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Introduction to Voltage Surge Immunity Testing

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Voltage Surges

- Transient overvoltages on the ac power system are produced by events such as load switching, capacitor bank switching, equipment faults and lightning discharges

- The ability of equipment to withstand voltage surges can have a tremendous impact on field reliability

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The Nature of Transient Overvoltages

- Transient overvoltage events are usually of short duration, from several microseconds to a few milliseconds

- Waveforms can be oscillatory or non-oscillatory (impulsive)

- The rising wavefront is usually on the order of 0.5 µs to 10 µs

- The highest overvoltages are caused by direct lightning strikes to overhead power lines

- Transient overvoltages entering a facility typically range from 10 kV to 50 kV

- Voltage and current levels are attenuated as the surges propagate

  [1], [4] (References are on slide 14)

Transient Overvoltage Immunity Testing

How do you know if your designs are robust enough? Standardized surge testing procedures have been developed to help answer that question.

- **US standard:** ANSI/IEEE C62.41-1991, IEEE recommended practice on surge voltages in low-voltage ac power circuits
  Additional US standards: [7], [9]
  (Typically available in university libraries)

- **International standard:** IEC 61000-4-5, 2005 Electromagnetic Compatibility, Testing and measurement techniques–Surge immunity test
  Additional international standards: [5], [6]
 (Available for purchase at: http://webstore.iec.ch)

The Voltage Surge Test Method

- This presentation provides an overview of IEC 61000-4-5, including some of the standard waveforms, and the circuits that are used to produce those waveforms

- Voltage surge testing is typically done with commercially available surge test equipment

- The test equipment typically has a surge generator and a coupling/decoupling network (CDN)

- Combination wave generators produce a specified open circuit voltage waveform and a specified short-circuit current waveform

- Coupling/decoupling networks couple a surge generator to the equipment being tested and prevent dangerous voltages from being sent back into the ac power system

IEC 61000-4-5
Combination Wave Generator (CWG)

Energy is provided by the Voltage Source (U) which charges C_c through R_c. Once charged, the switch delivers energy into the wave shaping network made up of R_{S1}, R_{S2}, L_r and R_m. Component values are selected so that they will produce a defined voltage surge into an open circuit and a a defined current surge into a short circuit.
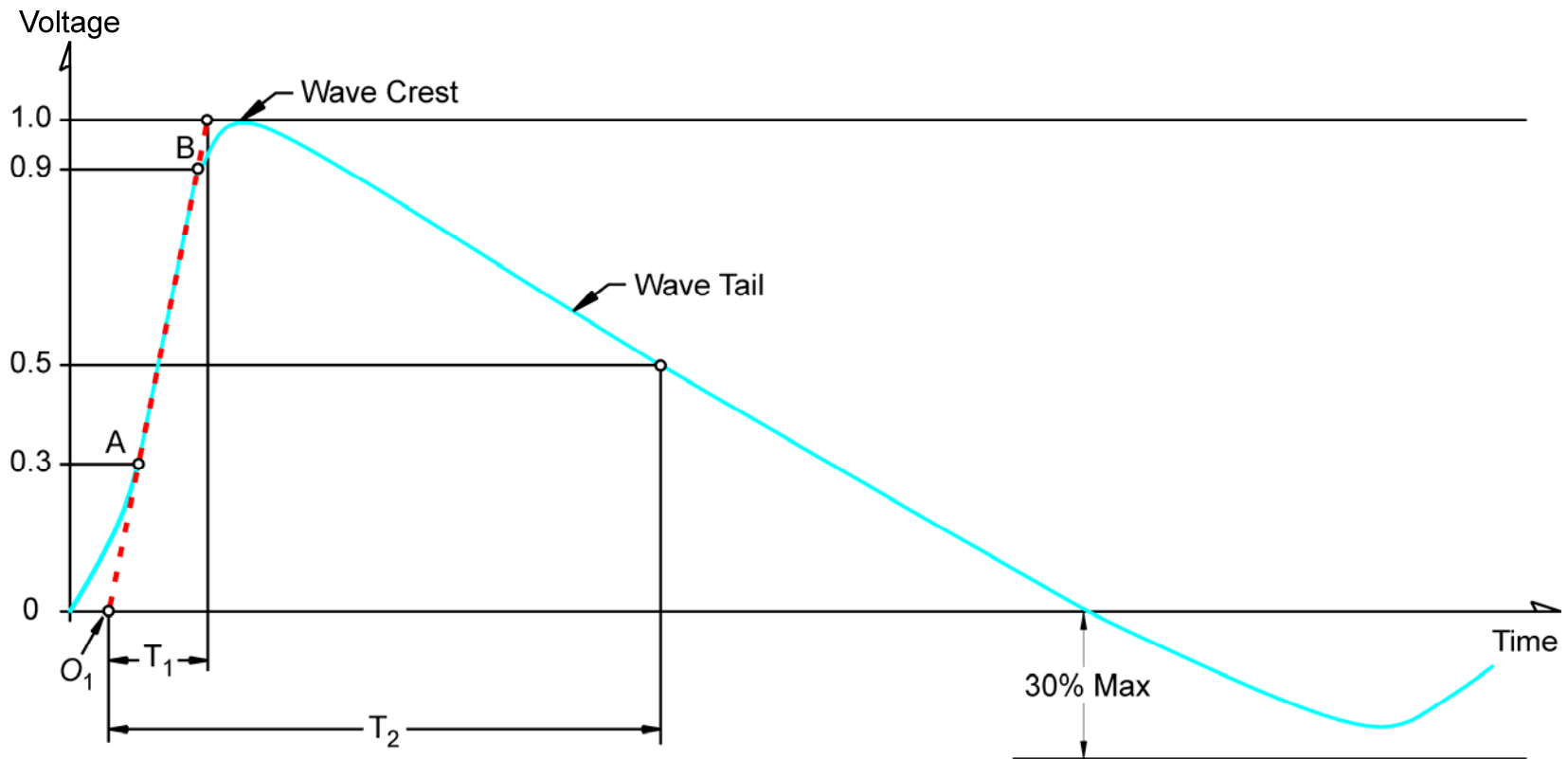

Combination Wave
Generator
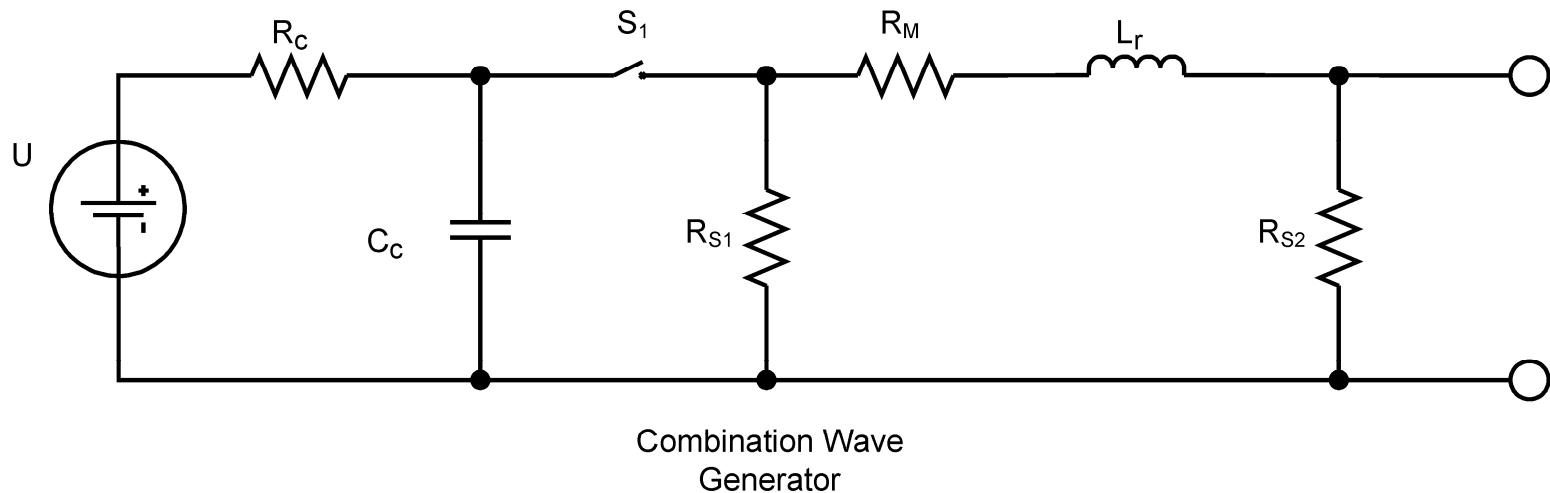
CWG 1.2/50 µs Voltage Surge Waveform

Open-circuit waveform characteristics:

T = Time B - Time A T_1=1.67T = 1.2 µs ± 30 % T_2 = 50 µs ± 20 %

Undershoot ≤ 30% of the crest.

CWG 8/20 µs Current Waveform

Short-circuit waveform characteristics:

T = Time B - Time C $T_1 = 1.25T = 8$ µs $\pm$ 30 % $T_2 = 20$ µs $\pm$ 20 %

Undershoot $\leq$ 30% of the crest.
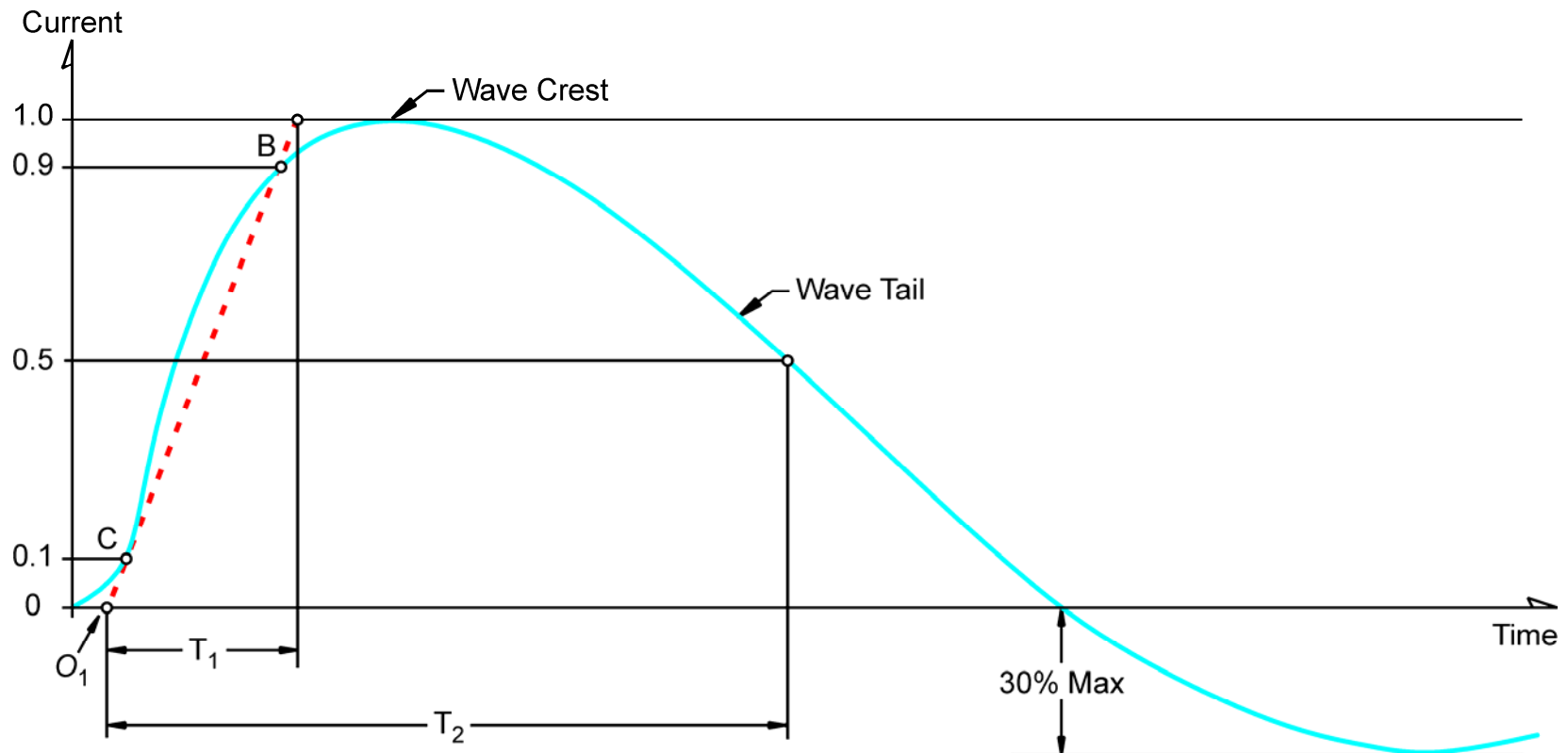
Coupler/Decoupler Network (CDN)

IEC 61000-4-5 defines several CDNs. These are devices intended to couple the CWG voltage surge into your product while simultaneously decoupling it from the facility power. The inductances should be large enough to have a minimal effect on the output of the CWG, while being small enough to allow the equipment under test to function normally. A typical value is 1.5 mH [3], [5]-[7].

Example of a single phase line-to-line CDN

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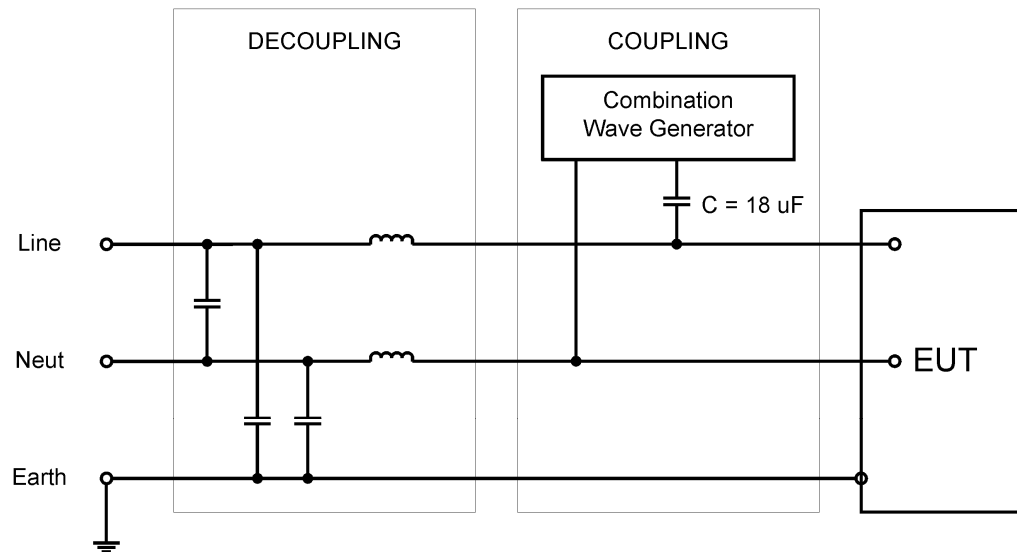
Coupler/Decoupler Network (CDN)

Example of a single phase line-to-earth CDN
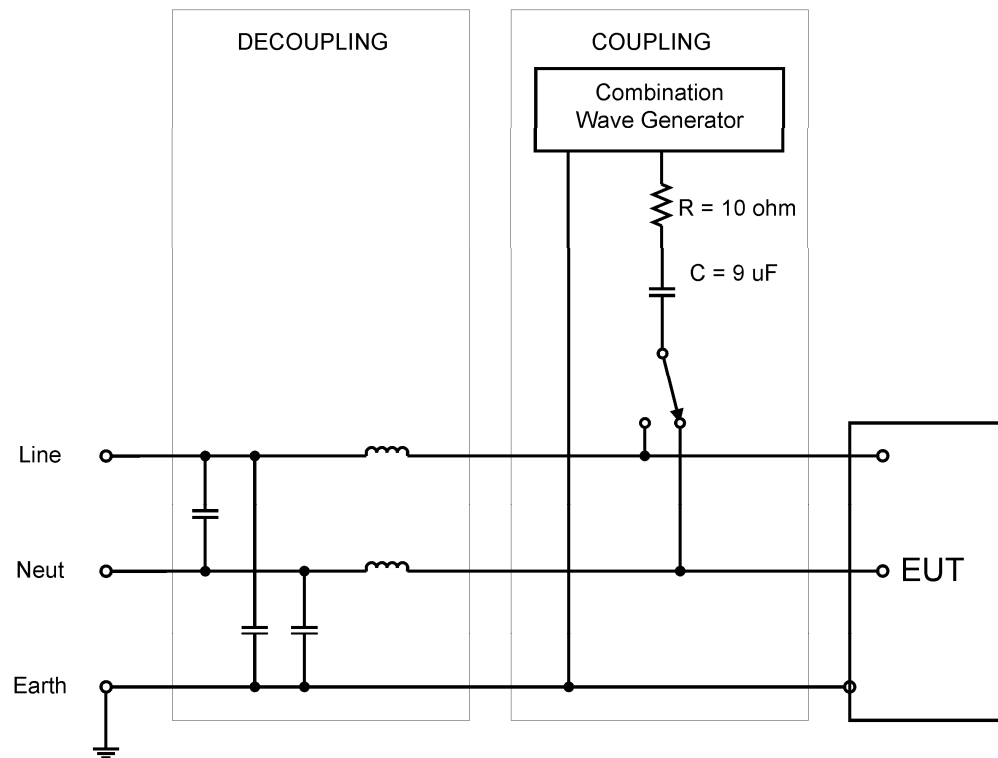
Coupler/Decoupler Network (CDN)
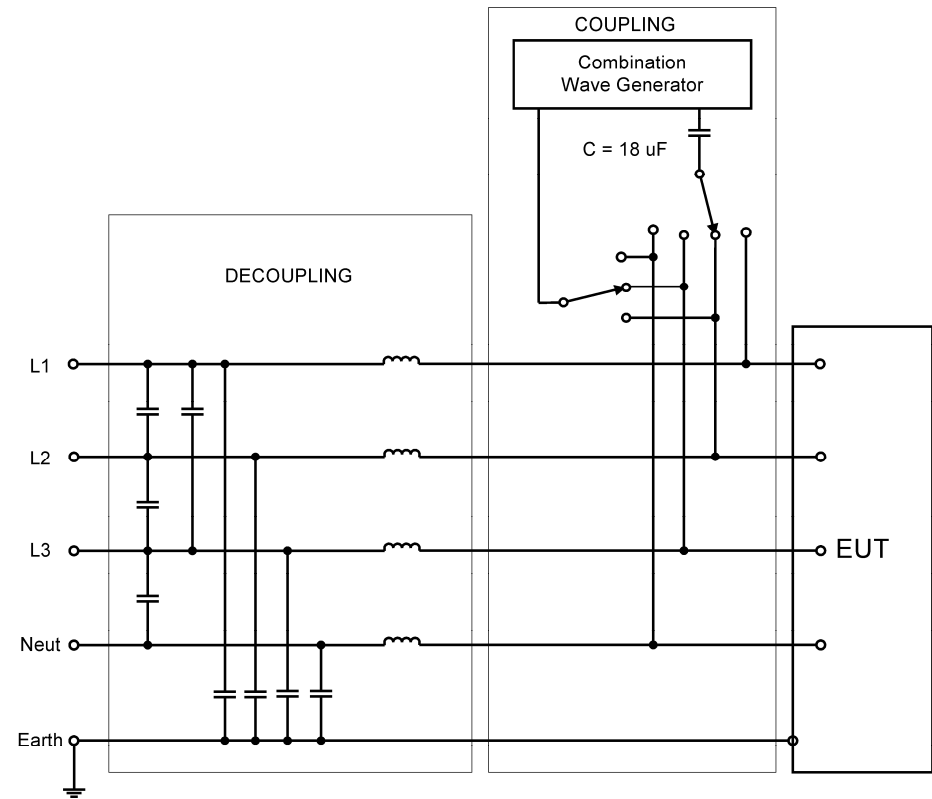
Examples of three phase line-to-earth and line-to-line CDNs
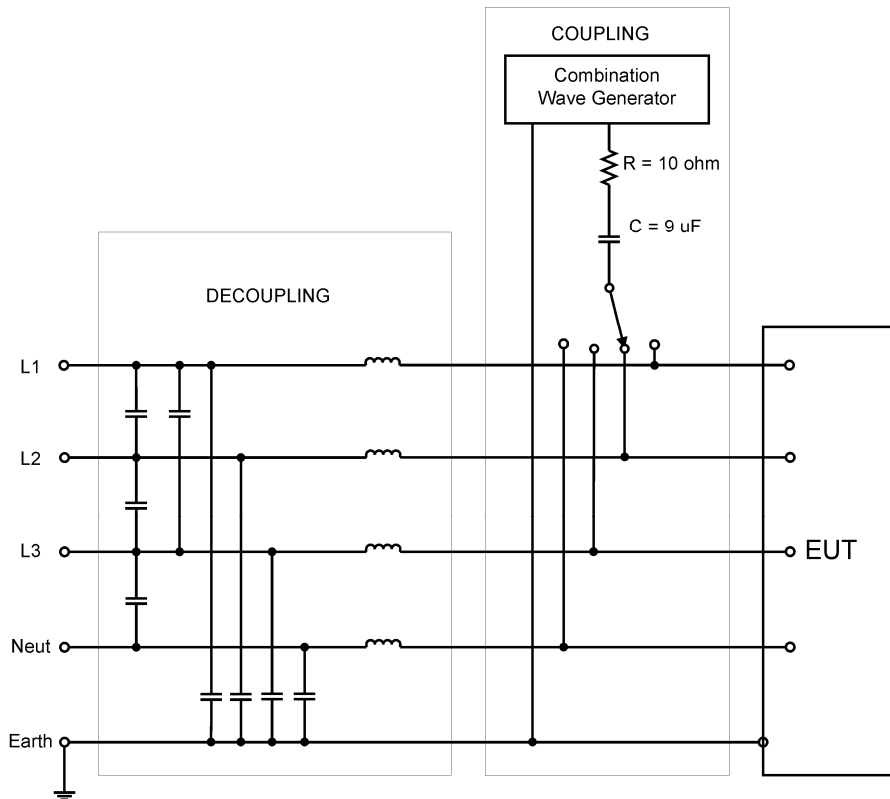
Coupler/Decoupler Network (CDN)

IEC 61000-4-5 provides a decision tree for selecting the correct CDN
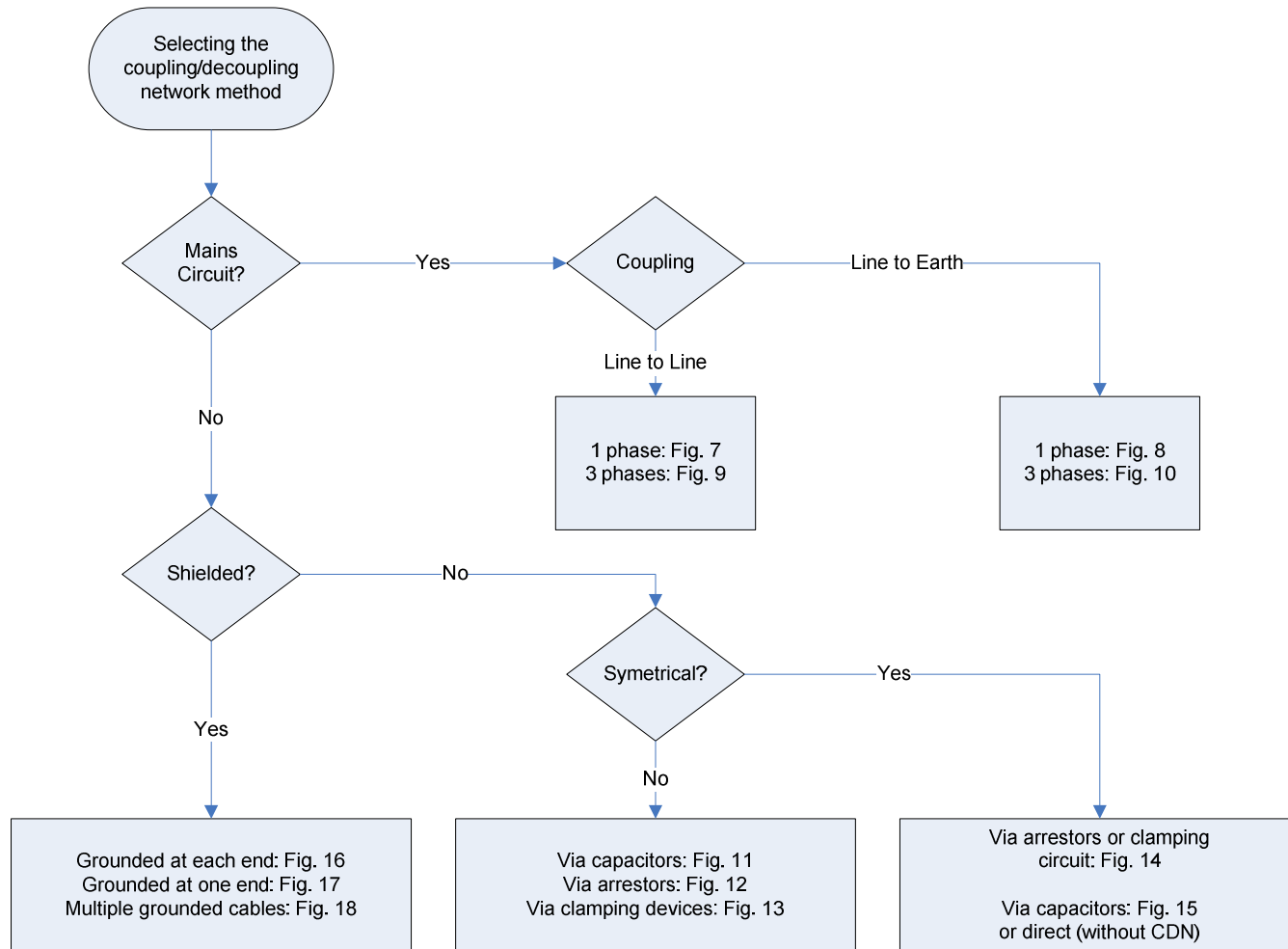
Links

Surge testing equipment

http://www.ramayes.com/Pulsed_EMI.htm (Local)
http://www.atecorp.com

Tutorial on surge testing

http://www.teseq.com/com/en/service_support/technical_information/Transient_immunity_testing_e_4.pdf

Application notes on surge testing

http://www.haefelyemc.com/pdf_downloads

Free LT Spice software

http://www.linear.com/designtools/software

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References

[1] Martzloff, F.D, "Coupling, propagation, and side effects of surges in an industrial building wiring system," Conference Record of IEEE 1988 Industry Applications Society Annual Meeting, 2-7 Oct. 1988, vol.2, pp. 1467 – 1476

[2] S.B Smith and R. B. Standler, "The effects of surges on electronic appliances," IEEE Transactions on Power Delivery, vol. 7, Issue 3, July 1992 pp. 1275 - 1282

[3] Peter Richman, "Criteria and designs for surge couplers and back-filters," Conference Record of IEEE1989 National Symposium on Electromagnetic Compatibility, 23-25 May 1989, pp. 202 – 207.

[4] Ronald B. Standler, Protection of Electronic Circuits from Overvoltages, New York: Wiley-Interscience, May 1989. Republished by Dover, December 2002.

[5] IEC 60255-22-1 (1988) Electrical disturbance tests for measuring relays and protection equipment. Part 1: 1MHz burst disturbance tests.

[6] IEC 61000-4-12 (2006) Electromagnetic compatibility (EMC): Testing and measurement techniques - Ring wave immunity test

[7] IEEE/ANSI C37.90.1-2002, IEEE standard for Surge withstand Capability (SWC) Tests for Relays and Relays Systems Associated with Electric Power Apparatus.

[8] IEC 61000-4-4 (2004) Testing and measurement techniques –Electrical fast transient/burst immunity test

[9] IEEE/ANSI C62.41.2-2002IEEE Recommended Practice on Characterization of Surges in Low-Voltage (1000 V and Less) AC Power Circuits

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Part 2 Simulating Surge Testing

- It would be great to be able to design equipment that passes the surge tests without having to be re-designed

- Performing circuit simulations of surge testing during the design phase can help you to understand component stress levels, and prevent costly re-design efforts.

- IEC 61000-4-5 provides schematic diagrams of standard surge generator circuits, and describes what waveforms they should produce, but no component values are given.

- The next part of the presentation reviews a Mathcad file that derives a suitable set of component values for the 1.2/50 µs voltage, 8/20 µs current combination wave generator

- The presentation concludes with a review of an LT Spice circuit simulation of the combination wave generator coupled to the input section of a power supply

Deriving Component Values using Mathcad

- Define the problem

- Derive Laplace domain circuit equations for open-circuit voltage and short-circuit current

- Determine time-domain responses using inverse-Laplace transforms

- Derive expressions for the peak voltage and the peak current

- Define functions for the waveform parameters in terms of the component values and the initial capacitor voltage

- Enter the target values of the waveform parameters

- Set up a Solve Block using the functions and target values

- Solve for the component values and the initial capacitor voltage

Combination Wave Surge Generator

Bryce Hesterman
September 15, 2007
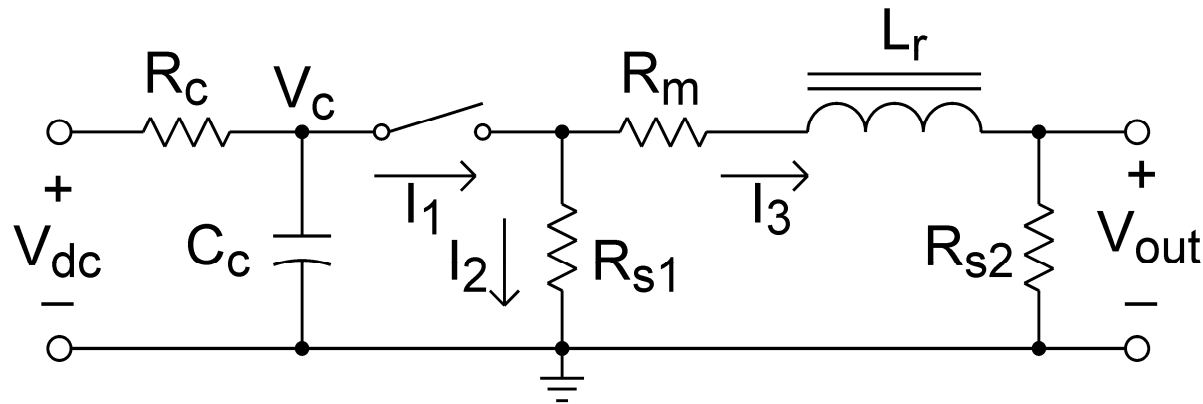
Figure 1. Combination wave surge generator.

Figure 1 is a circuit that can generate a 1.2/50 μs open-circuit voltage waveform and a 8/20 μs short-circuit current waveform. IEC 61000-4-5 shows this circuit in Figure 1 on page 25, but it does not give any component values [1]. Instead, Table 2 on page 27 presents two sets of waveform characteristics. The first set is based on IEC 60060-1. It defines each waveform in terms of the front time and time to half value. The definition for the front time makes it awkward to use for circuit synthesis. The second set of characteristics is based on IEC 60469-1, and it specifies the 10%-90% rise times and the 50%-50% duration times. It appears that it is easier to derive component values from the IEC 60469-1 definitions, so this document takes that approach.

Table 1. Waveform Definitions

	10%-90% Rise Time	50%-50% Duration Time
1.2/50μs Open-circuit Voltage Waveform	1μs	50μs
8/20μs Short-circuit Current Waveform	6.4μs	16μs

Figures 2 and 3 on page 29 of IEC 61000-4-5 provide graphical definitions of the waveforms. These figures also specify that the undershoot of the surge waveforms be limited to 30% of the peak value.

The circuit is first analyzed in the Laplace domain, after which time domain equations are derived. Functions for the waveforms and functions for computing the time to reach a specified level are then derived. The component values are derived using a solve block which seeks to meet the specified waveform characteristics.

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Derive Laplace domain equations for open-circuit voltage

Write Laplace equations for the three currents in Figure 1 for the time after the switch is closed at time t = 0. Assume that the capacitor is fully charged to V_{dc} , and that the initial inductor current is zero. Also, assume that the effects of the charging resistor R_c can be neglected.

$$I_1(s) = C_c \cdot \left(-s \cdot V_c(s) + V_{dc} \right) \tag{1}$$

$$I_2(s) = \frac{V_c(s)}{R_{s1}} \tag{2}$$

$$I_3(s) = \frac{V_c(s) - L_r \cdot s \cdot I_3(s)}{R_m + R_{s2}} \tag{3}$$

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Solve (3) for I_3.

$$I_3(s) = \frac{V_c(s)}{Rs2 + R_m + L_r \cdot s} \qquad (4)$$

Write a KCL equation for the three currents.

$$I_1(s) - I_2(s) - I_3(s) = 0 \qquad (5)$$

Substitute expressions for the currents from (1), (2), and (4) into (5).

$$C_c \cdot \left(-s \cdot V_c(s) + V_{dc}\right) - \frac{V_c(s)}{R_{s1}} - \frac{V_c(s)}{R_{s2} + R_m + L_r \cdot s} = 0 \qquad (6)$$

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Solve (6) for $V_c(s)$.

(7)

$$V_c(s) = \frac{V_{dc} \cdot R_{s1} \cdot C_c \cdot \left(R_{s2} + R_m + L_r \cdot s\right)}{s^2 \cdot R_{s1} \cdot L_r \cdot C_c + \left[C_c \cdot R_{s1} \cdot \left(R_{s2} + R_m\right) + L_r\right] \cdot s + R_{s1} + R_{s2} + R_m}$$

Write an equation for the open-circuit output voltage.

$$V_{oc}(s) = I_3(s) \cdot R_{s2}$$

(8)

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Laplace domain equation for open-circuit voltage

Substitute (4) and (7) into (8)

$$V_{oc}(s) = \frac{V_{dc} \cdot R_{s1} \cdot R_{s2} \cdot C_c \cdot \left(R_{s2} + R_m + L_r \cdot s\right)}{\left(R_{s2} + R_m + L_r \cdot s\right) \cdot \left[s^2 \cdot R_{s1} \cdot L_r \cdot C_c + \left[C_c \cdot R_{s1} \cdot \left(R_{s2} + R_m\right) + L_r\right] \cdot s + R_{s1} + R_{s2} + R_m\right]} \qquad (9)$$

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Use Inverse Laplace Transform to find a time domain equation for open-circuit voltage

Use the Mathcad Inverse Laplace function to find a time-domain equation for V_{out}.

(Some simplification steps are not shown.)

(10)

$$V_{oc} = \frac{2 \cdot V_{dc} \cdot R_{s1} \cdot R_{s2} \cdot C_c \cdot \sinh\left[\dfrac{\sqrt{R_{s1}^2 \cdot \left(R_{s2} + R_m\right)^2 \cdot C_c^2 - \left[2 \cdot R_{s1} \cdot \left(R_{s2} + R_m\right) + 4 \cdot R_{s1}^2\right] \cdot L_r \cdot C_c + L_r^2}}{2 \cdot R_{s1} \cdot L_r \cdot C_c} \cdot t\right]}{\sqrt{R_{s1}^2 \cdot \left(R_{s2} + R_m\right)^2 \cdot C_c^2 - \left[2 \cdot R_{s1} \cdot \left(R_{s2} + R_m\right) + 4 \cdot R_{s1}^2\right] \cdot L_r \cdot C_c + L_r^2} \cdot \exp\left[\dfrac{C_c \cdot R_{s1} \cdot \left(R_{s2} + R_m\right) + L_r}{2 \cdot R_{s1} \cdot L_r \cdot C_c} \cdot t\right]}$$

Simplified time domain equation
for open-circuit voltage

Expand the hyperbolic sine function in (10) and simplify.

$$V_{oc} = V_{dc} \cdot \tau_1 \cdot \frac{R_{s2}}{L_r} \cdot \left(1 - e^{\frac{-t}{\tau_1}}\right) \cdot e^{\frac{-t}{\tau_2}} \tag{11}$$

where

$$\tau_1 = \frac{R_{s1} \cdot L_r \cdot C_c}{\sqrt{R_{s1}^2 \cdot (R_{s2} + R_m)^2 \cdot C_c^2 - \left[2 \cdot R_{s1} \cdot (R_{s2} + R_m) + 4 \cdot R_{s1}^2\right] \cdot L_r \cdot C_c + L_r^2}} \tag{12}$$

$$\tau_2 = \frac{2 \cdot R_{s1} \cdot L_r \cdot C_c}{\left[C_c \cdot R_{s1} \cdot (R_{s2} + R_m) + L_r\right] - \sqrt{R_{s1}^2 \cdot (R_{s2} + R_m)^2 \cdot C_c^2 - \left[2 \cdot R_{s1} \cdot (R_{s2} + R_m) + 4 \cdot R_{s1}^2\right] \cdot L_r \cdot C_c + L_r^2}} \tag{13}$$

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The simplified time domain equation for open-circuit voltage (11) has the same form as the corresponding equation in [2]

An equation for the 1.2/50 μs waveform is given in [2] as:

$$V_{oc} = A \cdot V_p \cdot \left(1 - e^{\frac{-t}{\tau_1}} \right) \cdot e^{\frac{-t}{\tau_2}} \tag{14}$$

where $\quad$ A = 1.037 $\qquad$ $\tau_1 = 0.4074 \cdot 10^{-6}$ $\qquad$ $\tau_2 = 68.22 \cdot 10^{-6}$

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Determine when the peak of the open-circuit voltage occurs

Determine the peak value of the open-circuit output voltage by setting the time derivative of (11) equal to zero, and solve for t.

$$\frac{d}{dt}\left[V_{dc}\cdot\tau_1\cdot\frac{R_{s2}}{L_r}\cdot\left(1 - e^{\frac{-t}{\tau_1}}\right)\cdot e^{\frac{-t}{\tau_2}}\right] = V_{dc}\cdot\frac{R_{s2}}{L_r}\cdot\left[\exp\left(\frac{-t}{\tau_1}\right)\cdot\exp\left(\frac{-t}{\tau_2}\right) - \tau_1\cdot\left[\frac{\left(1 - \exp\left(\frac{-t}{\tau_1}\right)\right)}{\tau_2}\cdot\exp\left(\frac{-t}{\tau_2}\right)\right]\right] = 0 \tag{15}$$

(Simplification steps are not shown.)

$$t_{ocp} = \tau_1\cdot\ln\left(\frac{\tau_1 + \tau_2}{\tau_1}\right) \tag{16}$$

τ_1 and τ_2 are defined in (12) and (13).

Find the peak value of the open-circuit voltage

Determine the peak value of the open-circuit output voltage by substituting (16) into (11).

$$V_p = V_{dc} \cdot \frac{R_{s2}}{L_r} \cdot \tau_2 \cdot \left(\frac{\tau_1}{\tau_1 + \tau_2} \right)^{\frac{\tau_1 + \tau_2}{\tau_2}} \qquad (17)$$

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Derive Laplace domain equation for short-circuit current

Write a Laplace equation for the short-circuit output current by combining (4) and (7), and setting $R_{s2} = 0$.

$$I_{sc}(s) = \frac{V_{dc} \cdot R_{s1} \cdot C_c}{\left[s^2 \cdot R_{s1} \cdot L_r \cdot C_c + \left(R_{s1} \cdot R_m \cdot C_c + L_r \right) \cdot s + R_{s1} + R_m \right]} \tag{18}$$

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Use Inverse Laplace Transform to find a time domain equation for short-circuit current

Use the Mathcad Inverse Laplace function to find a time-domain equation for the short-circuit current and simplify.

$$I_{sc} = \frac{V_{dc} \cdot exp\left(\dfrac{-t}{\tau_{sc}}\right)}{L_r \cdot \omega_{sc}} \cdot sin(\omega_{sc} \cdot t) \tag{19}$$

where

$$\tau_{sc} = \frac{2 \cdot R_{s1} \cdot L_r \cdot C_c}{R_{s1} \cdot R_m \cdot C_c + L_r} \tag{20}$$

$$\omega_{sc} = \frac{\sqrt{\left(4 \cdot R_{s1} + 2 \cdot R_m\right) \cdot R_{s1} \cdot L_r \cdot C_c - R_{s1}^2 \cdot R_m^2 \cdot C_c^2 - L_r^2}}{2 \cdot R_{s1} \cdot L_r \cdot C_c} \tag{21}$$

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The simplified time domain equation for short-circuit current (19) doesn't have same form as the corresponding equation in [2]

Note that the equation given for the short-circuit current in [2] has a different form than (19).

$$I(t) = A \cdot I_p \cdot t^k \cdot \exp\left(\frac{-t}{\tau}\right) \qquad (22)$$

An equation of this form cannot be produced by an RLC circuit. It is only an approximation, and doesn't account for the undershoot.

Determine when the peak of the short-circuit current occurs

Find the time when the short-circuit current reaches its peak value by setting the time derivative of (19) equal to zero and solving for t.

$$(23)$$

$$\frac{d}{dt}\left(\frac{V_{dc}\cdot\exp\left(\frac{-t}{\tau_{sc}}\right)}{L_r\cdot\omega_{sc}}\cdot\sin\left(\omega_{sc}\cdot t\right)\right) = \frac{V_{dc}\cdot\sqrt{1+\tau_{sc}^{\,2}\cdot\omega_{sc}^{\,2}}}{L_r\cdot\tau_{sc}\cdot\omega_{sc}}\cdot\exp\left(\frac{-t}{\tau_{sc}}\right)\cdot\cos\left(\omega_{sc}\cdot t + \mathrm{atan}\left(\frac{1}{\tau_{sc}\cdot\omega_{sc}}\right)\right) = 0$$

(Simplification steps are not shown.)

$$t_{scp} = \frac{\mathrm{atan}\left(\tau_{sc}\cdot\omega_{sc}\right)}{\omega_{sc}} \qquad (24)$$

τ_{sc} and ω_{sc} are defined in (20) and (21).

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Find the peak value of the short-circuit current

Write an equation for the peak value of the short-circuit current by substituting (24) into (19).

$$I_p = \frac{V_{dc} \cdot \tau_{sc} \cdot \exp\left(\dfrac{-\operatorname{atan}\left(\tau_{sc} \cdot \omega_{sc}\right)}{\tau_{sc} \cdot \omega_{sc}}\right)}{L_r \cdot \sqrt{1 + \tau_{sc}^{\,2} \cdot \omega_{sc}^{\,2}}} \tag{25}$$

Find the peak undershoot of the short-circuit current

Inspection of (23) and (24) shows that the first negative peak of the short-circuit current occurs at:

$$t_{sc\_min} = \frac{atan\left(\tau_{sc} \cdot \omega_{sc}\right) + \pi}{\omega_{sc}} \tag{26}$$

The value of the first negative peak of the short-circuit current is found by substituting (26) into (19).

$$I_{sc\_min} = \frac{-V_{dc} \cdot \tau_{sc} \cdot exp\left[\dfrac{-\left(atan\left(\tau_{sc} \cdot \omega_{sc}\right) + \pi\right)}{\tau_{sc} \cdot \omega_{sc}}\right]}{L_r \cdot \sqrt{1 + \tau_{sc}^2 \cdot \omega_{sc}^2}} \tag{27}$$

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Define a vector of the unknown variables (component values and initial capacitor voltage)

Define a vector of the component values and the initial capacitor voltage.

$$X = \begin{pmatrix} C_c \\ L_r \\ R_{s1} \\ R_{s2} \\ R_m \\ V_{dc} \end{pmatrix} \tag{28}$$

Define a function for computing the open-circuit voltage

Define a function for computing the open-circuit voltage using (11)-(13).

$$
V_{oc}(X, t) := \begin{array}{|l}
C_c \leftarrow X_0 \\[4pt]
L_r \leftarrow X_1 \\[4pt]
R_{s1} \leftarrow X_2 \\[4pt]
R_{s2} \leftarrow X_3 \\[4pt]
R_m \leftarrow X_4 \\[4pt]
V_{dc} \leftarrow X_5 \\[4pt]
A \leftarrow \sqrt{R_{s1}^2 \cdot \left(R_{s2} + R_m\right)^2 \cdot C_c^2 - \left[2 \cdot R_{s1} \cdot \left(R_{s2} + R_m\right) + 4 \cdot R_{s1}^2\right] \cdot L_r \cdot C_c + L_r^2} \\[10pt]
\tau_1 \leftarrow \dfrac{R_{s1} \cdot L_r \cdot C_c}{A} \\[10pt]
\tau_2 \leftarrow \dfrac{2 \cdot R_{s1} \cdot L_r \cdot C_c}{\left[C_c \cdot R_{s1} \cdot \left(R_{s2} + R_m\right) + L_r\right] - A} \\[10pt]
V_{dc} \cdot \tau_1 \cdot \dfrac{R_{s2}}{L_r} \cdot \left(1 - e^{\frac{-t}{\tau_1}}\right) \cdot e^{\frac{-t}{\tau_2}}
\end{array}
$$

(29)

Define a function for computing the peak open-circuit voltage

Define a function for computing the peak open-circuit voltage using (12), 13), and (17).

$$V_p(X) := \begin{vmatrix} C_c \leftarrow X_0 \\ L_r \leftarrow X_1 \\ R_{s1} \leftarrow X_2 \\ R_{s2} \leftarrow X_3 \\ R_m \leftarrow X_4 \\ V_{dc} \leftarrow X_5 \\ A \leftarrow \sqrt{R_{s1}^2 \cdot (R_{s2} + R_m)^2 \cdot C_c^2 - \left[2 \cdot R_{s1} \cdot (R_{s2} + R_m) + 4 \cdot R_{s1}^2\right] \cdot L_r \cdot C_c + L_r^2} \\ \tau_1 \leftarrow \dfrac{R_{s1} \cdot L_r \cdot C_c}{A} \\ \tau_2 \leftarrow \dfrac{2 \cdot R_{s1} \cdot L_r \cdot C_c}{\left[C_c \cdot R_{s1} \cdot (R_{s2} + R_m) + L_r\right] - A} \\ V_{dc} \cdot \dfrac{R_{s2}}{L_r} \cdot \tau_2 \cdot \left(\dfrac{\tau_1}{\tau_1 + \tau_2}\right)^{\frac{\tau_1 + \tau_2}{\tau_2}} \end{vmatrix}$$

(30)

Define a function for computing the short-circuit current

Define a function for computing the short-circuit current using (19)-(21).

$$
I_{sc}(X,t) := \left| \begin{array}{l}
C_c \leftarrow X_0 \\[1mm]
L_r \leftarrow X_1 \\[1mm]
R_{s1} \leftarrow X_2 \\[1mm]
R_{s2} \leftarrow X_3 \\[1mm]
R_m \leftarrow X_4 \\[1mm]
V_{dc} \leftarrow X_5 \\[2mm]
\tau_{sc} \leftarrow \dfrac{2 \cdot R_{s1} \cdot L_r \cdot C_c}{R_{s1} \cdot R_m \cdot C_c + L_r} \\[4mm]
\omega_{sc} \leftarrow \dfrac{\sqrt{\left(4 \cdot R_{s1} + 2 \cdot R_m\right) \cdot R_{s1} \cdot L_r \cdot C_c - R_{s1}^{\,2} \cdot R_m^{\,2} \cdot C_c^{\,2} - L_r^{\,2}}}{2 \cdot R_{s1} \cdot L_r \cdot C_c} \\[4mm]
\dfrac{V_{dc} \cdot \exp\!\left(\dfrac{-t}{\tau_{sc}}\right)}{L_r \cdot \omega_{sc}} \cdot \sin\!\left(\omega_{sc} \cdot t\right)
\end{array} \right.
$$

(31)

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Define a function for computing the peak short-circuit current

Define a function for computing the peak value of the short-circuit current using (25).

$$
I_p(X) := \left|
\begin{aligned}
&C_c \leftarrow X_0 \\
&L_r \leftarrow X_1 \\
&R_{s1} \leftarrow X_2 \\
&R_{s2} \leftarrow X_3 \\
&R_m \leftarrow X_4 \\
&V_{dc} \leftarrow X_5 \\
&\tau_{sc} \leftarrow \frac{2 \cdot R_{s1} \cdot L_r \cdot C_c}{R_{s1} \cdot R_m \cdot C_c + L_r} \\
&\omega_{sc} \leftarrow \frac{\sqrt{(4 \cdot R_{s1} + 2 \cdot R_m) \cdot R_{s1} \cdot L_r \cdot C_c - R_{s1}^2 \cdot R_m^2 \cdot C_c^2 - L_r^2}}{2 \cdot R_{s1} \cdot L_r \cdot C_c} \\
&\frac{V_{dc} \cdot \tau_{sc} \cdot \exp\left(\dfrac{-\operatorname{atan}\left(\tau_{sc} \cdot \omega_{sc}\right)}{\tau_{sc} \cdot \omega_{sc}} \right)}{L_r \cdot \sqrt{1 + \tau_{sc}^2 \cdot \omega_{sc}^2}}
\end{aligned}
\right.
\tag{32}
$$

Define a function for the peak undershoot of the short-circuit current

Define a function for computing the value of the first negative peak of the short-circuit current using (27).

$$
I_{min\_sc}(X) := \begin{vmatrix}
C_c \leftarrow X_0 \\[4pt]
L_r \leftarrow X_1 \\[4pt]
R_{s1} \leftarrow X_2 \\[4pt]
R_{s2} \leftarrow X_3 \\[4pt]
R_m \leftarrow X_4 \\[4pt]
V_{dc} \leftarrow X_5 \\[6pt]
\tau_{sc} \leftarrow \dfrac{2 \cdot R_{s1} \cdot L_r \cdot C_c}{R_{s1} \cdot R_m \cdot C_c + L_r} \\[14pt]
\omega_{sc} \leftarrow \dfrac{\sqrt{\left(4 \cdot R_{s1} + 2 \cdot R_m\right) \cdot R_{s1} \cdot L_r \cdot C_c - R_{s1}{}^2 \cdot R_m{}^2 \cdot C_c{}^2 - L_r{}^2}}{2 \cdot R_{s1} \cdot L_r \cdot C_c} \\[14pt]
\dfrac{-V_{dc} \cdot \tau_{sc} \cdot \exp\left[\dfrac{-\left(\operatorname{atan}\left(\tau_{sc} \cdot \omega_{sc}\right) + \pi\right)}{\tau_{sc} \cdot \omega_{sc}}\right]}{L_r \cdot \sqrt{1 + \tau_{sc}{}^2 \cdot \omega_{sc}{}^2}}
\end{vmatrix}
\qquad (33)
$$

Define a function for to determine when the open-circuit voltage reaches a specified percentage of the peak value

Define a function for computing the time at which the open-circuit voltage reaches a specified percentage of the peak value. The initial time value of the solve block can be used to get the function to find values before or after the peak.

Given

$$\frac{V_{oc}(X,t)}{V_p(X)} = \frac{P}{100}$$

(34)

$$t \cdot 10^7 > 0$$

$$T_{oc}(X,P,t) := Find(t)$$

Define a function for to determine when the short-circuit current reaches a specified percentage of the peak value

Define a function for computing the time at which the short-circuit current reaches a specified percentage of the peak value. The initial time value of the solve block can be used to get the function to find values before or after the peak.

Given

$$\frac{I_{sc}(X,t)}{I_p(X)} = \frac{P}{100}$$

$$t \cdot 10^7 > 0$$

(35)

$$T_{sc}(X,P,t) := Find(t)$$

Enter the target performance specifications

Enter the target peak open-circuit voltage:

$$V_{peak} := 1000$$

Enter the target 10%-90% rise time for the open-circuit voltage:

$$t_{ocr} := 1 \cdot 10^{-6}$$

Enter the target 50%-50% duration time for the open-circuit voltage:

$$t_{ocd} := 50 \cdot 10^{-6}$$

Enter the target 10%-90% rise time for the short-circuit current:

$$t_{scr} := 6.4 \cdot 10^{-6}$$

Enter the target 50%-50% duration time for the short-circuit current:

$$t_{scd} := 16 \cdot 10^{-6}$$

Enter the target percent undershoot for the short-circuit current:

$$P_{scu} := 25$$

Enter initial guess values

Enter initial guess values for the components and the initial capacitor voltage.

$$C_c := 10 \cdot 10^{-6} \qquad L_r := 10 \cdot 10^{-6} \qquad R_{s1} := 10$$

$$R_{s2} := 10 \qquad R_m := 1 \qquad V_{dc} := 1100$$

Define a vector of the initial guess values.

$$X := \begin{pmatrix} C_c \\ L_r \\ R_{s1} \\ R_{s2} \\ R_m \\ V_{dc} \end{pmatrix}$$

Compute the waveform parameters using the initial guesses and compare the results with the target values

Compute the 50%-50% duration time for the open-circuit voltage.

$$T_{oc}\left(X, 50, 5 \cdot 10^{-6}\right) - T_{oc}\left(X, 50, 500 \cdot 10^{-9}\right) = 40.1 \times 10^{-6}$$

Target value $\qquad t_{ocd} = 50.0 \times 10^{-6}$

Compute the peak value of the short-circuit current. $\qquad I_p(X) = 560$

Target value: $\qquad I_{peak} := \dfrac{V_{peak}}{2} \qquad I_{peak} = 500$

Compute the 10%-90% rise time for the short-circuit current.

$$T_{sc}\left(X, 90, 5 \cdot 10^{-6}\right) - T_{sc}\left(X, 10, 100 \cdot 10^{-9}\right) = 6.9 \times 10^{-6}$$

Target value $\quad t_{scr} = 6.40 \times 10^{-6}$

Compute the 50%-50% duration time for the short-circuit current.

$$T_{sc}\left(X, 50, 20 \cdot 10^{-6}\right) - T_{sc}\left(X, 50, 3 \cdot 10^{-6}\right) = 20.8 \times 10^{-6}$$

Target value $\quad t_{scd} = 16.0 \times 10^{-6}$

Compute the percent undershoot for the short-circuit current.

$$\frac{I_{min\_sc}(X)}{-I_p(X)} \cdot 100 = 14$$

Target value $\quad P_{scu} = 25$

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Enter weighting factors for each of the target values

The weighting factors help guide the solution to the desired outcome.

Enter the weighting factor for V_{peak}. $\qquad$ $K_{Vp} := 1$

Enter the weighting factor for t_{ocr}. $\qquad$ $K_{ocr} := 1$

Enter the weighting factor for t_{ocd} $\qquad$ $K_{ocd} := 1$

Enter the weighting factor for I_{peak}. $\qquad$ $K_{Ip} := 1$

Enter the weighting factor for t_{scr}. $\qquad$ $K_{scr} := 20$

Enter the weighting factor for t_{scd} $\qquad$ $K_{scd} := 20$

Enter the weighting factor for P_{scu} $\qquad$ $K_{scu} := 5$

Define a solve block to find the component values and the initial capacitor voltage

Given

$$\frac{V_p(X)}{V_{peak}} \cdot K_{Vp} = K_{Vp} \qquad\qquad \frac{I_p(X)}{I_{peak}} \cdot K_{Ip} = K_{Ip} \qquad\qquad (36)$$

$$\frac{T_{oc}\left(X, 90, 900 \cdot 10^{-9}\right) - T_{oc}\left(X, 10, 100 \cdot 10^{-9}\right)}{t_{ocr}} \cdot K_{ocr} = K_{ocr}$$

$$\frac{T_{oc}\left(X, 50, 5 \cdot 10^{-6}\right) - T_{oc}\left(X, 50, 500 \cdot 10^{-9}\right)}{t_{ocd}} \cdot K_{ocd} = K_{ocd}$$

$$\frac{T_{sc}\left(X, 90, 5 \cdot 10^{-6}\right) - T_{sc}\left(X, 10, 100 \cdot 10^{-9}\right)}{t_{scr}} \cdot K_{scr} = K_{scr}$$

$$\frac{T_{sc}\left(X, 50, 20 \cdot 10^{-6}\right) - T_{sc}\left(X, 50, 3 \cdot 10^{-6}\right)}{t_{scd}} \cdot K_{scd} = K_{scd}$$

$$\frac{I_{min\_sc}(X)}{-I_p(X)} \cdot \frac{100}{P_{scu}} \cdot K_{scu} < K_{scu}$$

$$\frac{T_{sc}\left(X, 90, 5 \cdot 10^{-6}\right) - T_{sc}\left(X, 10, 100 \cdot 10^{-9}\right)}{t_{scr}} \cdot K_{scr} = K_{scr}$$

$$\frac{T_{sc}\left(X, 50, 20 \cdot 10^{-6}\right) - T_{sc}\left(X, 50, 3 \cdot 10^{-6}\right)}{t_{scd}} \cdot K_{scd} = K_{scd}$$

$$\frac{I_{min\_sc}(X)}{-I_p(X)} \cdot \frac{100}{P_{scu}} \cdot K_{scu} < K_{scu}$$

$$X := Minerr(X) \qquad \begin{pmatrix} C_c \\ L_r \\ R_{s1} \\ R_{s2} \\ R_m \\ V_{dc} \end{pmatrix} := X$$

The solve block finds the component values and the initial capacitor voltage that minimize the error in the solve block equations

Computed component values and initial capacitor voltage

$$C_c = 6.038 \times 10^{-6} \qquad L_r = 10.37 \times 10^{-6} \qquad R_{s1} = 25.105$$

$$R_{s2} = 19.80 \qquad R_m = 0.941 \qquad V_{dc} = 1082$$

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Compute the waveform parameters using the solve block outputs and compare the results with the target values

Compute the peak value of the open-circuit voltage.

$$V_p(X) = 1000$$

Target value:

$$V_{peak} = 1000$$

Compute the 10%-90% rise time for the open-circuit voltage.

$$T_{oc}\left(X, 90, 900 \cdot 10^{-9}\right) - T_{oc}\left(X, 10, 100 \cdot 10^{-9}\right) = 1000 \times 10^{-9}$$

Target value

$$t_{ocr} = 1.00 \times 10^{-6}$$

Compute the 50%-50% duration time for the open-circuit voltage.

$$T_{oc}\left(X, 50, 5 \cdot 10^{-6}\right) - T_{oc}\left(X, 50, 500 \cdot 10^{-9}\right) = 50.0 \times 10^{-6}$$

Target value $\qquad t_{ocd} = 50.0 \times 10^{-6}$

Compute the peak value of the short-circuit current. $\qquad I_p(X) = 500$

Target value: $\qquad I_{peak} = 500$

Compute the 10%-90% rise time for the short-circuit current.

$$T_{sc}\left(X, 90, 5 \cdot 10^{-6}\right) - T_{sc}\left(X, 10, 100 \cdot 10^{-9}\right) = 6.12 \times 10^{-6}$$

Target value $\quad t_{scr} = 6.40 \times 10^{-6}$

Percent error $\quad \dfrac{T_{sc}\left(X, 90, 5 \cdot 10^{-6}\right) - T_{sc}\left(X, 10, 100 \cdot 10^{-9}\right) - t_{scr}}{t_{scr}} \cdot 100 = -4.3$

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Compute the 50%-50% duration time for the short-circuit current.

$$T_{sc}\left(X, 50, 20 \cdot 10^{-6}\right) - T_{sc}\left(X, 50, 3 \cdot 10^{-6}\right) = 16.6 \times 10^{-6}$$

Target value $\quad t_{scd} = 16.0 \times 10^{-6}$

Percent error $\quad \dfrac{T_{sc}\left(X, 50, 20 \cdot 10^{-6}\right) - T_{sc}\left(X, 50, 3 \cdot 10^{-6}\right) - t_{scd}}{t_{scd}} \cdot 100 = 4.0$

Compute the percent undershoot for the short-circuit current.

$$\dfrac{I_{min\_sc}(X)}{-I_p(X)} \cdot 100 = 27.7$$

Target value $\leq 30\%$

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Compute the ratio of the initial capacitor voltage to the peak open-circuit voltage.

$$\frac{V_{dc}}{V_p(X)} = 1.08$$

Compute τ_1, τ_2, τ_{sc} and ω_{sc} .

$$\tau_1 := \frac{R_{s1} \cdot L_r \cdot C_c}{\sqrt{R_{s1}^2 \cdot (R_{s2} + R_m)^2 \cdot C_c^2 - \left[2 \cdot R_{s1} \cdot (R_{s2} + R_m) + 4 \cdot R_{s1}^2\right] \cdot L_r \cdot C_c + L_r^2}}$$

$$\tau_1 = 505.7 \times 10^{-9}$$

$$\tau_2 := \frac{2 \cdot R_{s1} \cdot L_r \cdot C_c}{\left[C_c \cdot R_{s1} \cdot (R_{s2} + R_m) + L_r\right] - \sqrt{R_{s1}^2 \cdot (R_{s2} + R_m)^2 \cdot C_c^2 - \left[2 \cdot R_{s1} \cdot (R_{s2} + R_m) + 4 \cdot R_{s1}^2\right] \cdot L_r \cdot C_c + L_r^2}}$$

$$\tau_2 = 68.30 \times 10^{-6}$$

$$\tau_{sc} := \frac{2 \cdot R_{s1} \cdot L_r \cdot C_c}{R_{s1} \cdot R_m \cdot C_c + L_r}$$

$$\tau_{sc} = 20.55 \times 10^{-6}$$

$$\omega_{sc} := \frac{\sqrt{(4 \cdot R_{s1} + 2 \cdot R_m) \cdot R_{s1} \cdot L_r \cdot C_c - R_{s1}^2 \cdot R_m^2 \cdot C_c^2 - L_r^2}}{2 \cdot R_{s1} \cdot L_r \cdot C_c}$$

$$\omega_{sc} = 119.2 \times 10^3$$

Set up a range variable for graphing. $n := 0 .. 200$ $t_n := \dfrac{n}{200} \cdot 100 \cdot 10^{-6}$

$V_{oc}(X, t_n)$

—

$I_{sc}(X, t_n)$

—

$-0.3 \cdot I_{peak}$

— .
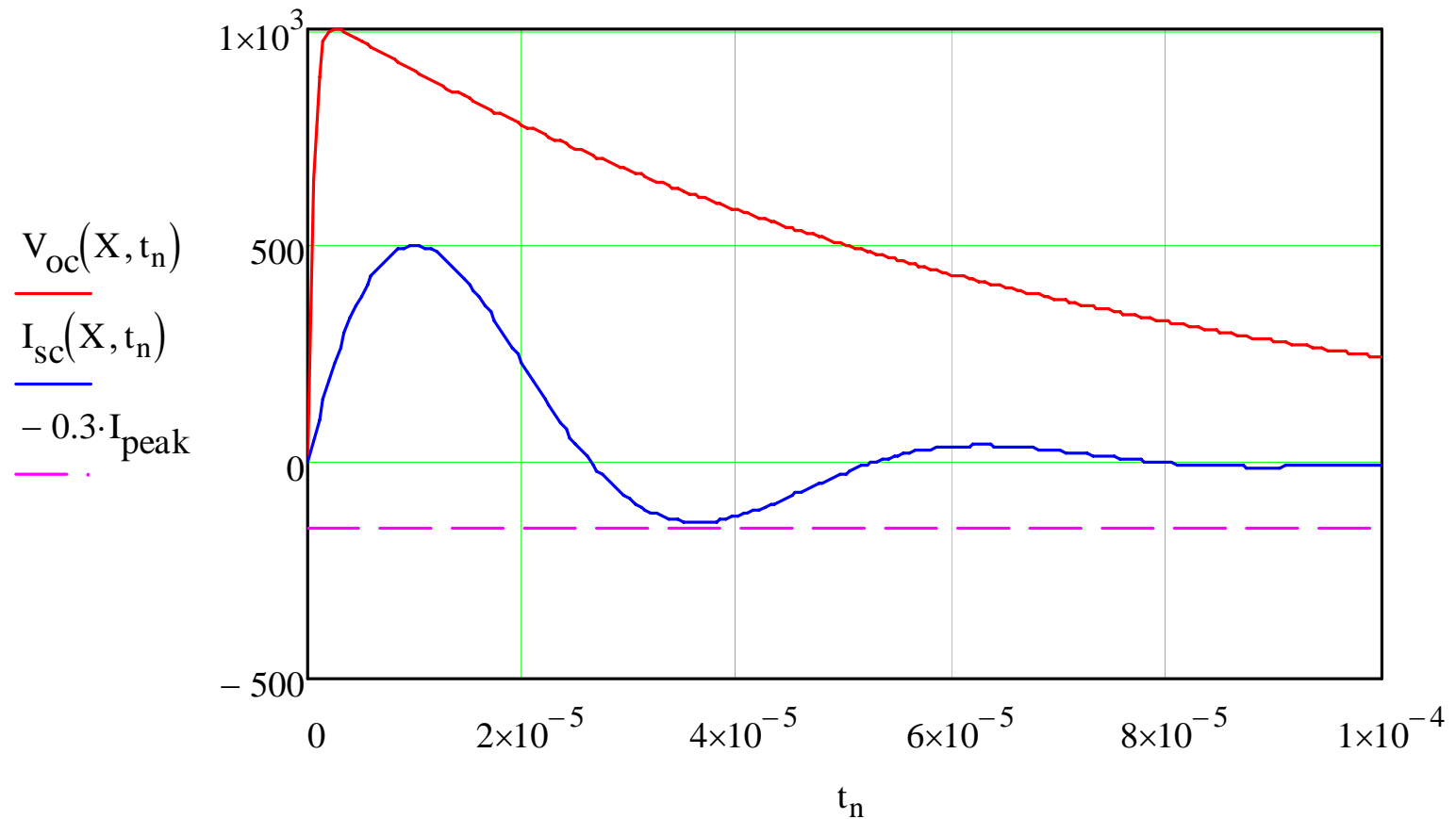
Figure 2. Open-circuit voltage and short-circuit current.

It appears that it is not possible to exactly meet the specifications using this circuit. The problem is meeting the short-circuit rise and duration times while keeping the current undershoot less than 30%. The errors in the current timing parameters are less than 5% when using the calculated component values.

Information about the origin of the combination wave test is provided in [3],[6]. An analysis of a surge generator that takes shunt stray capacitance on the output is given in [4]. The US surge standard, which closely follows the international standard, provides additional information [5].

References

[1]   IEC 61000-4-5 (2005) Electromagnetic Compatibility: Testing and measurement techniques–Surge immunity test .

[2]   Ronald B. Standler, "Equations for some transient overvoltage test waveforms," IEEE Transactions on Electromagnetic Compatibility, Vol. 30, No. 1, Feb. 1988.

[3]   Peter Richman, "Single-output, voltage and current surge generation for testing electronic systems," IEEE International Symposium on Electromagnetic Compatibility, August, 1983, pp. 47-51.

[4]   Robert Siegert and Osama Mohammed, "Evaluation of a hybrid surge testing generator configuration using computer based simulations," IEEE Southeastcon, March 1999, pp. 193-196.

[5]   ANSI/IEEE C62.41-1991, "IEEE recommended practice on surge voltages in low-voltage ac power circuits."

[6] Ronald B. Standler, *Protection of Electronic Circuits from Overvoltages,* New York: Wiley-Interscience, May 1989. Republished by Dover, December 2002.

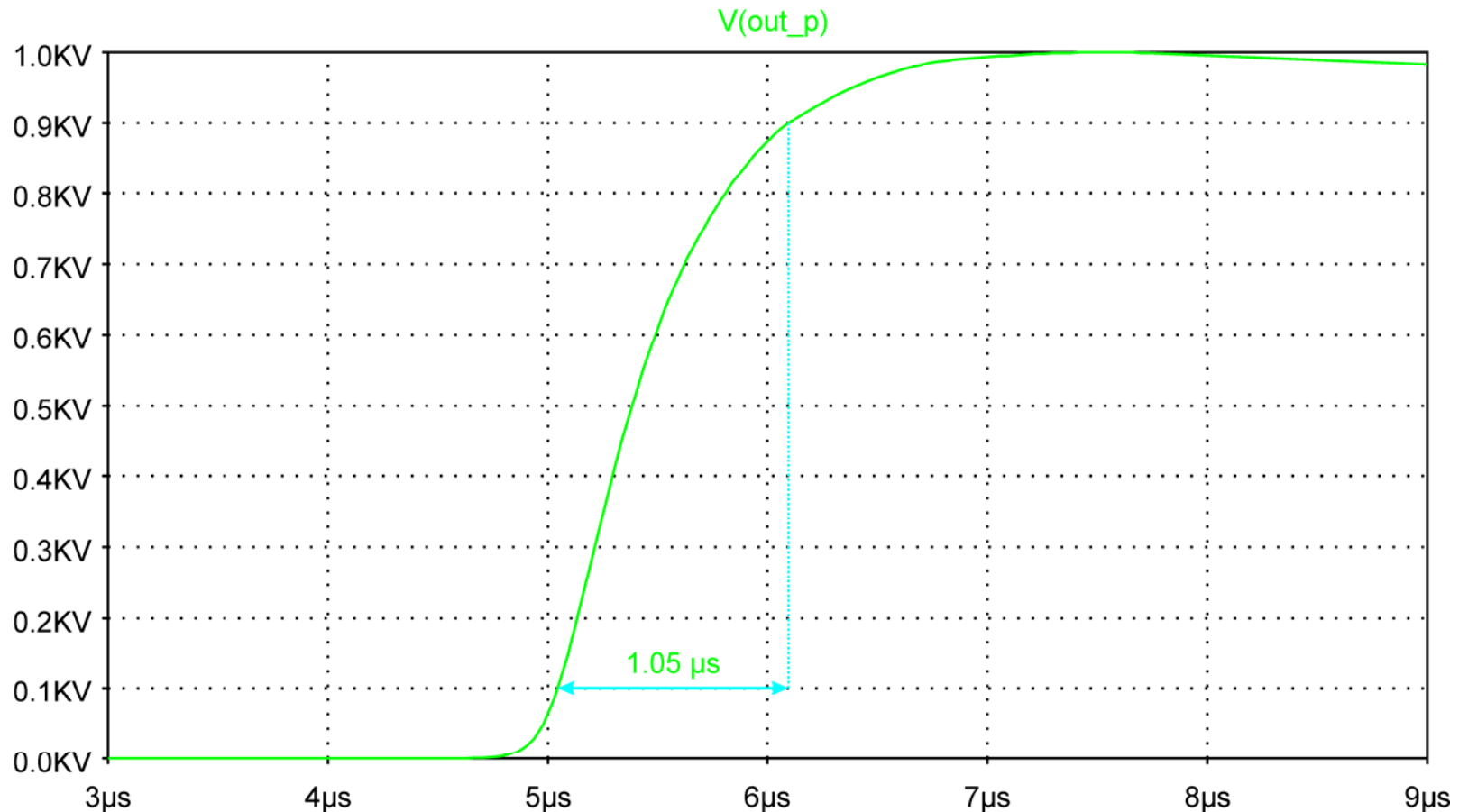# 1.2/50 μs Voltage, 8/20 μs Current Combination Wave Generator
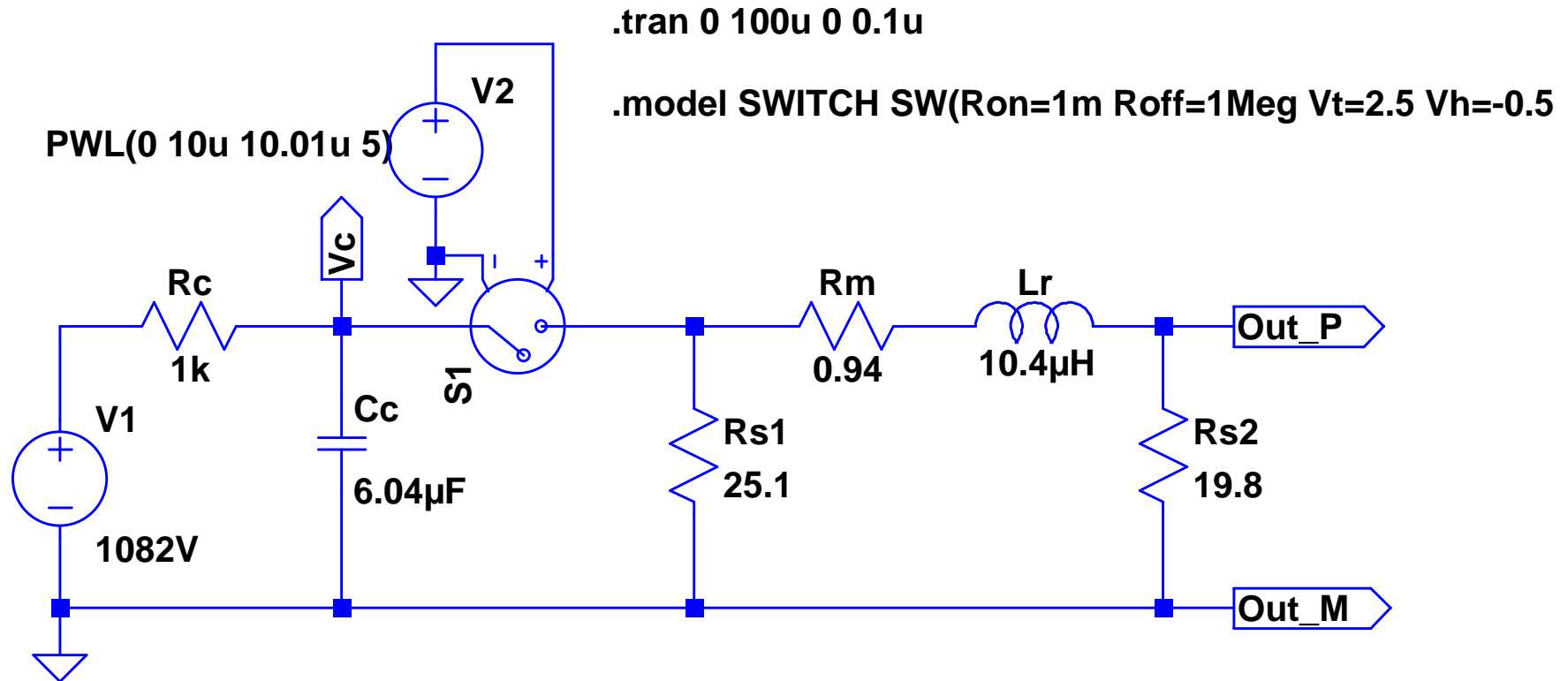
1.2/50 µs Voltage Waveform

50% − 50% duration = 50.4 µs   (Target = 50 µs)

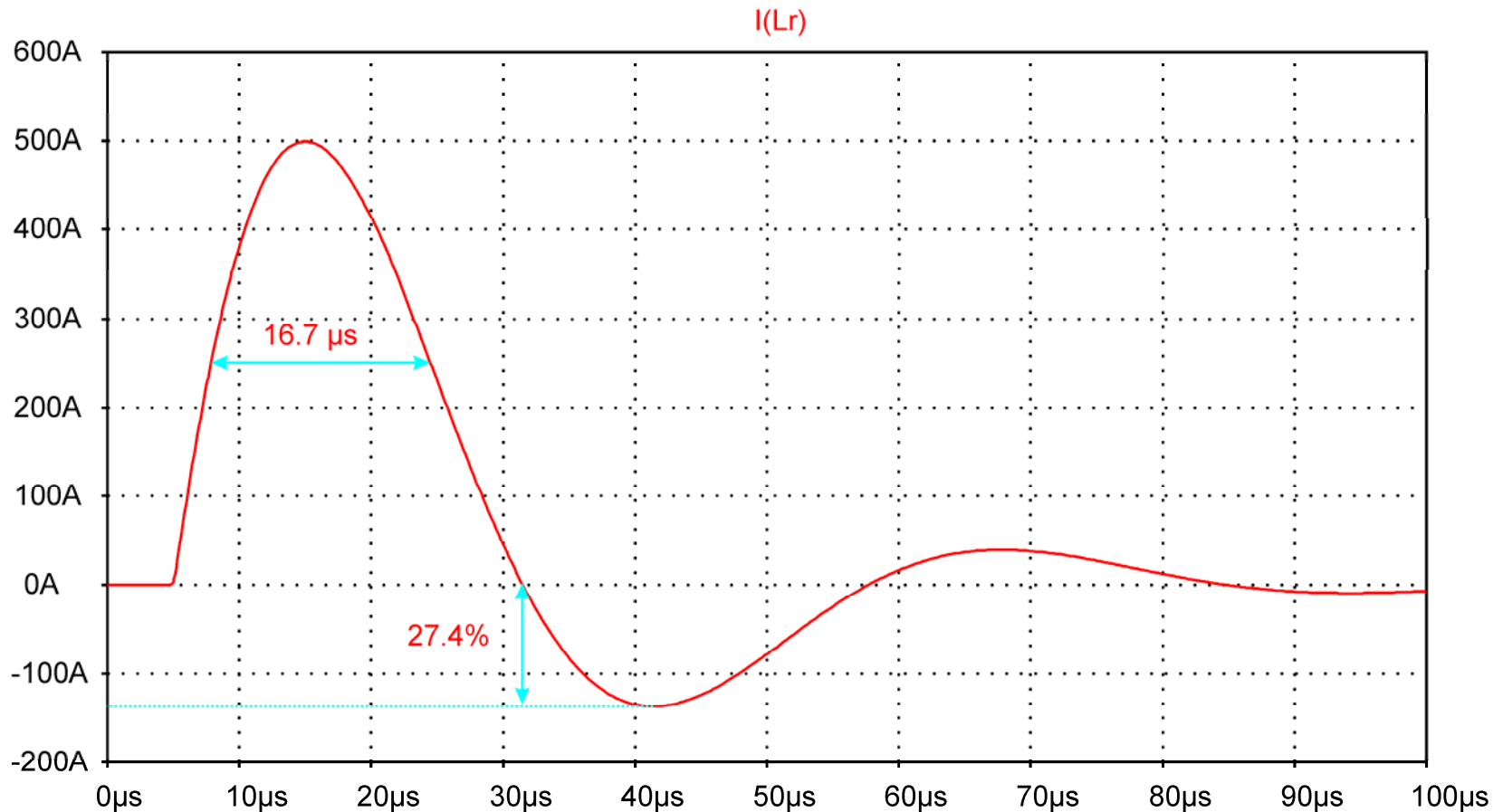V(out_p)

50.4 µs
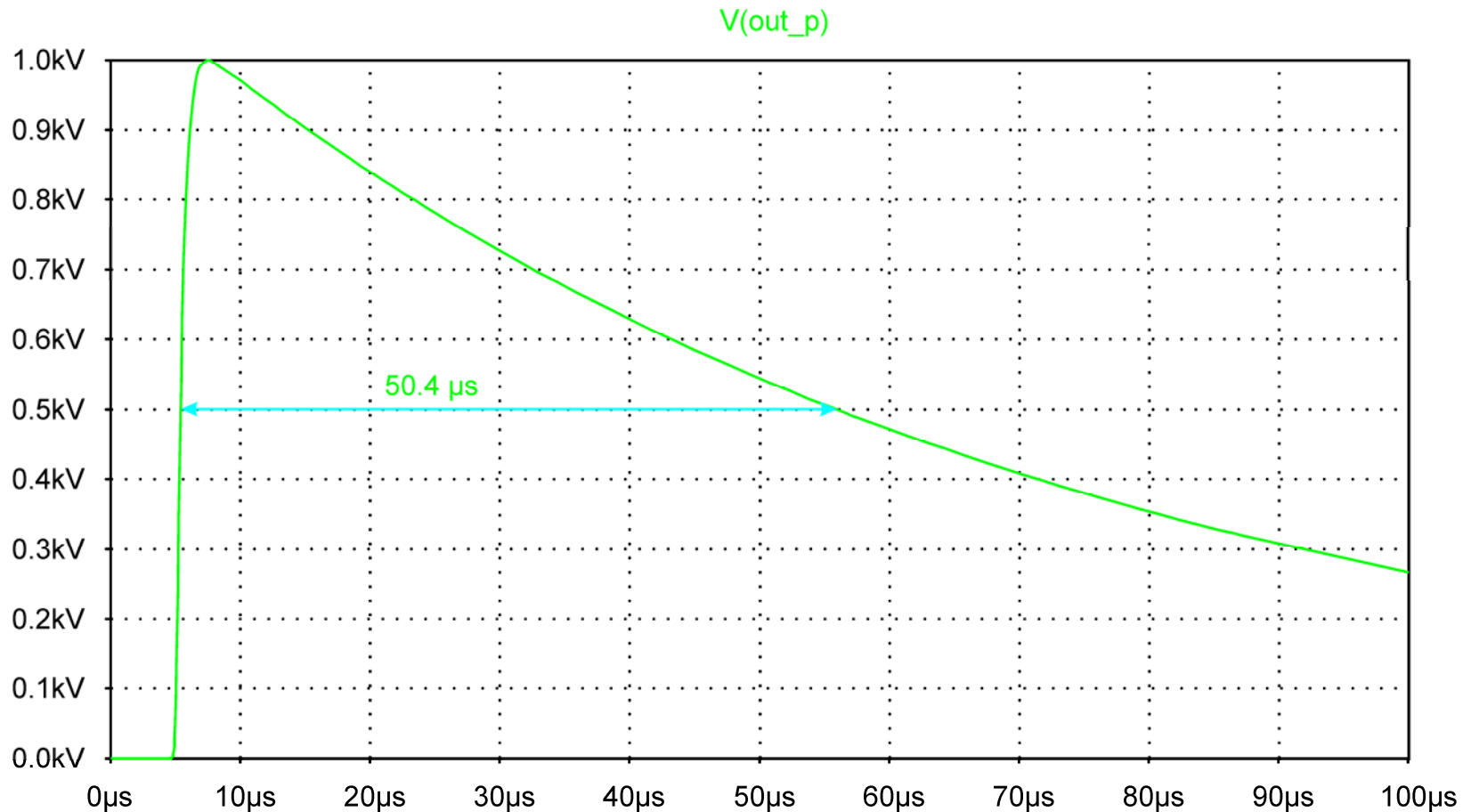
1.2/50 µs Voltage Waveform

10% -90% rise time = 1.05 µs   (Target = 1.0 µs)
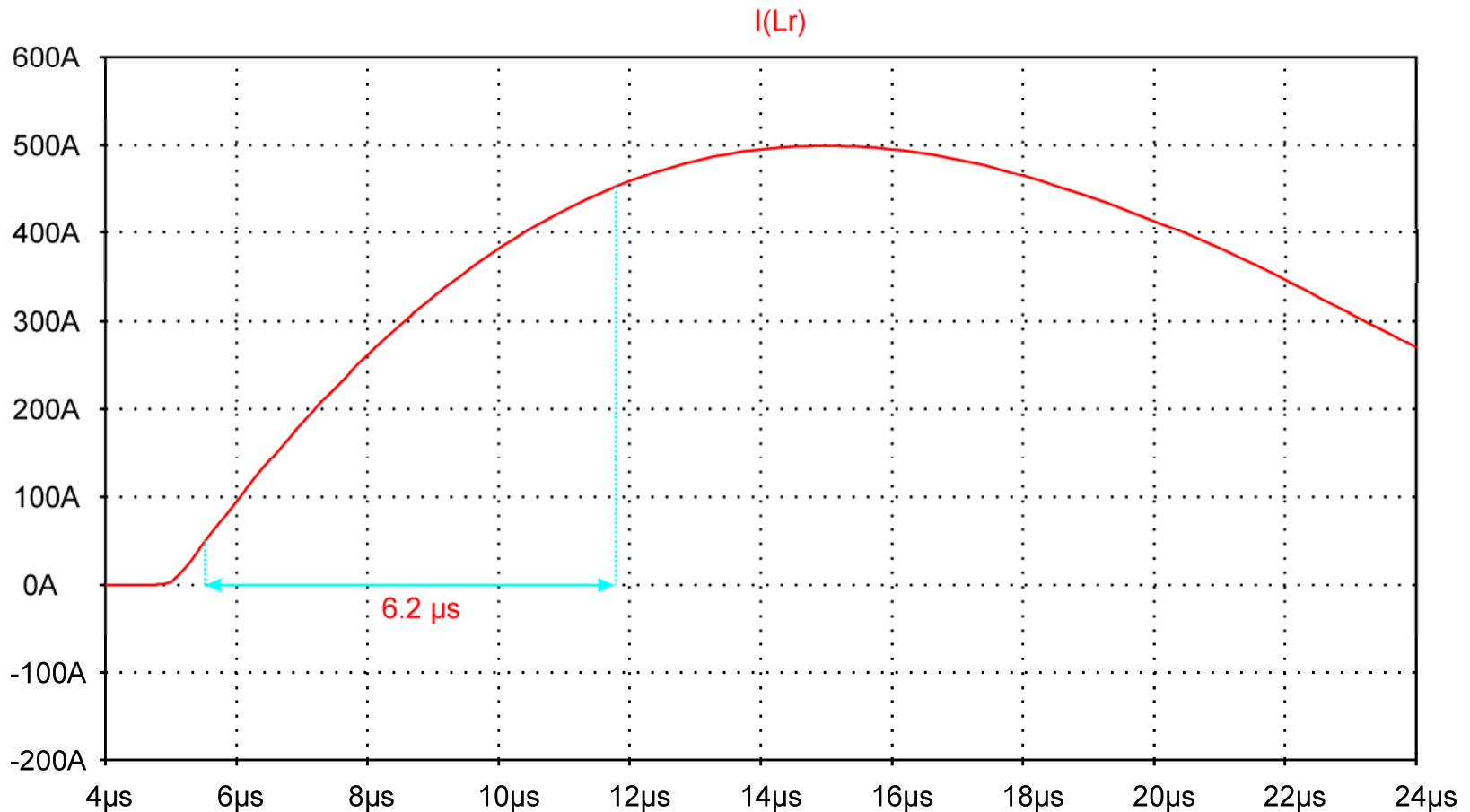
8/20 µs Current Waveform

50% -50% duration = 16.7 µs   (Target = 16 µs)
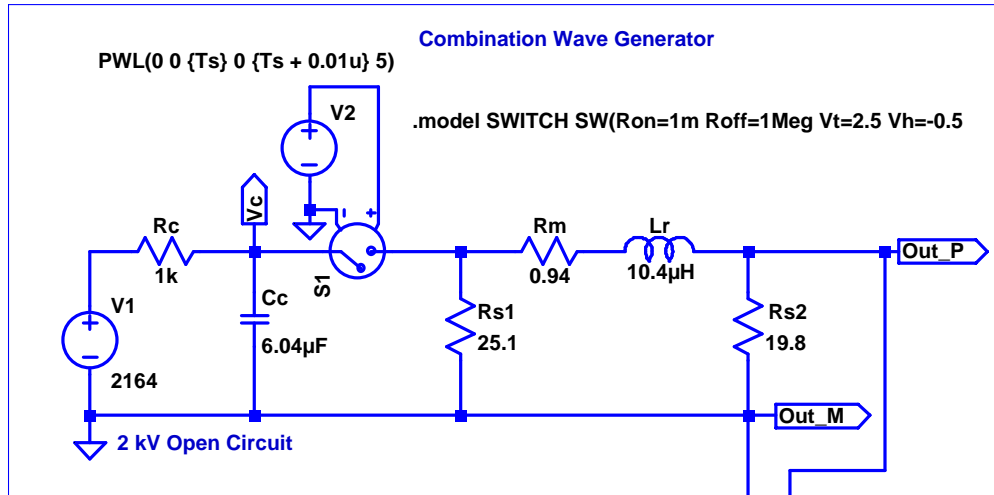
Undershoot = 27.4%   (Target ≤ 30%)

8/20 µs Current Waveform
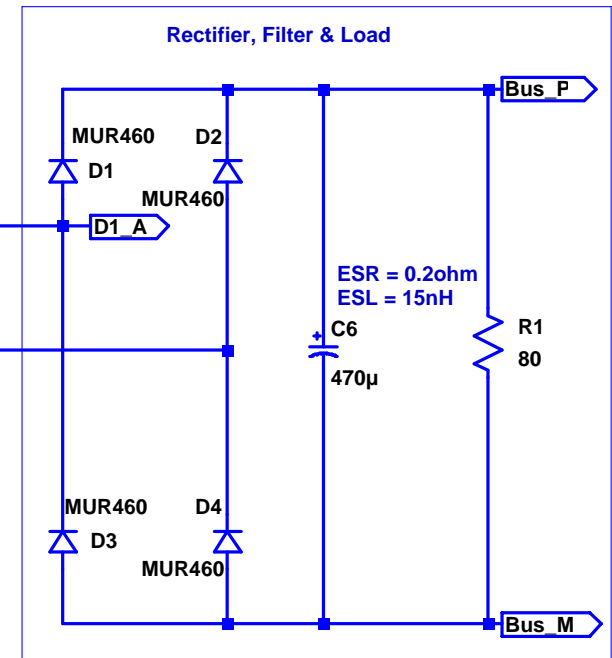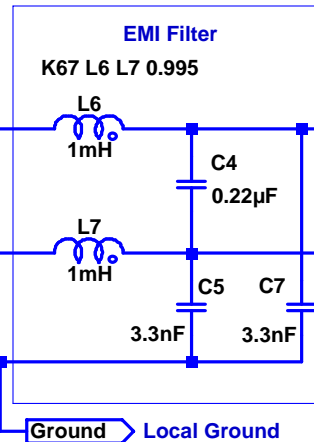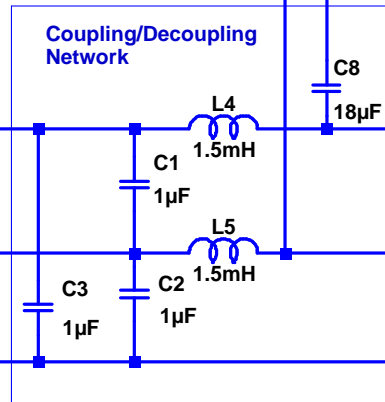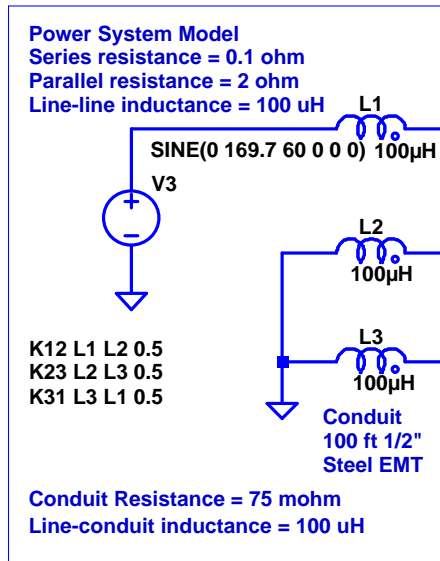
10% -90% rise time = 6.2 µs   (Target = 6.4 µs)

8/20 µs CWG with CDN and Power Supply
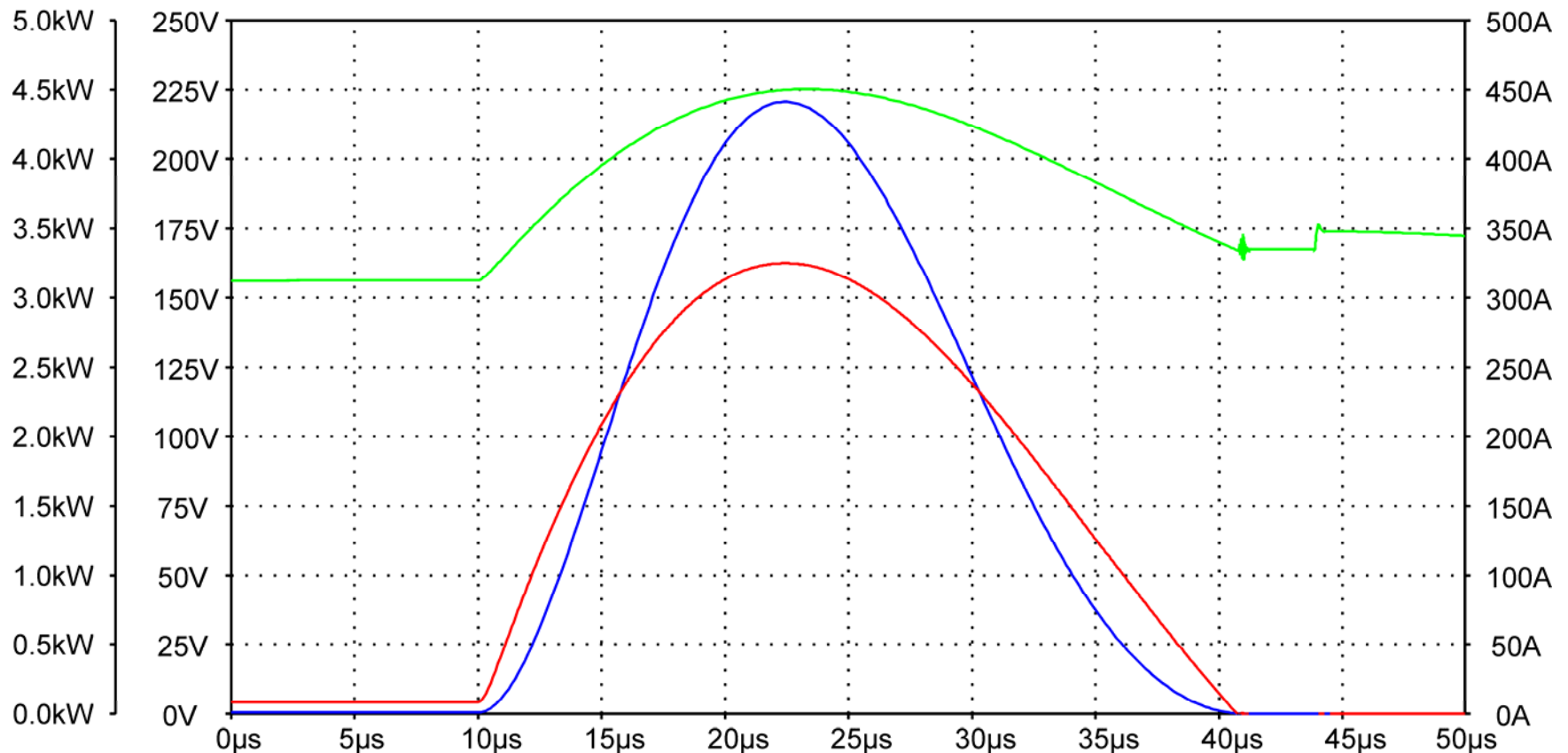

http://www.steelconduit.org/pdf/groundingpart1.PDF

8/20 µs Combination Waveform

Peak Open-circuit voltage = 1 kV

Diode Power = $(I(D1)*(V(D1\_A)-V(Bus\_P)))$
Peak Power = 4.4 kW
Pulse Energy = 67 mJ

Bus Voltage = $V(Bus\_P)-V(Bus\_M)$
Peak Voltage = 225 V

Diode Current = $I(D1)$
Peak Current = 325 A

8/20 µs Combination Waveform

Peak Open-circuit voltage = 2 kV

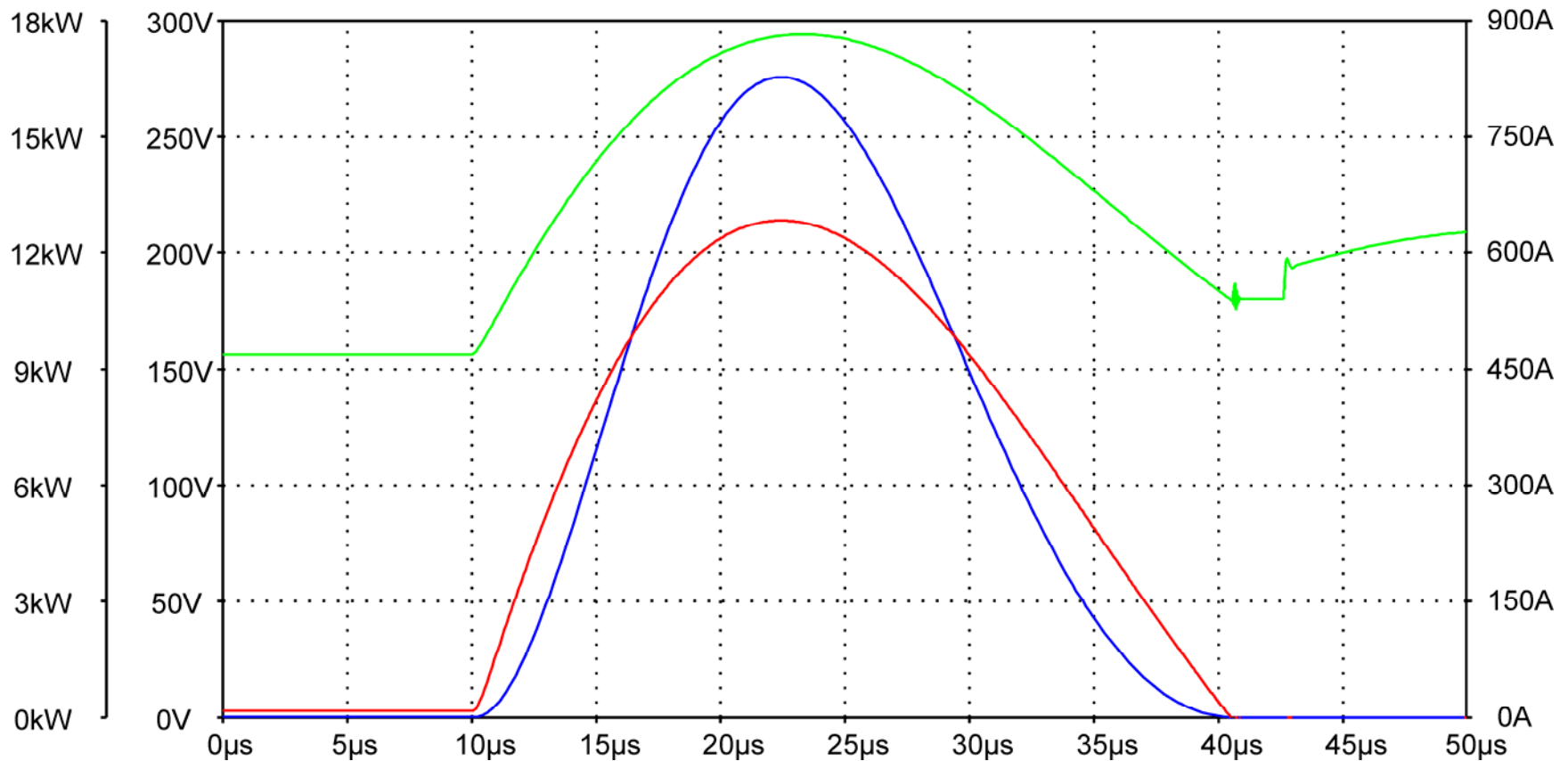Diode Power = (I(D1)*(V(D1_A)-V(Bus_P)))
Peak Power   = 16.5 kW
Pulse Energy = 246 mJ

Bus Voltage   = V(Bus_P)-V(Bus_M)
Peak Voltage = 294 V

Diode Current = I(D1)
Peak Current = 642 A