Achieving Exceptional ECL Based Surge Protection In VDSL Applications With Minimal Impact on Performance

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What Makes VDSL2 Protection So Difficult?

Here are some of the major problems we have found:

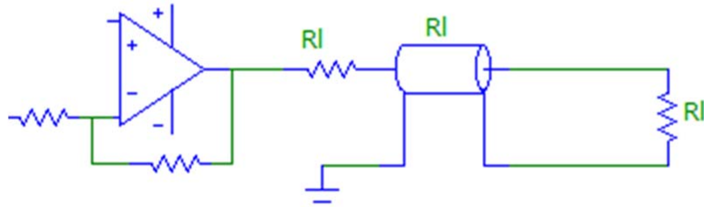
- **Adoption of "Active Termination" to reduce power**
  - **Older systems typically used simple Passive termination**
- **Class H drivers becoming popular to reduce power**
  - **Older systems typically used Class A/B**
- **"Oscillating" GDT's are a significant source of threat**

This makes protecting the new generation of high speed, power efficient VDSL2 drivers increasingly difficult

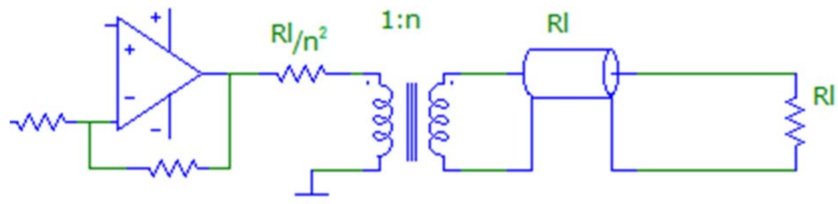
Quick Review of Passive Termination

- **Single ended, direct termination**

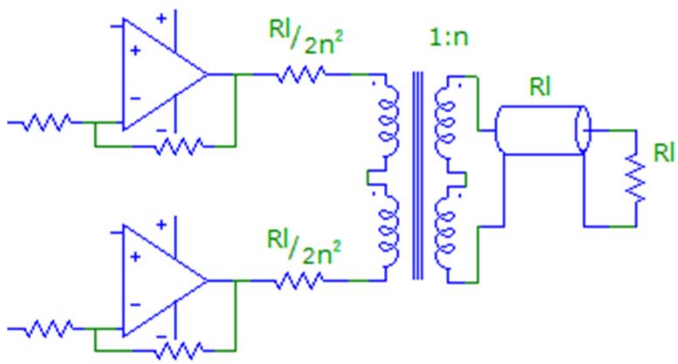
LOW OUTPUT
RESISTANCE
VOLTAGE DRIVER



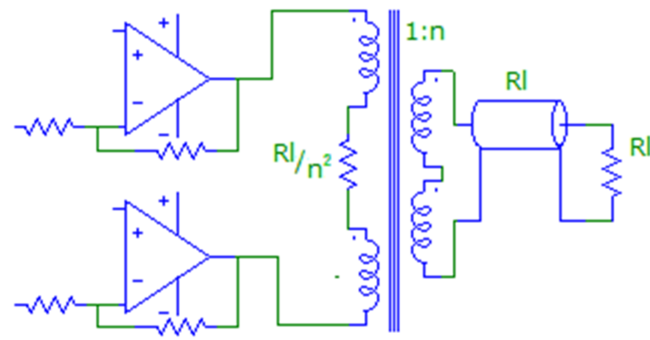
- **Equivalent single ended, transformer coupled termination**



- **Equivalent differential, transformer coupled termination**



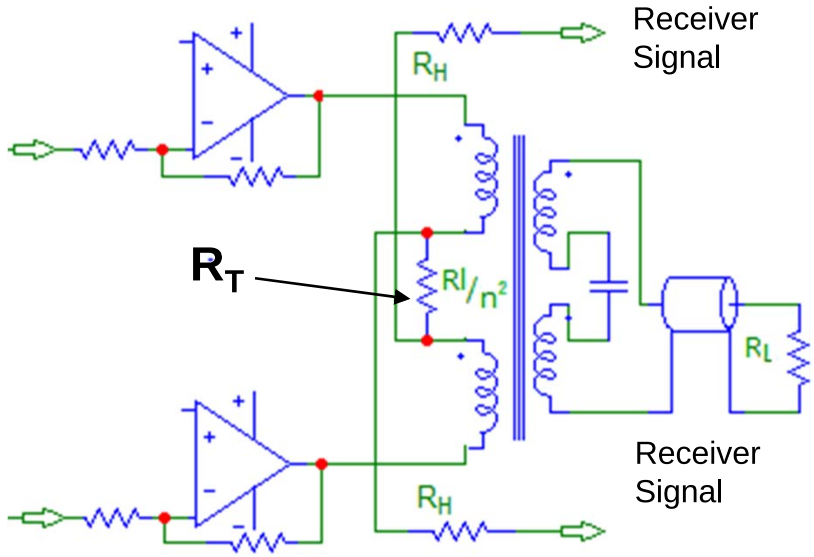
SPLIT OR DUAL TERMINATION



SINGLE TERMINATION

- **We'll focus on the differential, single termination for discussion**

Passive Termination



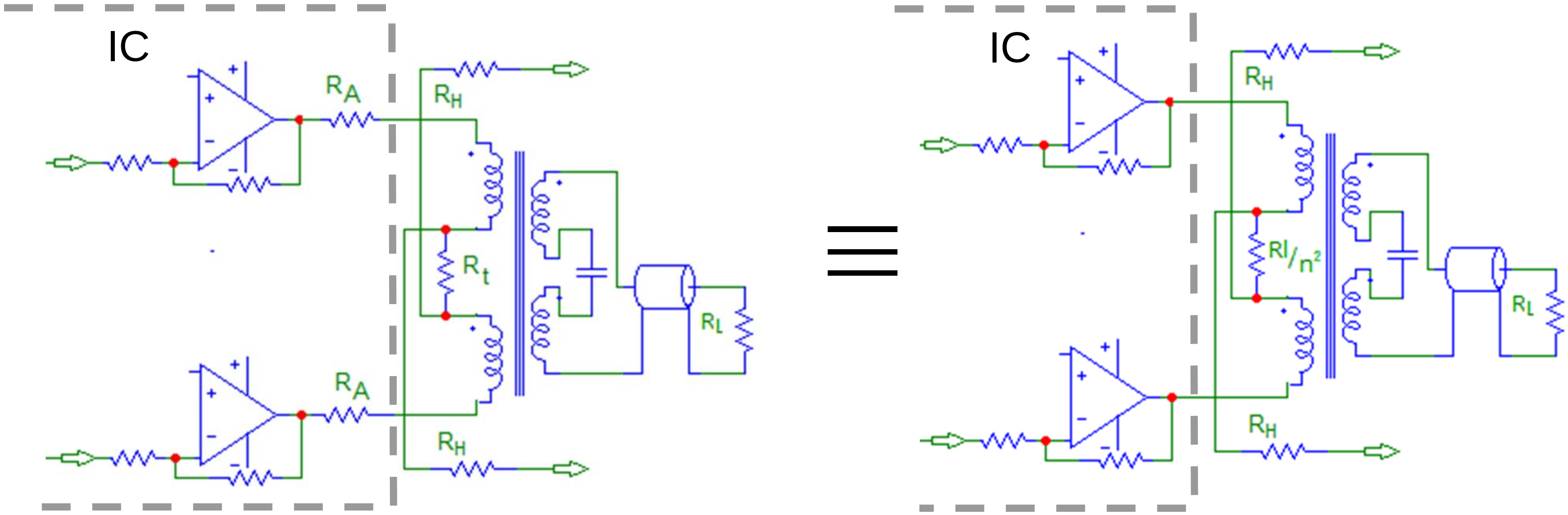
- **50% of the drive signal is lost in the termination resistance R_T where:**

$$R_T = \frac{R_L}{n^2}$$

- **Driver must have voltage headroom equal to double the peak signal voltage transmitted down the line**

$\Rightarrow$ **Total power dissipation is high!**

Active (Synthesized) Single Termination



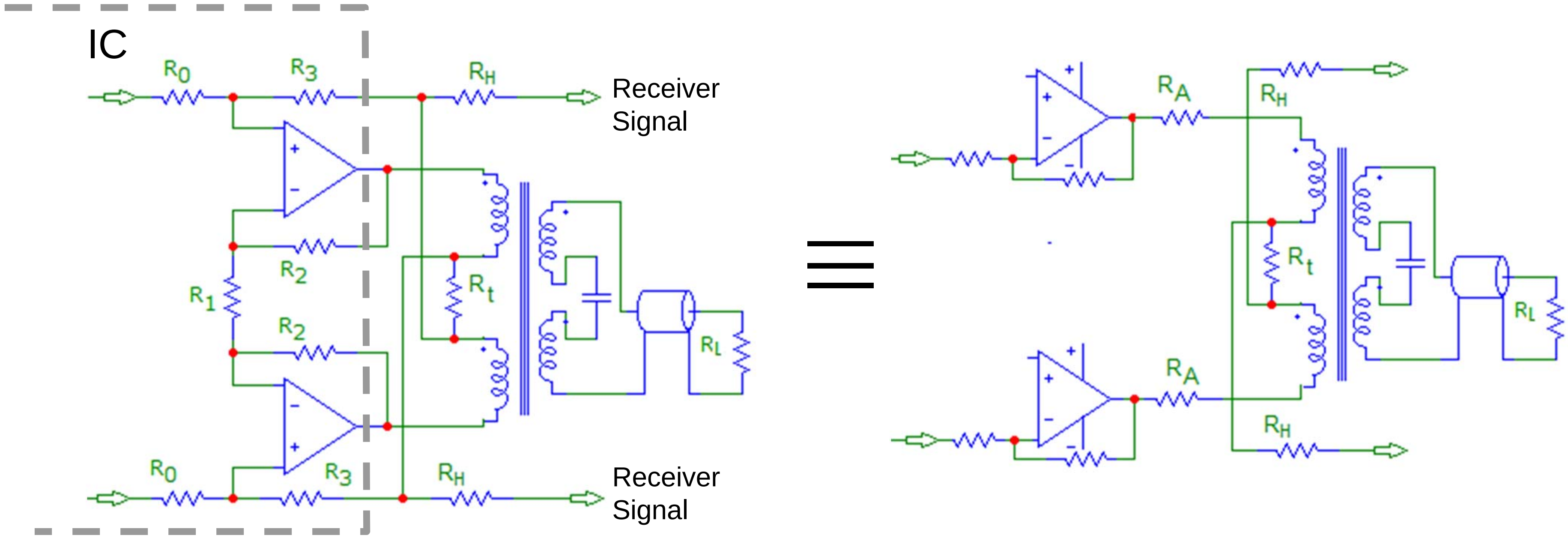
- **A portion of the termination resistance can be replaced with driver amplifier output impedance (R_A)**
- **For correct termination:**

$$(2*R_A)+R_t=\frac{R_L}{n^2}$$

- **We can define a constant, 'm', as:**

$$m=\frac{2*R_A}{R_t}$$

Active Single Termination

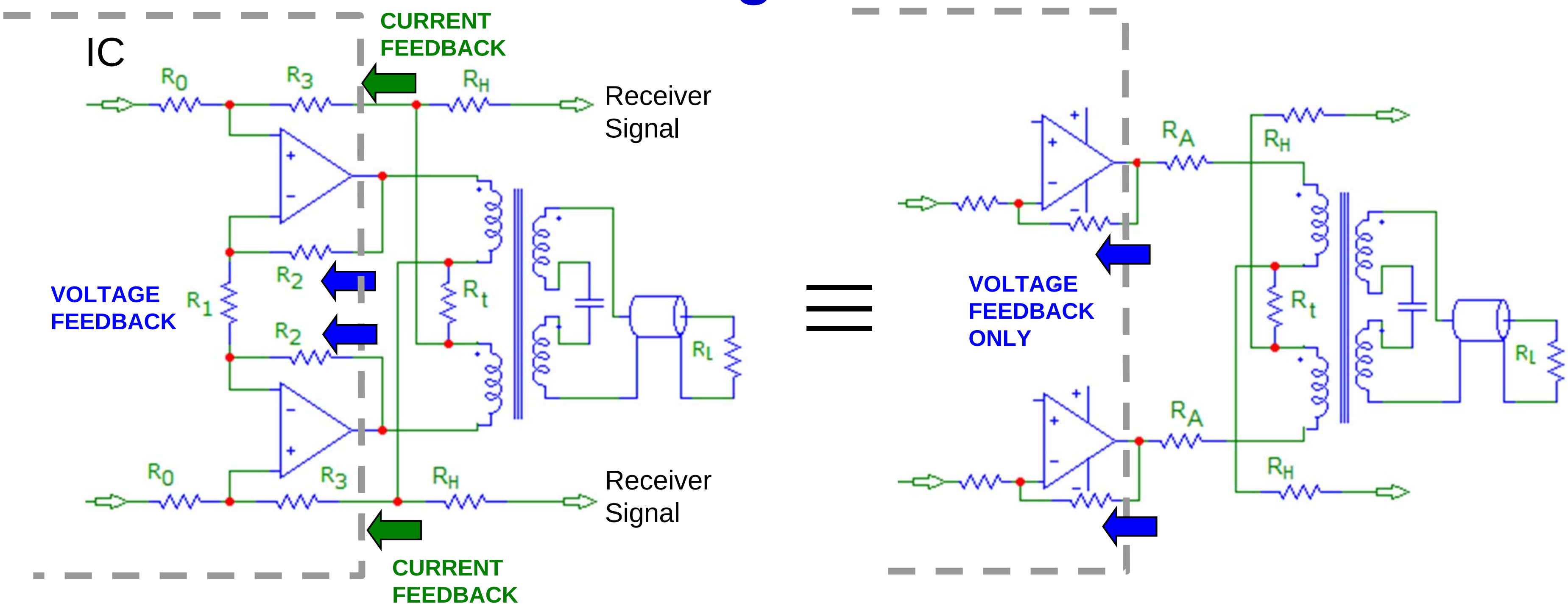


Here's the trick!

The output resistance R_A is not a physical resistor!

- **The combination of current and voltage feedback creates "virtual resistance", R_A**
- **Virtual R_A**
  1) **does not dissipate power => lower power, higher efficiency**
  2) **does not require amplifier voltage headroom => lower power supply rails**

Active Single Termination



- **Rt acts as a sense resistor for driver current and receiver signal**

For a high gain amplifier:

$$R_A = \left\{ \frac{R_t * \left\{ 1 + \left\{ \frac{2 * R_2}{R_1} \right\} \right\}}{2 * \left\{ 1 + \left\{ \frac{R_3}{R_0} \right\} \right\}} \right\}$$

Or: $R_A = \frac{R_t * m}{2}$

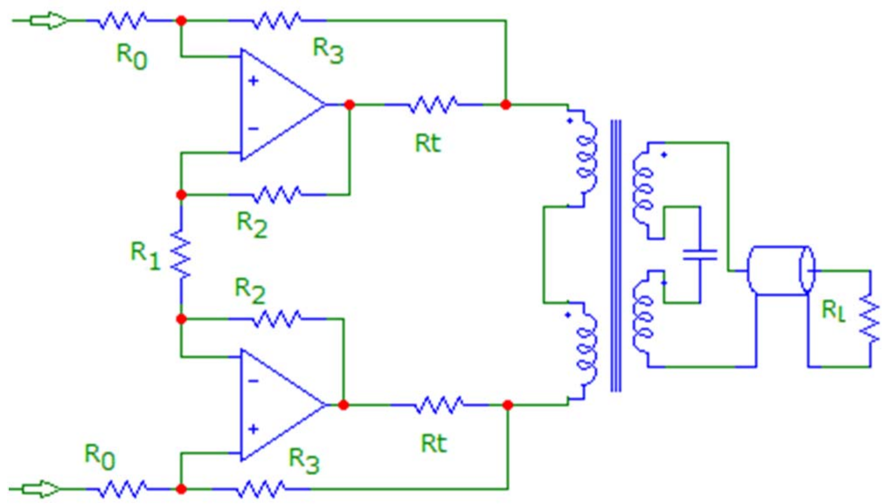
where:

$$m = \frac{\left\{ 1 + \left\{ \frac{2 * R_2}{R_1} \right\} \right\}}{\left\{ 1 + \left\{ \frac{R_3}{R_0} \right\} \right\}}$$

For n=1.4, m ~4

$\Rightarrow R_t \sim 10\ \Omega$

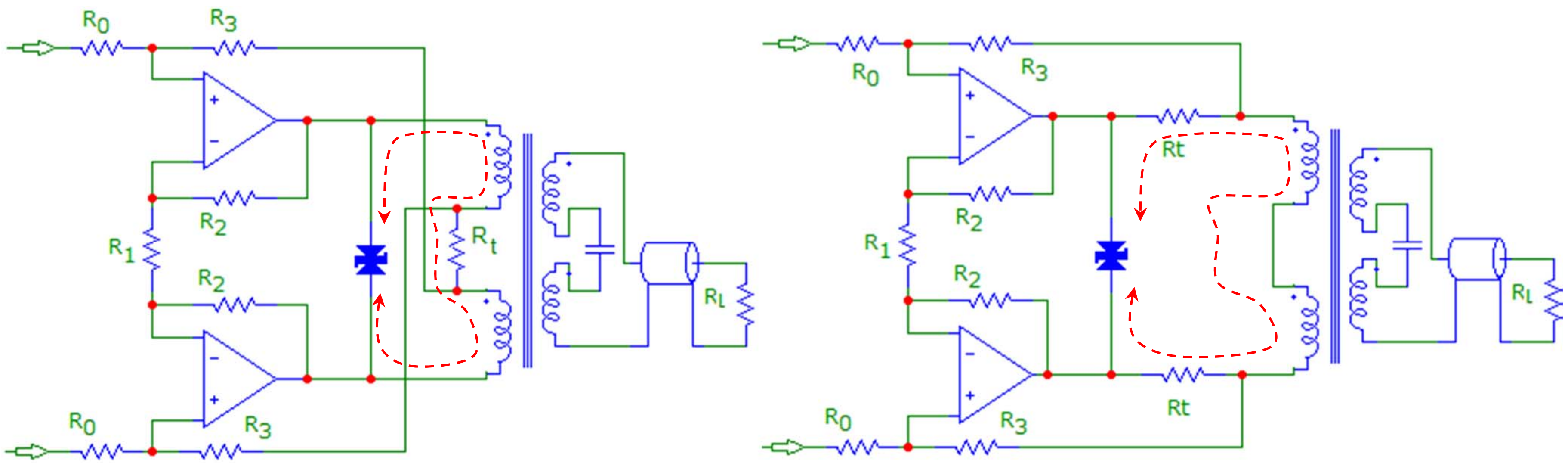
Active Dual Termination



- **Current sense resistor is split and moved to the driver side**
  - **eg typically each resistor R_t is 5 Ω for n = 1.4**
- **Similar, but the output resistance is now given by:**

$$R_A = \frac{R_t * \left\{1 + \left\{\frac{2 * R_2}{R_1}\right\}\right\}}{\left\{\left\{\frac{R_3}{R_0}\right\} - \left\{\frac{2 * R_2}{R_1}\right\}\right\}}$$

Dual and Single Termination Under Surge

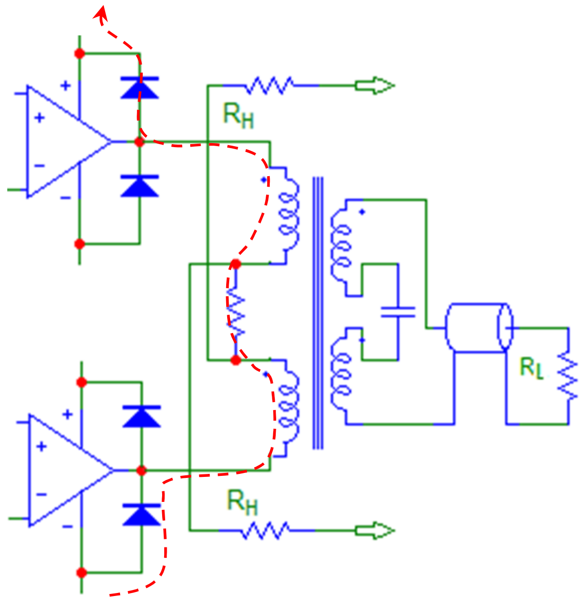


- **For protection, the TVS should normally be close to the driver,**
- **R_t acts as series resistance to reduce peak current in both cases**

Let's take a closer look at Active Termination under surge…

Active Termination Under Surge

- **Under surge, high secondary current forces the amplifier output to its ESD clamps**

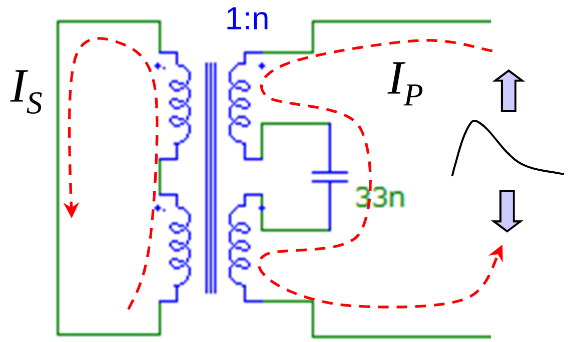


- **Linear control is lost, and therefore Active Termination is lost…**
- **Only physical resistance remains (eg 10 Ω vs 50 Ω for passive)**

How much does the lower secondary resistance affect surge performance in Active Termination circuits?

Surge to VDSL System – Shorted Secondary

- Let's look at the extreme case: Secondary shorted:



- Shorted transformer primary has little impedance
- Primary capacitor is charged/discharged by surge
- Surge current is dictated by size of capacitor:

$$I_P = C\frac{dV}{dt}$$

- Secondary current set by turns ratio, n:

$$I_S = n * I_P$$

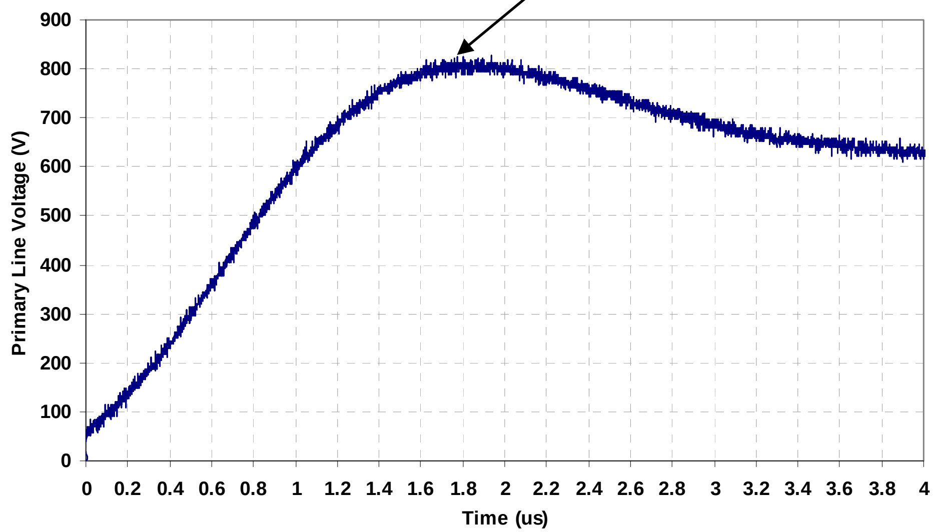
Surge Waveforms

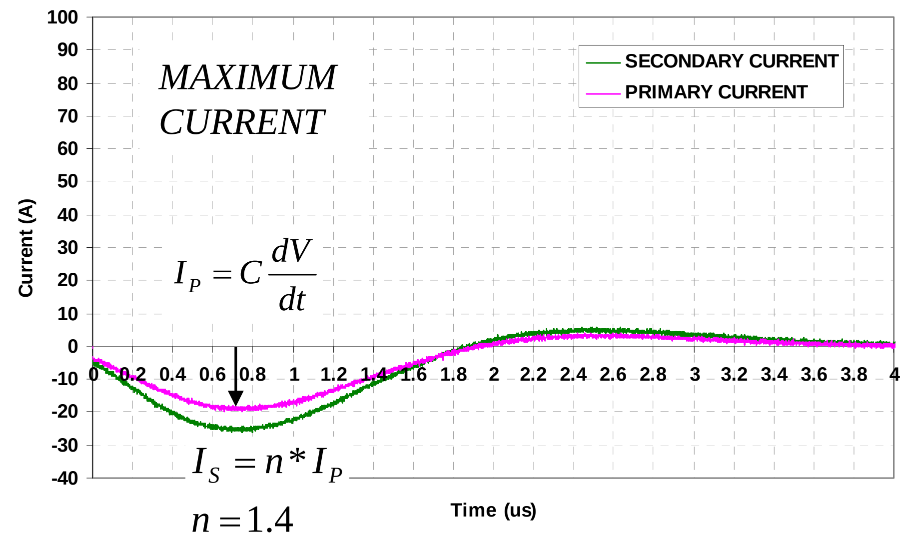
- **Current is at a maximum when rate of capacitance changing is highest**
- **Energy stored in the capacitor is given by:**

$$E = \frac{1}{2}CV^2$$

Note that because of the capacitor, the transformer does not saturate

$$E = \frac{1}{2}CV_{max}{}^2$$





$n = 1.4$

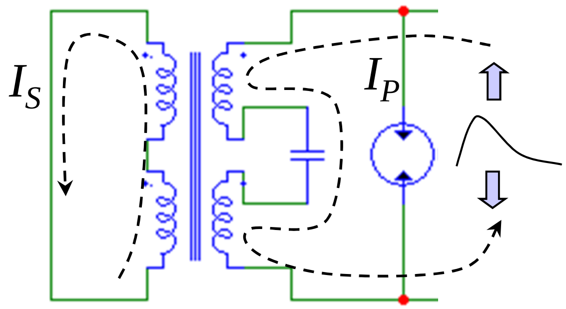
$I_S(PK)$: $I_P(PK)$

-26 A : -18.5 A

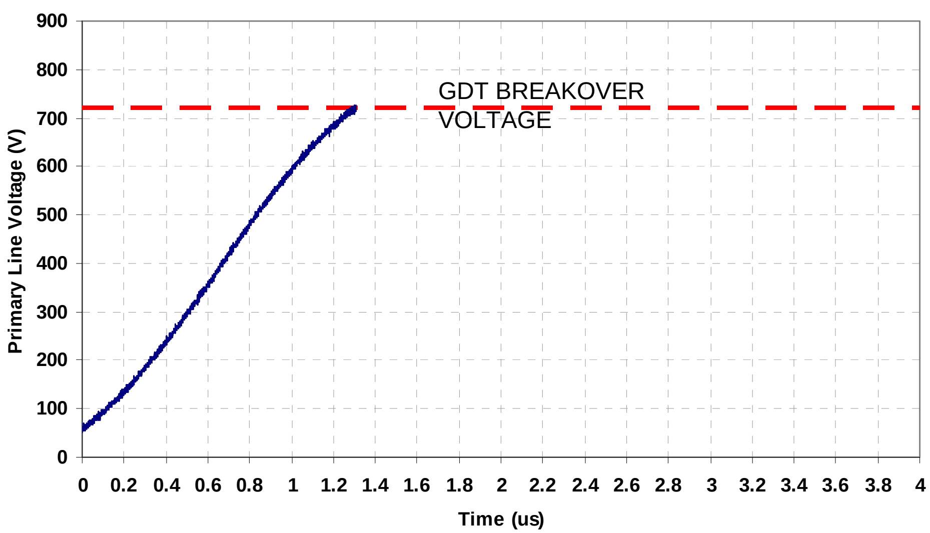
1.41 : 1

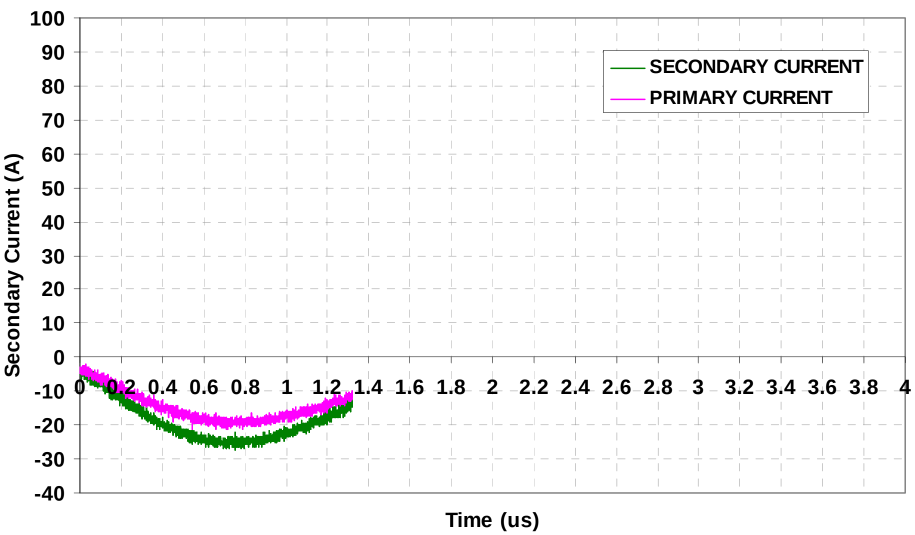
Surge With GDT

When a GDT is present in the system, the picture changes…



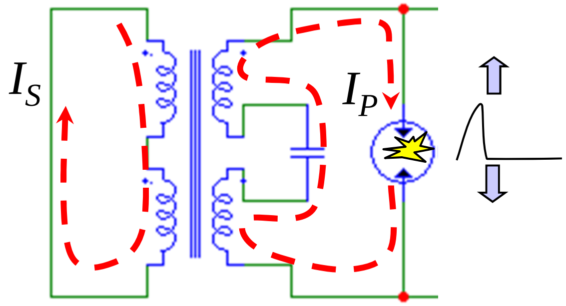
- **Primary capacitor begins to charge, current flows as before…**



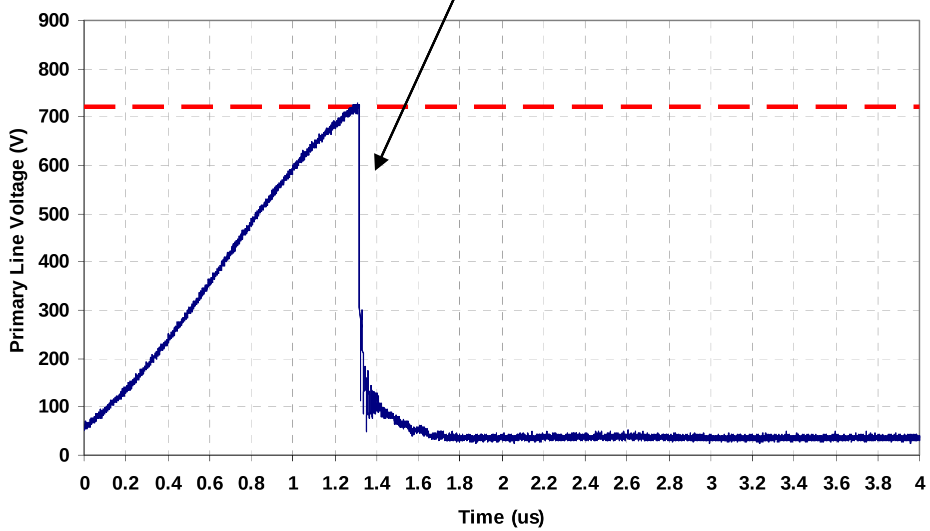


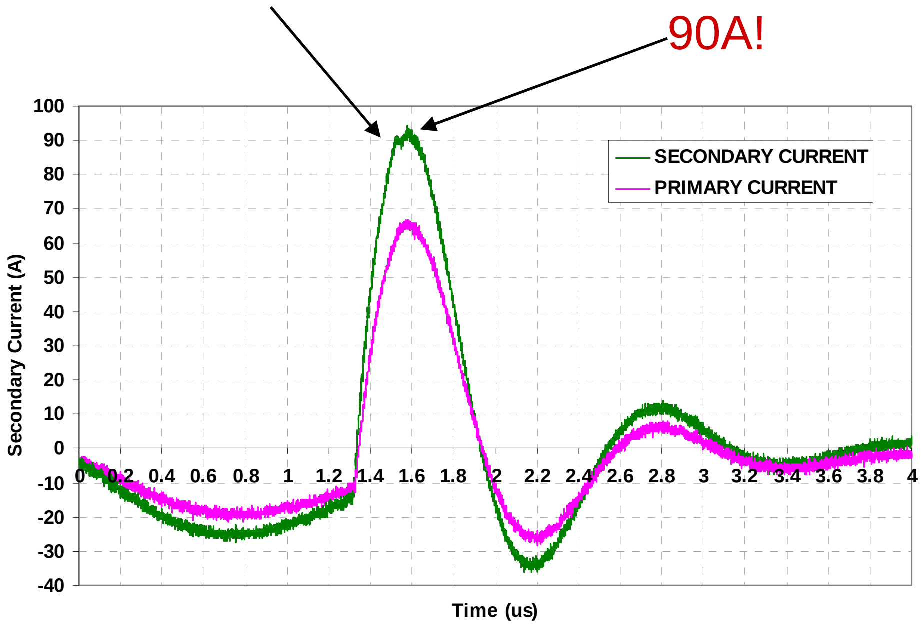
Surge to Transformer

When the GDT fires:



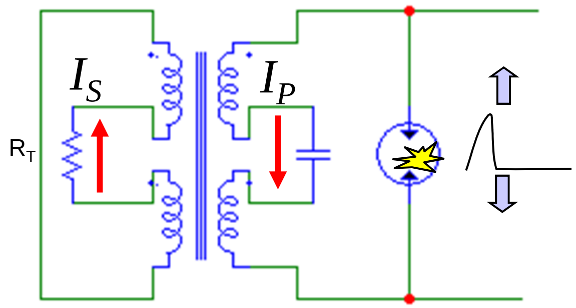
- **Capacitor is shorted by GDT, and rapidly discharges**
- **Very high dV/dt causes very high discharge current…**





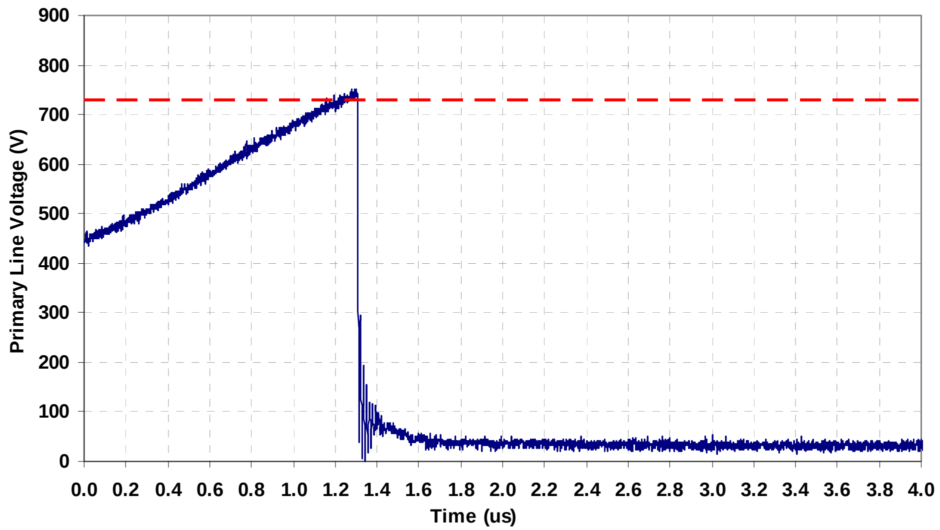
Surge With Passive R_T

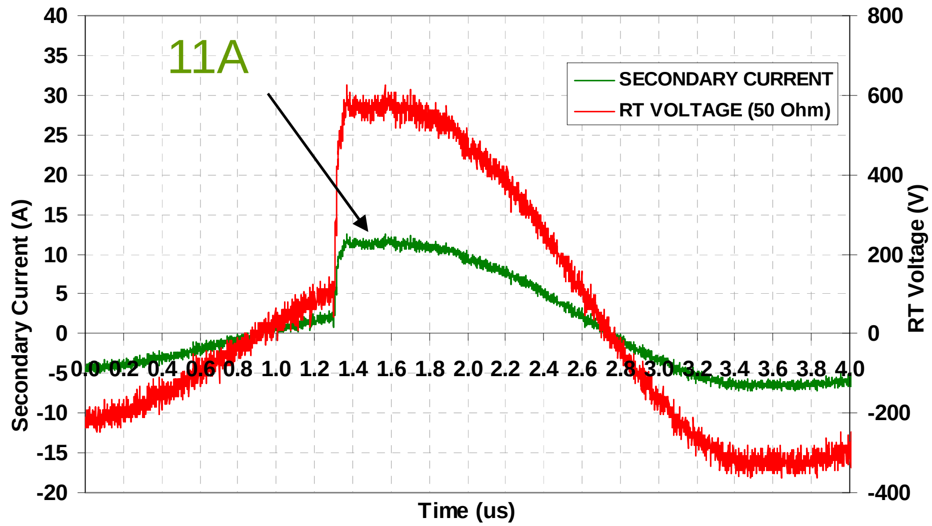
- **Fortunately, passive termination resistance, R_T, drastically reduces the peak current**



For n=1.4

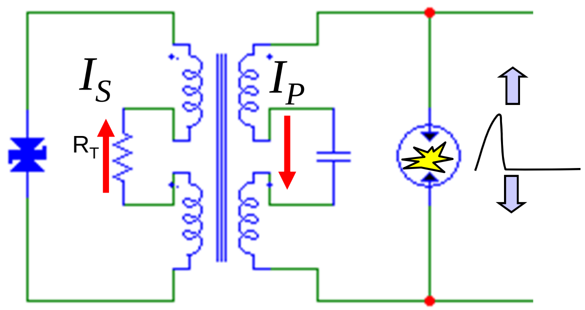
$R_T = R_L / n^2 = 50\ \Omega$





Surge With Passive R_T and TVS

- **Replacing the Line short with a low ESR (Effective Series Resistance) TVS has little impact on secondary current**



For n=1.4

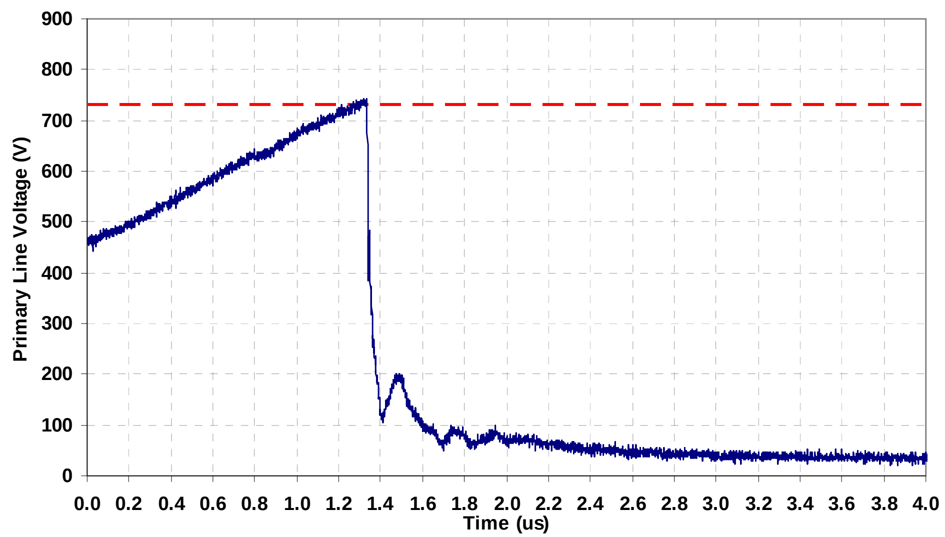
$R_T = R_L / n^2 = 50\ \Omega$

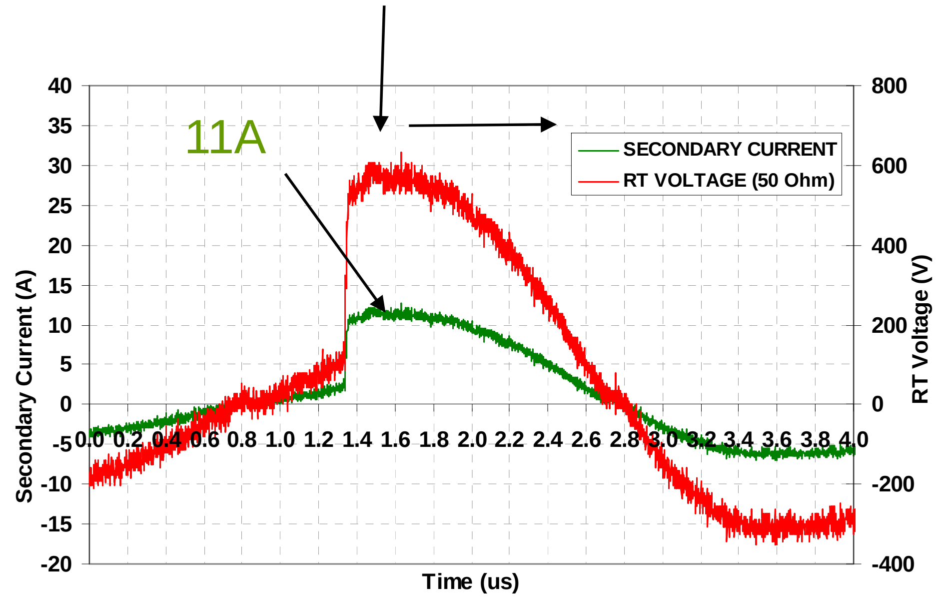
Special Note: peak voltage across the termination resistance can be very high!!!

11 A * 50 Ω = 550 V

- ***Use multiple series resistors!***
- **Receiver I/O's may need protecting**

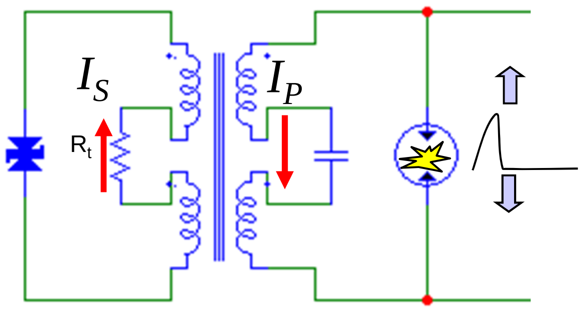
DON'T PUT A TVS ACROSS R_T!!!





Surge With Active Termination Resistor

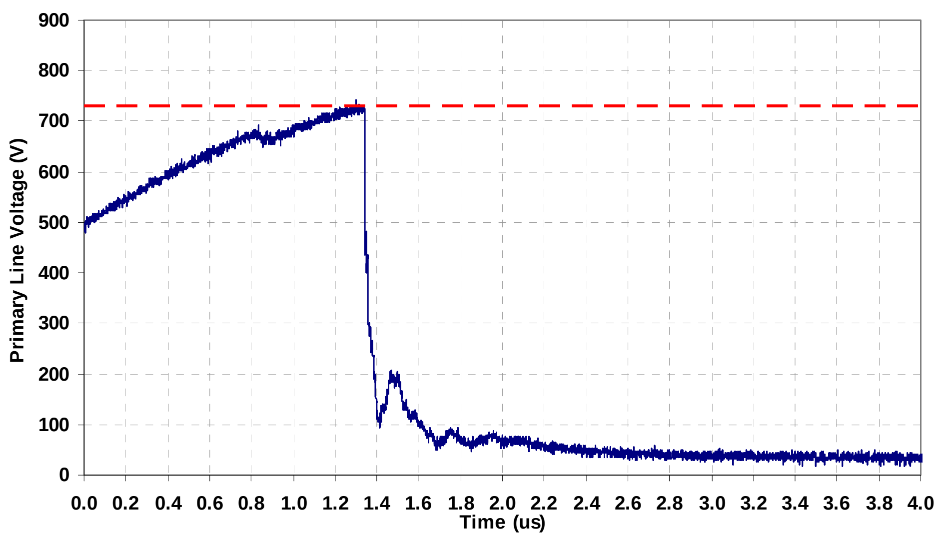
- **Unfortunately, *Active* termination resistance, R_t, is much lower value, significantly increasing the peak current**

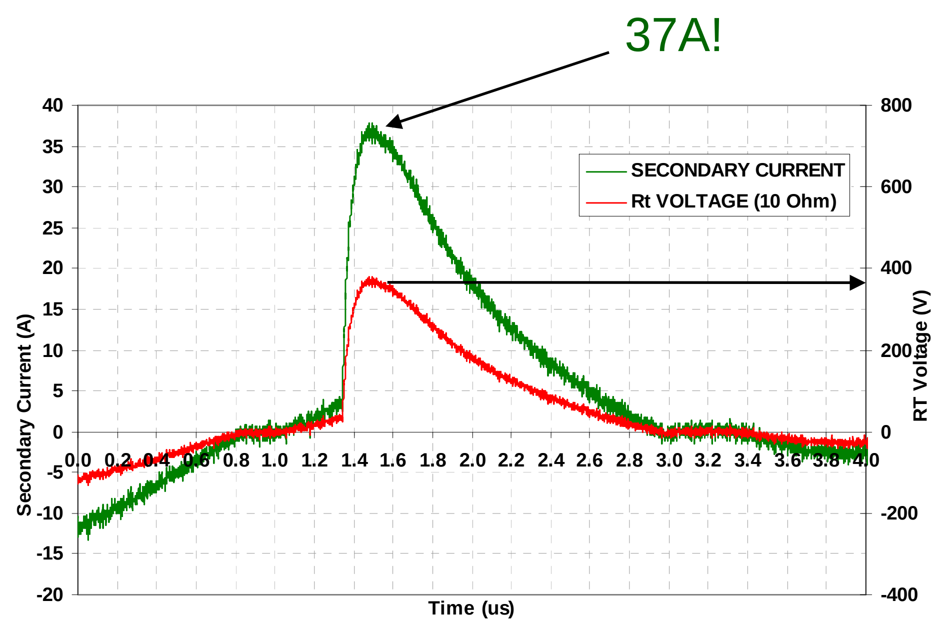


For n=1.4, m = 4
$R_t = R_L / ((1+m)*n^{2)} = 10\ \Omega$

Note: peak voltage across R_t = 37*10 = 370V

Note: Both receiver <u>and</u> current feedback I/O's may need protecting





Surge Issues With Active Termination

1) Lower resistance results in much higher secondary current
2) TVS must be much higher rated than with passive termination

   ~3X the current or more!

3) Additional current sensing feedback I/O's need to be protected

Larger secondary currents means:

- Larger secondary TVS required
- Often additional primary side MOV's or TVS's required
- Greater impact on sensitive VDSL signal by high capacitance clamping devices, causing data corruption

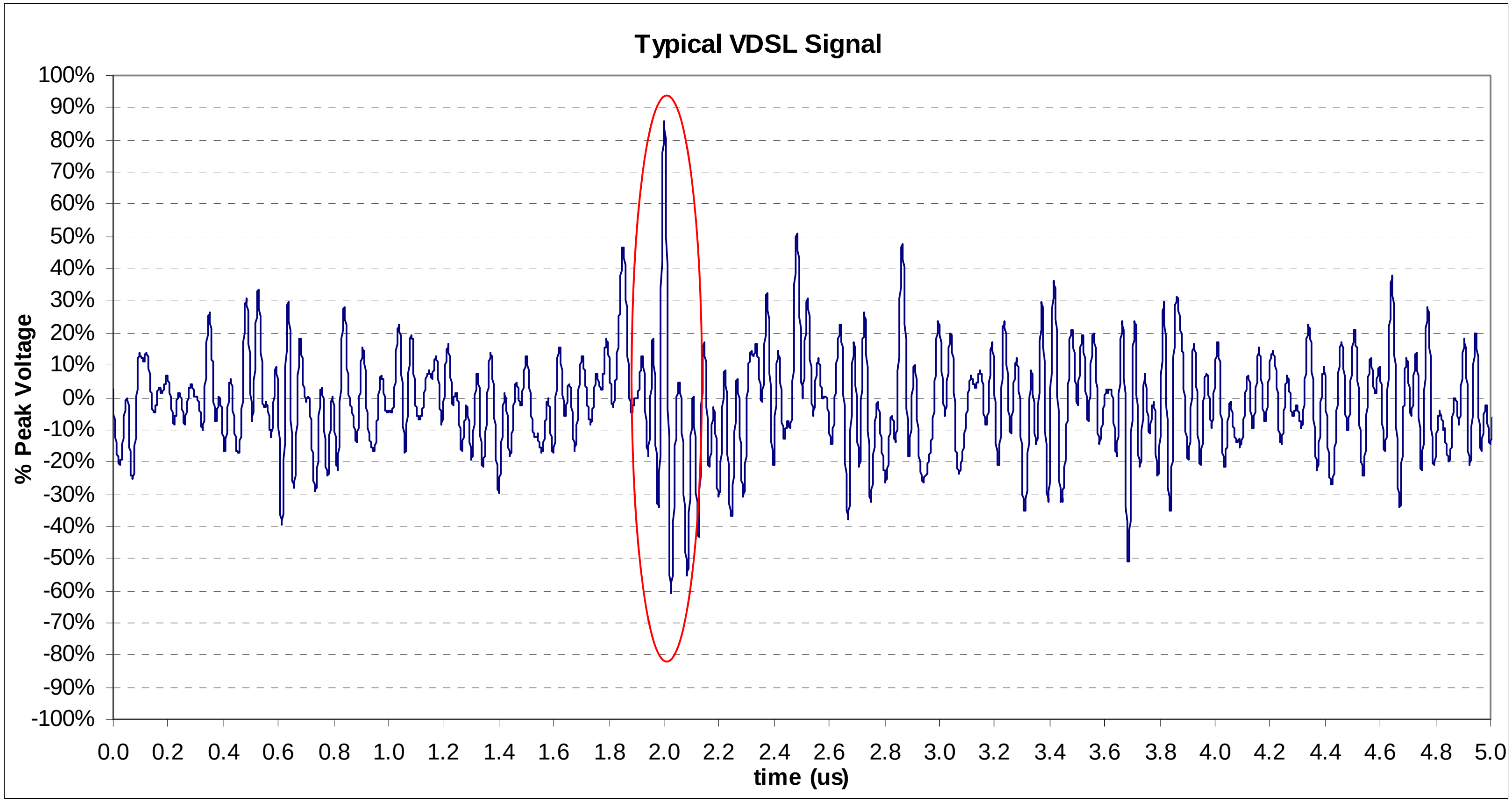
⇒ Higher cost

So, Active Termination significantly reduces power, but makes handling surge more difficult…

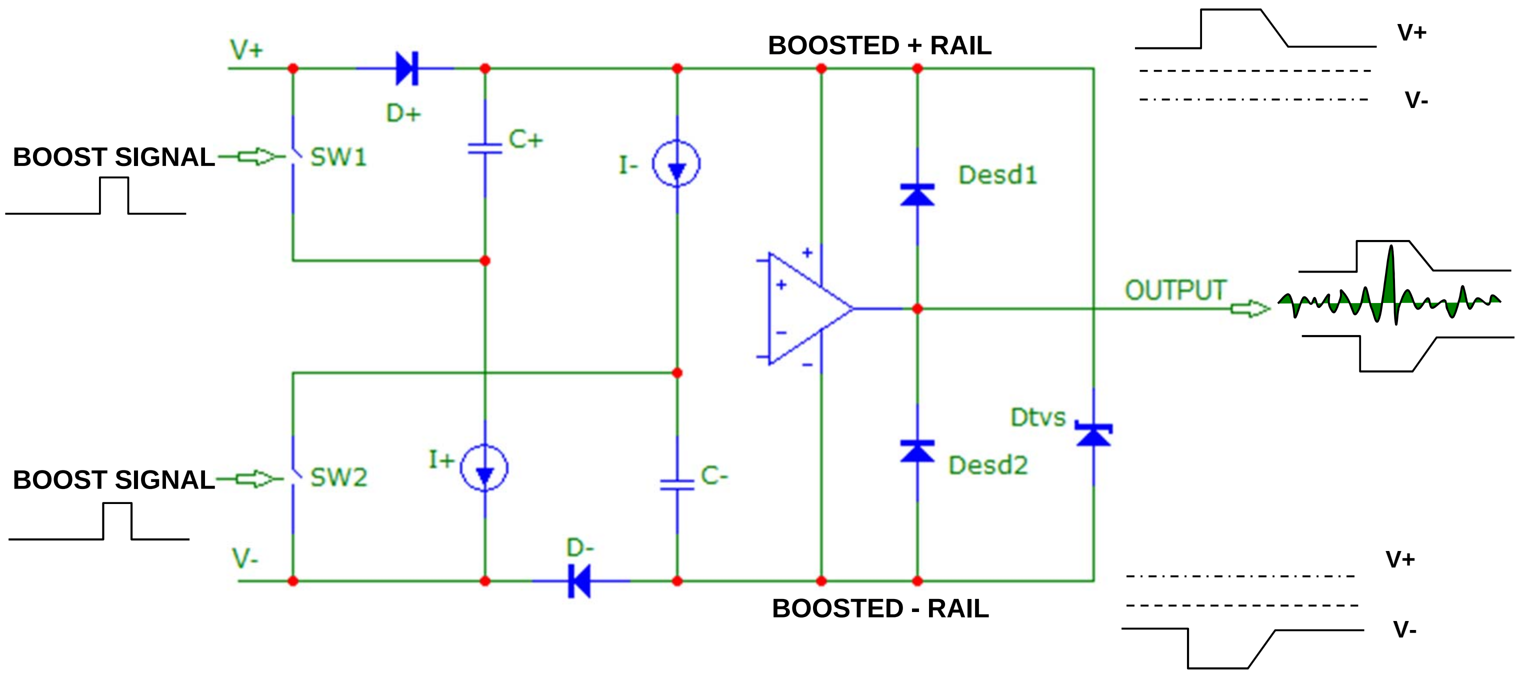
What about the other power saving development, Class H drivers?

Class A/B Drivers

- Older Class A/B drivers run directly from the supply rails
- Voltage must be high enough to handle signal peaks
- Typical VDSL signal wastes lots of power due to high peak to average ratio:



Class H Operation

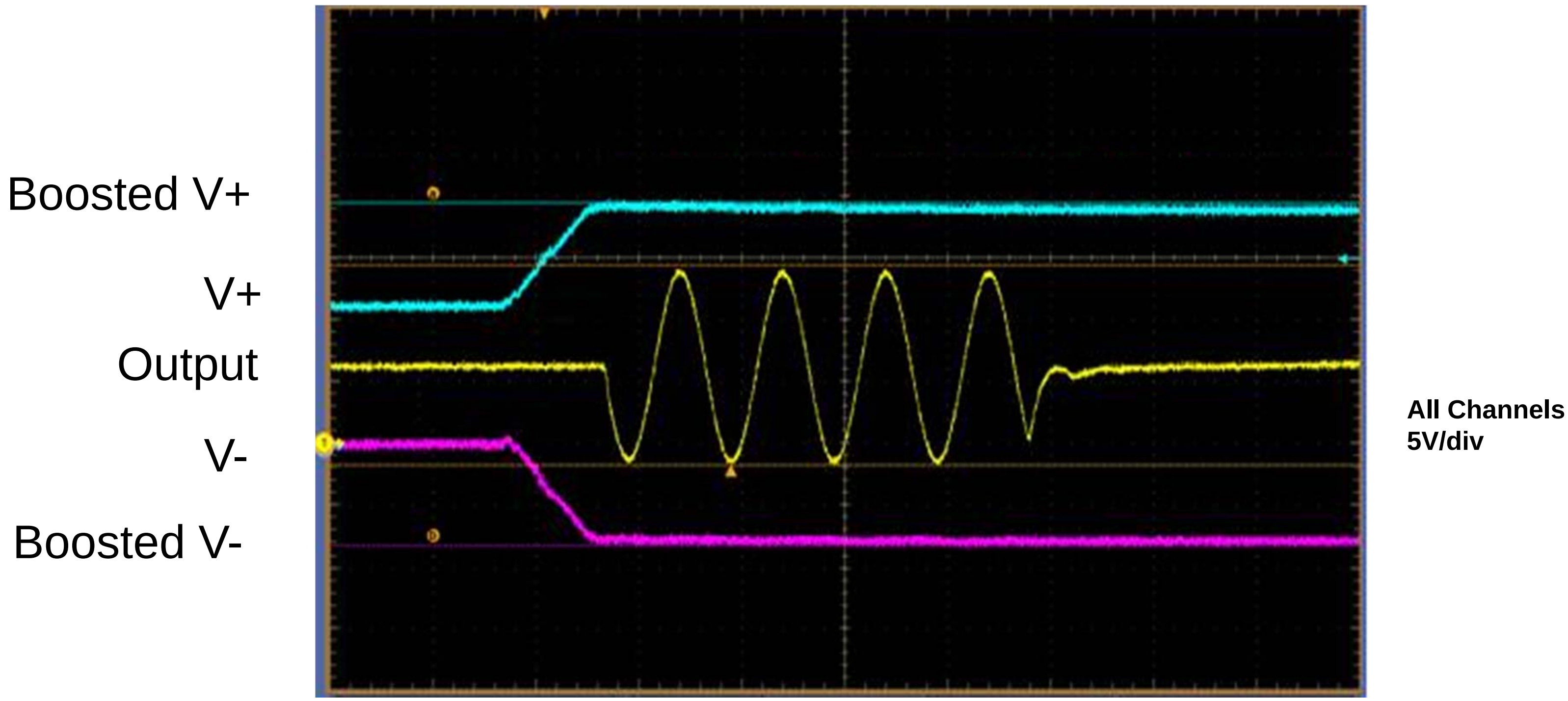


During Operation:

- **Capacitors C+ and C- charge to the supply rail voltage**
- **Boost signal turns on switches SW1, SW2 during short peaks**
- **Boosted rail gives temporary higher voltage for peaks**

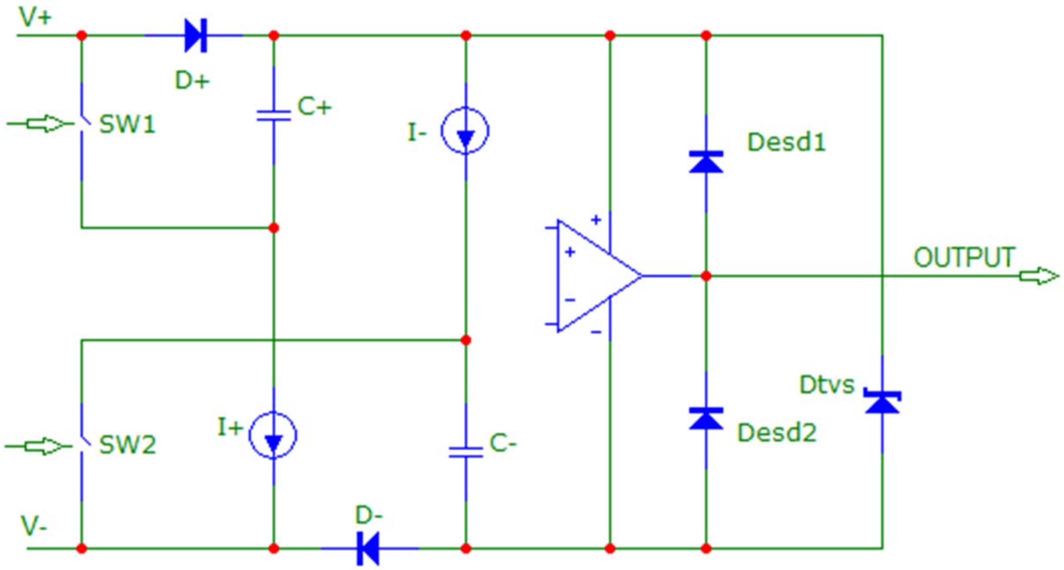
Class H Drivers

- **Combined with Active termination, these driver save a lot of power…**



VDSL CLASS H DRIVER IN OPERATION

Class H Under Surge



All surge energy must be dissipated, either internally or externally

- **Class H drivers have no direct supply rail to clamp to during surge**
- **Small internal ESD diodes and TVS provide very limited protection**
- **External surge protection must ensure very little energy is let through**

Driver's internal protection may be easily damaged if overdriven during high energy surge!

Active Termination significantly reduces power, but makes surge more difficult…

Class H drivers save even more power, but are even harder to protect…

So, what else… ????

AC Power Cross / Induction

- **When the GDT fires every half cycle, the result is like a lightning surge**

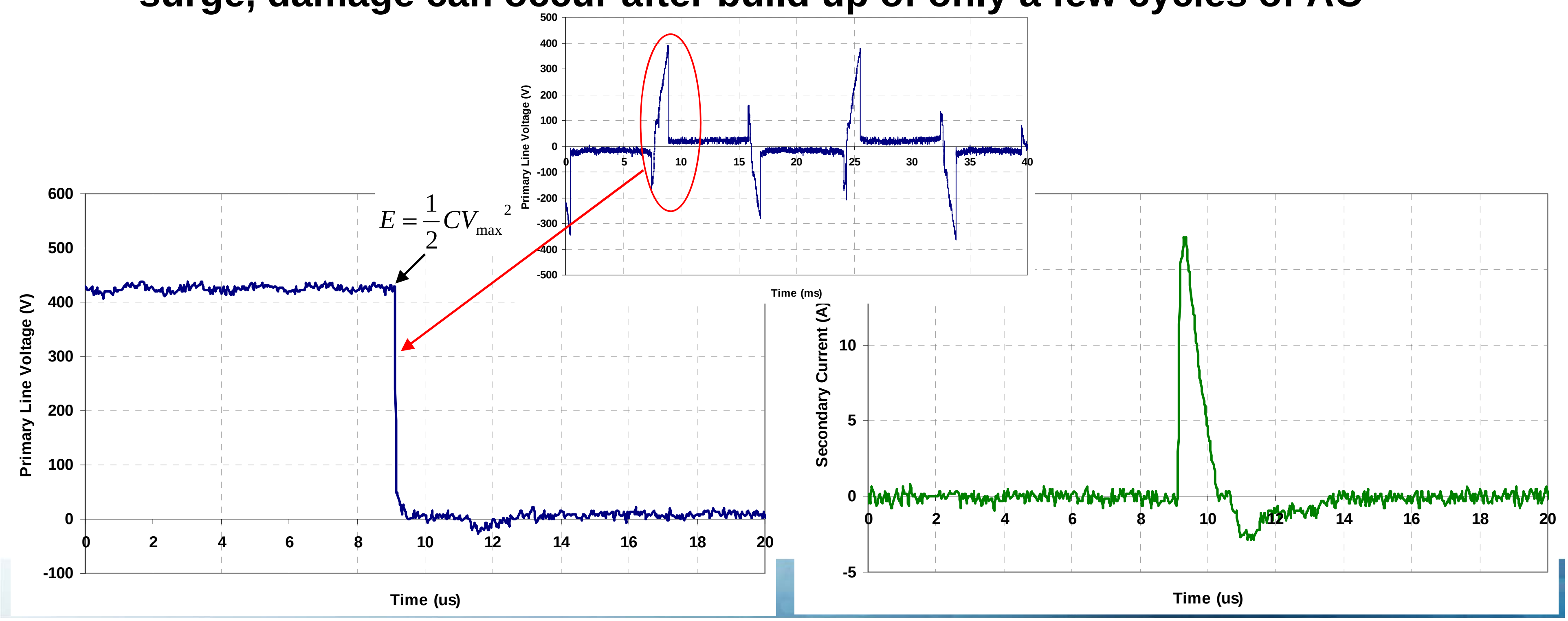
  1second AC = 100 lightning strikes in 50Hz Europe, 120 in 60Hz USA!

- **Each pulse of capacitor energy ($1/2CV^2$) increments the protection device temperature**

  eg: if each GDT impulse increments a junction by 1C, then

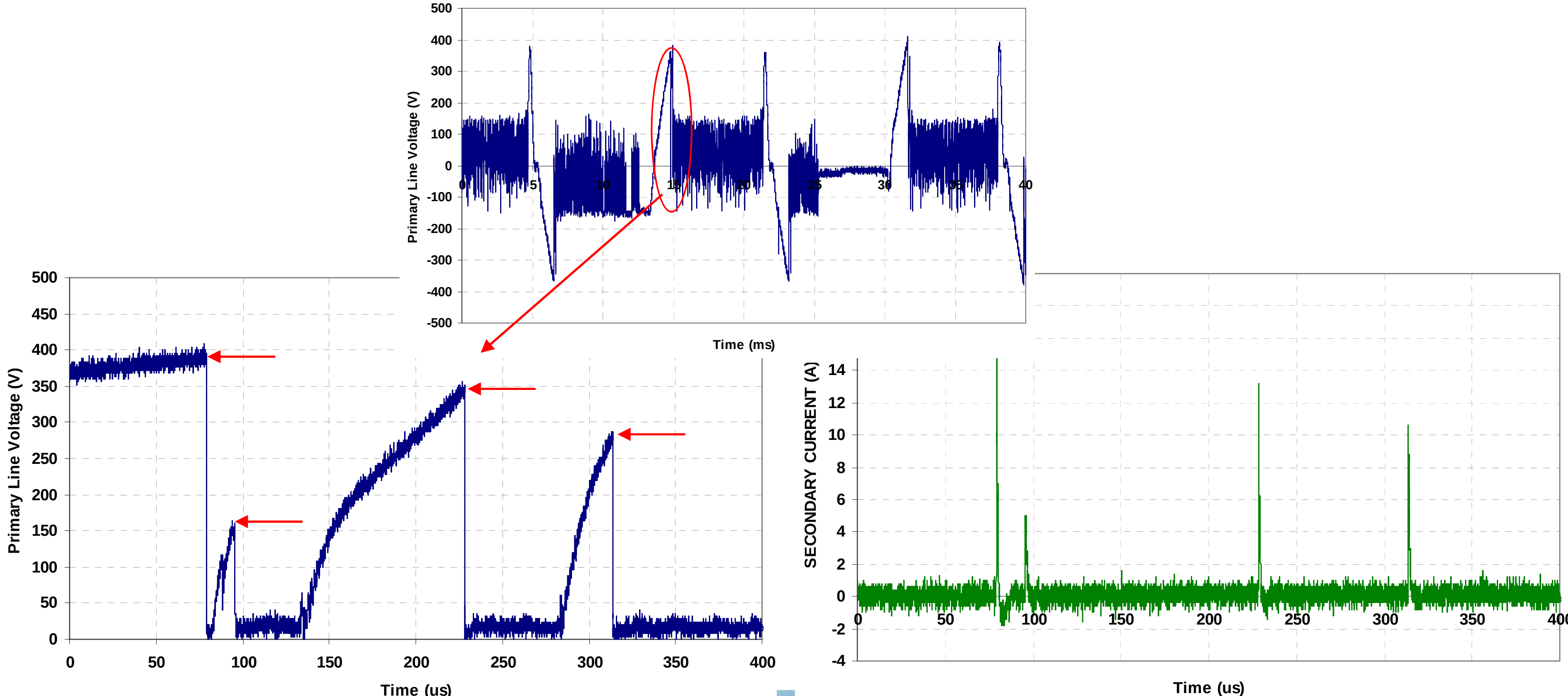
  1sec @ 60Hz AC $\Rightarrow$ ~120 C rise in T_j

Thus, even though peak voltages and currents are lower than lightning surge, damage can occur after build up of only a few cycles of AC



Zooming in on the Oscillating GDT

- **Fast GDT's can oscillate under AC, firing thousands of times/second**
- **Repetitive GDT firing greatly increases the transferred energy**
- **Large external TVS devices can dissipate the energy**
- **But small IC device temperatures can rapidly "staircase" to destruction with each $1/2CV^2$ energy dump**



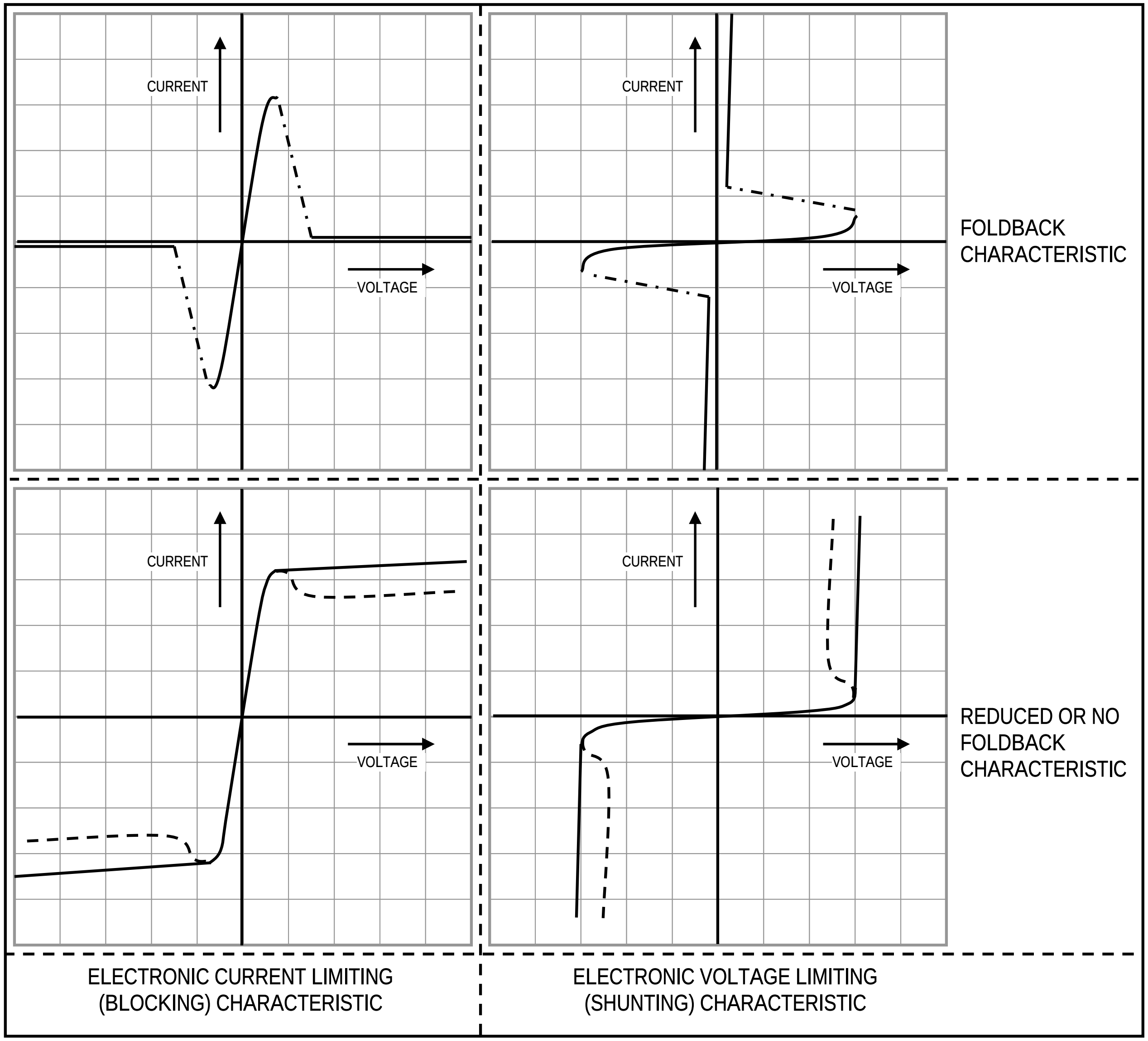
Eliminating the Driver / TVS Coordination Problem

- The issues we have seen require very close coordination between the Driver and the TVS voltage clamp

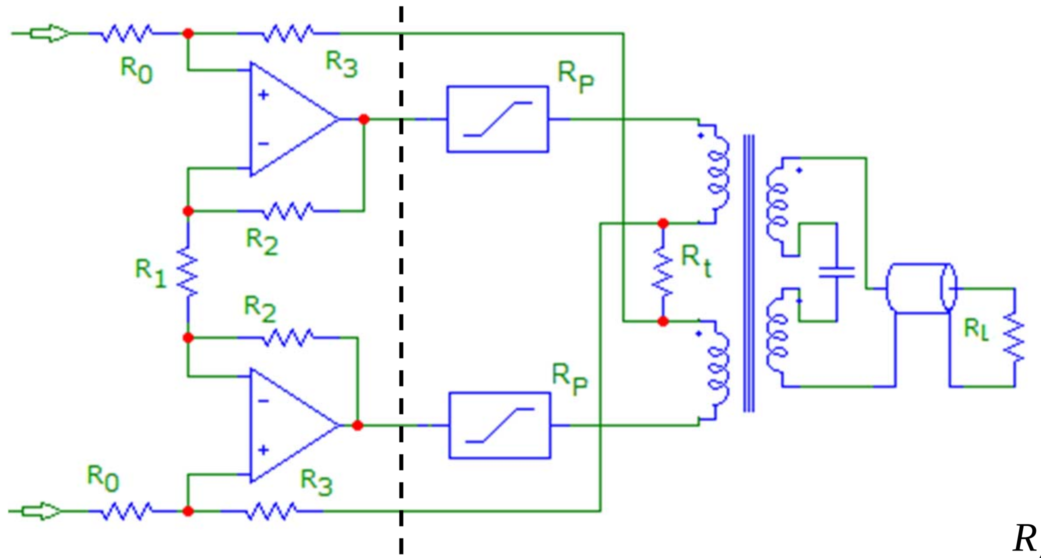
- Close coordination is critical in conventional solutions:
  - If TVS voltage is too low, signal distortion can occur impacting data error rate
  - If TVS voltage is too high, Driver stress occurs

Electronic Current Limiter (ECL) devices can be used to break the tight coordination requirements

Characteristics of Electronic Protection Devices



Typical Single Termination Configuration



$$R_A = \left\{ \frac{R_t * \left\{ 1 + \left\{ \frac{2 * R_2}{R_1} \right\} \right\}}{2 * \left\{ 1 + \left\{ \frac{R_3}{R_0} \right\} \right\}} \right\}$$

ECL resistance has very little impact:

$R_P << R_L, R_t, R_A$

- **R_A is not affected by R_t**
- **R_t can be adjusted to compensate gain & termination for additional ECL resistance**
- **Often ECL replaces 1ohm series stability/protection resistor in same location (R_P)**

Typical ECL Resistance tolerance is 3σ ~ +/-15%

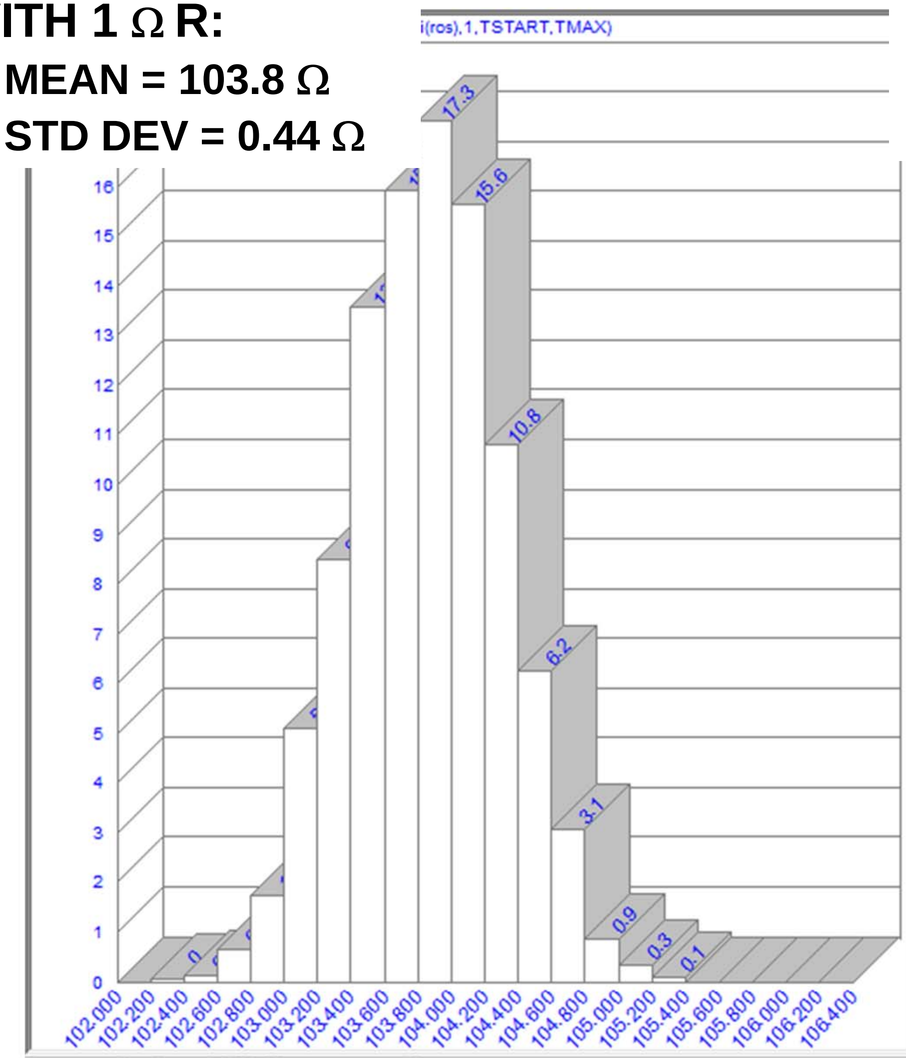
What is the impact on nominal line termination (100 Ω) and gain, and variation tolerance?

Comparing Line Termination Variation

WITH 1 Ω R:

MEAN = 103.8 Ω

STD DEV = 0.44 Ω

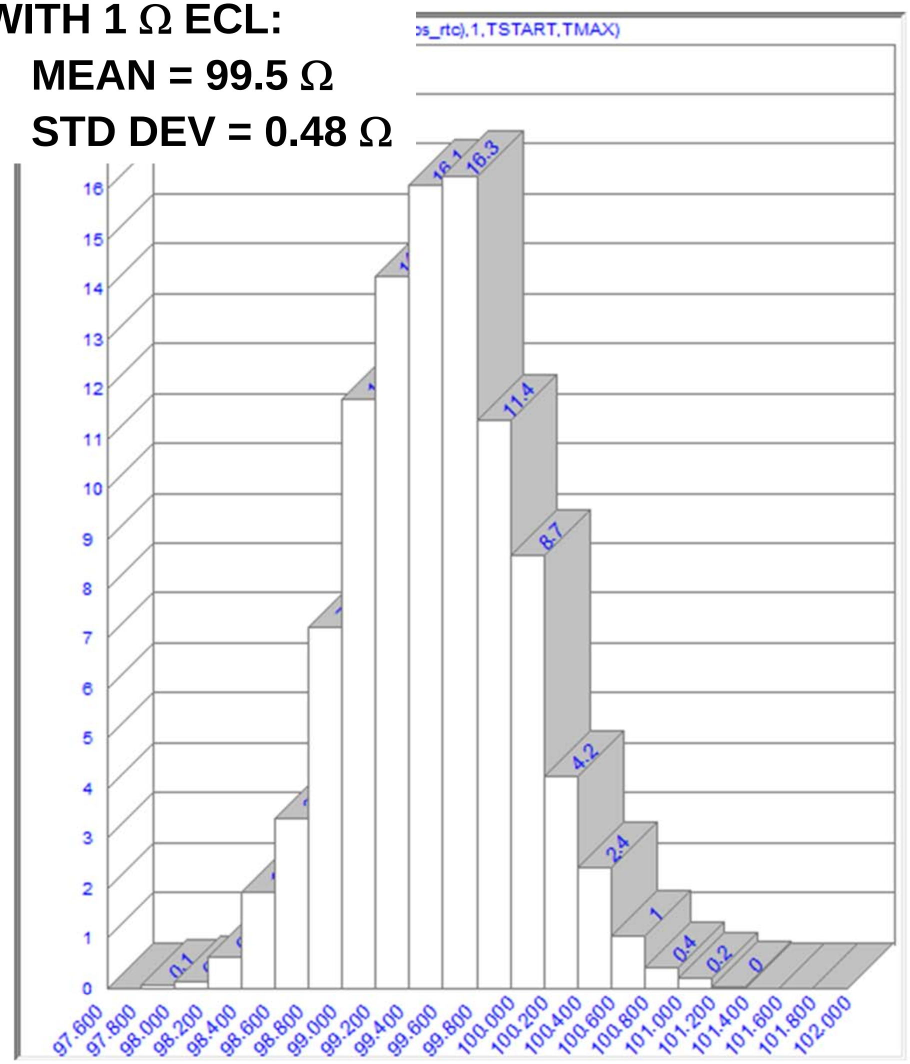


R_t= 10.2 Ω

WITH 1 Ω ECL:

MEAN = 99.5 Ω

STD DEV = 0.48 Ω



R_t= 9.76 Ω

1% External resistor variation

10% Absolute Driver internal resistance variation

0.5% Driver internal resistance matching

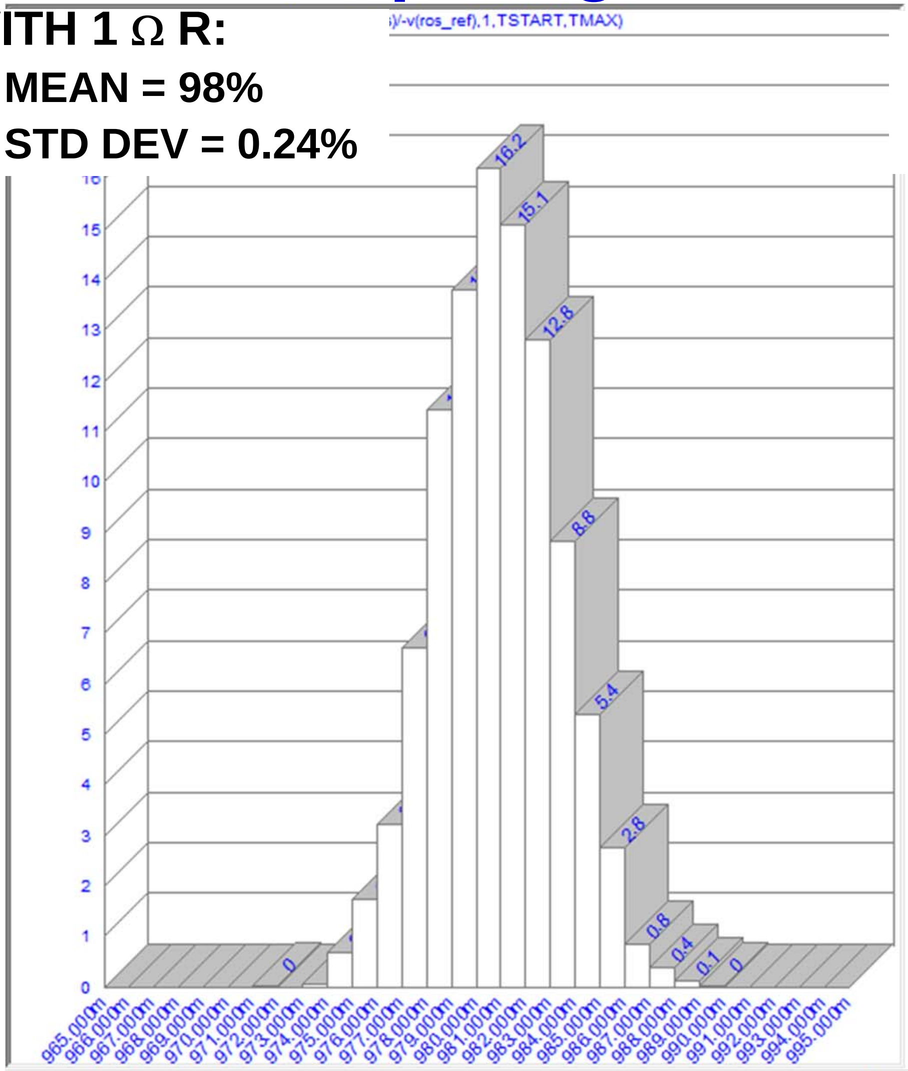
15% ECL Variation

Comparing Normalized Gain Variation

WITH 1 Ω R:

MEAN = 98%

STD DEV = 0.24%

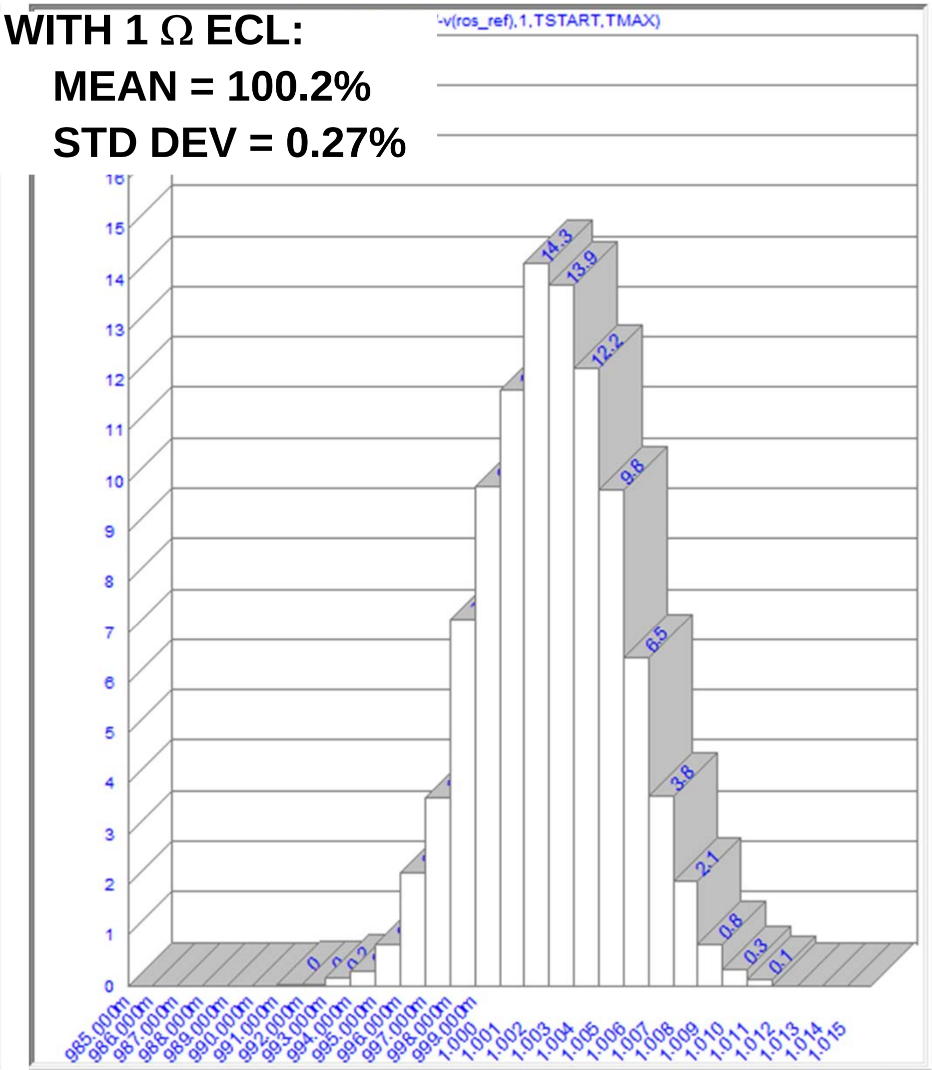


R_t= 10.2 Ω

WITH 1 Ω ECL:

MEAN = 100.2%

STD DEV = 0.27%



R_t= 9.76 Ω

1% External resistor variation

10% Absolute Driver internal resistance variation

0.5% Driver internal resistance matching

15% ECL Variation

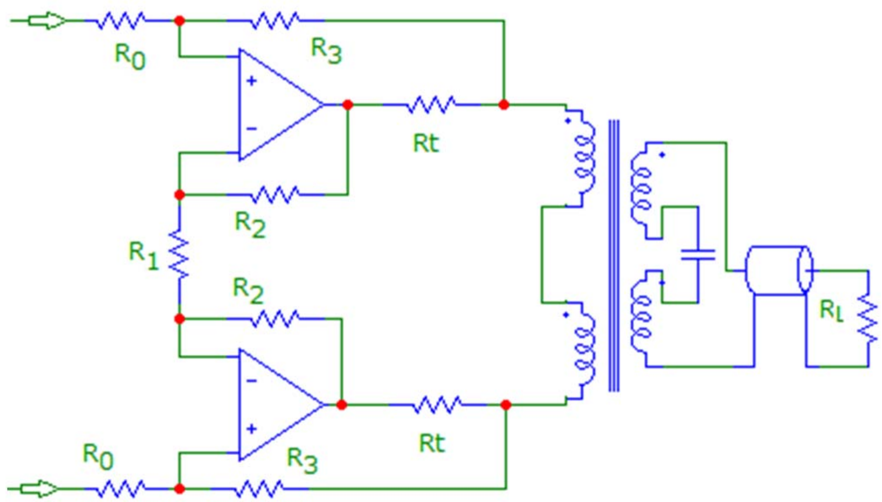
Higher Resistance ECL Devices

- **The analysis showed effect of ECL devices, using adjustment of R_t to center the termination and gain, compared to standard circuit**

EFFECT ON TERMINATION RESISTANCE	NONE	SMD 1% R	ECL 1	ECL 2	ECL 3
	0 Ω	1 Ω	1 Ω	1.4 Ω	2.3 Ω
TERMINATION RESISTANCE					
AVERAGE	**99.9 Ω**	103.8 Ω	99.5 Ω	98.9 Ω	100.2 Ω
σ	**0.44 Ω**	0.44 Ω	0.48 Ω	0.53 Ω	0.67 Ω

EFFECT ON GAIN	NONE	SMD 1% R	ECL 1	ECL 2	ECL 3
	0Ω	1 Ω	1 Ω	1.4 Ω	2.3 Ω
TERMINATION RESISTANCE					
AVERAGE	**100.0%**	98.1%	100.2%	100.5%	99.9%
σ	**0.25%**	0.24%	0.27%	0.30%	0.35%

Using ECL With Dual Termination

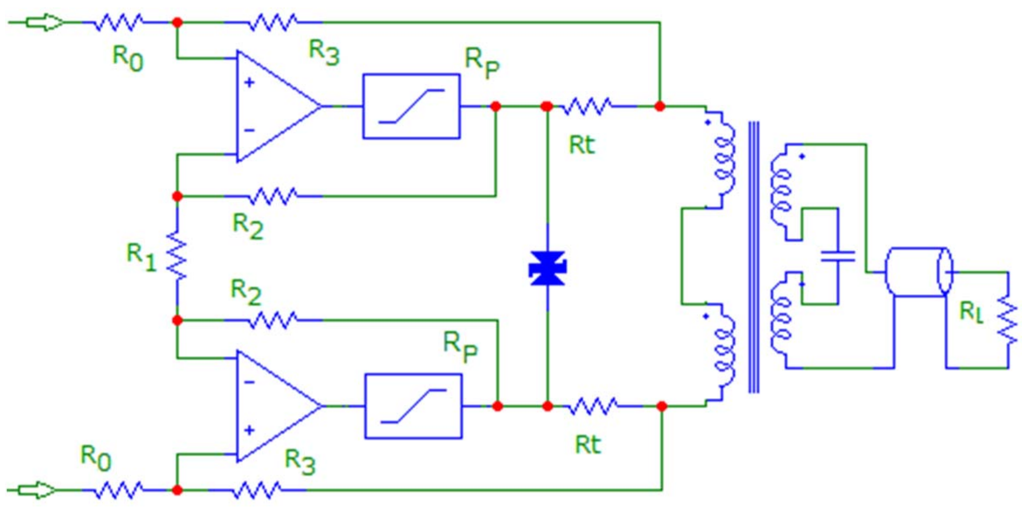


<u>The ECL device must NOT be used to replace R_t</u>

- **ECL tolerance will be multiplied by termination gain factor, as output resistance R_A is directly dependent upon R_t:**

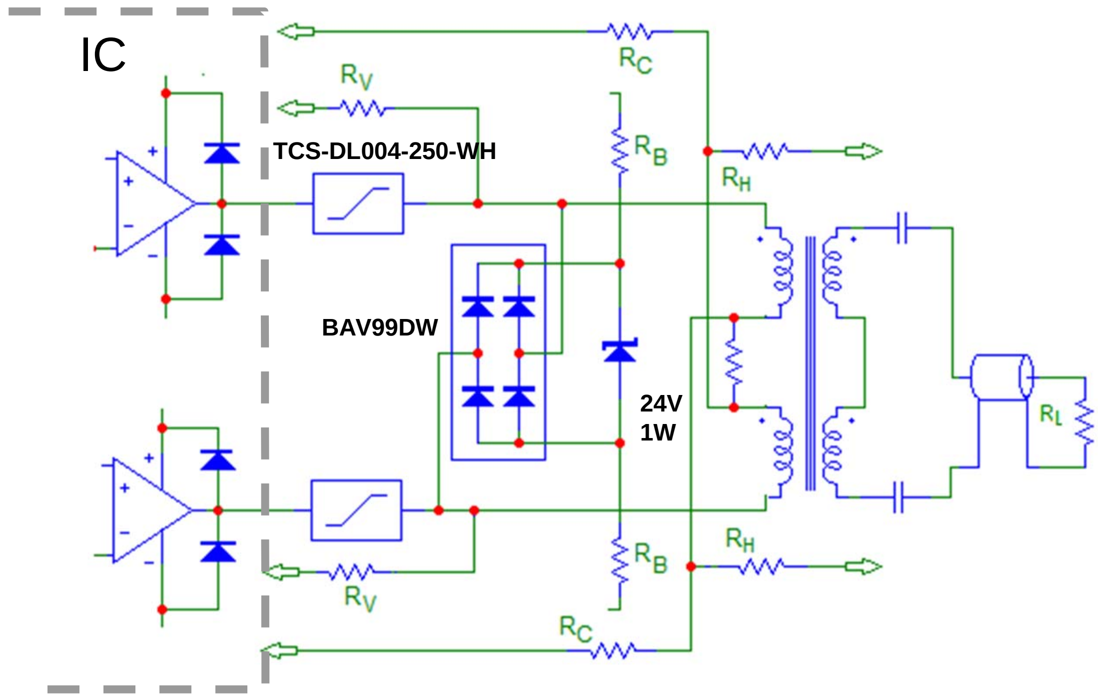
$$R_A = \frac{R_t * \left\{1 + \left\{\frac{2 * R_2}{R_1}\right\}\right\}}{\left\{\left\{\frac{R_3}{R_0}\right\} - \left\{\frac{2 * R_2}{R_1}\right\}\right\}}$$

Correct ECL Placement With Dual Termination



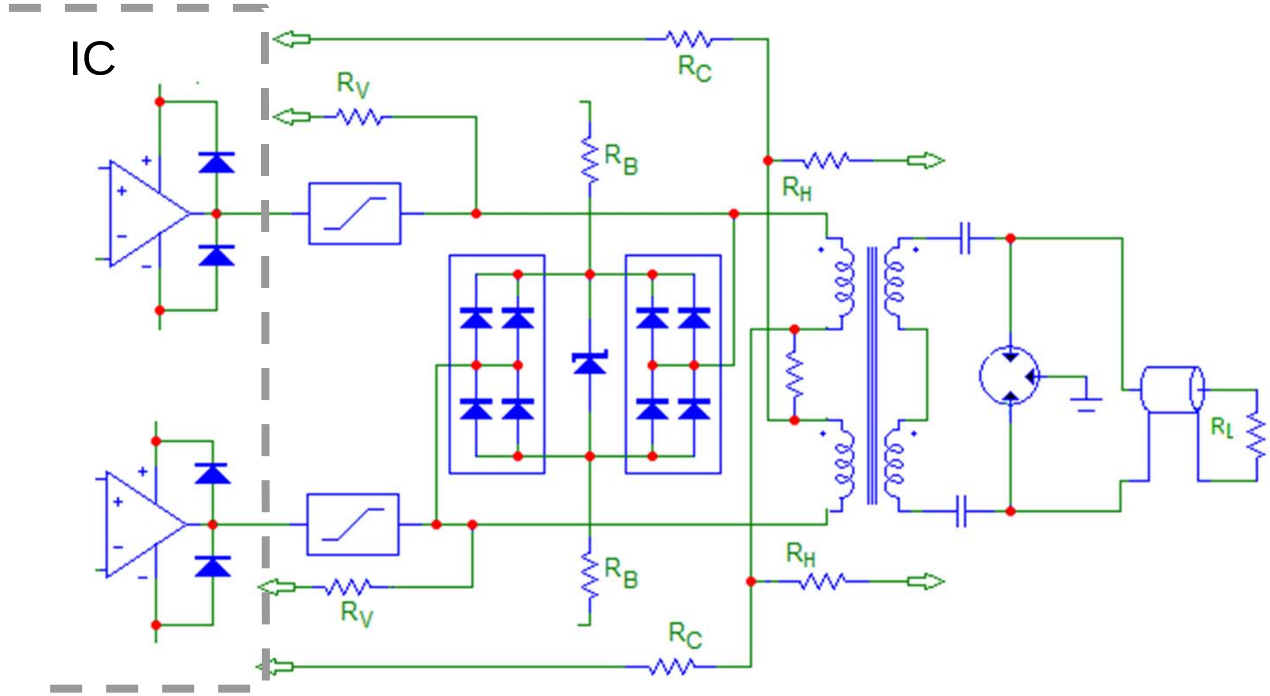
- The ECL device must be placed directly in series with the driver
- R_t provides current limiting into TVS
- Very similar results are obtained for gain and termination analysis (~0.5% termination, ~0.3% gain)

Example: 'Oscillating GDT–Proof' ITU-T Protection



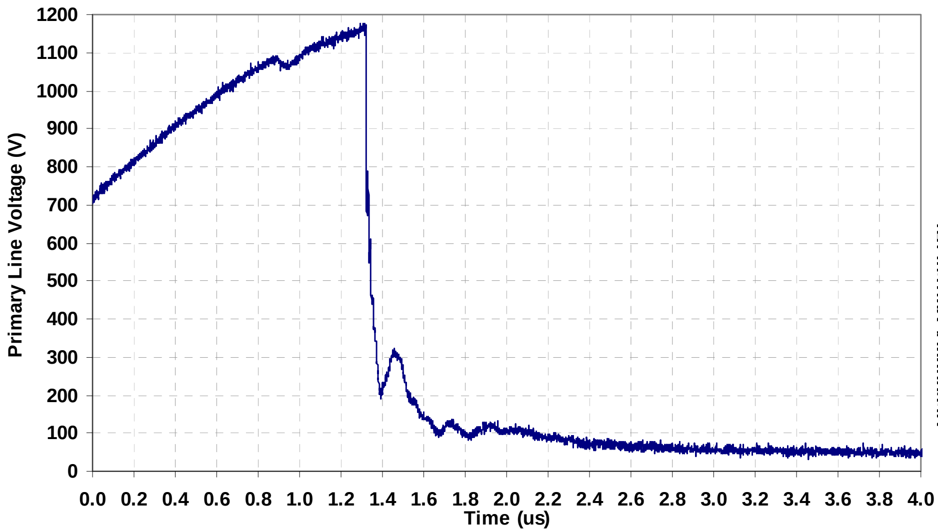
- **Single low cost (~$0.03) generic quad BAV99DW array used**
- **P-P Voltage across clamp is not critical, must stay below ~100V**
  - **Far higher than driver can withstand without ECL (typically ~30V)**
- **Energy safely dissipated in generic low cost 1W 24V external Zener diode (~$0.03)**
- **ECL device limits current to below ~2A**

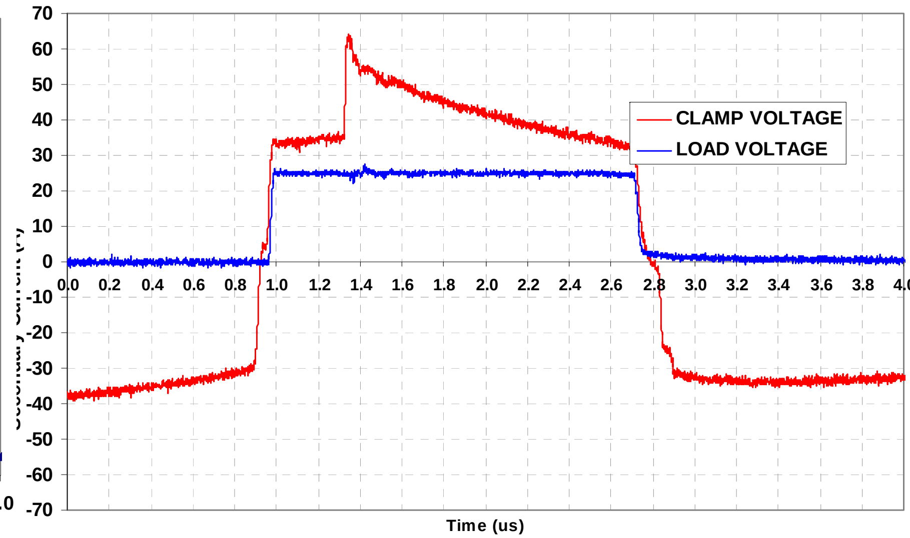
Example: Fully Resettable Level 1/3/5 GR1089



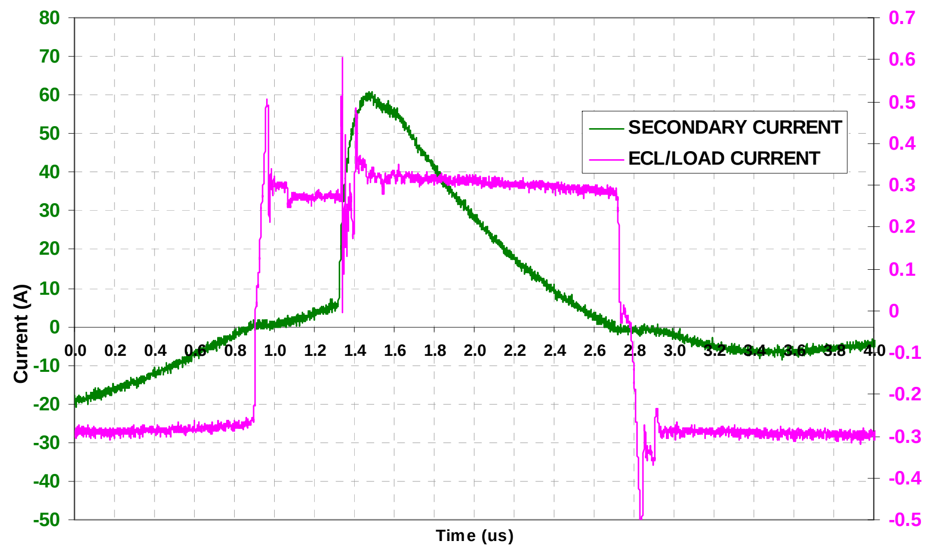
- **800V GDT does not fire under 425VAC power cross**
  - ***<u>no fuses required to pass 425VAC / 40A test</u>***
- **GDT fires ~1.3kV under surge, giving higher clamp current**
- **Two low cost quad BAV99DW arrays used to clamp voltage to a 1W 24V generic Zener diode, to maintain clamp voltage <~100V**
- **Eliminates costly GDT, fuses etc**

Fully Resettable Level 1/3/5 GR1089 Performance

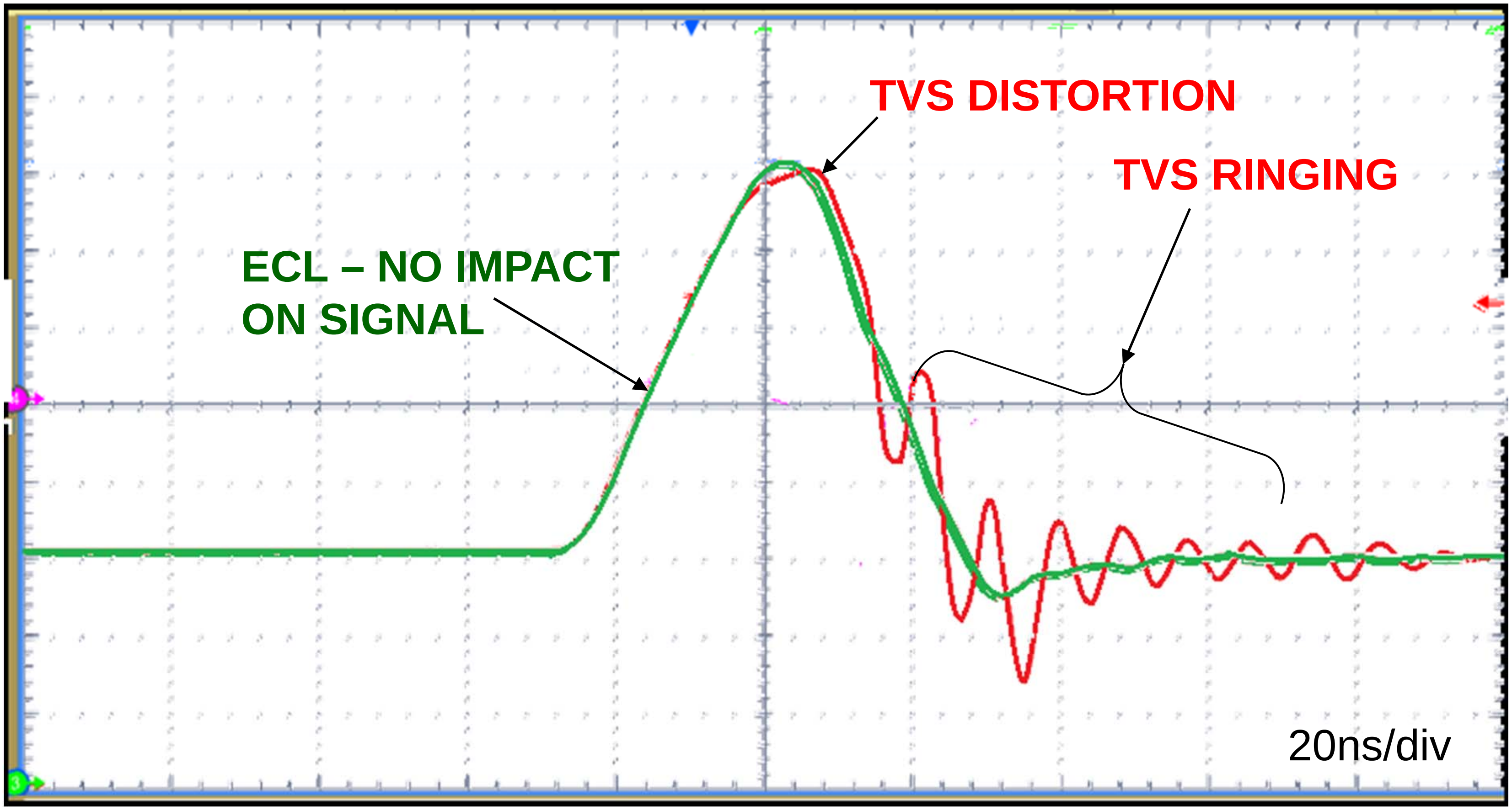




- **GDT fires at ~1200V**
- **Secondary current ~ 60A**
- **Peak clamp voltage ~63V**
- **375mA nominal ECL maintains Driver current below 600mA**



ECL Single Signal Peak Response



- **RED: Single peak pulse at output is distorted by typical large biased TVS clamp circuit**
- **GREEN: Single peak pulse is virtually unaffected by ECL circuit and biased clamp**

- **Signal distortion can cause VDSL2 amplifier to ring**
- **Signal distortion and ringing causes Bit Errors in VDSL data transmission**

Summary

- Today's VDSL2 designs seek lower power, higher performance
- Conventional TVS protection struggles to achieve coordination
- Real world may present repetitive firing GDT's that further stress conventional surge protection
- ECL based protection can provide higher protection performance, without the impact of large TVS's on data bit error rates
- Fuses, failsafe GDT's can be eliminated from GR1089 designs to provide fully resettable design passing level 1/3/5

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NO DRIVERS WERE HARMED DURING THE MAKING OF THIS PRESENTATION