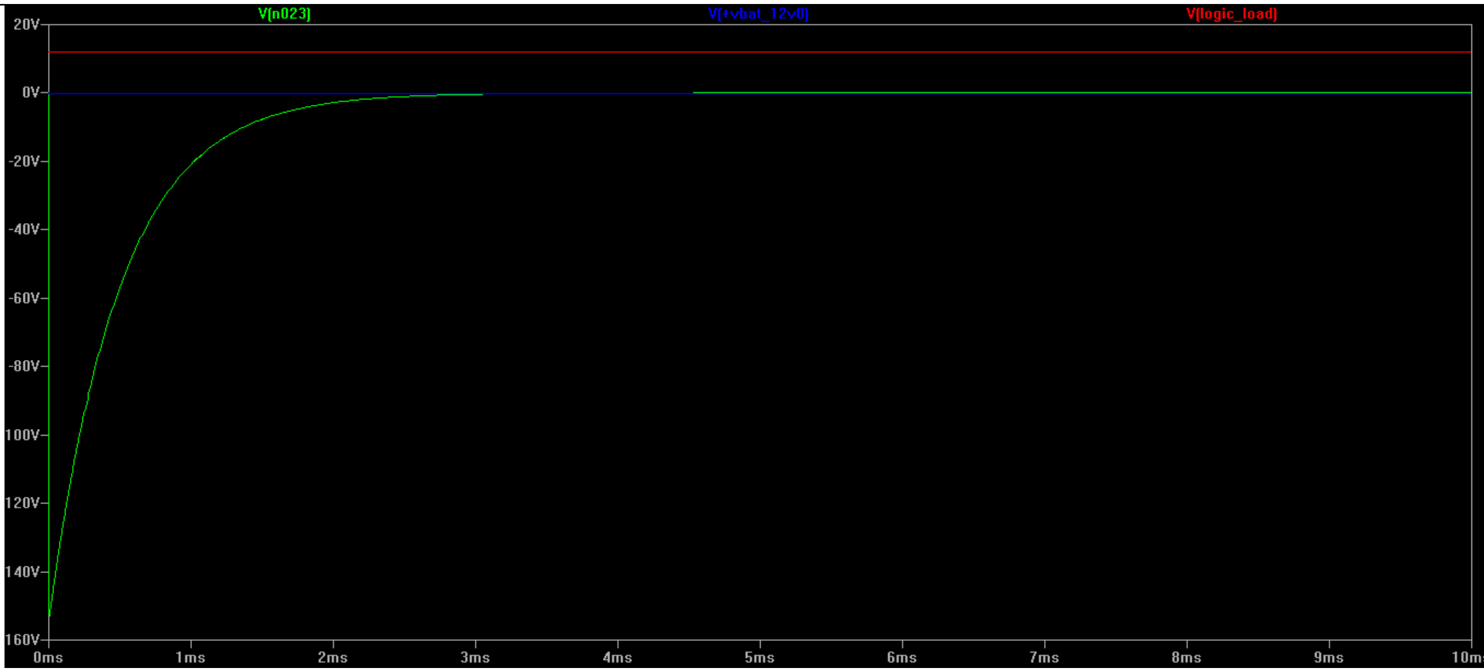

Figure 28: ISO7637-2 pulse 1 voltage plot

From Figure 28 one could observe the effect of the transient ISO7637-2 Pulse 1 (green on graph) on the power load voltage (blue on graph) and logic load voltage (red on graph). As expected the power load voltage is 0 due to the P type mosfet preventing any negative voltage from passing through to the loads, and the power path switch has changed the logic loads voltage supply to the auxiliary battery.

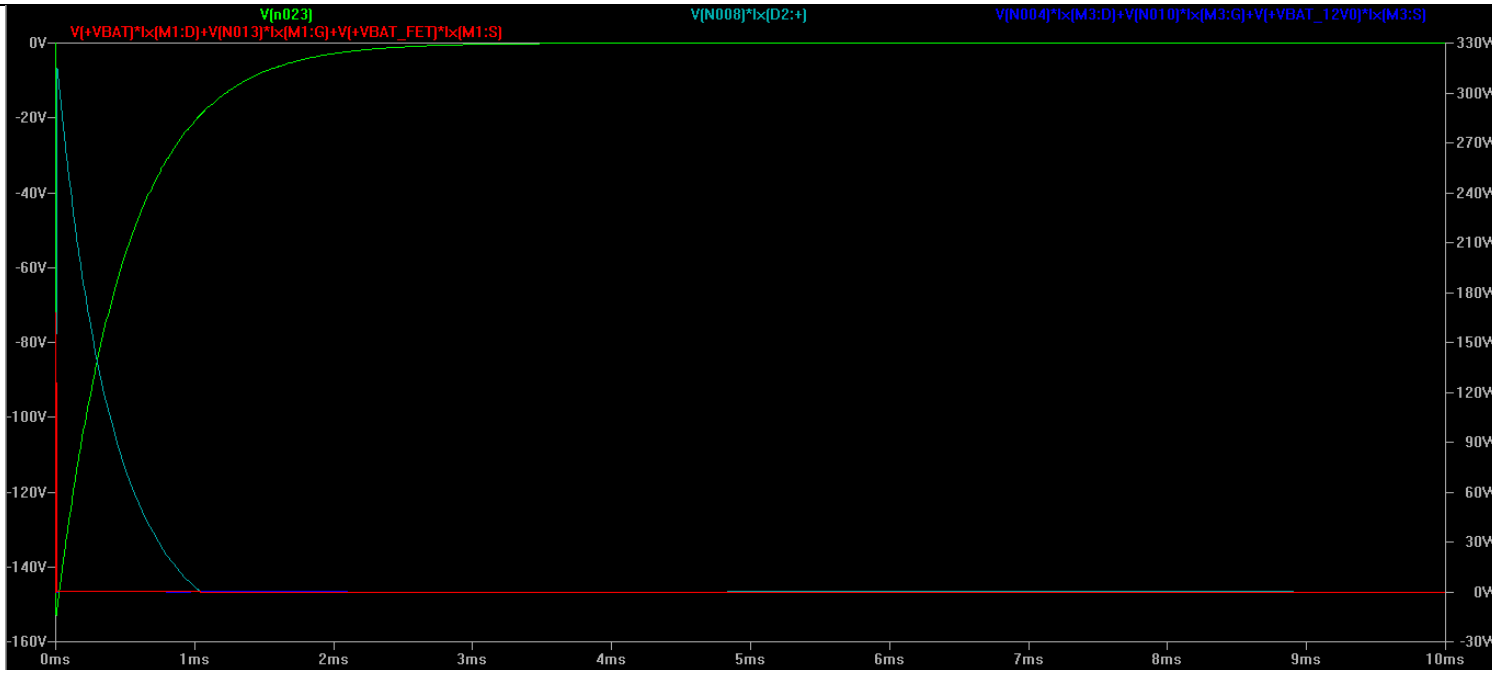

Figure 29: ISO7637-2 pulse 1 power plot

From Figure 29 one could observe the effect of the transient ISO7637-2 pulse 1 (green on graph) on the power dissipation of the N type pass mosfet (blue on graph, M3 in schematic), P type pass mosfet (red on graph, M1 in schematic) and TVS diode (light blue on graph, D2 in schematic).

The only component dissipating a large amount of energy was the TVS diode D2, which performed in reverse breakdown at the large negative voltage. From visual inspection the pulse width of the transient was approximately 2ms, which when plotted on the power dissipation graph in figure 21 led to a max power dissipation of 200W. The simulation results showed however a max power dissipation of 300W, which is greater than the limit of the TVS diodes. As a result, it is expected that a future version of the circuit will have a larger power dissipation rating.

5.3.5. ISO7637-2 Pulse 2A

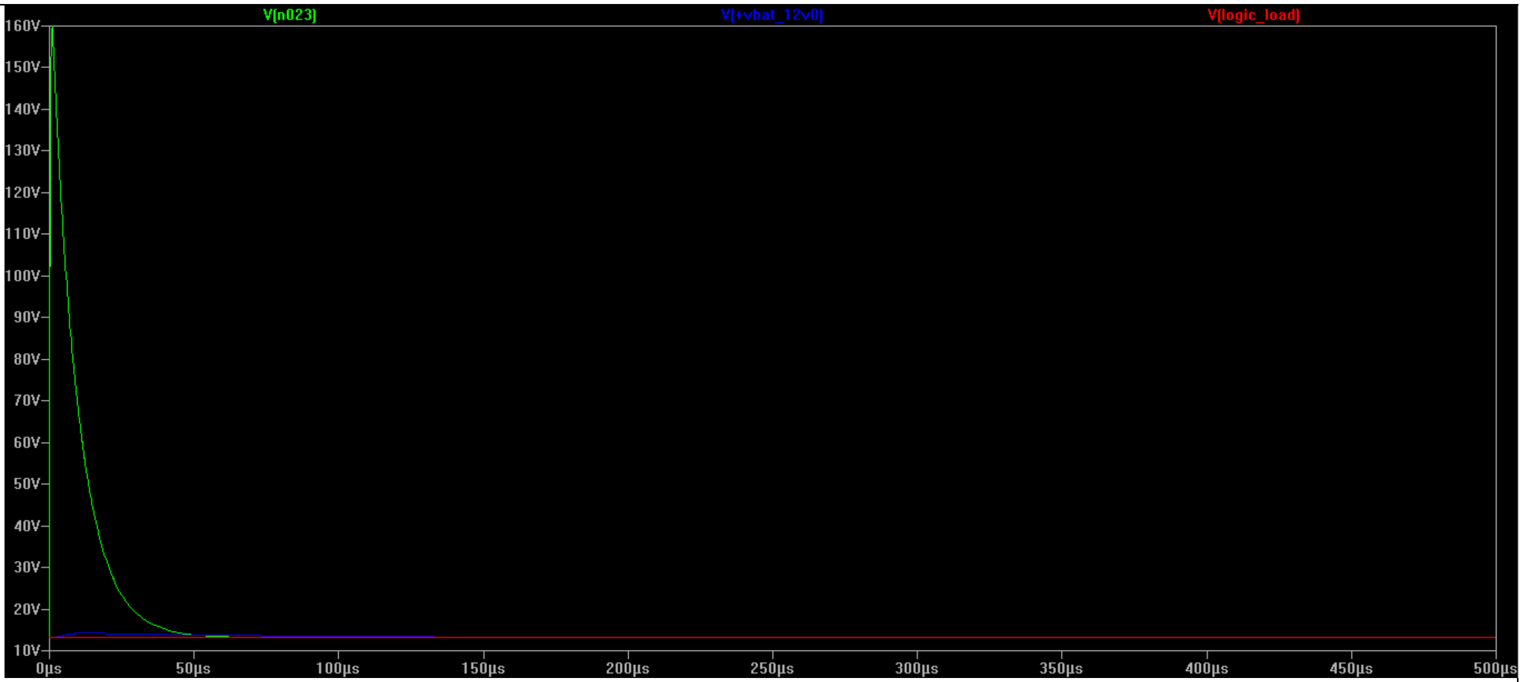

Figure 30: ISO7637-2 pulse 2a voltage plot

From Figure 30 one could observe the effect of the transient ISO7637-2 Pulse 2a (green on graph) on the power load voltage (blue on graph) and logic load voltage (red on graph). The duration of this pulse was short enough that the waveform was absorbed by the 330uF bulk capacitance of the power load, and hence there was little visible effect on the logic and power load voltages.

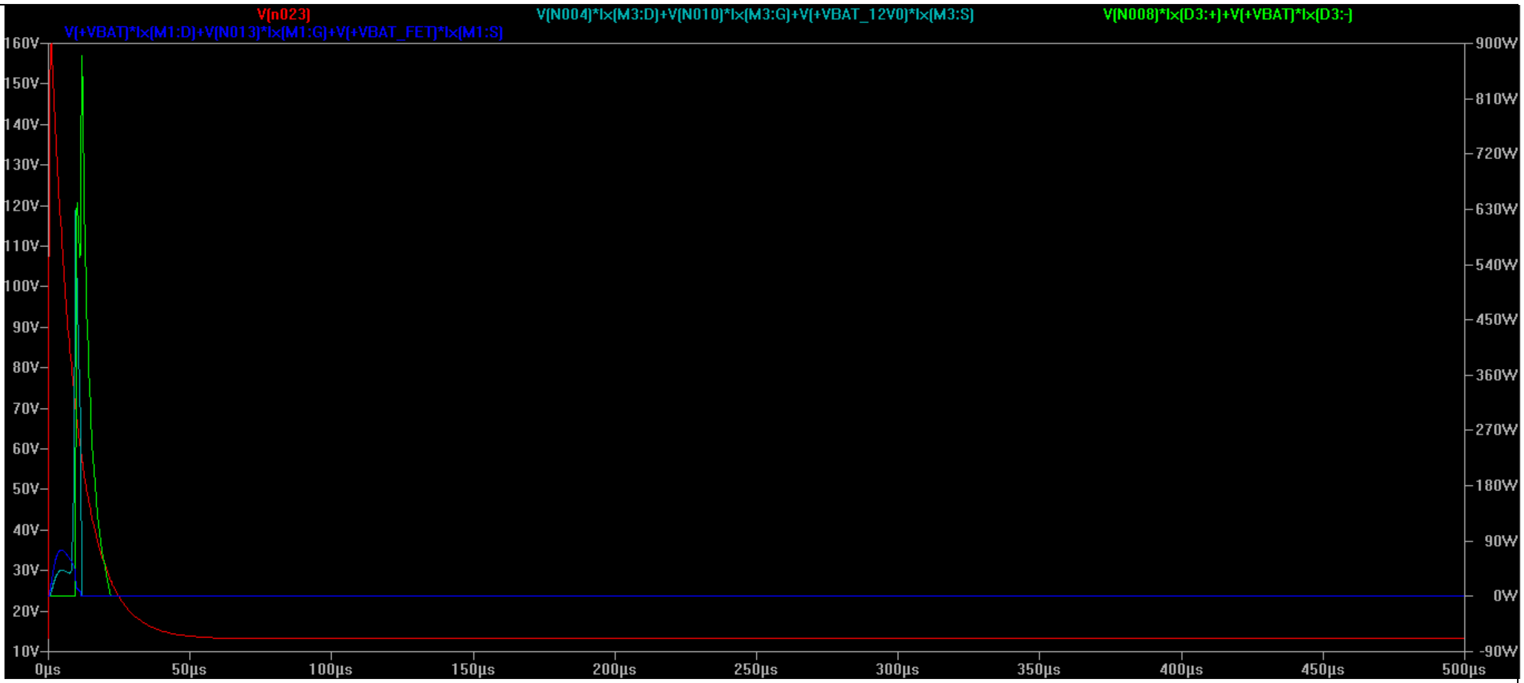

Figure 31: ISO7637-2 pulse 2a power plot

From Figure 31 one could observe the effect of the transient ISO7637-2 pulse 2a (red on graph) on the power dissipation of the N type pass mosfet (light blue on graph, M3 in schematic), P type pass mosfet (blue on graph, M1 in schematic) and TVS diode (green on graph, D3 in schematic). From visual inspection the TVS diode dissipates almost 900W, but because of the brief nature (under 20us) of the transient the power dissipation is within the range of the sourced TVS diodes.

5.3.6. ISO7637-2 Pulse 3A and 3B

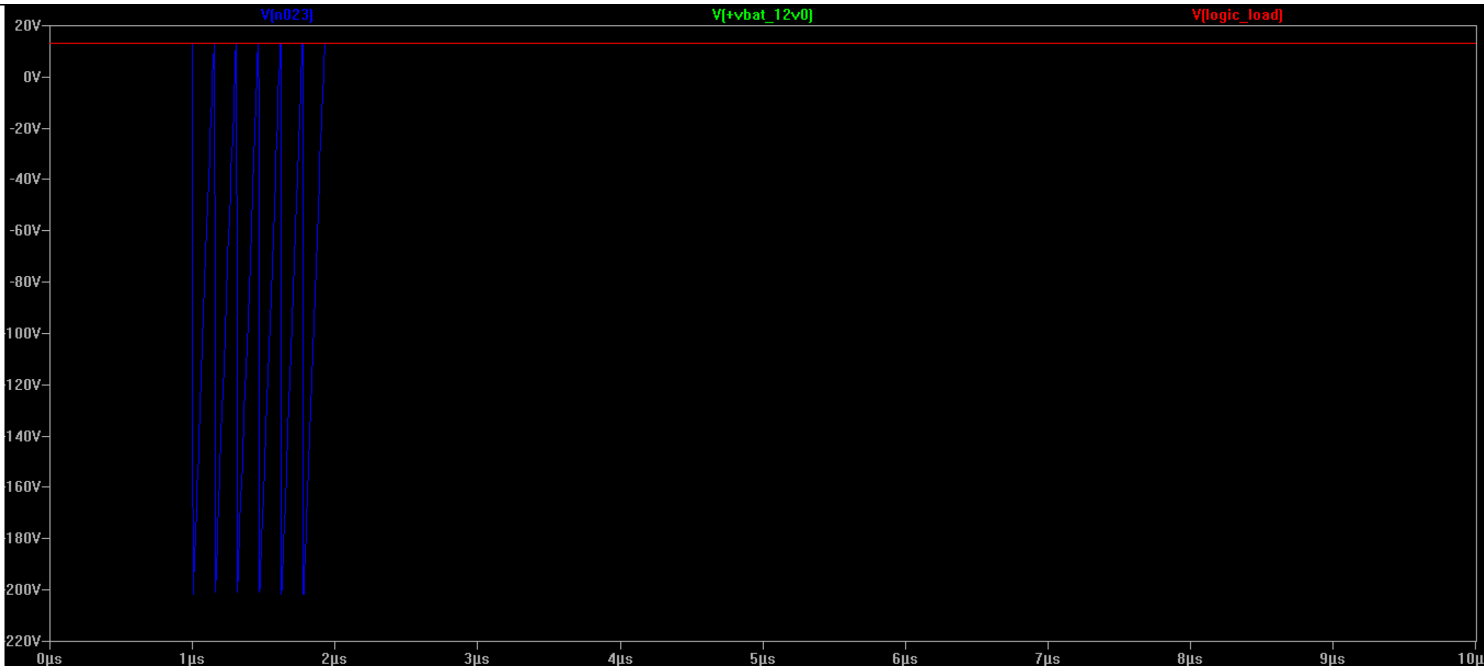

Figure 32: ISO7637-2 Pulse 3A voltage plot

From Figure 32 one could observe the effect of the transient ISO7637-2 Pulse 3a (blue on graph) on the power load voltage (green on graph) and logic load voltage (red on graph). Similar to the result shown in figure 30, the duration of this pulse was short enough that the waveform was absorbed by the 330uF bulk capacitance of the power load. This meant almost no effect was visible on the logic and power load voltages. A power dissipation plot was not included because the power dissipation across the crucial components of the circuit were not significant.

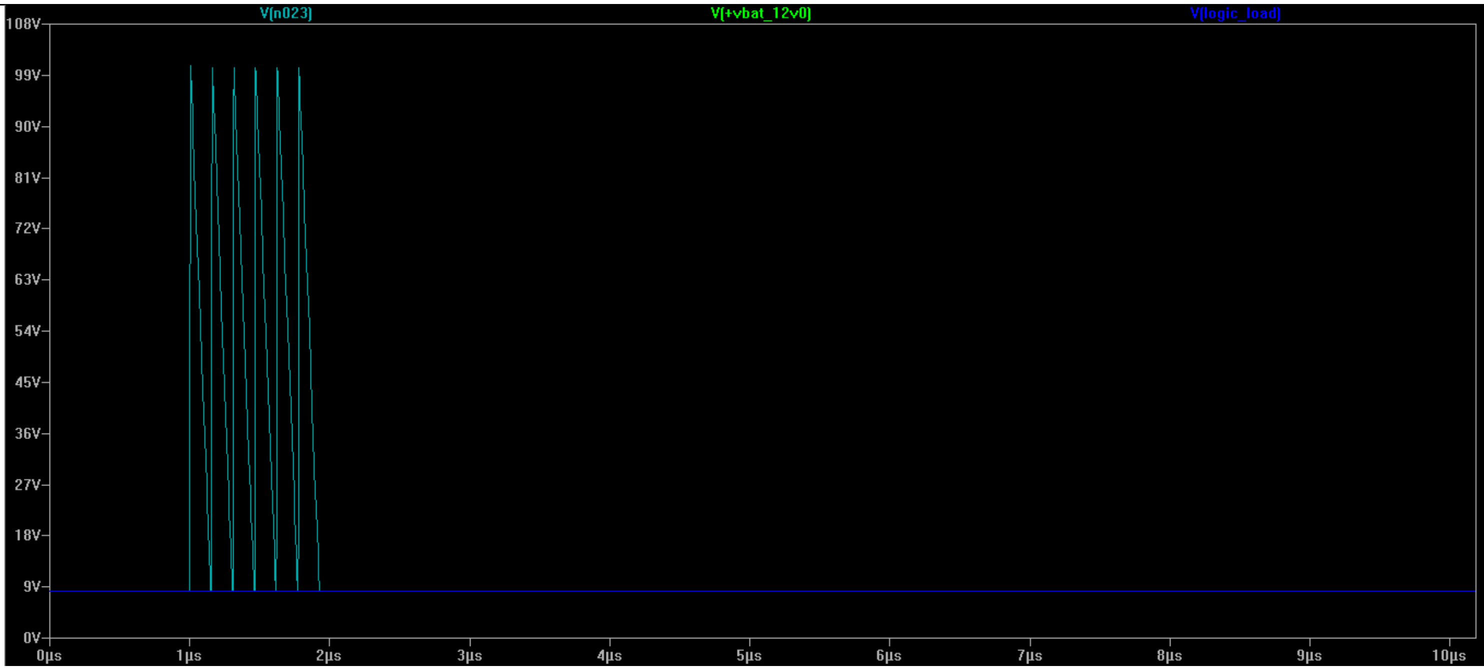

Figure 33: ISO7637-2 pulse 3b voltage plot

From Figure 34 one could observe the effect of the transient ISO7637-2 Pulse 3a (light blue on graph) on the power load voltage (green on graph) and logic load voltage (blue on graph). Similar to the results shown in figure 30 and 32, the duration of this pulse was short enough that the waveform was absorbed by the 330uF bulk capacitance of the power load. This meant almost no effect was visible on the logic and power load voltages. A power dissipation plot was not included because the power dissipation across the crucial components of the circuit was not significant.

5.3.7. ISO7637-3 Fast Pulse + and –

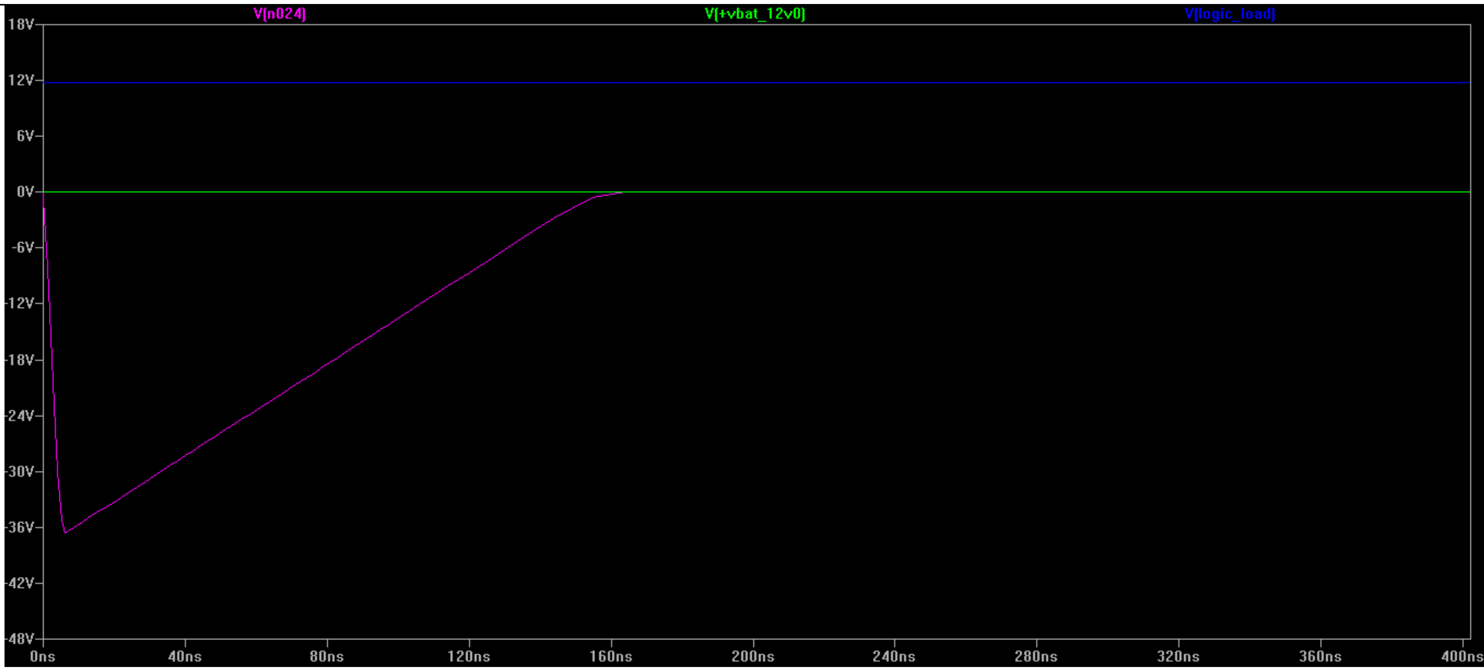

Figure 34: ISO7637-3 fast pulse -

From Figure 36 one could observe the effect of the transient ISO7637-3 fast pulse - (purple on graph) on the power load voltage (green on graph) and logic load voltage (blue on graph). Similar to the transient ISO7637-2 pulse 1 described in 5.3.4, the auxiliary power path can be seen with the logic load voltage and the reverse input blocking nature of the p type mosfet can be seen with the power load voltage. A power dissipation plot was not included for this transient because of the low dissipation.

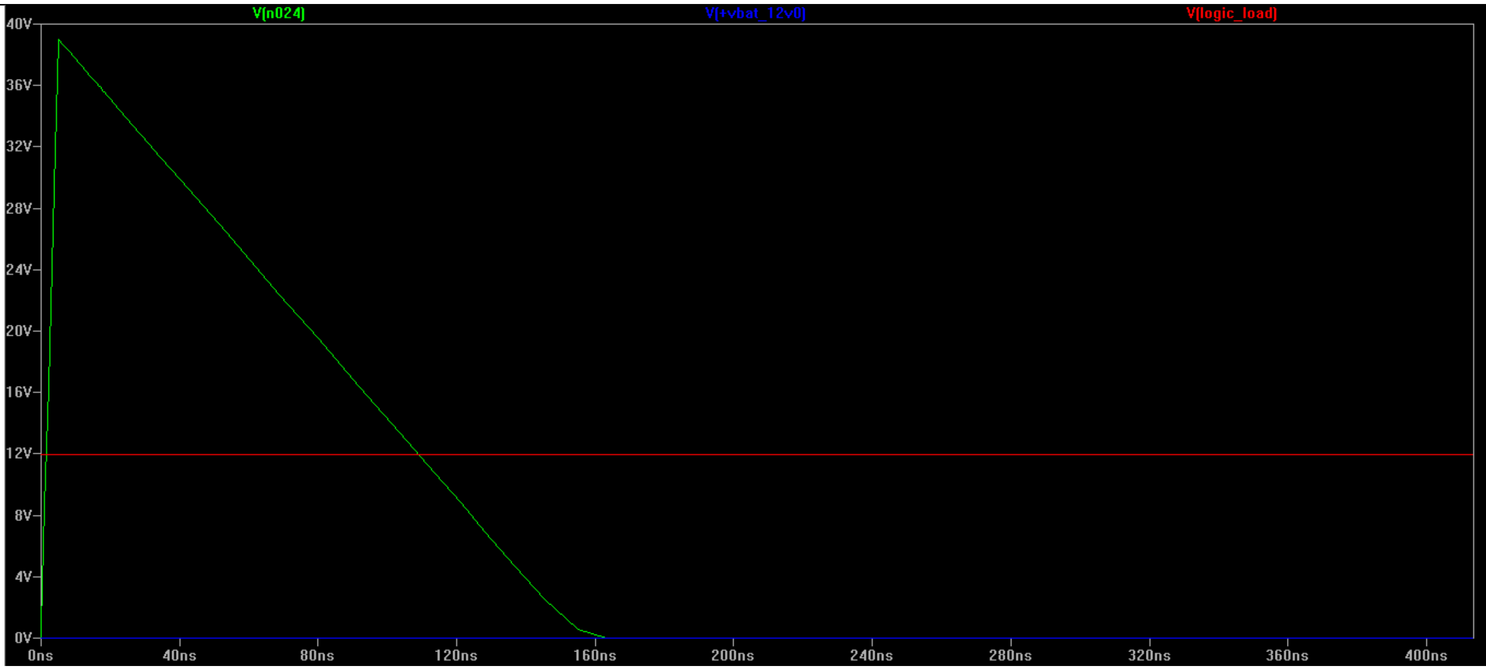

Figure 35: ISO7637-3 fast pulse + voltage plot

From Figure 37 one could observe the effect of the transient ISO7637-3 fast pulse + (green on graph) on the power load voltage (blue on graph) and logic load voltage (red on graph). A power dissipation plot was not included for this transient because of the insignificant power dissipation.

5.3.8. ISO7637-3 Slow Pulse + and -

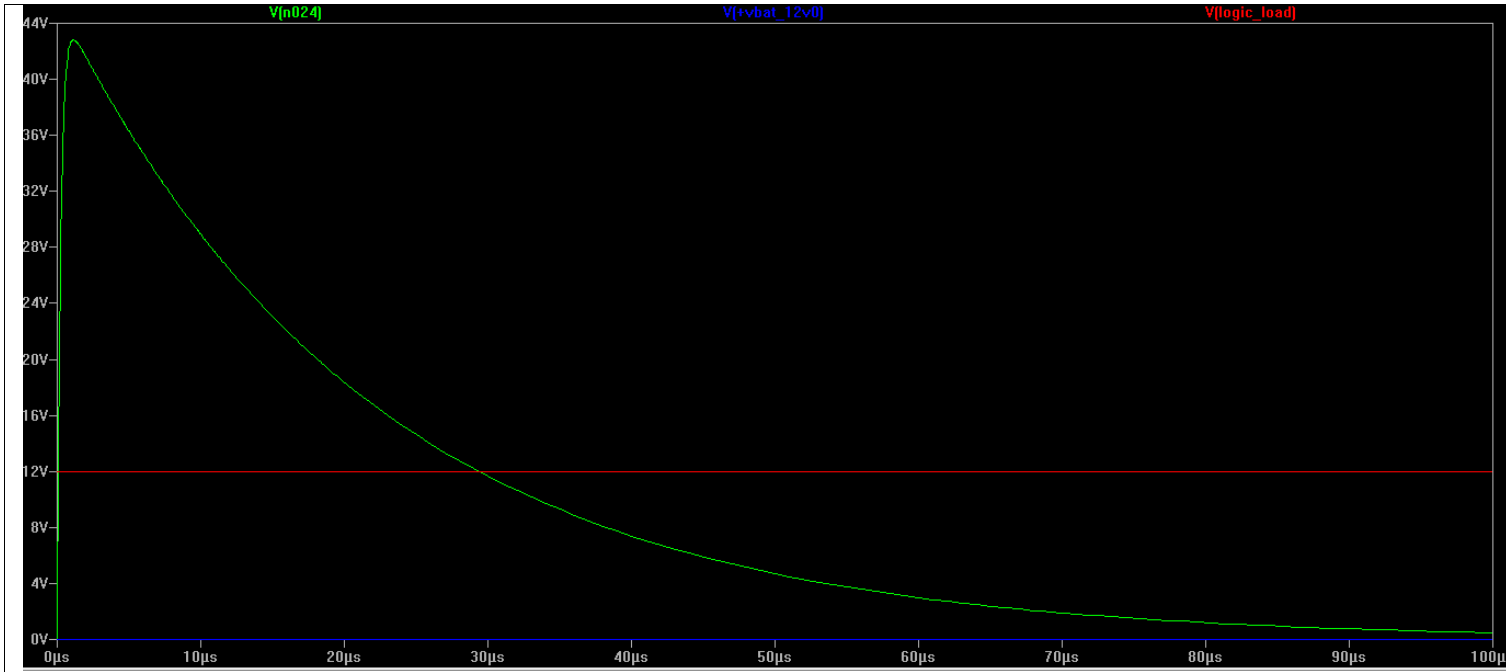

Figure 36: ISO7637-3 slow pulse + voltage plot

From Figure 37 one could observe the effect of the transient ISO7637-3 slow pulse + (green on graph) on the power load voltage (blue on graph) and logic load voltage (red on graph). A power dissipation plot was not included for this transient because each component's power dissipation was within their listed maximum rating.

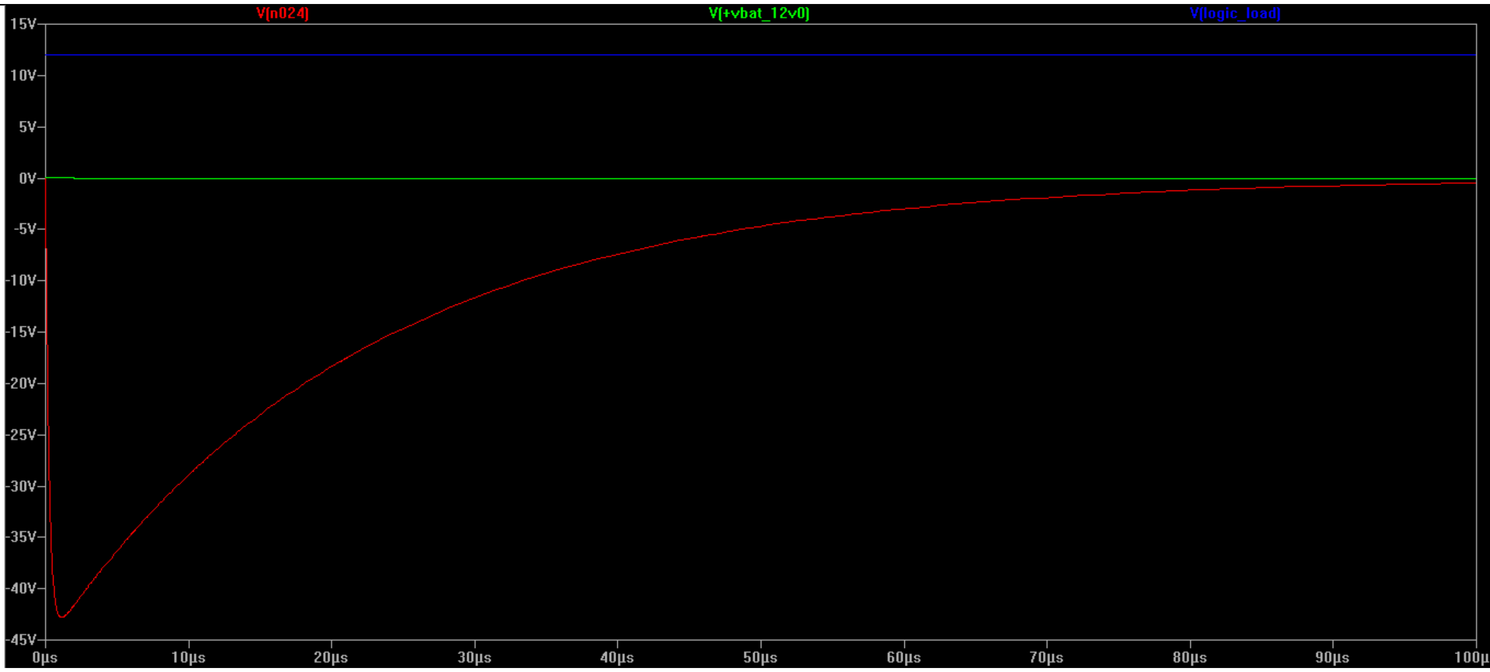

Figure 37: ISO7637-3 slow pulse - voltage plot

From Figure 37 one could observe the effect of the transient ISO7637-3 slow pulse - (red on graph) on the power load voltage (green on graph) and logic load voltage (blue on graph). Similar to ISO7637-2 pulse 1 described in 5.3.4 and ISO7637-3 fast pulse described in 5.3.7, the negative voltage is blocked by the P type mosfet, and the logic load has been configured by the power path switch to be supplied by the auxiliary battery. A power dissipation plot was not included for this transient because each component's power dissipation was within their listed maximum rating.

6. Conclusions and Recommendations

6.1. Lessons Learned

1. **Discrete surge stopper IC's cannot handle voltage transients on their own**.
   The voltage transients outlined in the Ford EMC and ISO7637 standards often have voltage amplitudes far greater than the limits of the surge stopper IC. In order to protect the surge stopper an clamping TVS diode needs to be placed in shunt with the IC. Sourcing a surge stopper IC that has a larger voltage input range would be beneficial.
2. **Automotive transients are very high energy.**
   This is most visible when analyzing the simulation results and the amount of power each element needs to dissipate. The large amount of power often dissipated from these transients (ranging in the 100's of watts) requires large packaged components. This reduces available board space and significantly increases cost.

6.2. Future Steps

1. **Prototype circuit to confirm functionality**
   Circuit simulations have limitations in terms of accuracy. A number of assumptions and simplifications were made in order to conduct the simulation (such as load impedance, ideal passive components, etc.). Prototyping the circuit will allow for the behaviour of the surge stopper to be better analyzed and will help to ensure that the design is valid. It will also help bring to light any restrictions on board layout
2. **Cost Optimization and re-source components**
   Being a first design, some components did not have a high enough power dissipation rating, and as such need to be re-sourced. The high power nature of these transients requires high cost components. A future step

would be to test and develop different methods of providing the same level of protection at a more economical cost. A possibility would be duplicating components such as pass mosfets, in order to distribute the power dissipation amongst two identical components –which in turn allow for smaller and more cheaper elements to be used.

7. REFERENCES

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