SPICE-ify Your Vishay Ametherm Inrush Current Limiters With QSPICE® From Qorvo®

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INTRODUCTION

Negative temperature coefficient (NTC) ceramic components have been used for decades to protect power supplies, motors, lighting ballasts, and inverter drives against inrush current at startup. This functionality, commonly referred to as surge or inrush current limiting (SL / ICL), is critical in power supplies across a wide range of applications - from industrial systems to consumer electronics.

Vishay Ametherm inrush current limiters (ICLs) have been widely adopted in switch mode power supplies (SMPS), particularly where large banks of smoothing capacitors and large toroidal transformers are used, such as in audio amplifiers. These capacitors can cause high current spikes that may damage input rectifiers and other sensitive power components or have the safety fuse trip. Vishay Ametherm ICLs are also frequently integrated into motor drives, welders, charging equipment, circuit breakers, industrial automation systems, and airport logistics systems, where they serve to protect the circuitry during power-on surges.

In the imaging sector - particularly in medical and security equipment - toroidal transformers are often used, which generate significant inrush currents. Many equipment designers in this space have adopted specialized Vishay Ametherm AS Series ICLs to mitigate this risk. Similarly, Vishay Ametherm solutions have been trusted by various manufacturers of medical-grade power supplies.

Finally, in the renewable energy and charging infrastructure sectors, reliable inrush current protection is vital to system stability. ICLs have proven essential in the performance and longevity of inverter systems, where a dependable limiter can mean the difference between a failed switch-on and a successful and soft start-up without any transients. Vishay Ametherm ICLs continue to be a preferred choice among power electronics designers in these high demand industries because of their smaller size, higher power density, and robust design and performance.

The following article summarizes how the values and size of NTC ICLs must be adapted in a classical way to the characteristics of SMPS, motor drives, audio amplifiers, imaging equipment, inverters, or any other unwanted surge events. Then, going further into these applications, we will see how we can SPICE-ify these components and even design our whole application with the help of a powerful SPICE program, in this case QSPICE® from Qorvo® [4].

HOW TO SELECT AN NTC INRUSH COMPONENT

Vishay Ametherm has been producing ICLs for more than 30 years, and provides numerous tutorials to assist with the design-in process [1].

The fundamental criteria are divided into three essential steps. The user must determine:

- The minimum resistance, which determines the maximum allowed inrush current (mainly defined by the presence of a current breaker)
- The maximum steady current (keeping the component at a sustainable temperature)
- The joule energy that the component must be able to sustain during capacitor loading. This can be quantified using the constitutive equations describing the component characteristics, as we will see later in this article

These steps can be accomplished with the provided calculators [1], in which the user inputs their circuit data, including input voltage, output current, power, and capacitance value.

Then, as the application becomes more complex, the next steps to accomplish are less evident, and could leave the user a little more dubitative as they begin to deal with other concepts, such as:

- Reset time: the time allowed between two consecutive on / off switches for the SMPS device
- Power supplies with one or three phases: form factors must be applied here
- Scope trace: how the inrush wave looks on an oscilloscope
- Diode bridge voltage drop

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The words “time”, “scope”, and “trace” immediately recall the idea of analyzing such applications with dynamic circuit SPICE analysis. So, why not proceed directly to the design of these ICLs at the heart of the real application? Well, to do this we first need SPICE models, and not all suppliers provide them. Vishay Ametherm is no exception. So, we need to SPICE-ify them first.

THE BUILDING OF SPICE MODELS FOR THESE PARTS (AND MANY OTHERS)

First of all, we must state that the SPICE program chosen for this article is QSPICE® from Qorvo®. It is free, flexible, and has proven to be the fastest software for this task. In practice, the netlist used is compatible with Berkeley SPICE and thus can be integrated into any SPICE software.

Secondly, a bigger problem is ahead of us: how to build SPICE models from scratch for such ICL components (or more generally, for any component series)? Well, first you need to gather the part numbers list and all parameter values used to describe the electrical and thermal behaviors.

The main equations for determining the electrical and thermal behavior of an ICL device are:

$$R(T) = R_{25} \times \exp\left(A + \frac{B}{T} + \frac{C}{T^2} + \frac{D}{T^3}\right) \qquad (1)$$

$$C_{th} \times \frac{dT(t)}{dt} = D \times (T_{ambient} - T(t)) + R(T(t)) \times I(t)^2 \qquad (2)$$

$$\tau = \frac{C_{th}}{D} \qquad (3)$$

$$\alpha = \frac{1}{R} \times \frac{dR}{dT} \qquad (4)$$

where:

- R(T) is the NTC electrical resistance as a function of the temperature T (in K) (the coefficients A to D describe the material curve)
- R_{25} is the electrical resistance at 25 °C
- C_{th} is the thermal capacity (J/K)
- D is the dissipation coefficient (W/K)
- τ is the response time and a combination of C_{th} and D
- The temperature coefficient α is the percental change in resistance when T increases

In the case of Vishay Ametherm ICL ranges, we are talking about a range of a little more than 200 components, which would normally take a lot of time to analyze manually. A smarter way to build SPICE models is to first analyze the structure of the datasheets available on the website. As an example, the datasheet URLs of two of these components are:

- SL320R230
- SL2216005

You can see that the only variable part of these URLs is the part number itself, and if you follow those links you'll observe that the structure of the datasheets is uniform from webpage to webpage. That allows a program like the VBA macro for Excel™ [2] to gather all data necessary to build the SPICE netlist, including the R_{25}, tolerance, thermal capacity, dissipation coefficient, and NTC curve reference (material type for beta and curve).

Now that we have a global netlist for the 200 parts, we still need to build the symbols. It is well known that repetitive symbol building in SPICE software is considered tedious work by engineers. Fortunately, we only have to build one element according to the method in the EE Power article “Importing 3rd Party Models into QSPICE” [3], and the rest can be automatically generated.

A symbol file in QSPICE is nothing more than a text file, in which only some bits change from one part number to another in a series. Such text files can be opened, modified (with the help of the Excel function “concatenate”), and saved with the proper extension (“.qsym” for QSPICE), once again by a loop in the VBA macro for Excel.

NTC ICLs are special thermal resistors. Instead of building a two-pin model, which would be connected electrically to the circuit, it is advantageous to introduce a third pin (output read-out only), allowing for monitoring of the variable resistance in time. This will prove particularly useful when analyzing AC circuits, in which visualizing the resistance value by dividing the voltage by the current can often become undefined (AC current passes periodically through zero).

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The ICL SPICE symbol (which is presented in Fig. 1) will present the part number, R_{25} value, the maximal rated current I in steady-state, and the joule rating J. We have explained the reasons for the choice of R_{25} and I. What about the joule rating? Well, at switch-on of a voltage V on the circuit of the thermistor (with a thermal mass C_{th}) and the C capacitor in series, the surge current reaches the value V/R_{25} at t = 0.

$$V = R\,I + \frac{1}{C}\int I\,dt \tag{5}$$

The thermistor heats up quickly, and if you do not want the surge current to increase further while the capacitor is charging, we need to state that dI/dt = 0 at time 0. Using the equations (2), (4), and (5) after derivation, it is very easy to reach the condition where the surge current will not increase further at t = 0:

$$\frac{|\alpha| C\,V^2}{C_{th}} = 1 \tag{6}$$

This means that to limit the maximal current to the initial value, the thermal mass of the thermistor must be equal or higher than $CV^2 \times \alpha$. It is possible to verify the statement with the following circuit (Fig. 1 and Fig. 2).

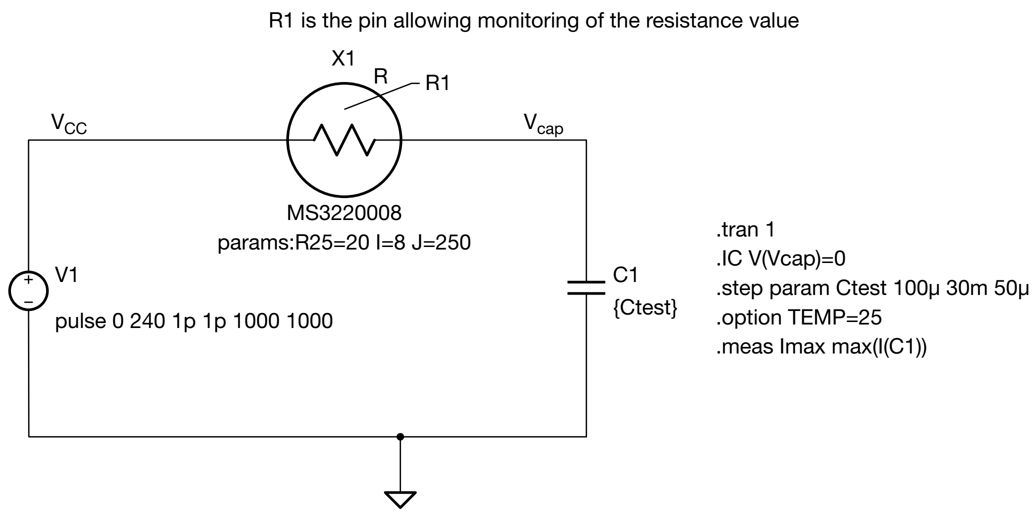

Fig. 1

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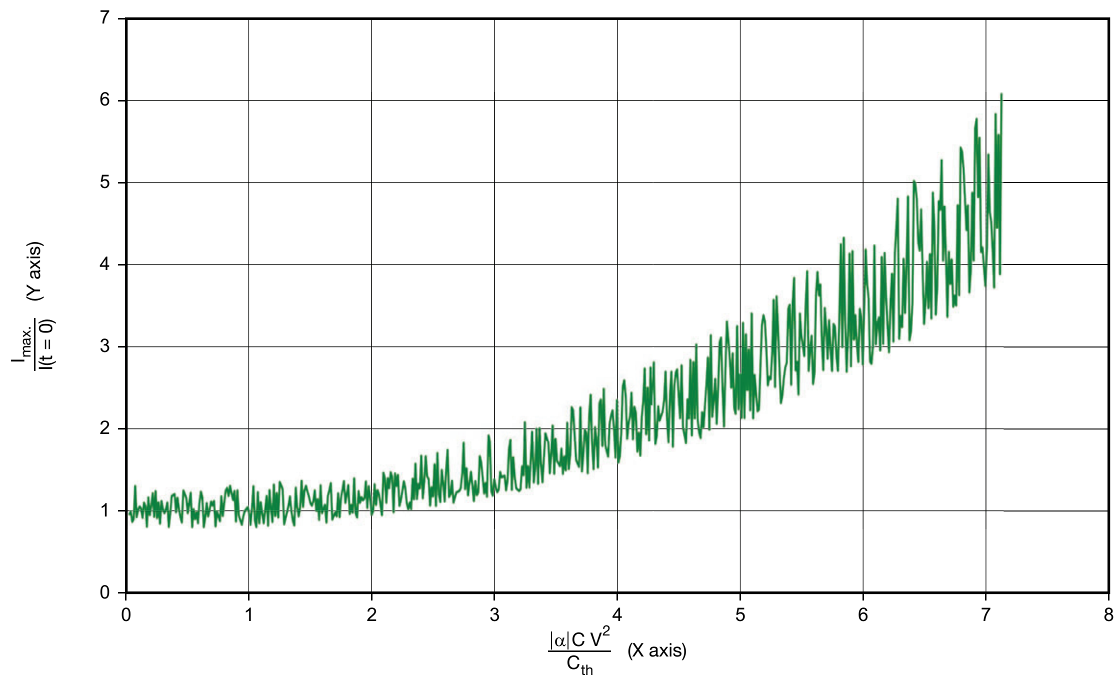

Fig. 2

We see in the simulation results of Fig. 2 that the ratio between the maximum current through the capacitor and the nominal surge current (240 V / 20 Ω) is equal to 1 for the ratio $\frac{|\alpha| C V^2}{C_{th}}$ lower than 1, and then begins slowly to increase non-linearly above. The rratio $\frac{|\alpha| C V^2}{C_{th}}$ should be kept under 2, for example, if we do not want the surge current to be excessive.

THE BUILDING OF THE APPLICATION CIRCUIT AND INTEGRATION OF THE ICL COMPONENT

After verifying on a simple circuit (Fig. 3) that our NTC ICL SPICE models work well (Fig. 4), and that the computed residual resistances at 50 % and 100 % of the maximal rated current match the original specifications, we can directly enter into the real application circuit (Fig. 5).

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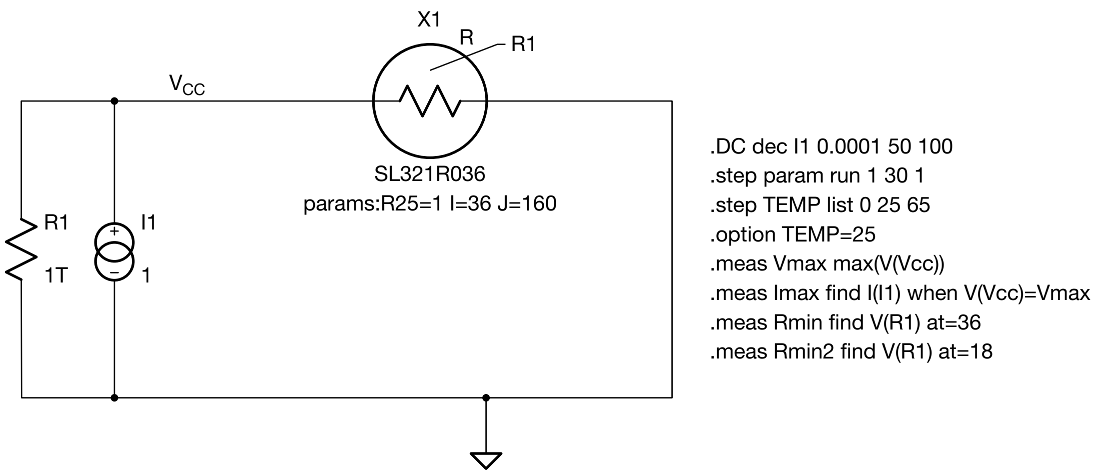

Fig. 3

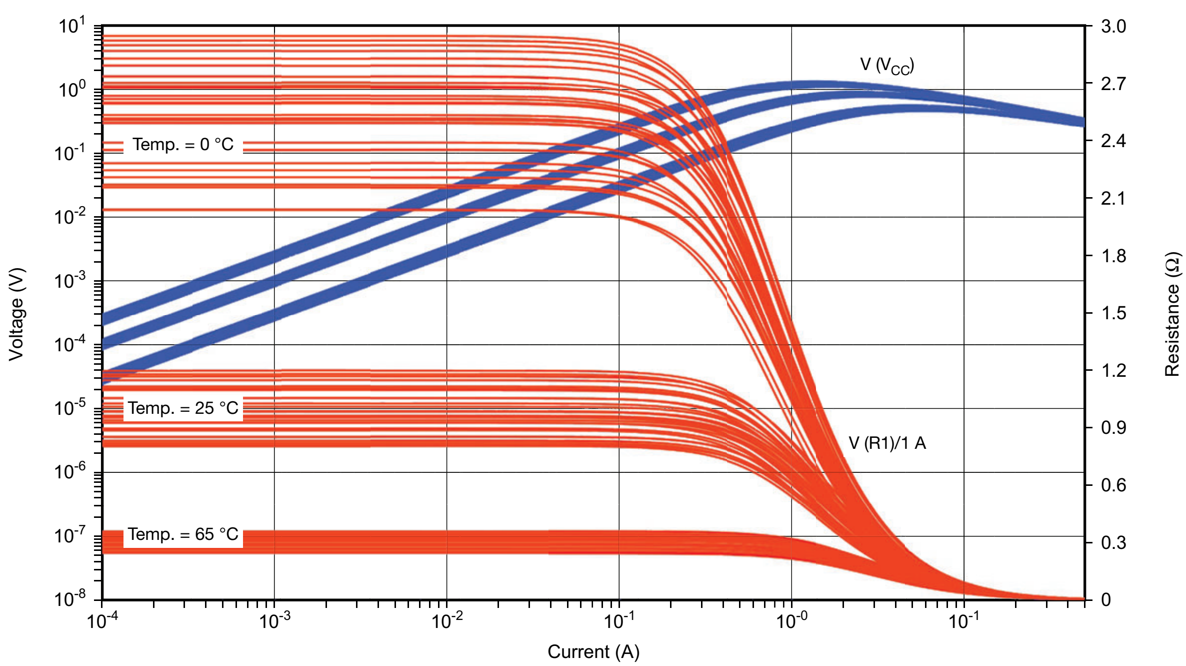

Fig. 4

The computed residual resistance at 100 % $I_{max.}$ (36 A) is from 0.0065 Ω up to 0.011 Ω (spec 0.01 Ω).

The computed residual resistance at 50 % $I_{max.}$ (18 A) is from 0.016 Ω up to 0.028 Ω (spec 0.03 Ω).

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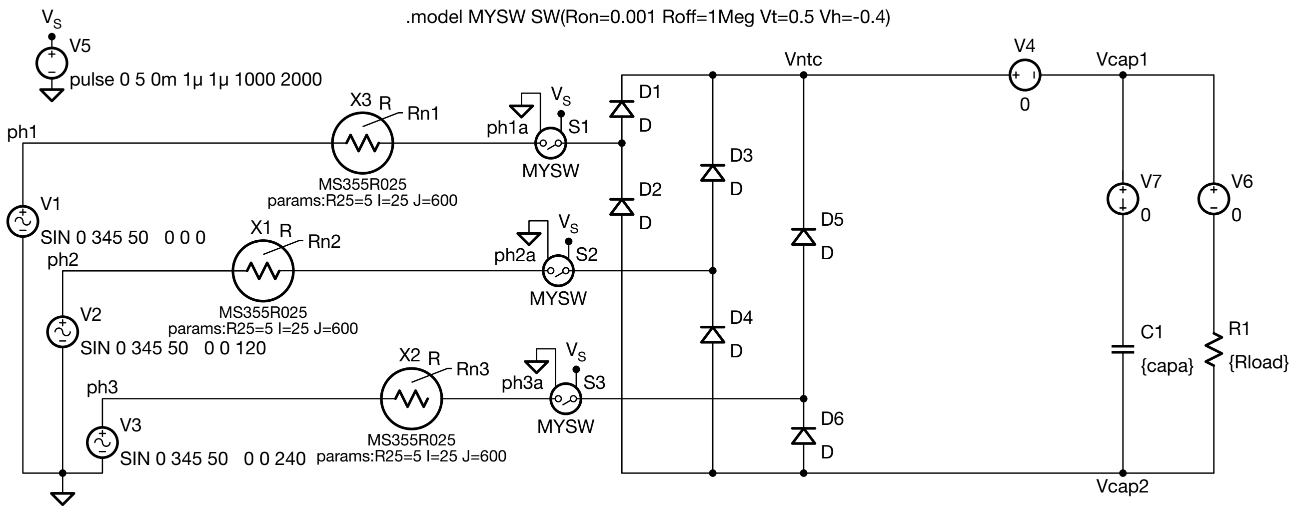


```
.tran 20s 20s 0 100µ
.IC V(Vcap1)=0
.IC V(Vcap2)=0
;.step param run 1 10 1
.param Rload=50
;.step param Rload list 50 1T
.param capa=8000µ
.meas Iph1 rms(I(V1)) from 19 to 20
.meas Iph2 rms(I(V2)) from 19 to 20
.meas Iph3 rms(I(V3)) from 19 to 20

.meas Ir1 rms(I(V4)) from 19 to 20
.meas Pow rms((V(vcap1)-V(vcop2))*I(R1)) from 19 to 20
.meas Encap integ((abs(V(vcap1)-V(vcap2)))*abs(I(V7)))
.meas Vfincap find (V(vcap1)-V(vcap2)) at=20
.meas Enntc1 integ((V(ph1a)-V(ph1))*(I(V1)))
.meas Enntc2 integ((V(ph2a)-V(ph2))*(I(V2)))
.meas Enntc3 integ((V(ph3a)-V(ph3))*(I(V3)))
.meas Imax1 max (abs(I(V1)))
.meas Imax2 max (abs(I(V2)))

.meas Imax3 max (abs(I(V3)))
.meas Imax4 max (abs(I(V4)))
.meas formfactor param (Enntc1+Enntc2+Enntc3)/Encap
.meas Rin1 V(Rn1) at=0
.meas Rin2 V(Rn2) at=0
.meas Rin3 V(Rn3) at=0
.meas Rfin1 v(Rn1) at=20
.meas Rfin2 v(Rn2) at=20
.meas Rfin3 v(Rn3) at=20
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Fig. 5

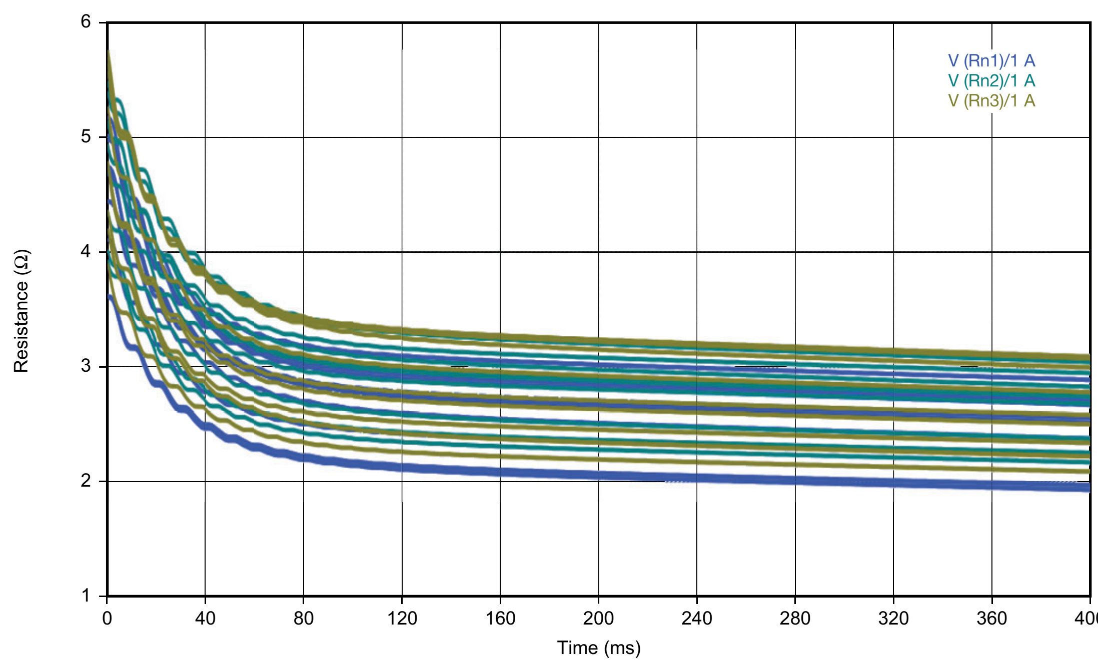

Fig. 6

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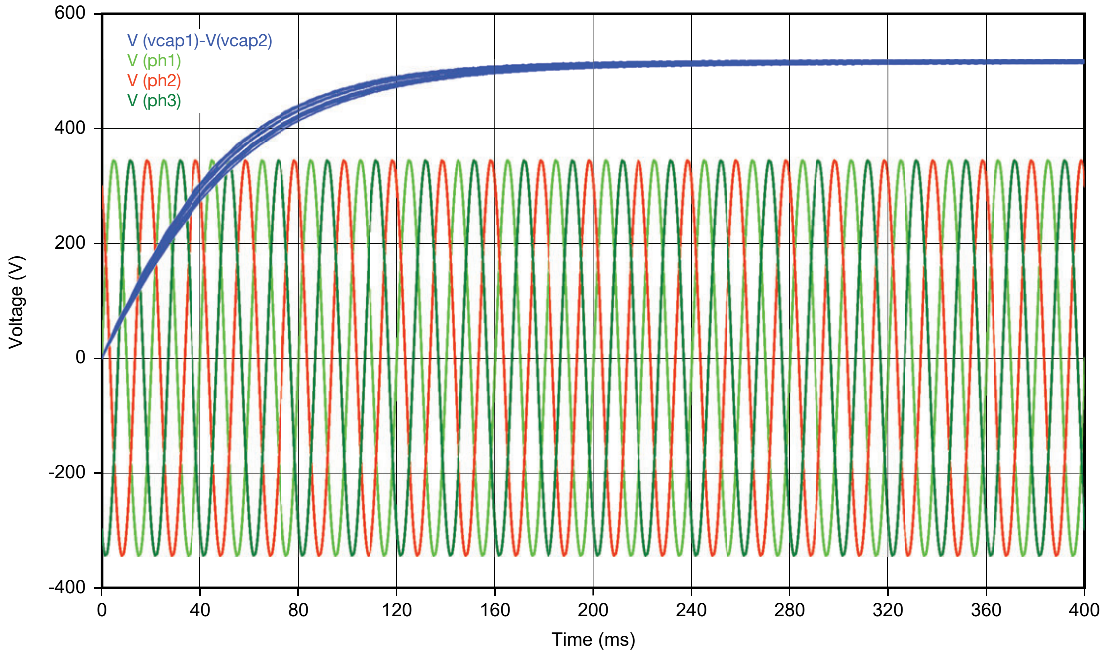

Fig. 7

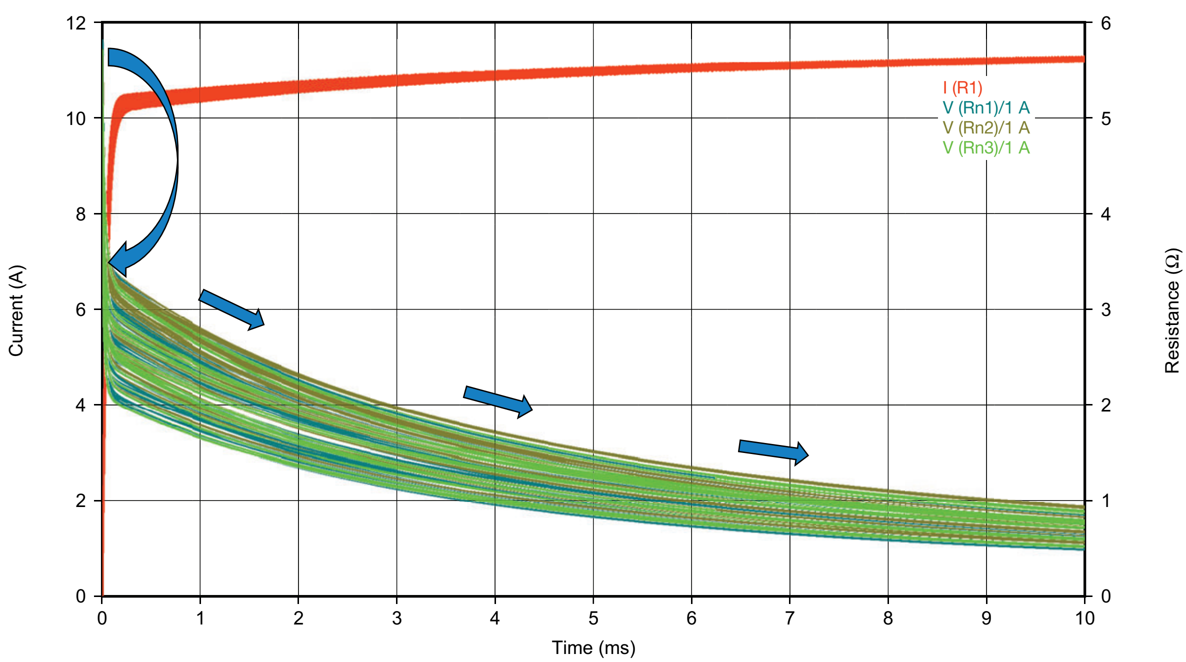

Fig. 8

SPICE-ify Your Vishay Ametherm Inrush Current Limiters With QSPICE® From Qorvo®

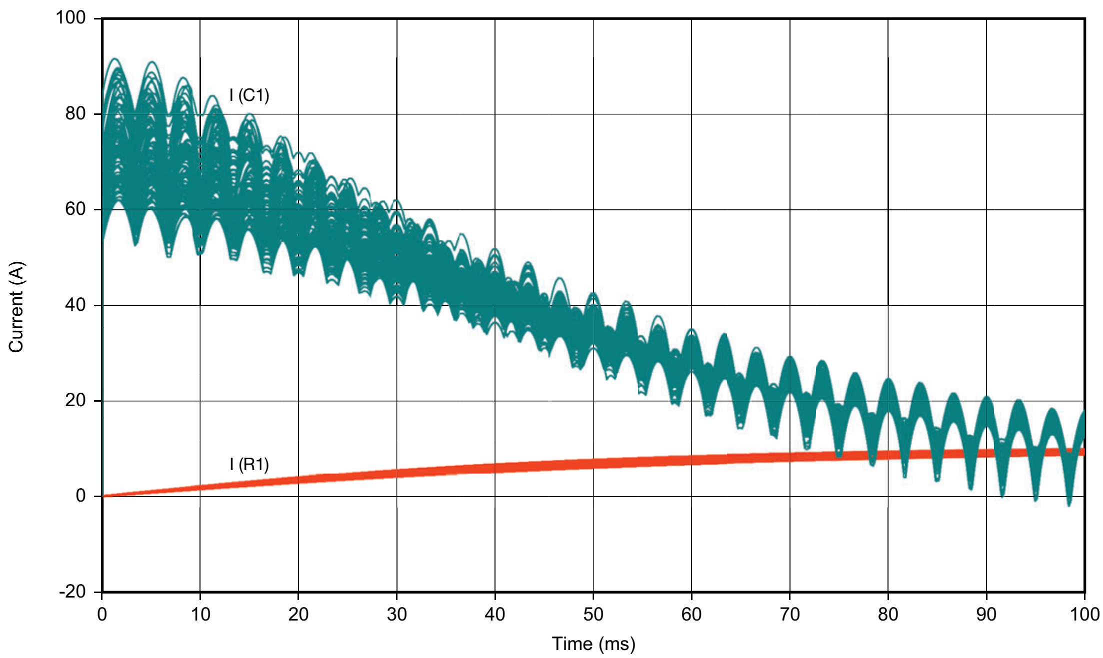

Fig. 9

Looking at the circuit in Fig. 6, we can see that we jumped directly to a triphasic power supply, with whole voltages (345 V peak) de-phased by 120° cumulate to be rectified and fed a load R_1, with a smooth capacitor C_1 rectifying the voltage.

We are interested in the transient period after the switching on of this circuit (S1 / S2 / S3) until the time when the capacitor will be loaded, and then the mid-term period during which the NTC X_1, X_2, and X_3 will reach their hot temperature / low resistance steady state.

The SPICE directives on the left of Fig. 3 compute all critical parameters of the circuit:

- The peak current in the capacitor is 75 A to 100 A (Fig. 8) and the current in the resistor R_1 is from 0 A to 20 A (Fig. 8 and Fig. 9)
- The RMS current through the load, after stabilization (I(V4)), is 19 A
- The final capacitor voltage after the bridge V_{fincap} is 595 V
- The energy stored in the capacitor (C x $V_{fincap}{}^2/2$) is 1416 J
- The joule energy dissipated into the three NTCs during the charge (this can be done with a simulation in which you replace R_1 (50 Ω) with an open circuit 1T) is 400 J to 450 J
- The form factor given by the sum of energy dissipated into each of the three ICL thermistors, and the energy stored in the capacitor, is 0.893
- The initial and steady-state residual NTC resistance values (see Fig. 6 and Fig. 8)
- Any other quantity you would like to compute at short term (100 ms) or mid-term (10 s)

Fig. 6 shows the capacitor charging joule effect on the three NTC components, with the initial resistance drop immediately after 100 ms. Then the resistance drop will be more progressive until a steady state is reached after more than 10 s (Fig. 7).

This leads directly to the notion of recovery time. For example, what happens if several on / off switches are performed during the first second? There is no problem simulating this, all we need to do is to program the profile of the switch source V_5 in Fig. 5.

Fig. 10 shows what happens when a few on / off resets are performed during the first second at each switch: a slight increase of the surge occurs. It is thus easy to evaluate the circuit behavior in any scenario.

The design process can be performed by SPICE analysis, and the proper component can then be chosen from the library (more than 190 components available) according to the need for R_{25}, steady-state current, and joule capacity.

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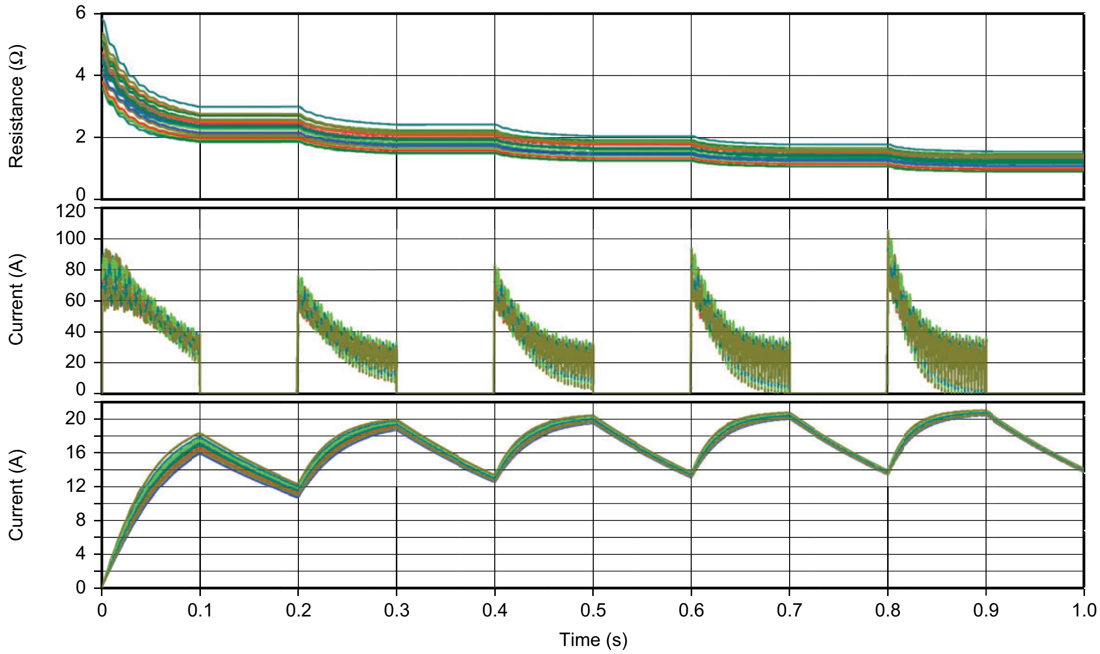

Fig. 10

IN CONCLUSION, DO WE RECOMMEND THE SPICE ANALYSIS OR THE CLASSICAL TUTORIAL METHOD?

This question, while provocative, is actually completely irrelevant. We do not advocate any design approach over another. The tutorial design and SPICE analysis are complementary to each other. The tutorials can help customers find the basic parameters needed in inrush current limiters. These basic parameters consist of the following:

- Minimum resistance needed to limit inrush current
- Maximum energy needed to limit inrush current
- Calculate the steady-state current for the ICL to operate and be transparent in the circuit

However, in conjunction with the SPICE model, you can determine a specific model of ICL to suit your exact application. The SPICE analysis allows you to test your circuit as you would do in a lab, only with less concern about the possibility of blowing up any physical fuse. It helps you develop intuition about your application, driving you to find answers to the numerous questions that specialists must constantly ask themselves. It will complement your design finalization in the sense that you will be capable of visualizing every signal at any node and let QSPICE® compute the essential design parameters. In the end, do not forget to check the results against common sense.

Finally, the SPICE simulation method can make your final SMPS application more robust, predictable, and accurate. All this thanks to Qorvo®'s QSPICE models of Vishay Ametherm ICL NTC components.

REFERENCES

[1] Limiting Inrush Current with NTC and PTC Thermistors

[2] Excel 2007 VBA Programmer's Reference, Green, Bullen, Bovey, Alexander, wrox, pages 525 to 536

[3] Importing 3rd Party Models into QSPICE - Videos (eepower.com)

[4] QSPICE Simulator - Qorvo