Choking the Life out of Surge

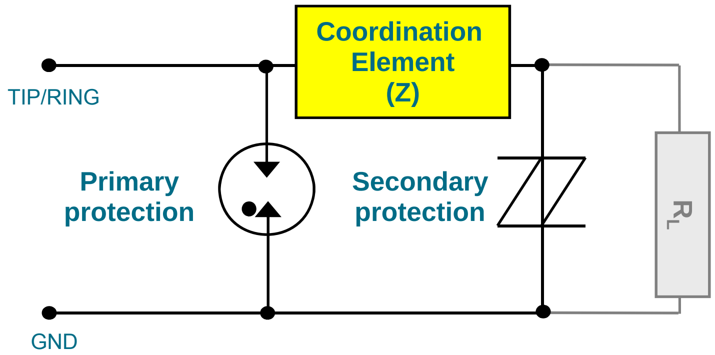
A Practical Approach To Coordination

Part 3

BY: TIM ARDLEY
COMPLIANCE ENGINEER

ATIS-PEG-2013

Types of Coordination Elements

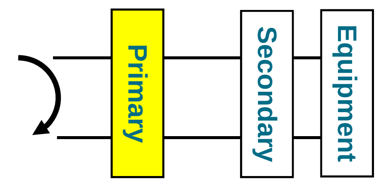


- Cable.
- Capacitor.
- Ceramic Line Feed Resistor.
- **Common Mode Choke.**
- Electronic Current Limiter.
- Fuse.
- Inductor.
- Polymer & Ceramic PTC thermistor.

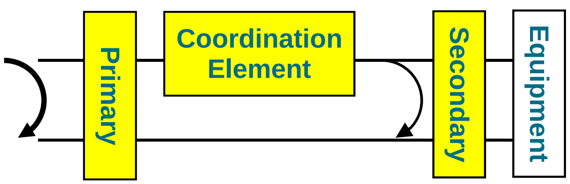
The coordination elements highlighted in grey were covered in PEG-2011 & PEG-2012 presentations

Types of Coordination

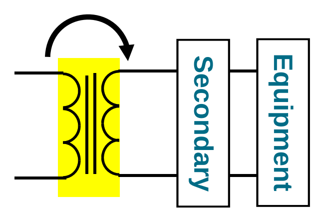
- Voltage-type coordination
  - *Primary operates before the secondary*.

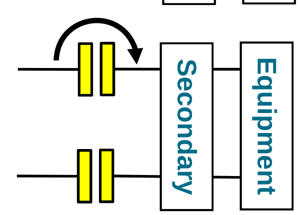


- Current-type coordination
  - *Secondary* operates *before* the primary.
  - Most common method for coordination.



- System coordination
  - No failures occur up to a pre-defined fault criteria.
  - Primary protector may or may not operate.
- Insulation coordination
  - No failures occur up to a pre-defined voltage criteria,
    - Combination of VOLTAGE/SYSTEM type coordination.
    - Relying on an isolation barrier.



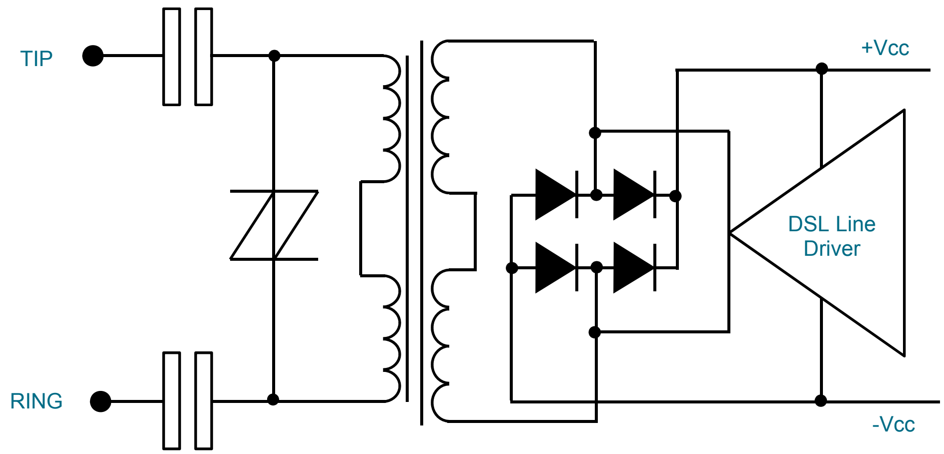


Introduction

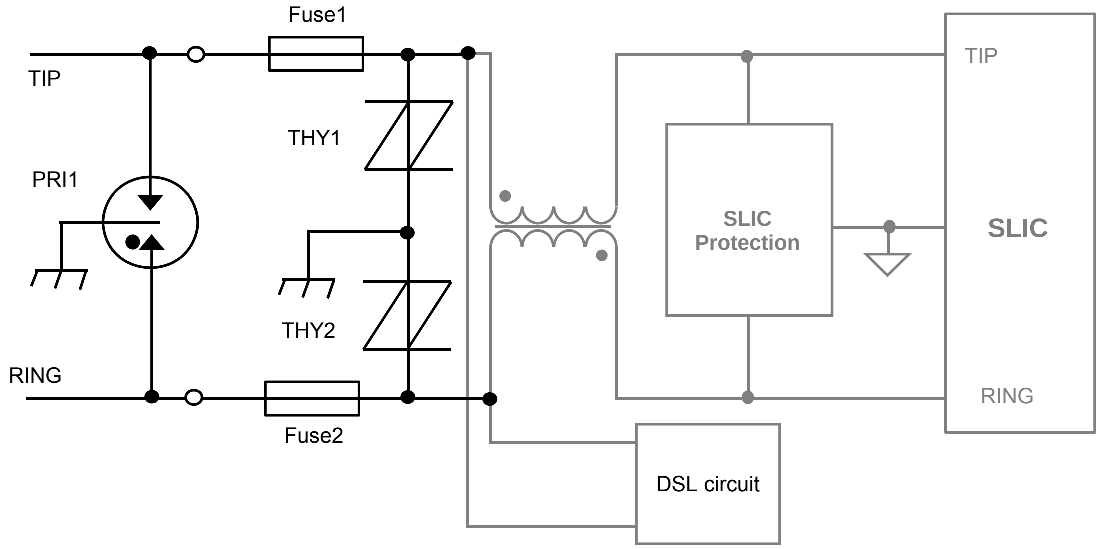
- Field returns were seeing damage to POTS ports on the combo (DSL+VOICE) interfaces.
- Field return numbers were not high enough to trigger an investigation for a re-design.
- A new VDSL2 combo interface was in the pipeline.
  - VDSL2 protection topology required a redesign allowing the POTS ports to also be addressed.
    - Meet required data rates vs line reach on next generation VDSL2.
    - Design to be cheaper.
    - Design to have “Zero” field returns.
    - Products can also have integrated primary protection.

VDSL2 Design

- VDSL2 interface was designed to use Insulation coordination.
  - Capacitor coupling technique was used.
    - This coordination technique was covered in PEG-2012 presentation.
  - Significantly simplified secondary protection.
    - Low capacitance and cost over voltage protection was only needed to protect the line driver.
    - Have been unable to get a VDSL2 port to fail in the lab.
    - Passes 6 kV 1.2/50 metallic surges WITHOUT a primary protector!
  - Various platforms are now being deployed with this topology.

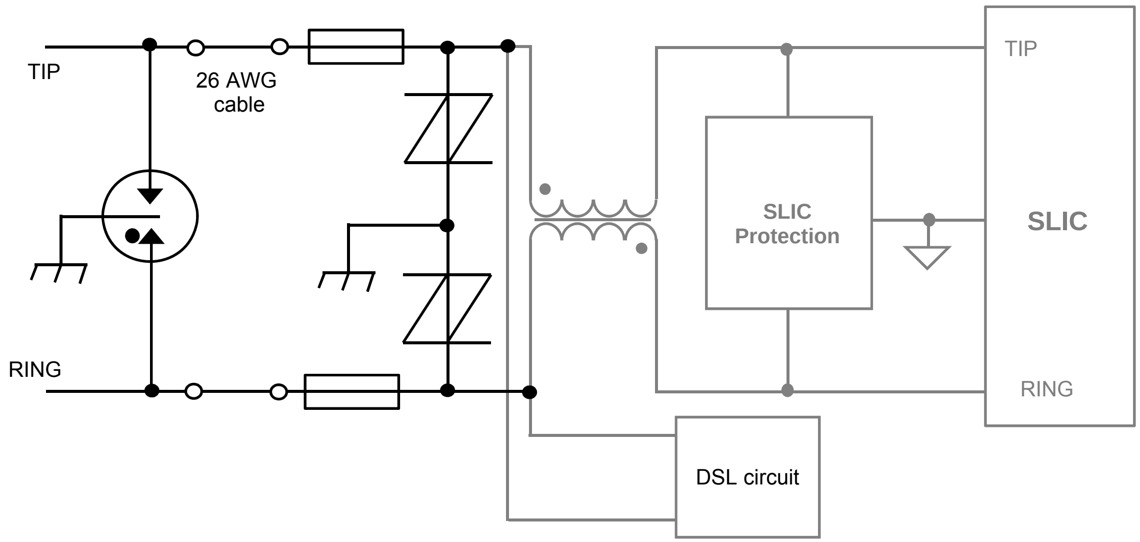


Current Solution Observations



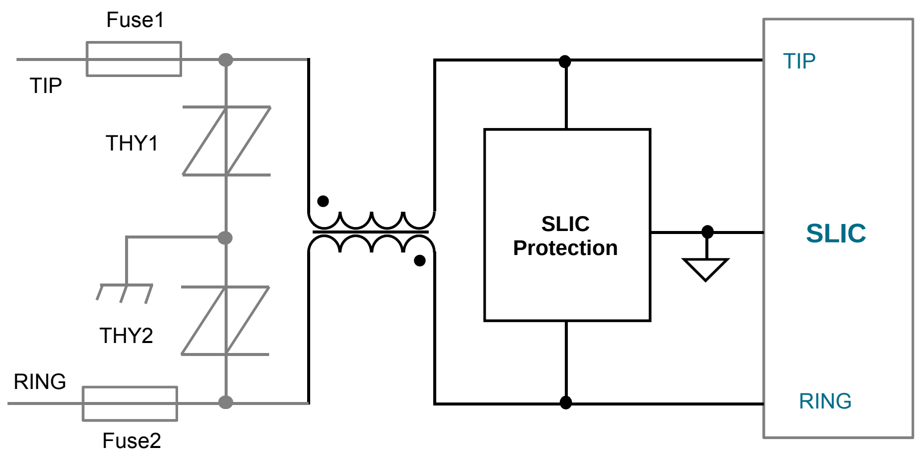
- 5-pin GDT primary protector in the product.
- Uses current-type coordination.
  - 1.25 A telecom fuses.
  - 100 A 10/1000 fixed voltage thyristors.
    - Thyristor breakover voltage rating of 280 V.
    - Uses bias voltage circuit (not shown) to reduce thyristor capacitance.

Current Solution Observations



- The product has a short cable between the 5pin receptacle and PCB.
  - 2011 presentation highlighted minimum of 20 ft for coordination where 100 ft (30 meters) is ideal.
  - Fuses don't provide any measurable impedance to surge.

Current POTS Solution Observations



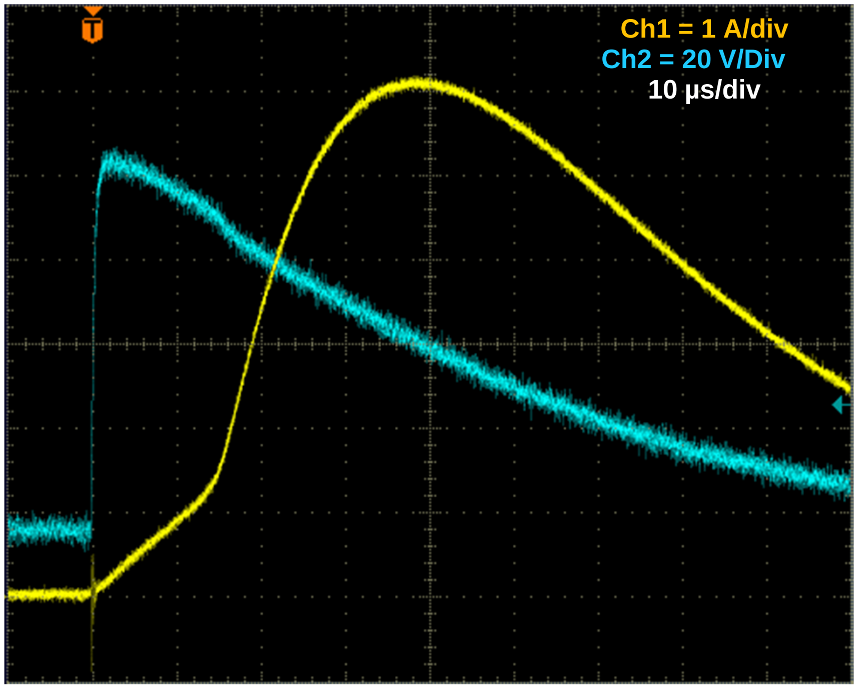
- Choke provides the coordination element.
  - DC resistance of Choke is 1.9 Ω.
  - Choke also looked to be wired incorrectly.
- 30 A 10/1000 battery tracking SLIC protection.
  - 280 V, 100 A fixed voltage thyrisor needs a minimum impedance of 9 Ω.

$$\left(\frac{280V}{30A} = 9.3\Omega\right)$$

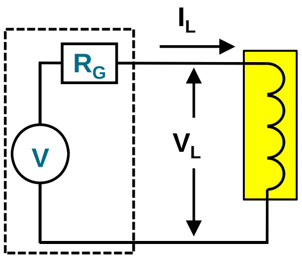
How did it pass GR-1089-CORE issue 5 testing?

From last years presentation on Inductors

- Don't normally recommend Inductors for coordination elements.
  - Maximum current when the inductor saturates.
    - Once saturated, current is only limited by its DC Resistance and generator resistance.
    - Places additional stress on the over-voltage protection.
    - The stored energy in the inductor is also discharged into over-voltage protection.

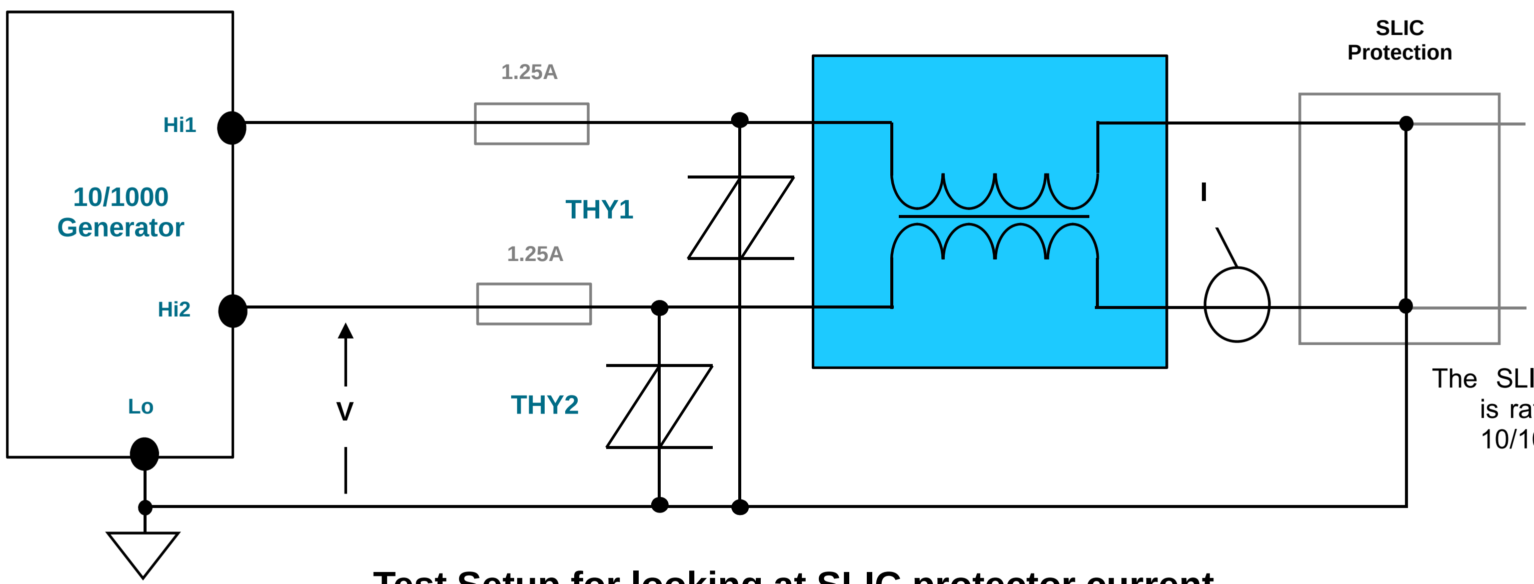


VGEN = 100 V
1.2/50-8/20 combination generator.



Solution MUST rely on the choke not saturating.

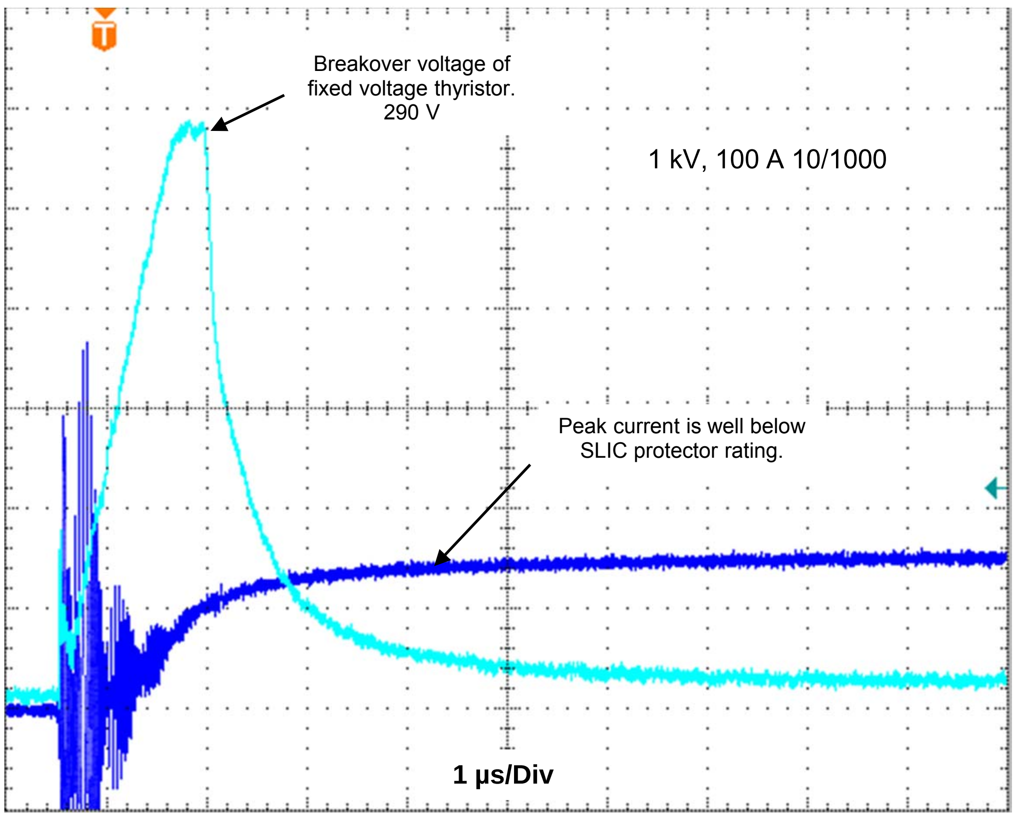
What is the SLIC Protector Current?



The SLIC protector is rated for 30 A 10/1000.

Test Setup for looking at SLIC protector current

Protector + Choke Measurement

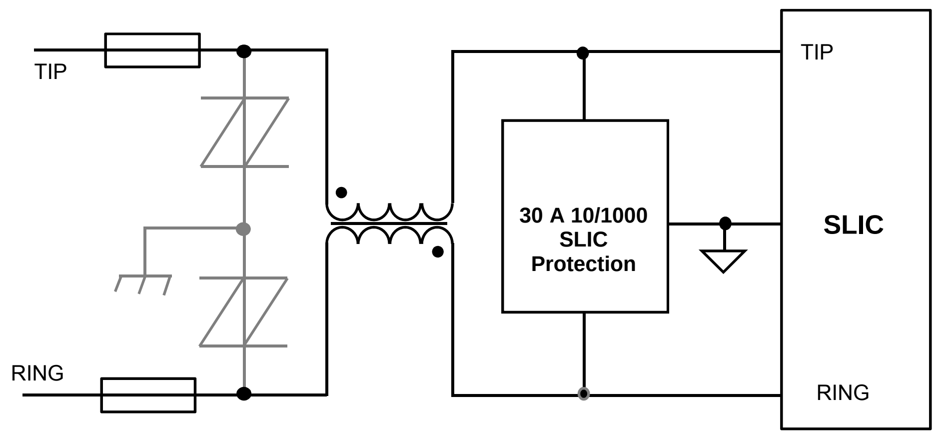


Ch1 = Current 2A/div
Ch2 = Voltage 50V/div

- The choke didn't saturate during the surge before the fixed voltage thyristor breakover voltage was achieved.
- The current in the SLIC protector is determined by the thryistor on-state voltage + DC resistance of choke.
- Solution will easily pass GR-1089-CORE, issue 5/6 1 kV 10/1000.
  - The SLIC protector is just seeing 3 A!

Why field failures?

Where is the Stress Point?



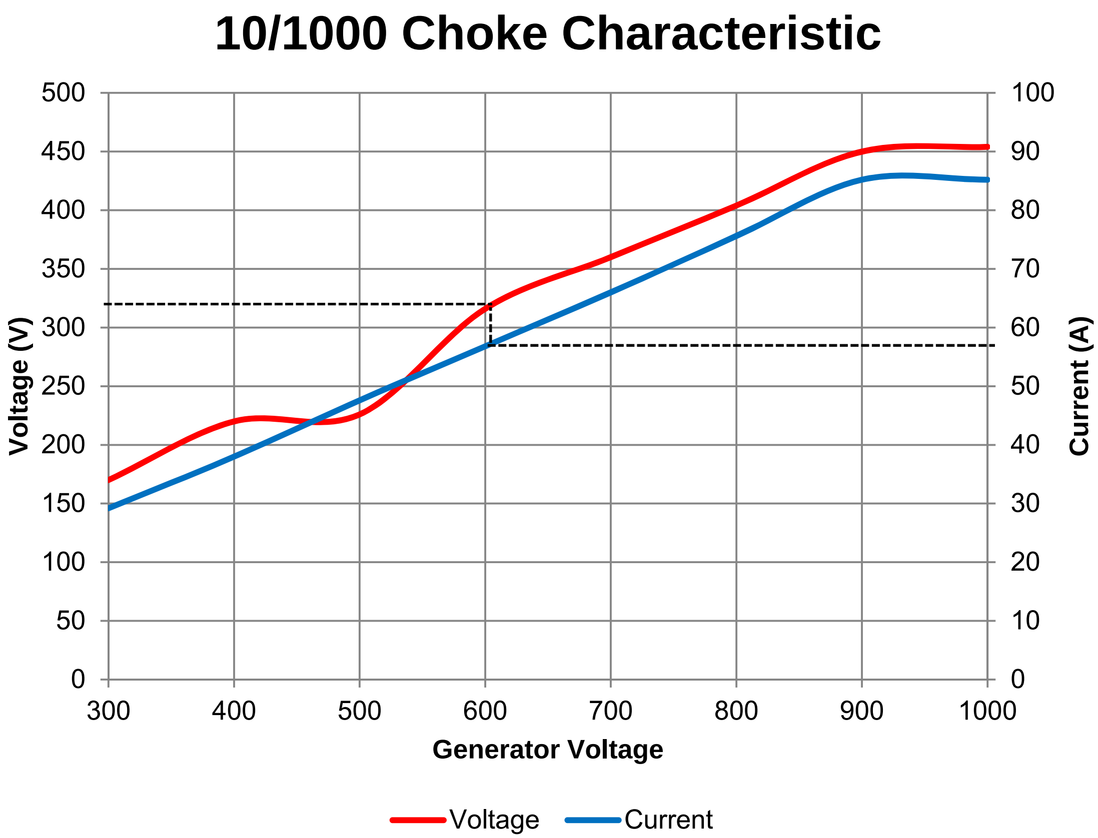
Consider the stress BEFORE the over-voltage protection operates.

A simple concept but there have been “circuit protection experts” that have missed this one!

Choke Surge Characteristic

V_{GEN} (V)	V_{MAX} (V)	I_{MAX} (A)
300	170	**29.2**
400	220	38
500	**226 (276)**	47.6
600	**316**	**56.8**
700	360	66
800	404	75.6
900	450	85.2
1000	454	85.2

- With V_{MAX} of 170 V, the fixed voltage thyristors have not operated.
- At V_{MAX} of 170 V, the SLIC protector surge current rating has been reached!
- Thyristor breakover voltage is expected to be max 322 V. The SLIC protector current rating has been exceeded by 1.9x where failure will be permanent short.

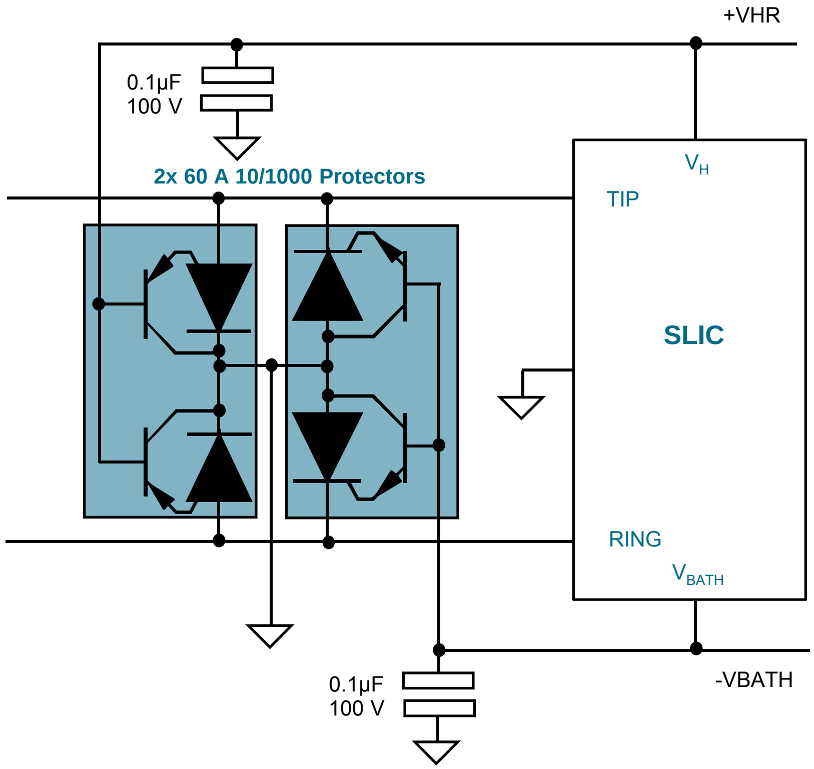


Current Solution Summary

- The current solution will pass the 1 kV, 100 A 10/1000 test.
- But……
  - There is a small hole in the protection scheme before the fixed voltage thyristors operate.
    - There is a difference between <u>typical system test</u> and <u>worst case DESIGN</u>.
  - How to Fix it?
    - Increase the SLIC current protection rating.

    or
    - Change the common mode choke.
      - Increase the DC resistance to reduce the peak current let-through.

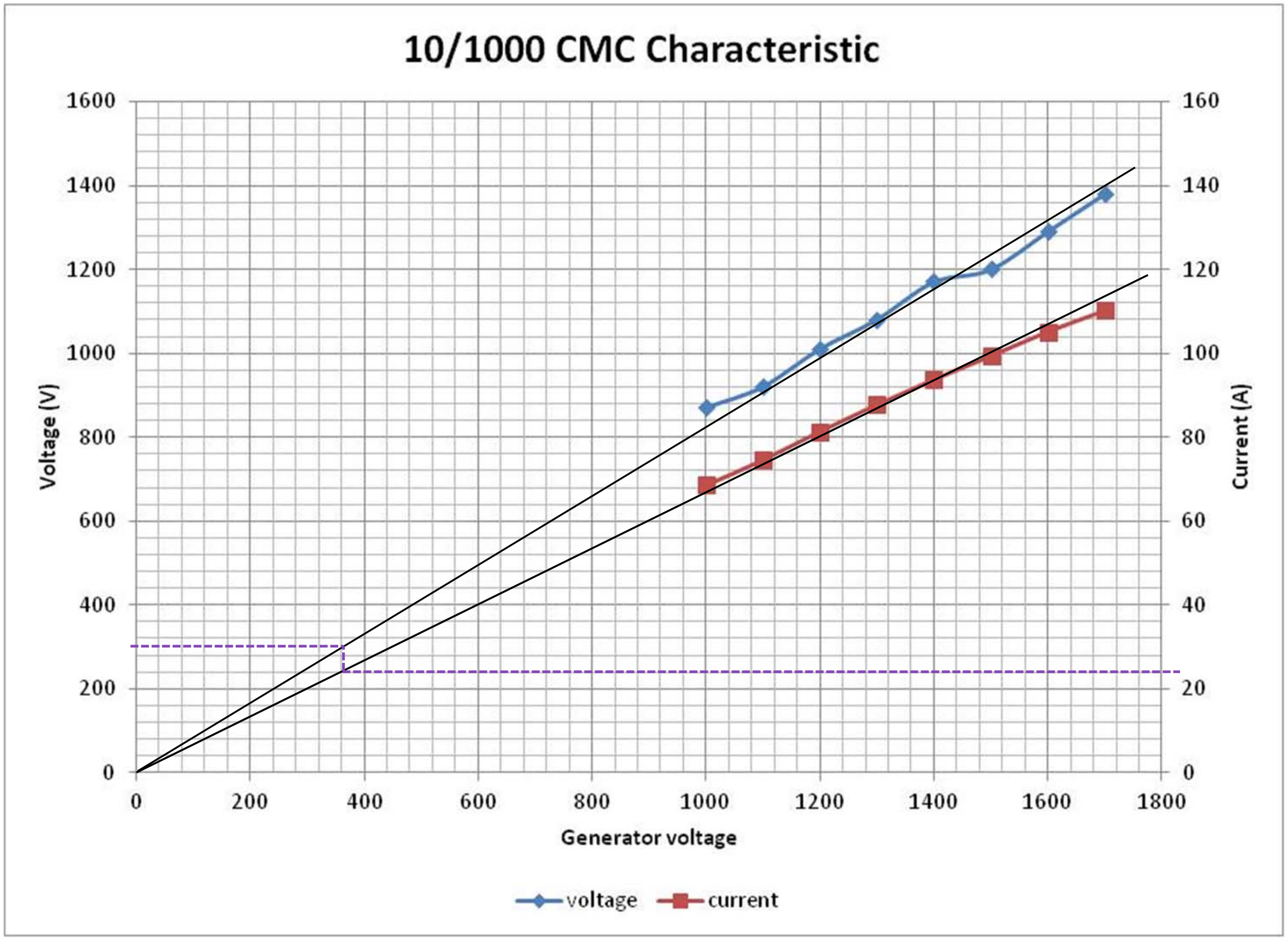
Recommendations for the existing Line Card



- Upgrade the SLIC protection.
  - Minimum of 60 A 10/1000 protectors are required.
    - 2 device option found.
  - Stumbling blocks
    - Redesign of the board is needed rather than a component upgrade.
      - Two devices are now needed.
        - » Manufacturer can't provide a single 60 A 10/1000 option in a wide body SOIC-8 package.
        - » Increased real estate is needed.
        - » SLIC protector will become sole sourced.

Design was therefore reluctant to change the current design to this option.

New (larger) Choke Option



- Choke characteristics:-
  - 2.26 mH and DCR of 5.5 Ω.
- Extrapolated testing on transformer shows that when V_{MAX} is at 300 V, the typical current will be 24 A.
  - The 30 A SLIC protector is protected.
- There is a second source option for SLIC protector and this choke.
- Height and size limits on existing card.

Design will stay with current solution.

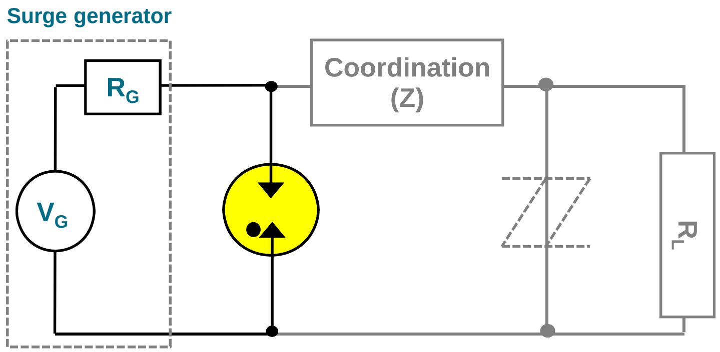
Next Generation POTS Interface Design

Requirements

- No fixed voltage thyristors due to VDSL2.
  - Variation of capacitance vs voltage hurts data rates.
    - Bias voltage thryristors also proved to be problematic.
    - 3-phase bridge diode network consumed too much real estate.
- Coordination with the Primary Protector.
    - Ideally want to achieve 1000 V (impulse) at equipment terminals.
  - Primary protector becomes the ONLY over voltage protector in the front-end interface.

Design will rely on the choke being the primary coordination element.

Primary Protector Operating Voltage



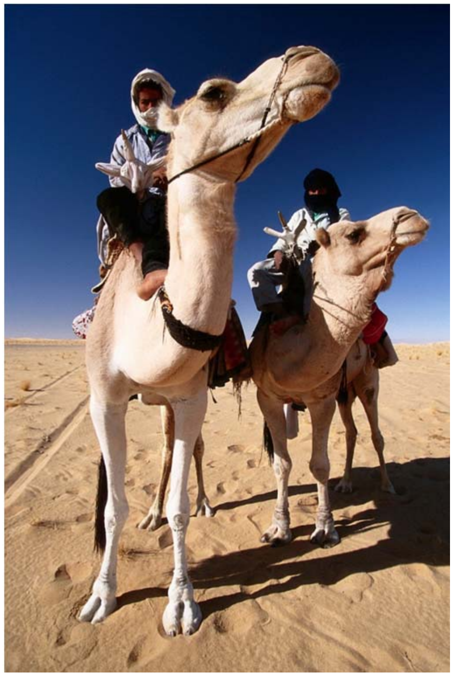
- Specified in GR-974-CORE.
  - 1000 V for high voltage limiting.
    - Gas Discharge Tube (GDT).
    - DSLAM units also has SPAN power capability.
  - 600 V for medium voltage limiting.
    - Gas Discharge Tube + Voltage Clamp (Hybrid).
  - 400 V for low voltage limiting.
    - Solid State (thyristor).
  - 425 V RMS for AC.
    - For all types of primary protector.
- Maximum 1000 V/µs impulse sparkover rating for discrete GDT's.
  - This is a good rule of thumb where 350 V DC breakdown versions are recommended that have 850 V @ 1000 V/µs impulse rating.

GR-1089-CORE Standards

- GR-1089-CORE, Issue 6
  - Standard Test Procedure.
    - 10/1000 generator voltage is increased in increments until:
      - Current into the port exceeds 95 A or
      - Voltage at the port exceeds 950 V.
  - Alternative Test Procedure
    - Show that interface will generate >95A or >950V with 10/1000 generator set to 1 kV.
    - Surge ±25 times at V_{GEN} set to 1 kV.

Finding Subject Material

POT + combo interfaces have been around for a long time…...



but found that there was no basic understanding of GR-1089-CORE and its test procedures and how to meet them in the magnetics community.

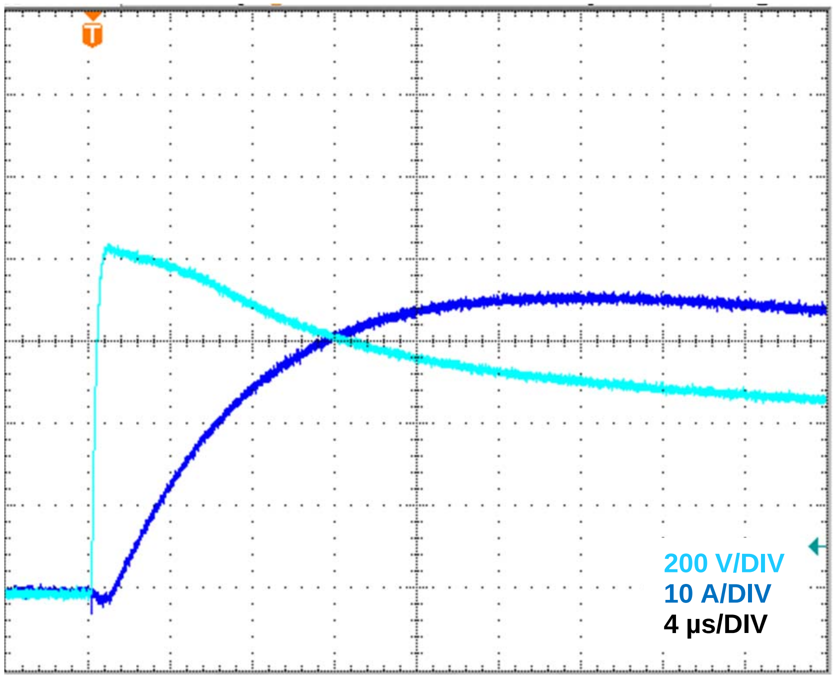
They work with a set of design criteria for the component , but I didn't know where the sweet spots are to meet the surge and AC of GR-1089-CORE!

One supplier was willing to wind engineering samples for us to test.

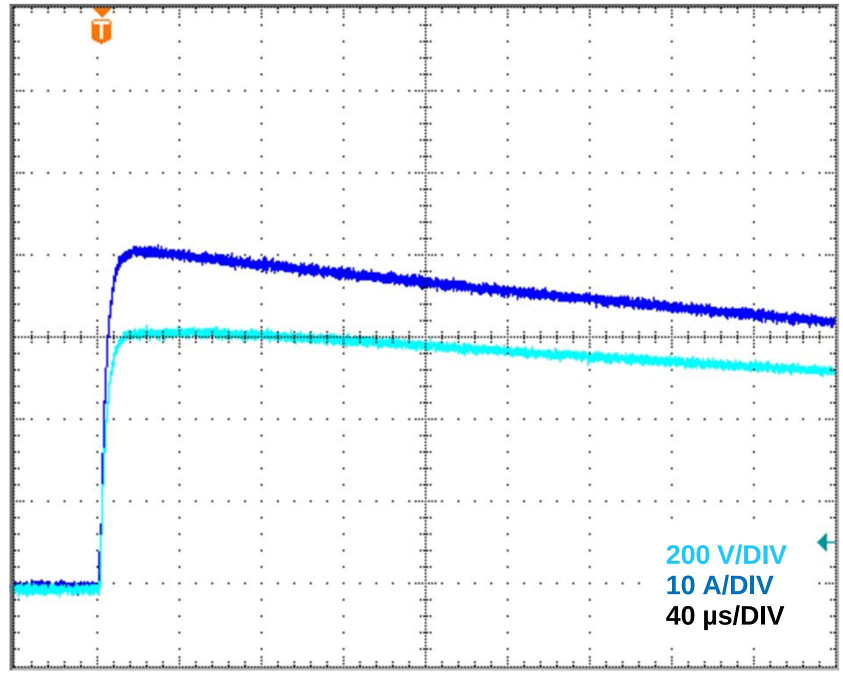
Choke

First Looked at Common Mode Choke Orientation.

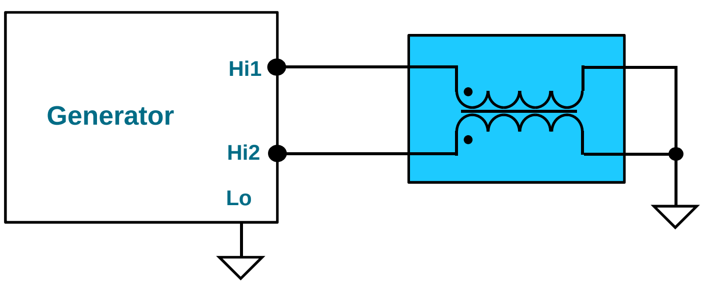
Traditional CM Choke

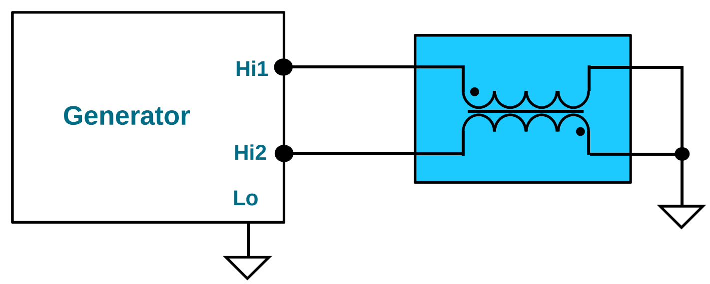


Looking as an Impedance

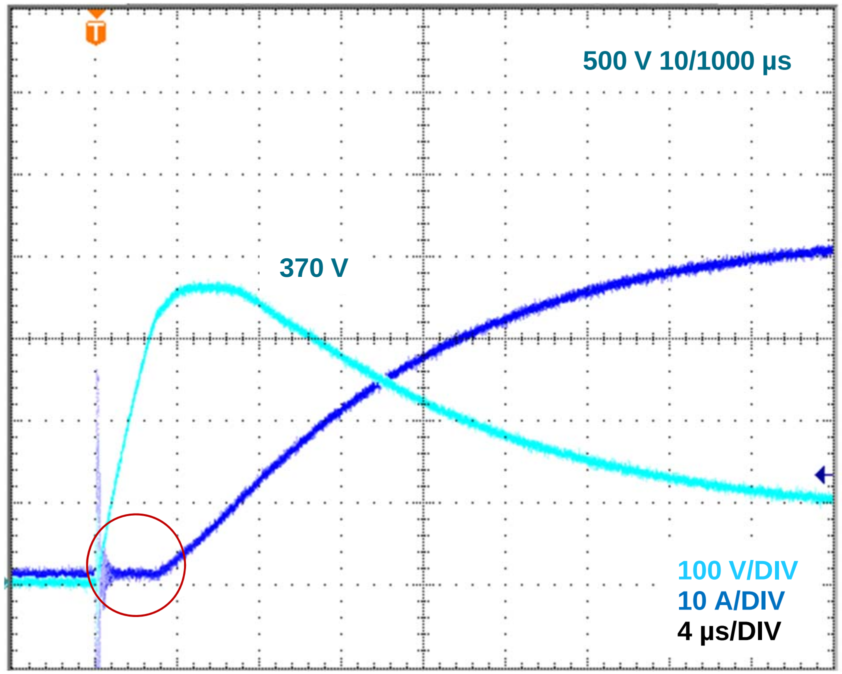


Looks like Resistance

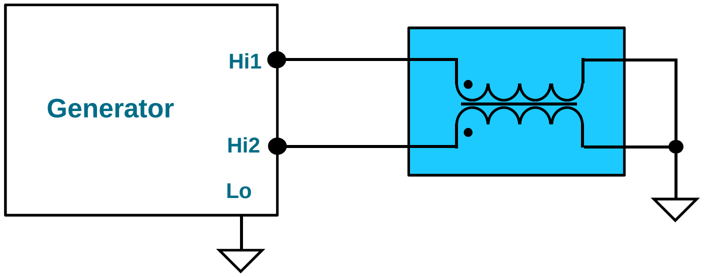


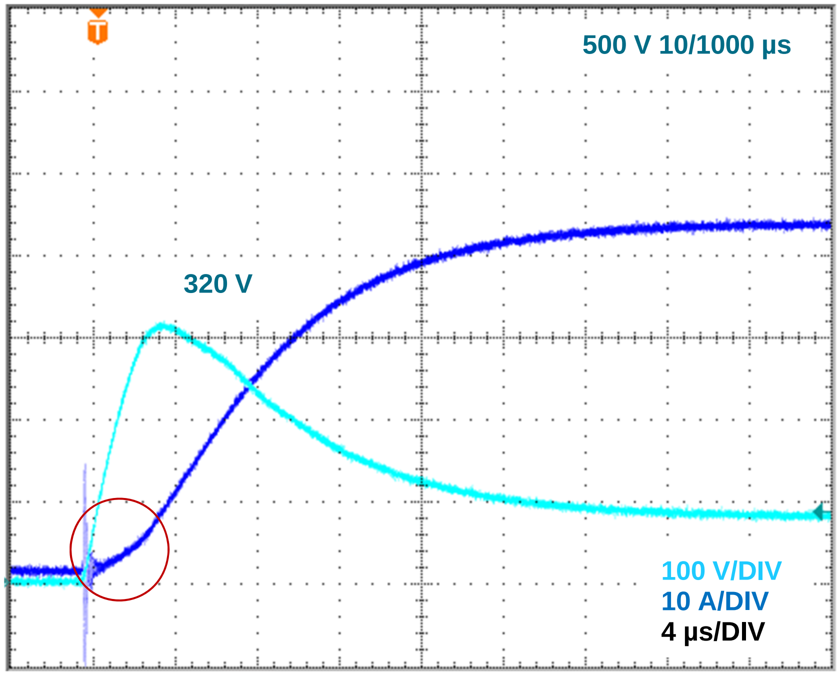


Inductor Choke

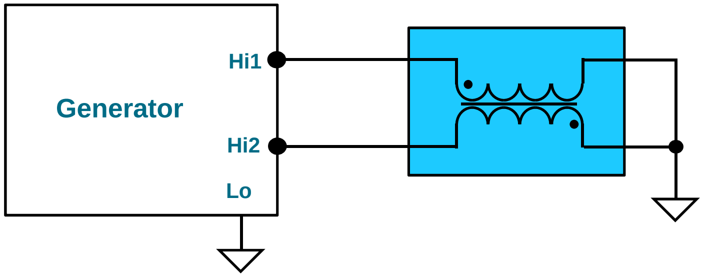


Looking as an Impedance

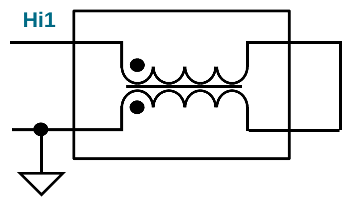
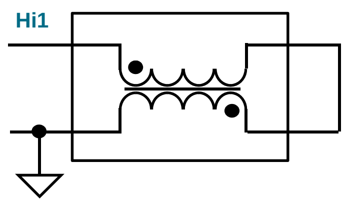
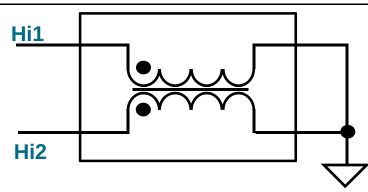
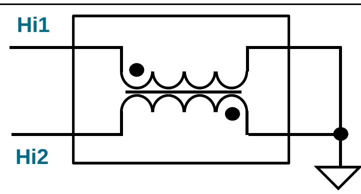




Looking as an Impedance

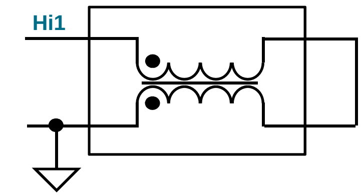
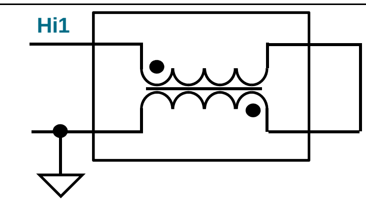
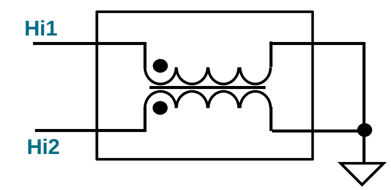
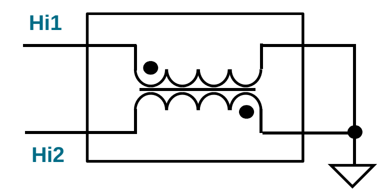


Common Mode Choke

Part	Test Setup	Waveform	Imax (A)	Vmax (V)	Notes
9 mH DCR = 1Ω max		500 V, 10 Ω, 10/1000	47.2	57.2	Resistance
		500 V, 10 Ω, 2/10	52.8	62.2	Resistance
		**Waveform**	**Imax (A)**	**Vmax (V)**	**Notes**
		500 V, 10 Ω, 10/1000	47.4	188	Inductance
		500 V, 10 Ω, 2/10	48.6	343	Inductance
		**Waveform**	**Imax (A)**	**Vmax (V)**	**Notes**
		500 V, 10 Ω, 10/1000	94.8	137	Inductance
		500 V, 10 Ω, 2/10	106	266	Inductance
		**Waveform**	**Imax (A)**	**Vmax (V)**	**Notes**
		500 V, 10 Ω, 10/1000	101	35.2	Resistance
		500 V, 10 Ω, 2/10	104	30.4	Resistance

A traditional common mode choke provides no significant benefit in coordination.

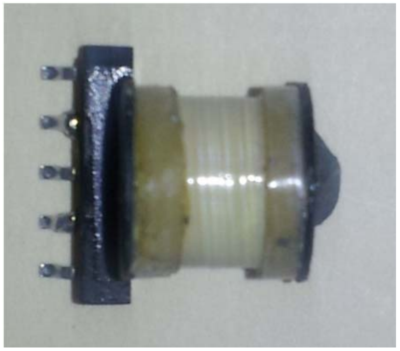
Inductor Choke

Part	Test Setup	Waveform	Imax (A)	Vmax (V)	Notes
6.8 mH DCR = 1.9Ω		500V, 10Ω, 10/1000	38.2	362	Inductance
		500V, 10Ω, 2/10	18.2	442	Inductance
		**Waveform**	**Imax (A)**	**Vmax (V)**	**Notes**
		500V, 10Ω, 10/1000	37.2	416	Inductance
		500V, 10Ω, 2/10	12.3	478	Inductance
		**Waveform**	**Imax (A)**	**Vmax (V)**	**Notes**
		500V, 10Ω, 10/1000	88	376	Inductance
		500V, 10Ω, 2/10	41.2	448	Inductance
		This orientation maximizes voltage. VDSL2 Engineer didn't like this configuration as it impacts data performance. Inter-winding capacitance is max 5pF?			
		**Waveform**	**Imax (A)**	**Vmax (V)**	**Notes**
		500V, 10Ω, 10/1000	88.8	288	Inductance
		500V, 10Ω, 2/10	56.4	418	Inductance
		This orientation gives up voltage with increase in current. VDSL2 Engineer liked this configuration.			

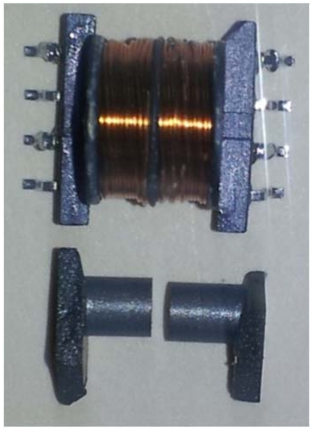
There are performance differences when looking at the orientation in Inductor chokes.

Mechanical Construction

- Two types of construction for these filters:-



  – Using a single bobbin with:-
    - Single windings (Inductor/transformer).
    - Bifilar wound (common mode).



  – Construction using two separate bobbin compartments.
    - I am calling it an "Inductor Choke".
    - Most common option seen on our DSL cards.

The construction of the chokes are not disclosed on the data sheets. There is also no differentiation of schematic symbols being used either!

Inductor Choke

Electrical Characteristics to Achieve Coordination

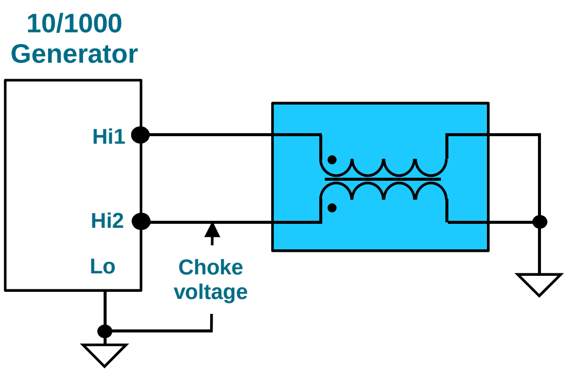
Selecting Test Samples

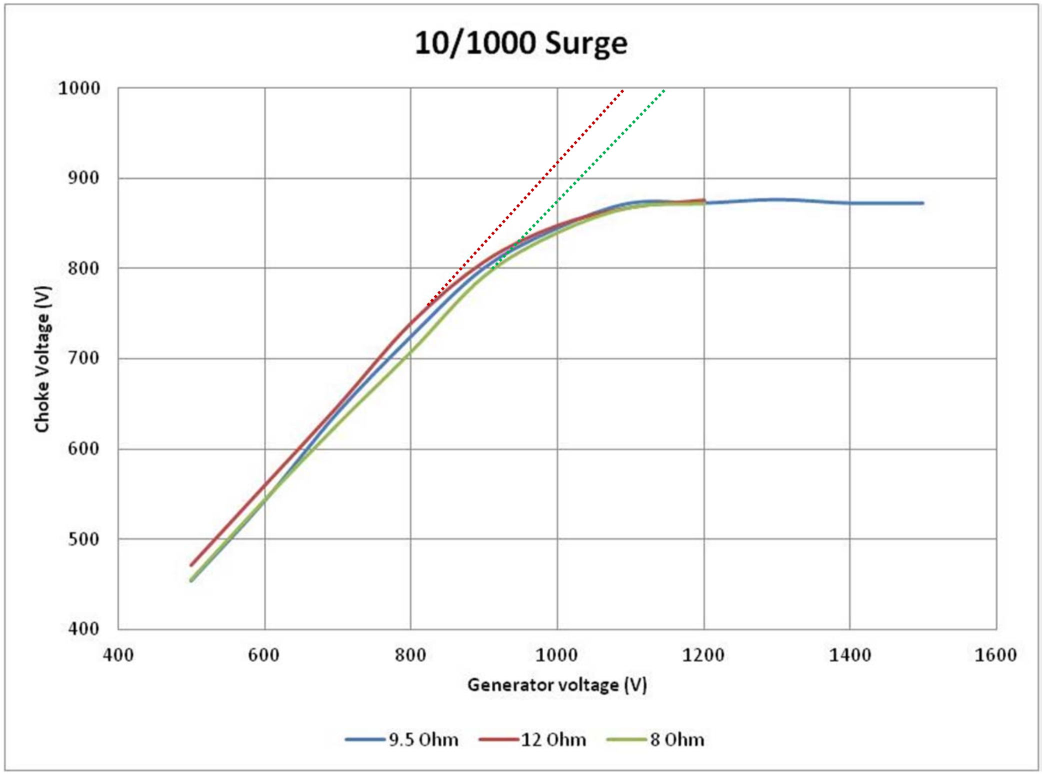
- From inductor presentation last year:-
  - Select the largest inductor value.
  - Select an inductor with suitable current withstand.
  - Select an inductor that achieves coordination voltage before saturation.
    - Test with the slowest rise time surge.
    - Highest DC resistance (watch out for AC tests).

    - Current option used is 6.8 mH and a DCR of 2 Ω.
- Sample A
  - 12 mH with 36 AWG and DCR of 8 Ω.
- Sample B
  - 3.8 mH with 36.5 AWG and DCR of 9.5 Ω with 180 ºC wire.
- Sample C
  - 13 mH with 37 AWG and DCR of 12 Ω.

OSP Interface Test to 1 kV

- Sample A
  - 12 mH with 36 AWG and DCR of 8 Ω.
- Sample B
  - 3.8 mH with 36.5 AWG and DCR of 9.5 Ω with 180 ºC wire.
- Sample C
  - 13 mH with 37 AWG and DCR of 12 Ω.

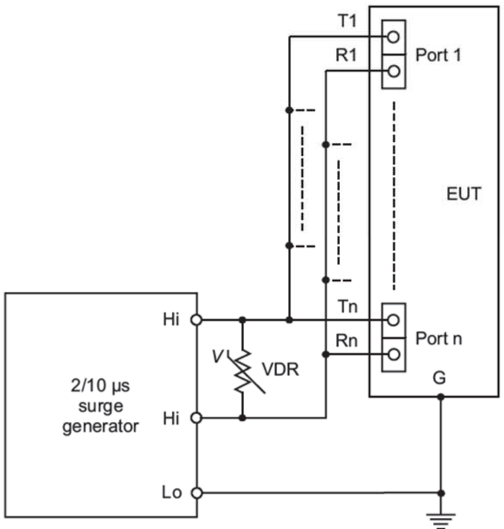




- Choke was saturating before achieving 1000 V!
  - Highlighting the Ferrite core is key parameter to consider.
    - No room for increasing the inductor size in current solution.

Inductive Kick Test

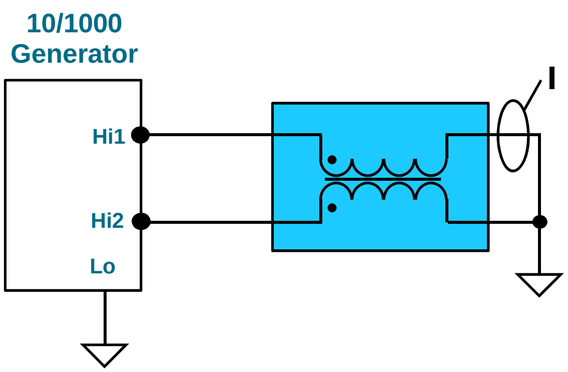
- 2.5 kV, 500 A 2/10.
  - Transformer was screaming on each surge but it didn't fail!
  - Peak currents were 23 A (12 Ω) and 33 A (8 Ω).
    - No threat to over voltage protection

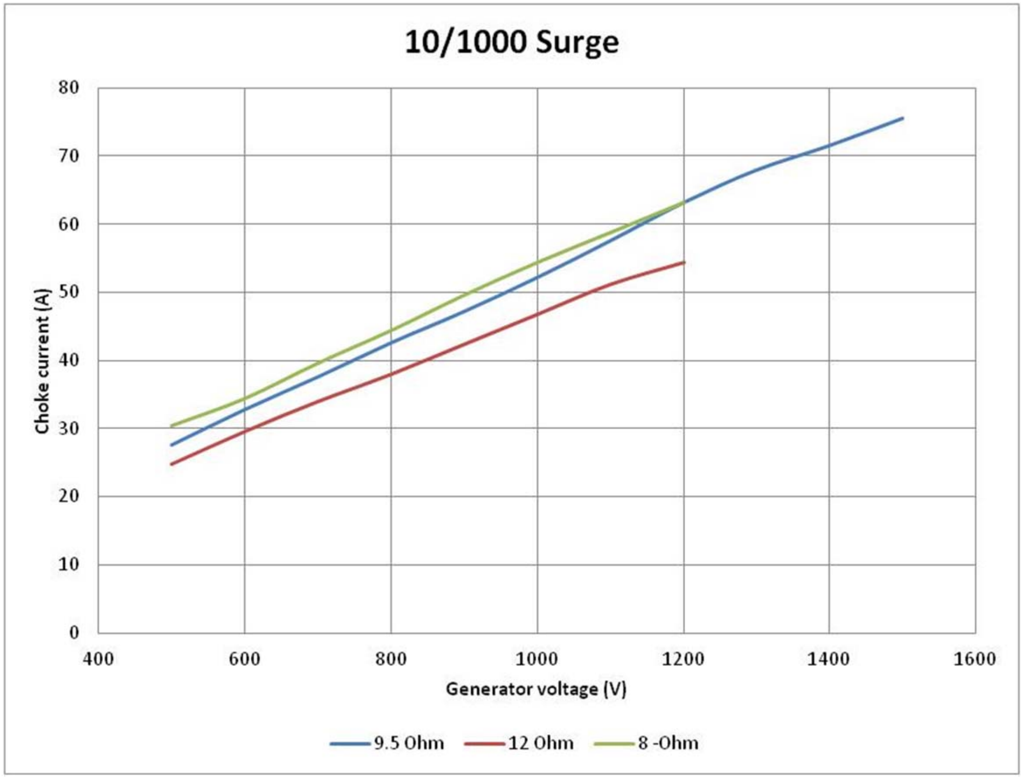


- Sample A
  - 12 mH with 36 AWG and DCR of 8 Ω.
- Sample C
  - 13 mH with 37 AWG and DCR of 12 Ω.

OSP Interface to 100 A

- Sample A
  - 12 mH with 36 AWG and DCR of 8 Ω.
- Sample B
  - 3.8 mH with 36.5 AWG and DCR of 9.5 Ω with 180 ºC wire.
- Sample C
  - 13 mH with 37 AWG and DCR of 12 Ω.





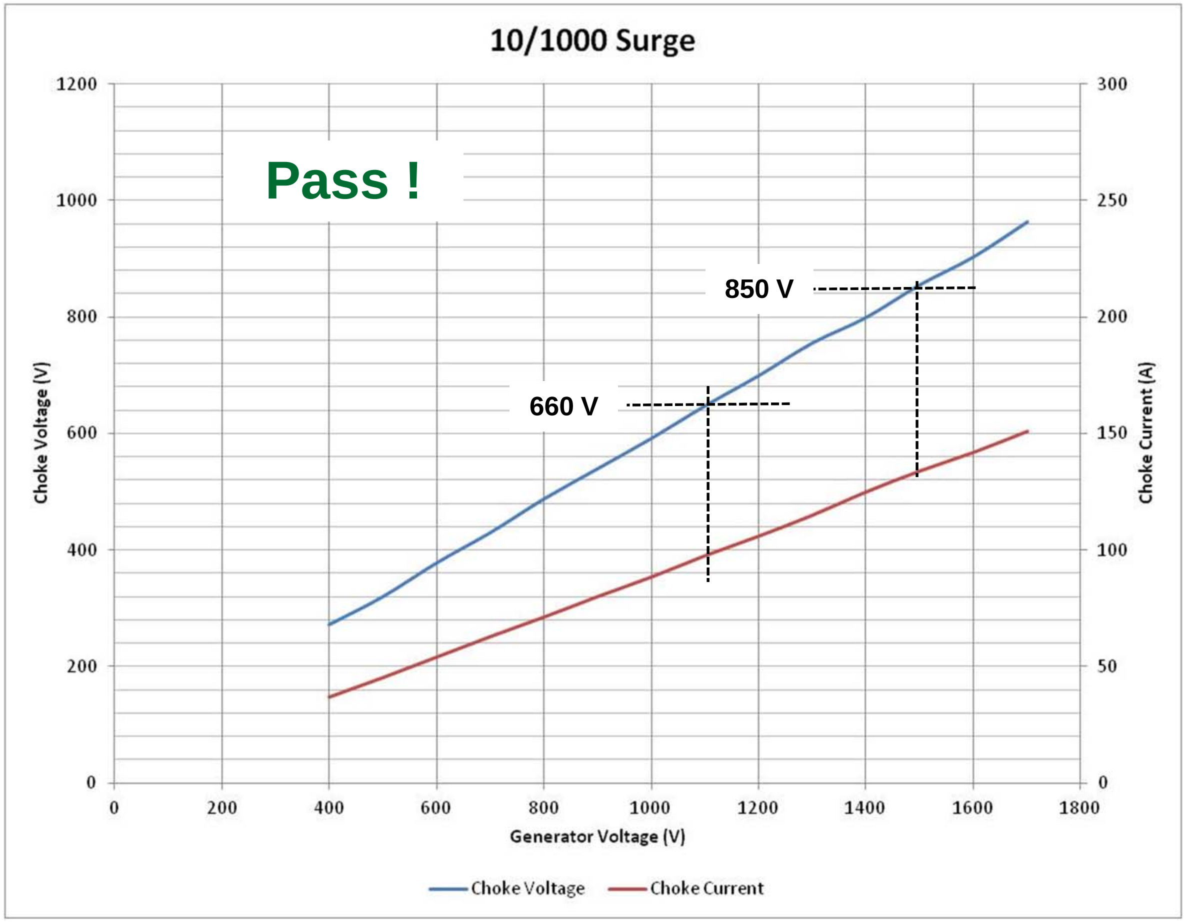
Choke design will not meet 100 A either!

Achieving 100 A 10/1000 in the Equipment Terminals

- Sample D
- Previous testing showed the transformer was saturating early.
  - Increase the wire thickness.
    - Lowers DC resistance.
    - Increase current handling capability.
    - Reduces Inductance.

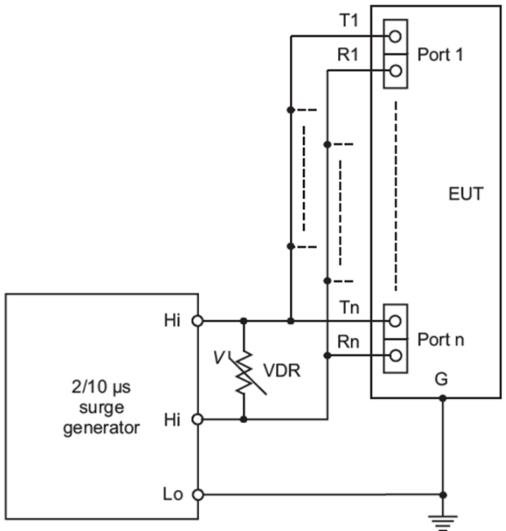
From the graph, the typical voltage generated at the port will be 660 V during a 10/1000 type surge. That is just enough to operate a 350 V GDT used in primary protection.

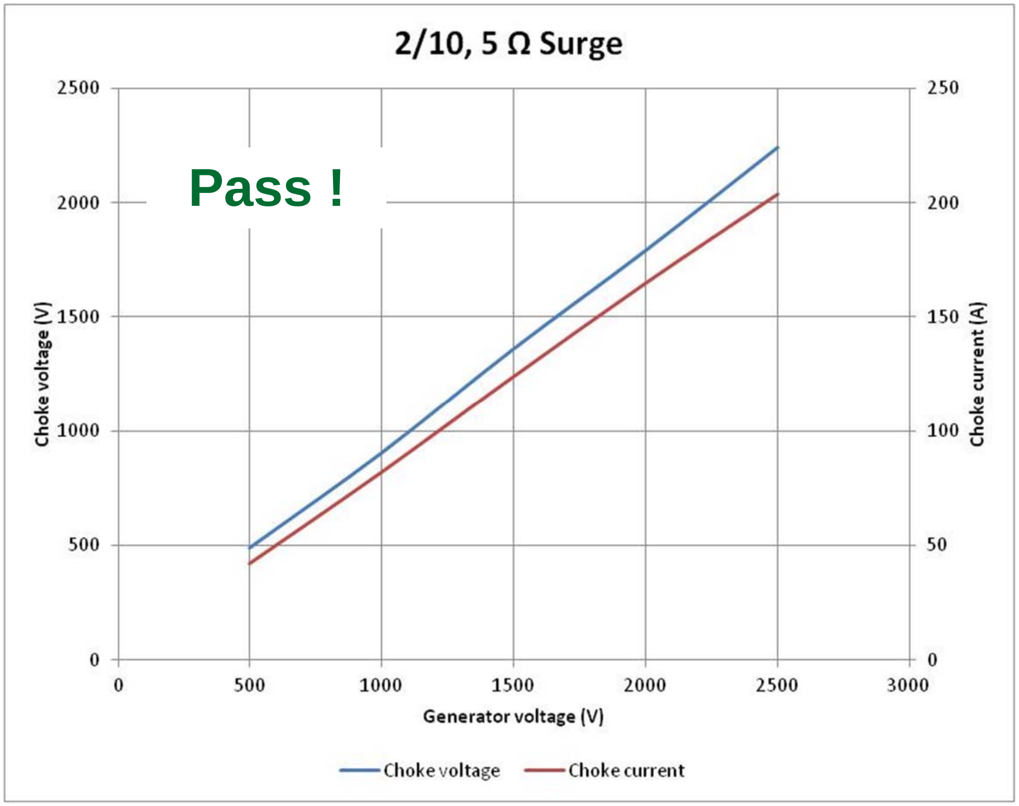
Using 1000V/ μs specification of 850 V is also within the choke capability.



Inductive Kick Test

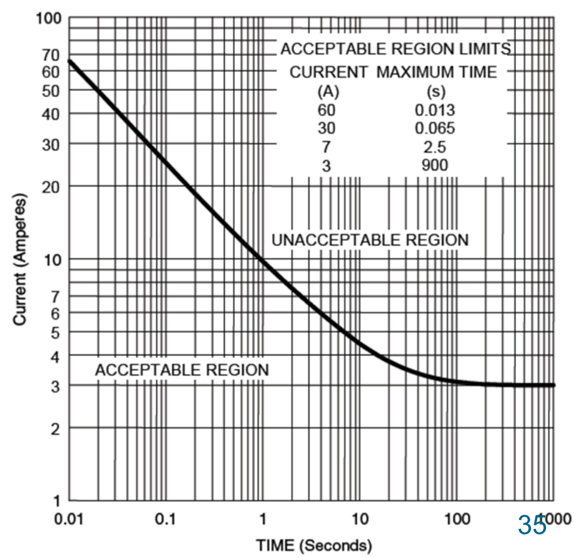
- 2.5 kV, 500 A 2/10
  - Layout/spacing rules are critical.
    - Design to 3 kV due to tolerance.
    - Choke sounded like it is arcing but it wasn't.





Choke AC Characteristics

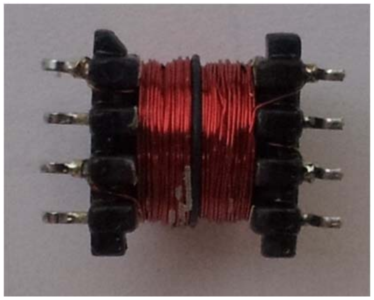
- First level AC tests. **Pass!**
  - Checked performance by measuring the DCR before and after the tests. All tests passed.
    - No resistance change with 600 V, 3.3 A or 440 V, 2.2 A tests.
      - These were Issue 5 tests as the AC generator had not been reconfigured yet.
- Can the choke also act as the fuse?
  - Second level AC tests for port type 1.
    - Get an I^2t curve for the choke.
    - Plot it against GR-1089-CORE curve.

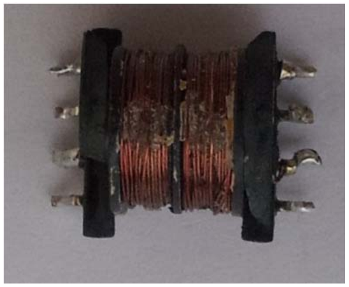


Choke as a Fuse

V_{GEN} (RMS)	R_{GEN} (Ω)	Current (A)	Single winding			Both windings		
			DCR (START)	DCR (FINISH)	Time (s)	DCR (START)	DCR (FINISH)	Time (s)
230 V	10	24.3					open	0.8
	20	12.2				2.2	0[1]	900
	40	5.87				2.2	0	900
	80	3.06	2.1	0	900	2.2	0	900
	160	1.57	2.1	0.6	900	2.2	0	900
	200	1.25	2.5	1.2	900	2.2	0.6	900
	300	0.83	2	2	900	2.2	1.1/1.7	900
	600	0.41				2.1	2.1	900

[1] Connect wires de-soldered due to excessive heat


Untested unit


3 A both windings

GR-1089-CORE Port Type 1

- Choke failed into a short circuit except for the very high current (24 A) tests.
  - Enamel burns off that shorts out the windings.
  - The current does not fuse the wire between the external pin and bobbin.
  - Wires clearing creates a nice arc and fails safely (no fire hazard or fragmentation).
- Choke needs to be protected by a suitable telecom fuse (1.25 A) to meet port type 1 solutions.

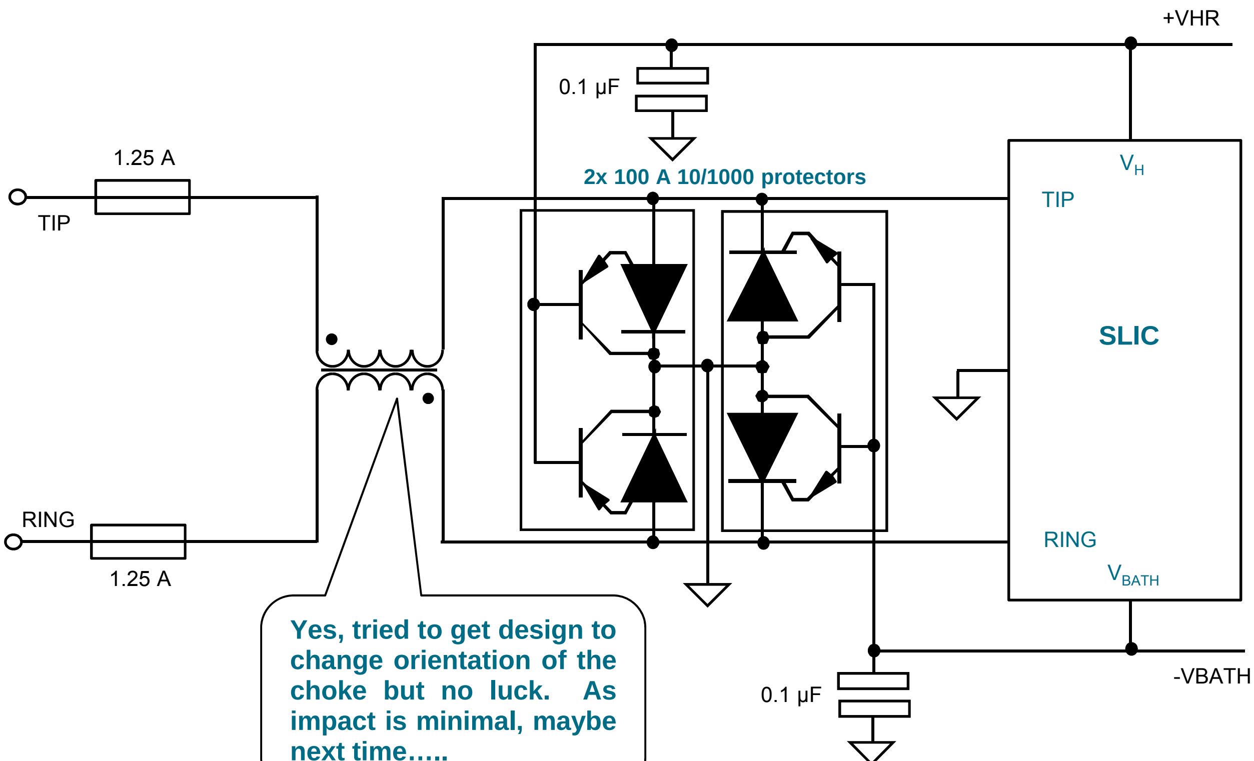
Choke as a Fuse

- GR-1089-CORE Integrated Primary Protection.
  - If the EUT has integrated primary protection, the wiring simulator is not required to be used and fusing of the OSP stub cable is permitted.

V_{GEN} (RMS)	Current (A)	Time (s)	State
120	25	900	OPEN
277	23	900	OPEN (in 200 ms)
425	46	1.5	OPEN
425	7	4	SHORT
425	30	4	OPEN (in 220 ms)
425	2.6	240	SHORT
425	10	4	SHORT

  - No safety hazard occurred (fire, fragmentation etc). Choke is good for this type of deployment.

VDSL2 Combo POTS Solution

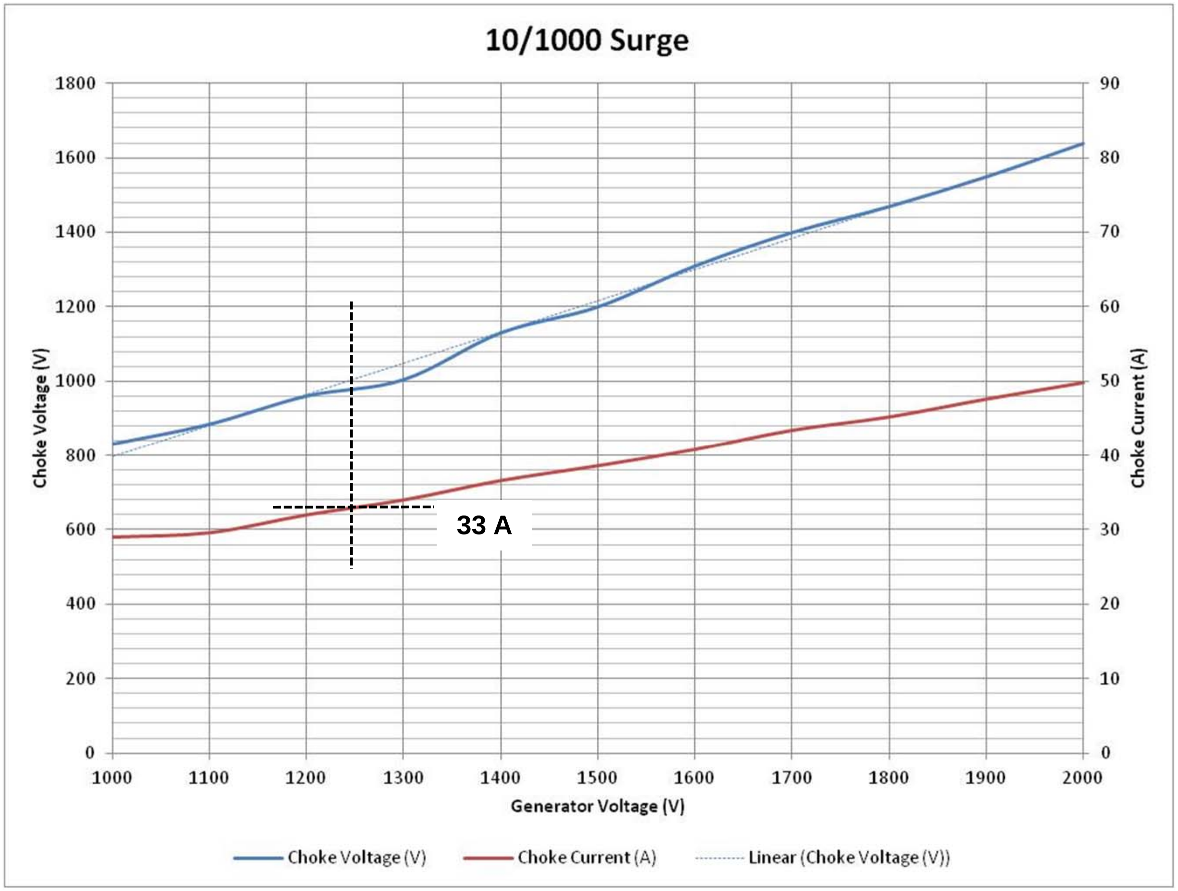


Yes, tried to get design to change orientation of the choke but no luck. As impact is minimal, maybe next time…..

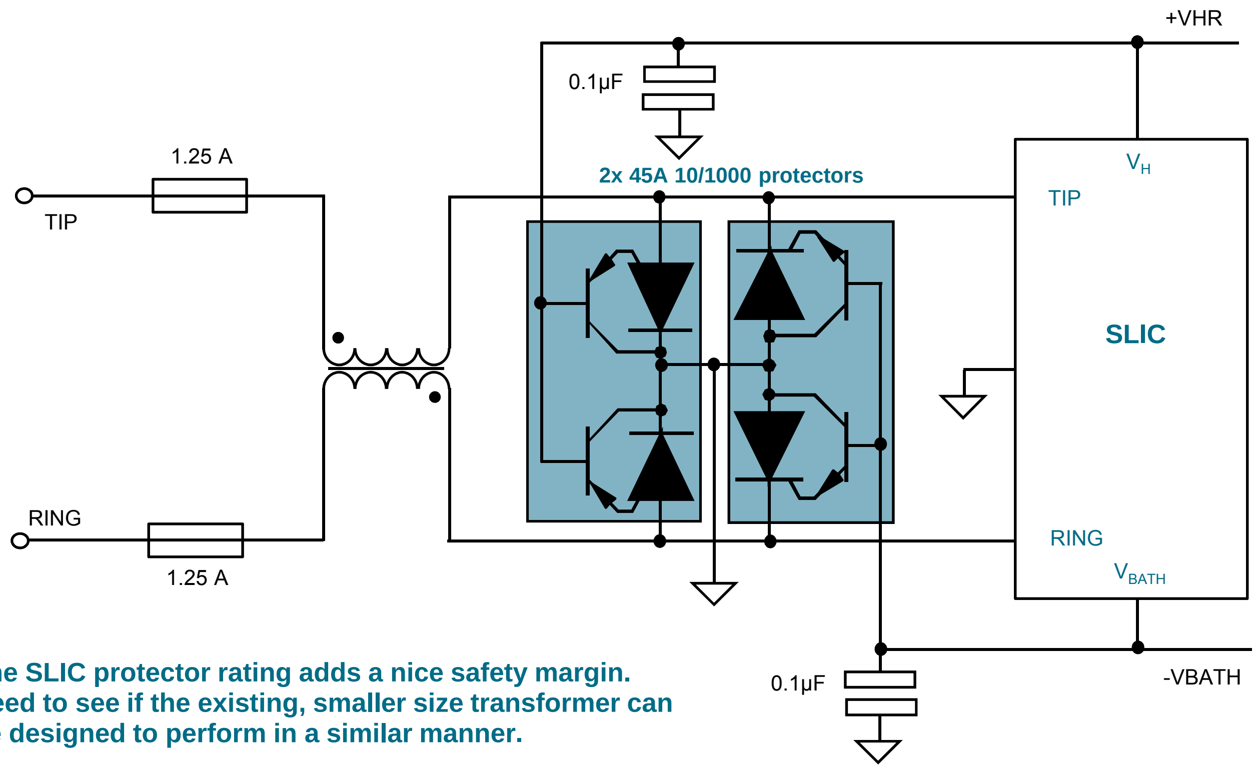
Generating 1 kV at Terminals

- Sample E
  - 7.25 mH and DCR of 4.5 Ω.
  - Larger core size.

- This choke solution will require a 35 A SLIC protector to be used.
  - Uses 2x IC's
    - Monolithic device would be ideal.
    - Second source option available.
- Increasing the DCR of the choke could allow the 30 A single chip option to be used.

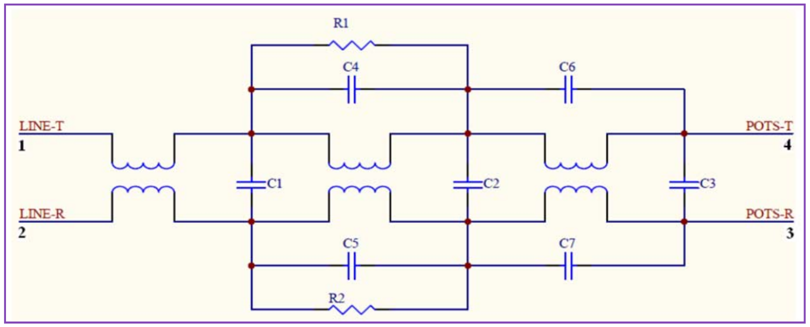


New Solution for Meeting GR-1089-CORE



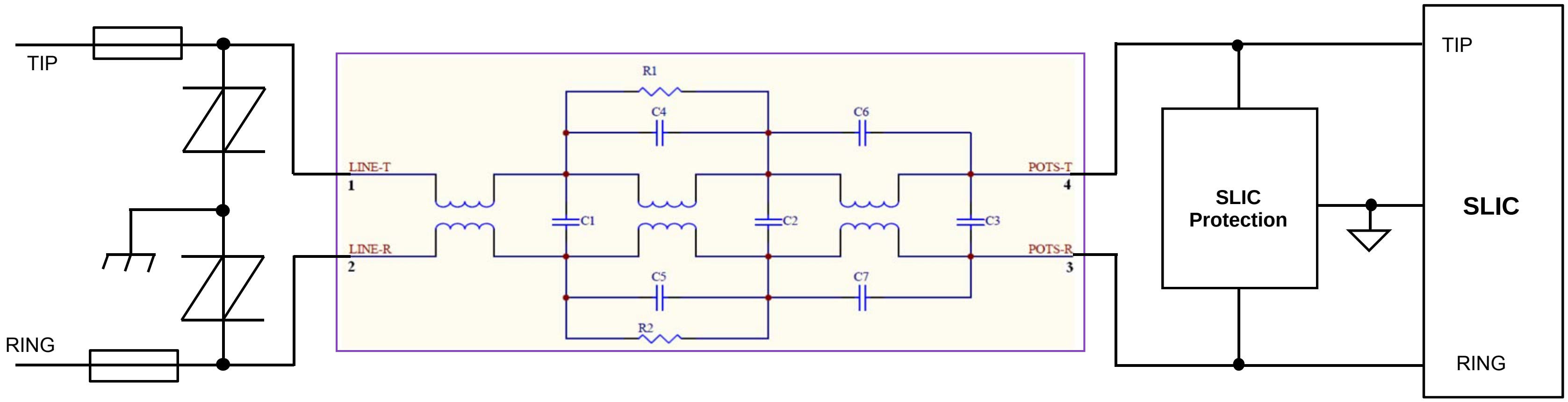
The SLIC protector rating adds a nice safety margin. Need to see if the existing, smaller size transformer can be designed to perform in a similar manner.

Integrated ANSI & ETSI Filters



(Filter in a box)

Low Pass Filter Module



- Front-end uses a biased fixed voltage thyristor option.
- After various Calls + e-mails…..
  - I was assured from the manufacturer that the ANSI filter will be able to pass GR-1089-CORE, issue 6 testing without any front-end protection. After all, the similar ETSI (European version) filter does not require any over voltage protection and can easily pass ITU-T with 4 kV surges…..

Low Pass Filter Module

- Got that worried feeling when you know they don't know what they are talking about, but think they do…and it sounds convincing?

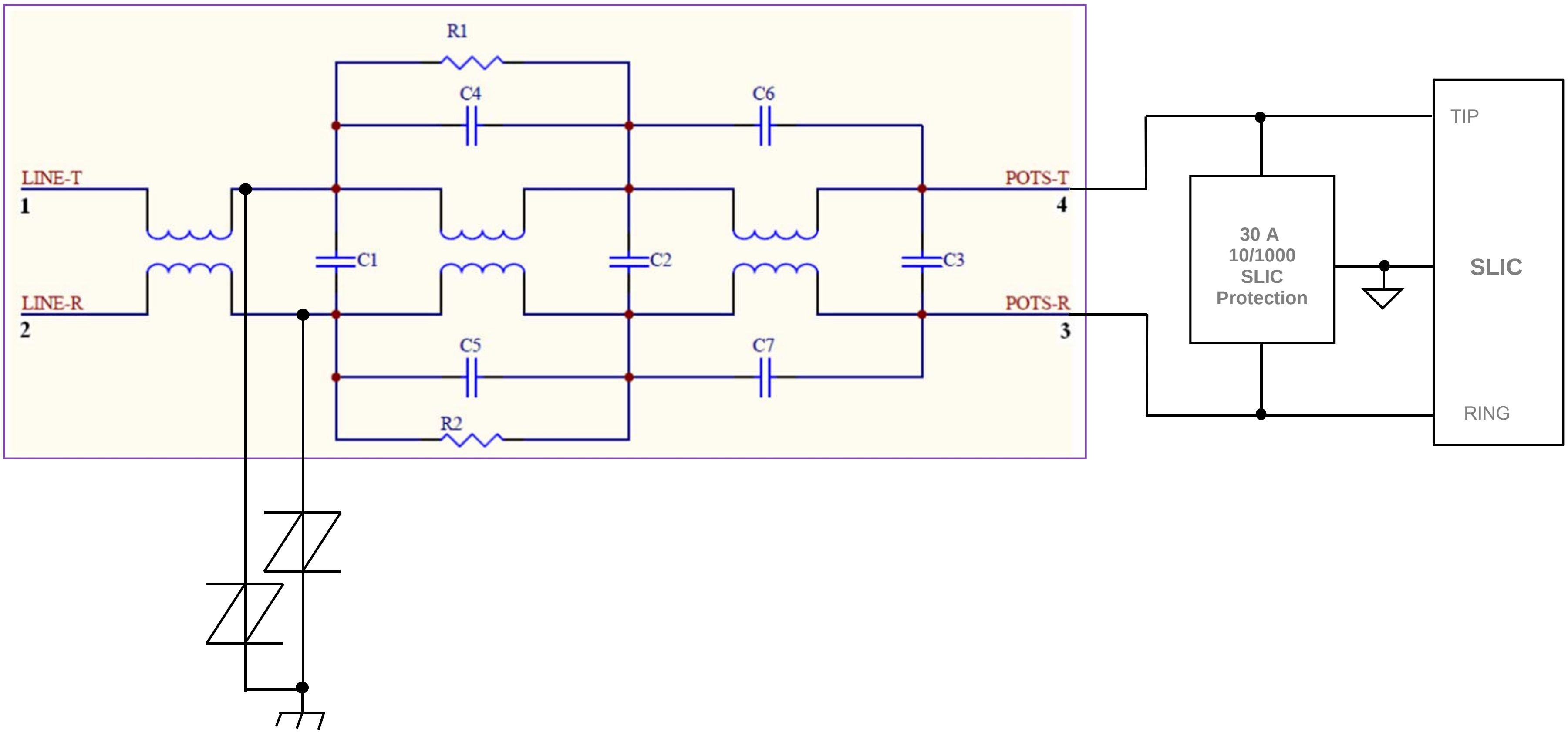
- The design Engineer has probably over-engineered it….time to test.

Testing the LFR’s

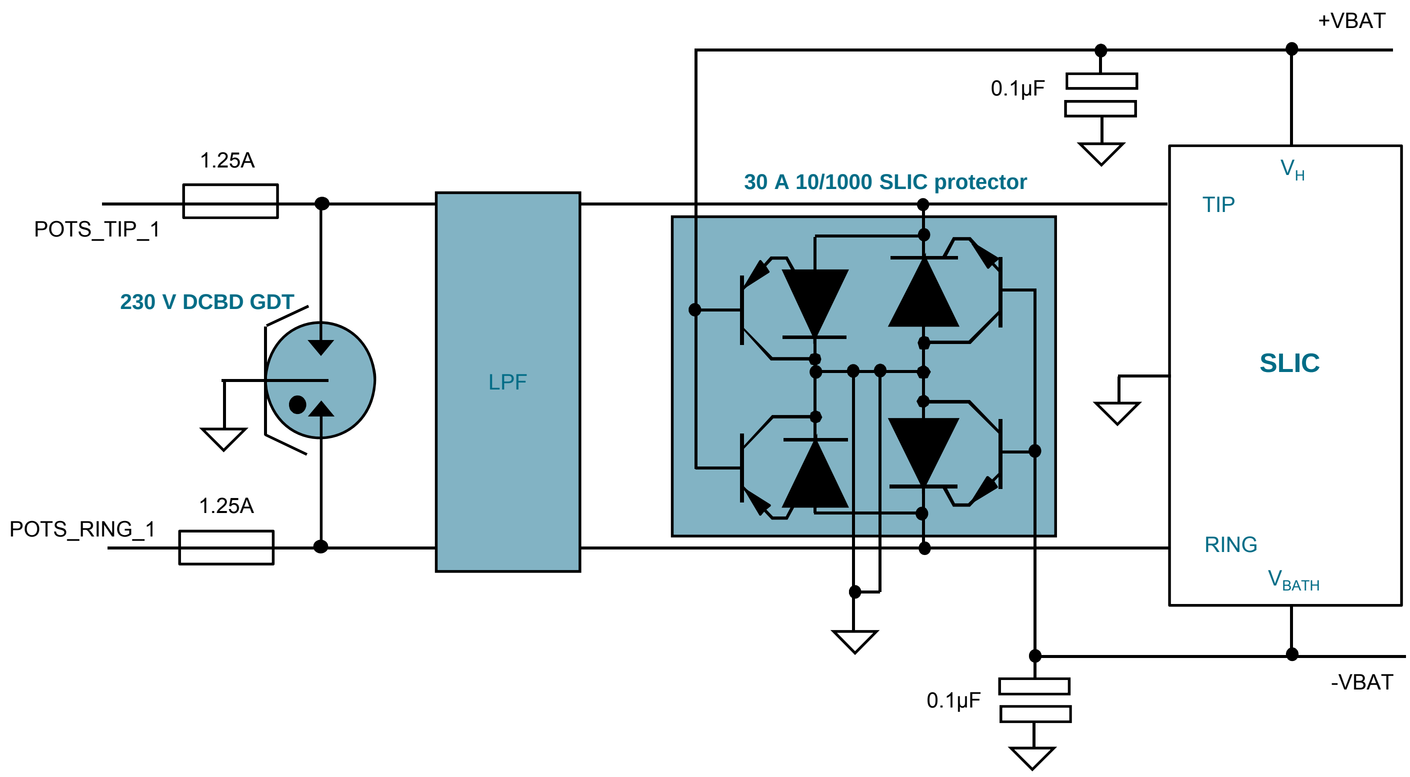
- From the 3 manufacturers:-
  - All failed the OSP Interface test (10/1000) where the last pass was 360 V longitudinal surge!
    - What happened to 1kV 10/1000 required for just passing issue 5?
    - ITU-T relies on the 40 Ω of the generator and the primary protector during the 4 kV surge to limit the voltage to pass!
    - There is no safety margin with a 350 V_{DCBD} GDT primary protector.
      - (350 +20%= 420 V).

- Is the choke reliable enough to be the coordination element?
    - It could pass with a 10/1000 generator of 1kV, but this only gave a peak voltage of 800 V @55 A. Good modification for future ITU-T solutions, but not for GR-1089-CORE applications.

Revised Solution for ITU-T



Final Solution for GR-1089-CORE



Summary

- Don’t just rely on testing with the biggest hammer.
- Test surge performance under the over voltage protector.
  - GR-1089-CORE, issue 6 tests under the over voltage protector.
  - Test at maximum let-through of over voltage protector.
- Characterize the components.
  - "One test result is worth one thousand expert opinions." Wernher Von Braun

Questions