



## MBHA001 – Update on simulations

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Thanks to J. Ludwin, M. Bednarek, F. Mangiarotti, A. Verweij and other colleagues involved (CERN)

10 March 2020



# Simulations of transient after installing an artificial short

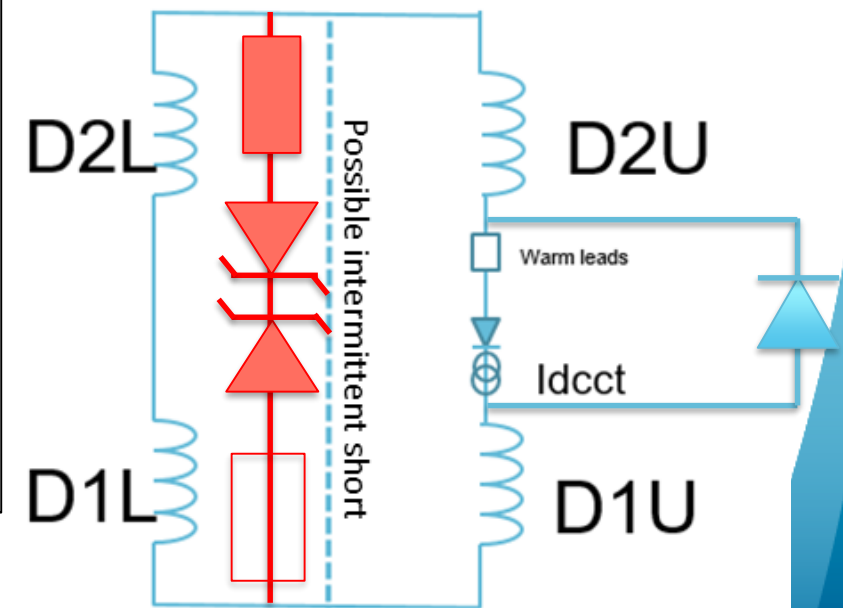
Type of parallel path installed	Peak current through the parallel path [A]	Peak voltage across D1L+D2L [V]	Peak temperature [K]	Fuse rating	We expect to reduce spikes
50 $\Omega$ Resistor + fuse	1.8 A	90 V	293 K	2 A	Yes, x2
10 $\Omega$ Resistor + fuse	9 A	90 V	296 K	10 A	Yes, x5
20 V Zener Diode + 10 $\Omega$ R + fuse	7.5 A	90 V	<296 K	10 A	Yes, x5
50 V Zener Diode + 10 $\Omega$ R + fuse	4.5 A	90 V	<296 K	5 A	Yes, x5
50 V Zener Diode + 25 $\Omega$ R + fuse	2 A	90 V	<295 K	2 A	Yes, x2

If the spikes are caused by an intermittent short, we should observe a reduction of the spike amplitude after installing the parallel branch, provided enough current flows through it [to completely suppress the spikes, tens of A needed...]

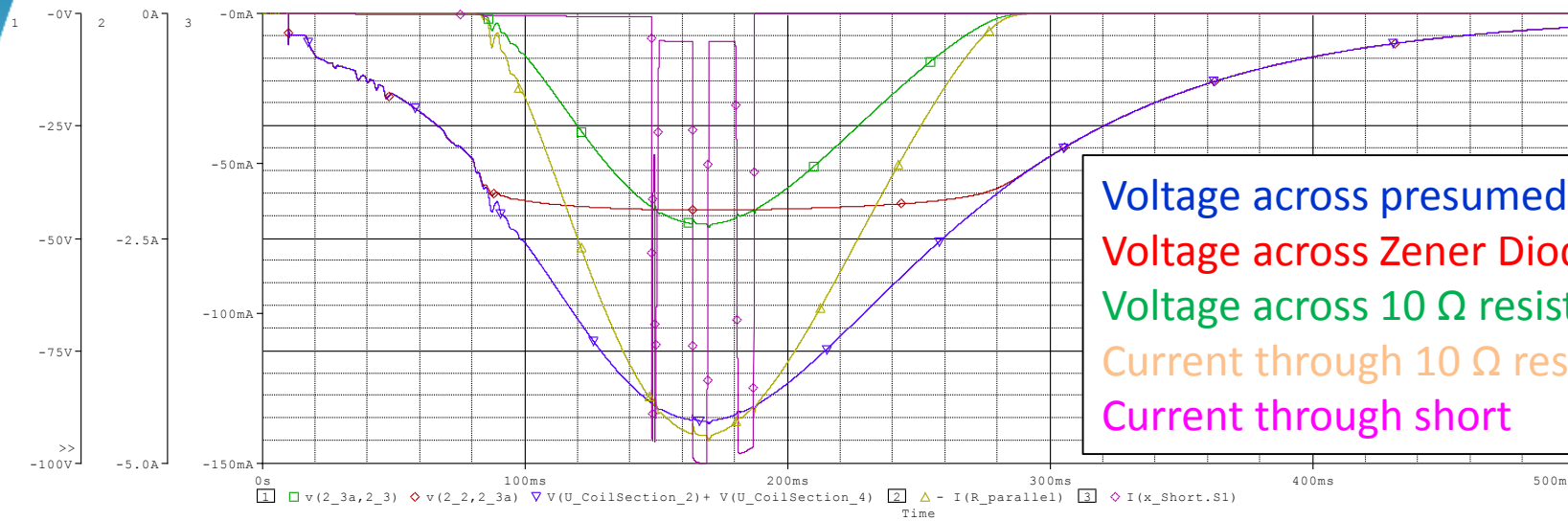
## Proposal (**please offer comments!**)

- R=10  $\Omega$  + 50 V Zener Diode: Peak current < **5 A** and peak temperature <300 K
- Fuse in series, rated to 5 A [**is this adequate?**]
- We could expect a reduction of a factor  $\sim 5$  in the spike amplitude
- Note: For tests at  $I > 9$  kA, the peak current and temperature would increase!

See next slide about voltage in case of fuse blowing-up

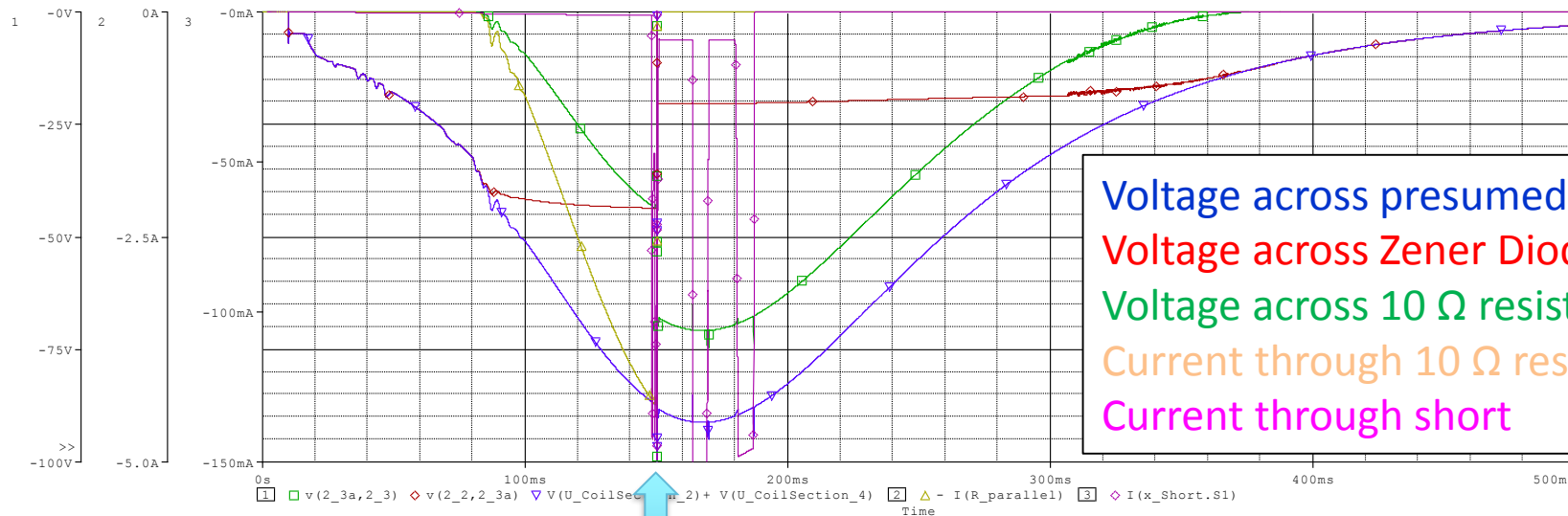


# Simulation of a 9 kA transient with Zener Diode + 10 $\Omega$ resistor



Voltage across presumed short  
Voltage across Zener Diodes  
Voltage across 10  $\Omega$  resistor  
Current through 10  $\Omega$  resistor  
Current through short

Fuse does not blow up



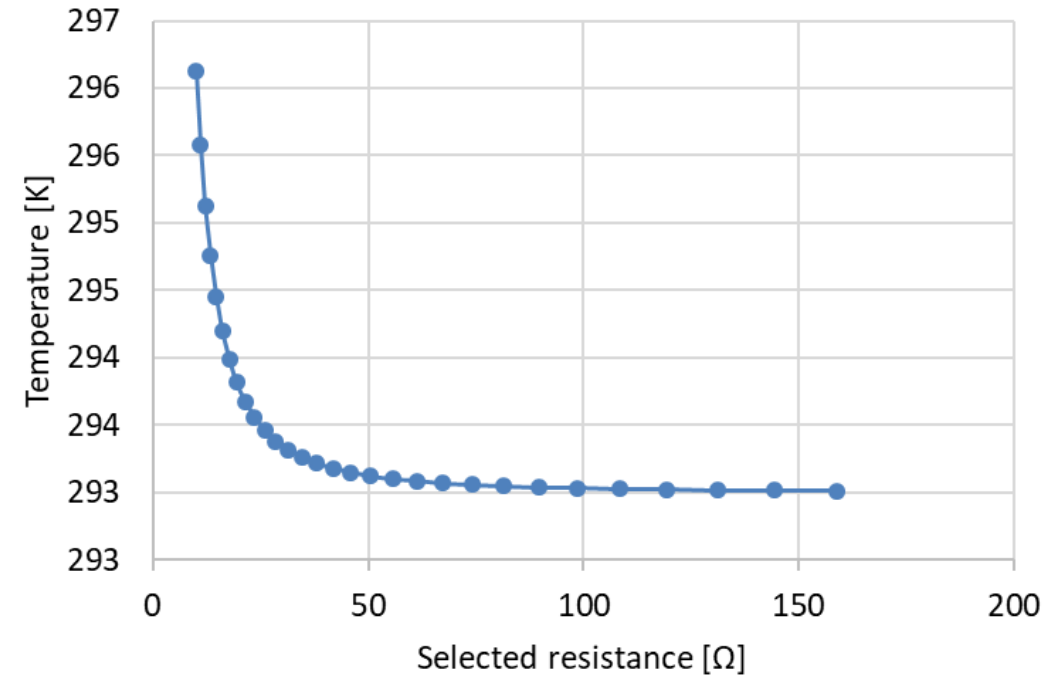
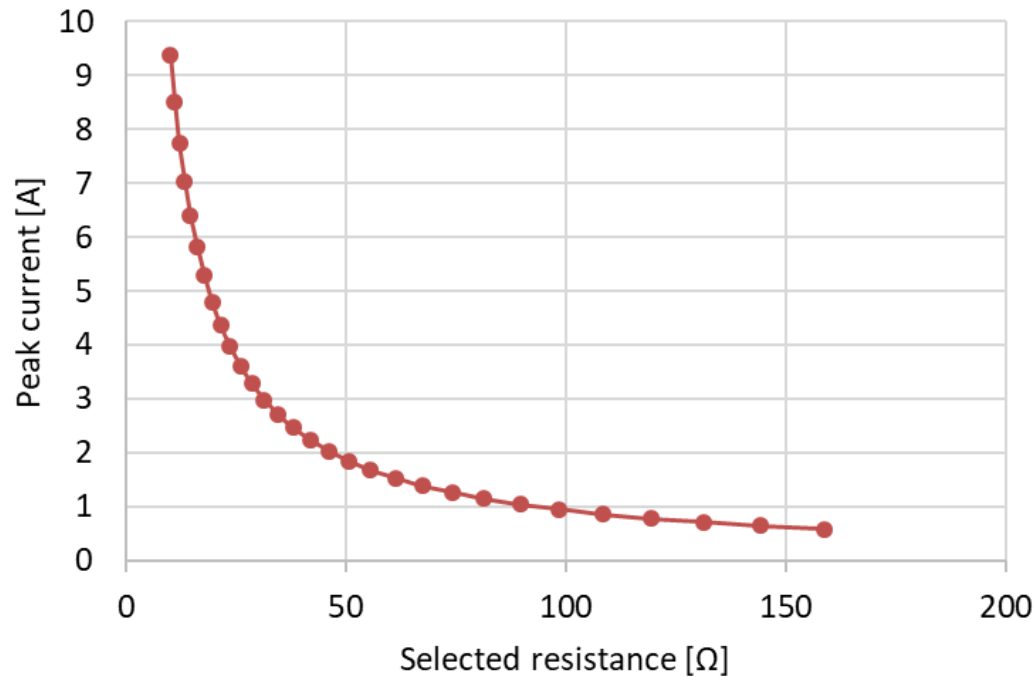
Voltage across presumed short  
Voltage across Zener Diodes  
Voltage across 10  $\Omega$  resistor  
Current through 10  $\Omega$  resistor  
Current through short

Fuse blows up at  $t=150$  ms  
(blow-up time: 10  $\mu$ s)

- **Voltage across the presumed short pikes up to 1.4 kV**
- Current through presumed short spikes up to 1.5 A
- Spike lasts  $\sim 50$   $\mu$ s

Fuse blows up

# Maximum current allowed through the voltage tap



## Assumptions

- AWG26, cross-section 0.129 mm<sup>2</sup>
- Cu, RRR=100, B=0
- Initial temperature = 293 K
- Applied voltage identical to the voltage measured during transient at 9 kA
- Zener Diode not present

## Results

- Peak current and temperature calculated as a function of the selected resistance of the artificial short circuit
- To maintain peak current <2 A, R>50 Ω needed
- For R=10 Ω: peak current <10 A and peak temperature <300 K
- Note: For tests at I>9 kA, the peak current and temperature would increase!

# Observed spike occurrence and new proposed tests

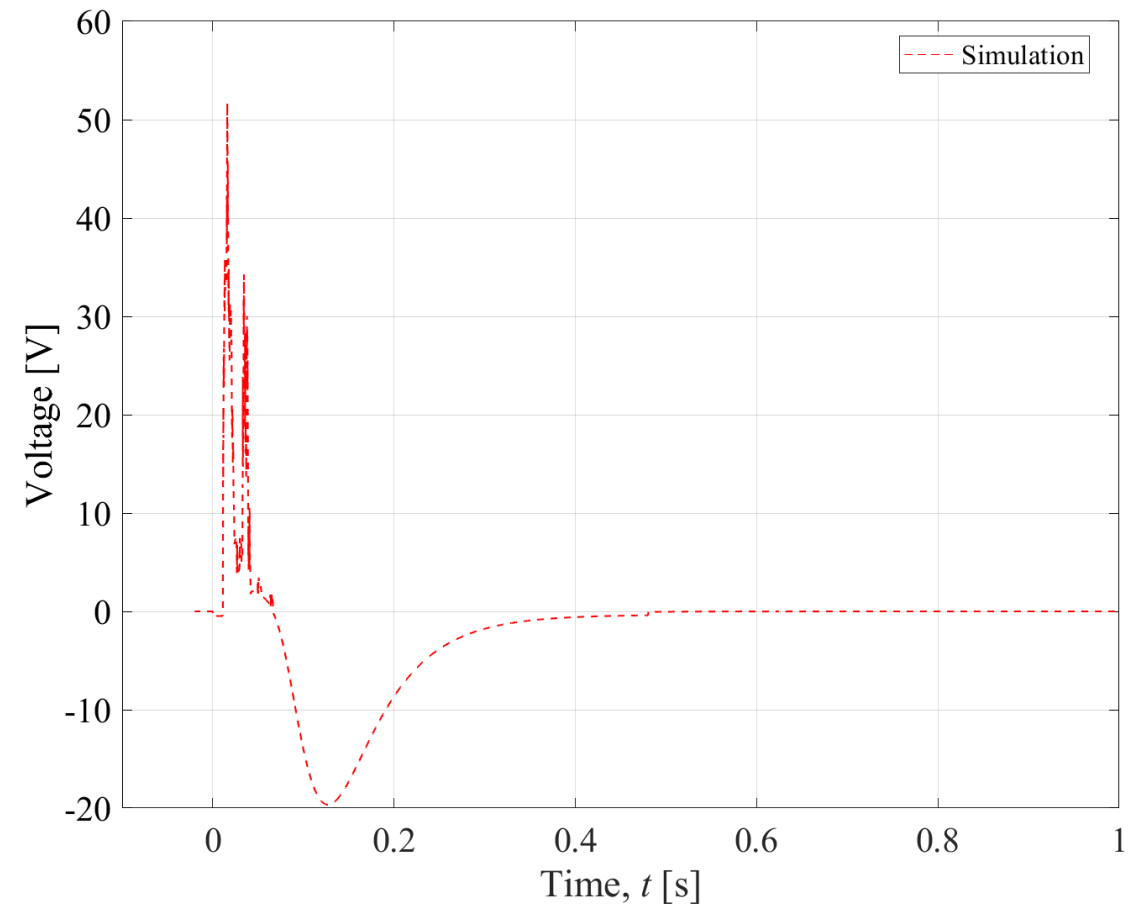
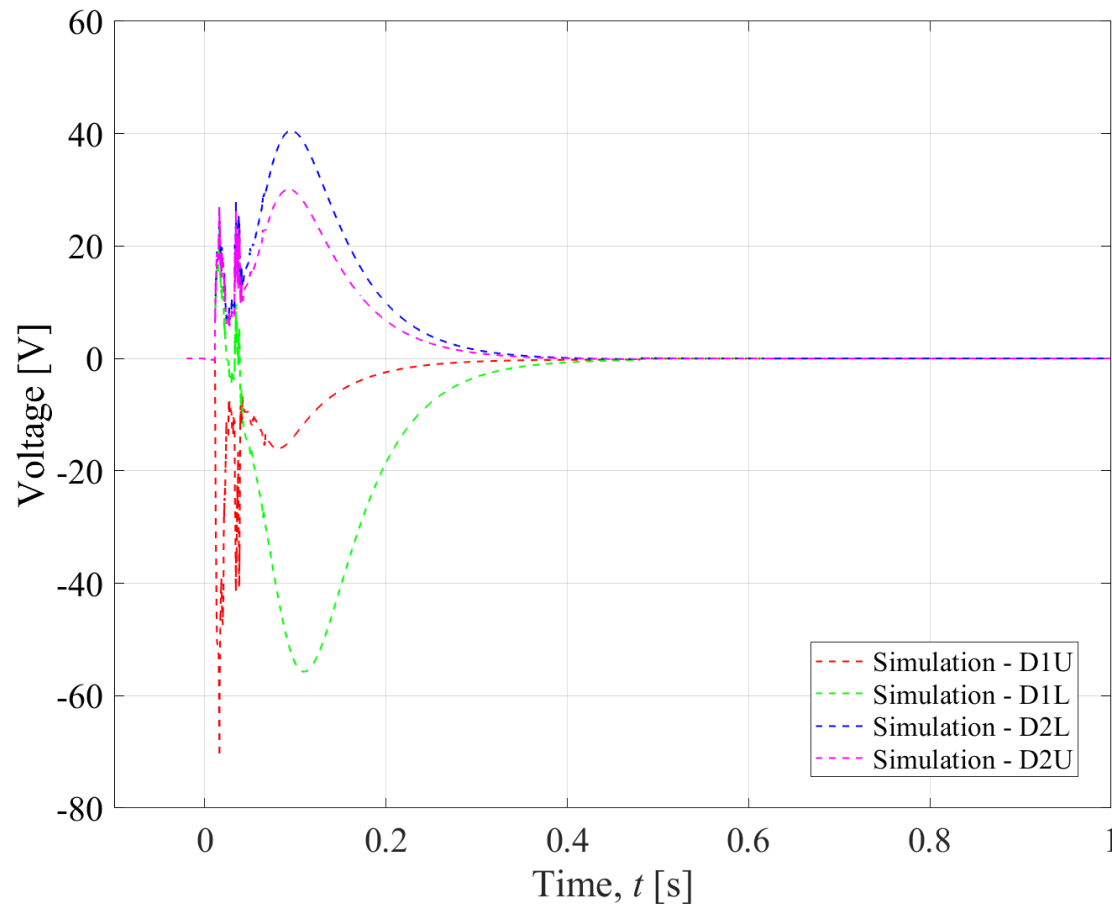
MBHA-001		Initial current [kA]				
		6	7.8	9	10.5	11.85
Peak voltage between aperture mid-points [V]	+90	no spikes				
	-20	no spikes		spikes		
	-60		spikes			
	-90			spikes		
	-120				one spike	one spike

Missing a test at high current and low voltage  
 Will we observe spikes, or just one spike?  
 → 11.85 kA, D1U-QH delayed by 5 ms  
 $U_{\text{short}} \sim 20 \text{ V}$ ,  $T_{\text{hot}} \sim 311 \text{ K}$

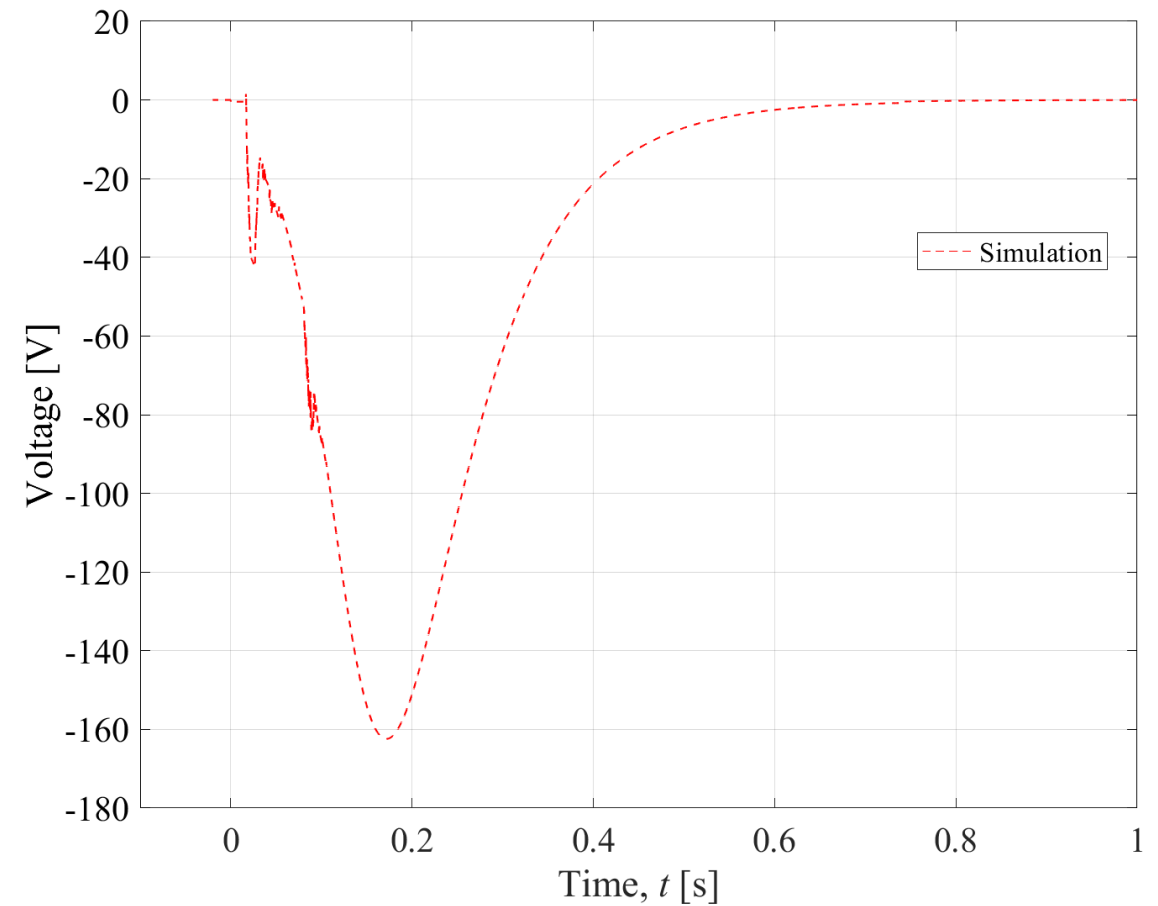
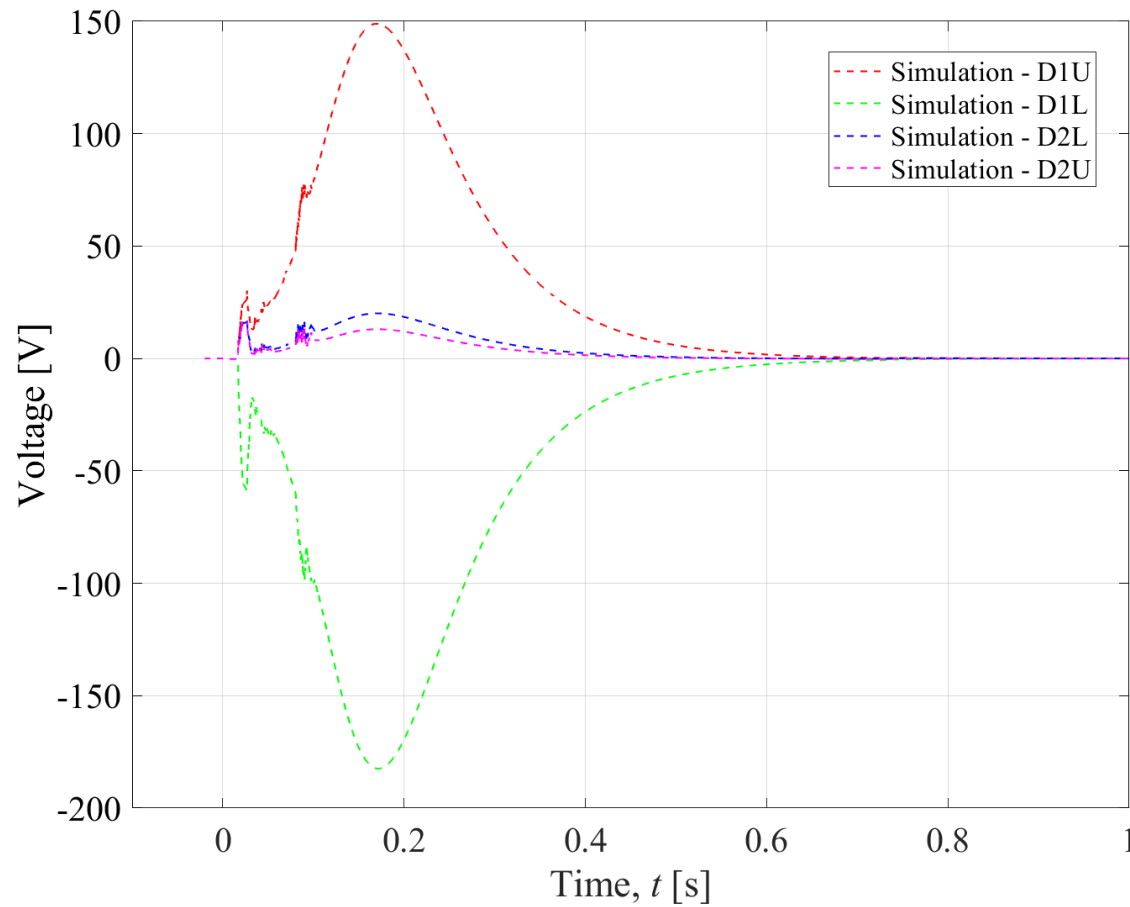
Missing a test at 6 kA and higher voltage with negative polarity  
 Will we observe spikes?  
 → 6 kA, **D1L**-QH delayed by 50 ms [note the different QH]  
 $U_{\text{short}} \sim 92 \text{ V}$ ,  $T_{\text{hot}} \sim 133 \text{ K}$

Missing a test at 9 kA and higher voltage  
 Will we observe spikes, or just one spike?  
 → 9 kA, **D1L**-QH delayed by 10 ms [note the different QH]  
 $U_{\text{short}} \sim 162 \text{ V}$ ,  $T_{\text{hot}} \sim 225 \text{ K}$

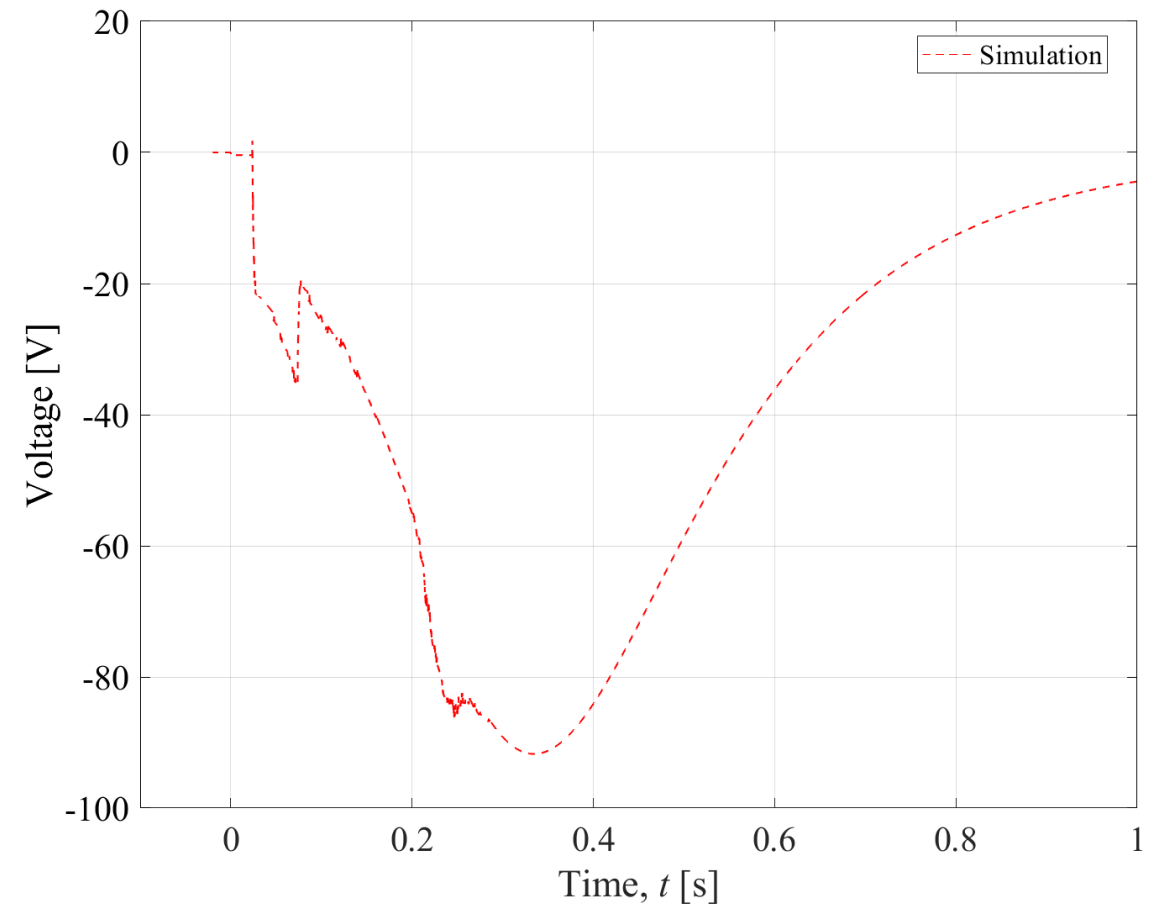
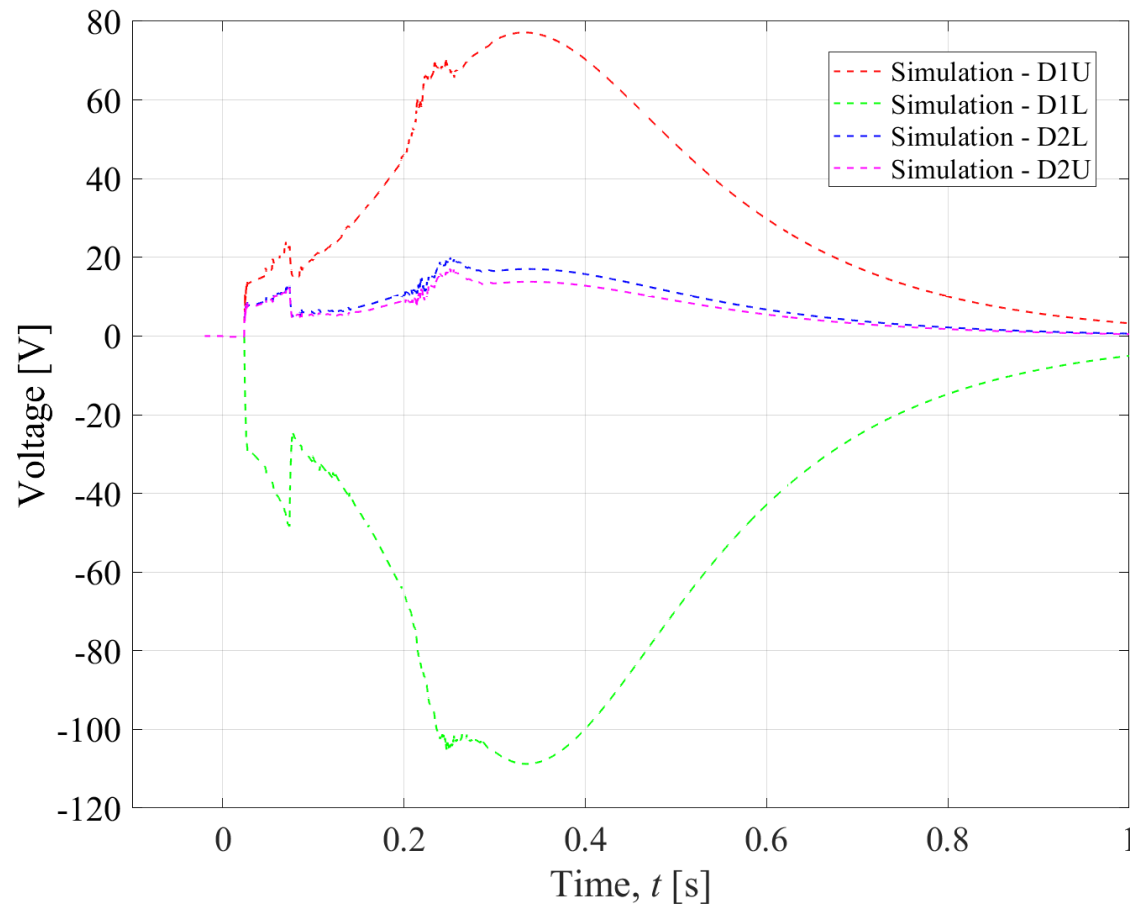
# Proposed test #1 – 11.85 kA, D1U-QHs delayed by 5 ms



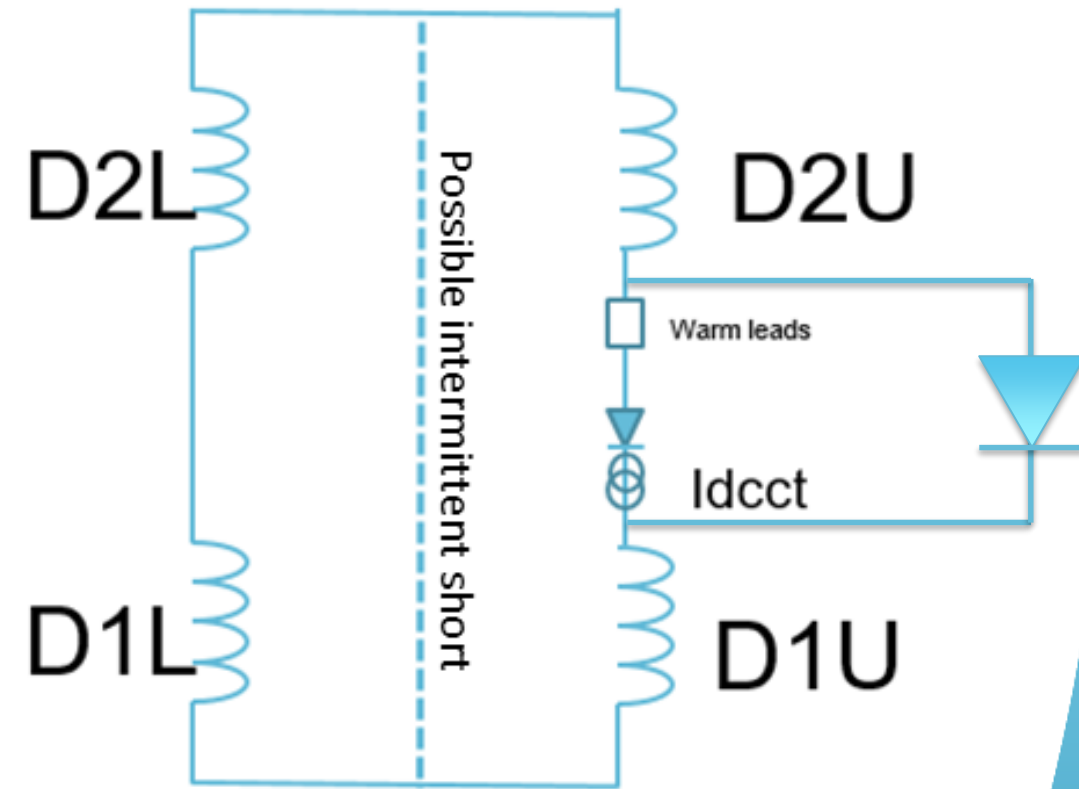
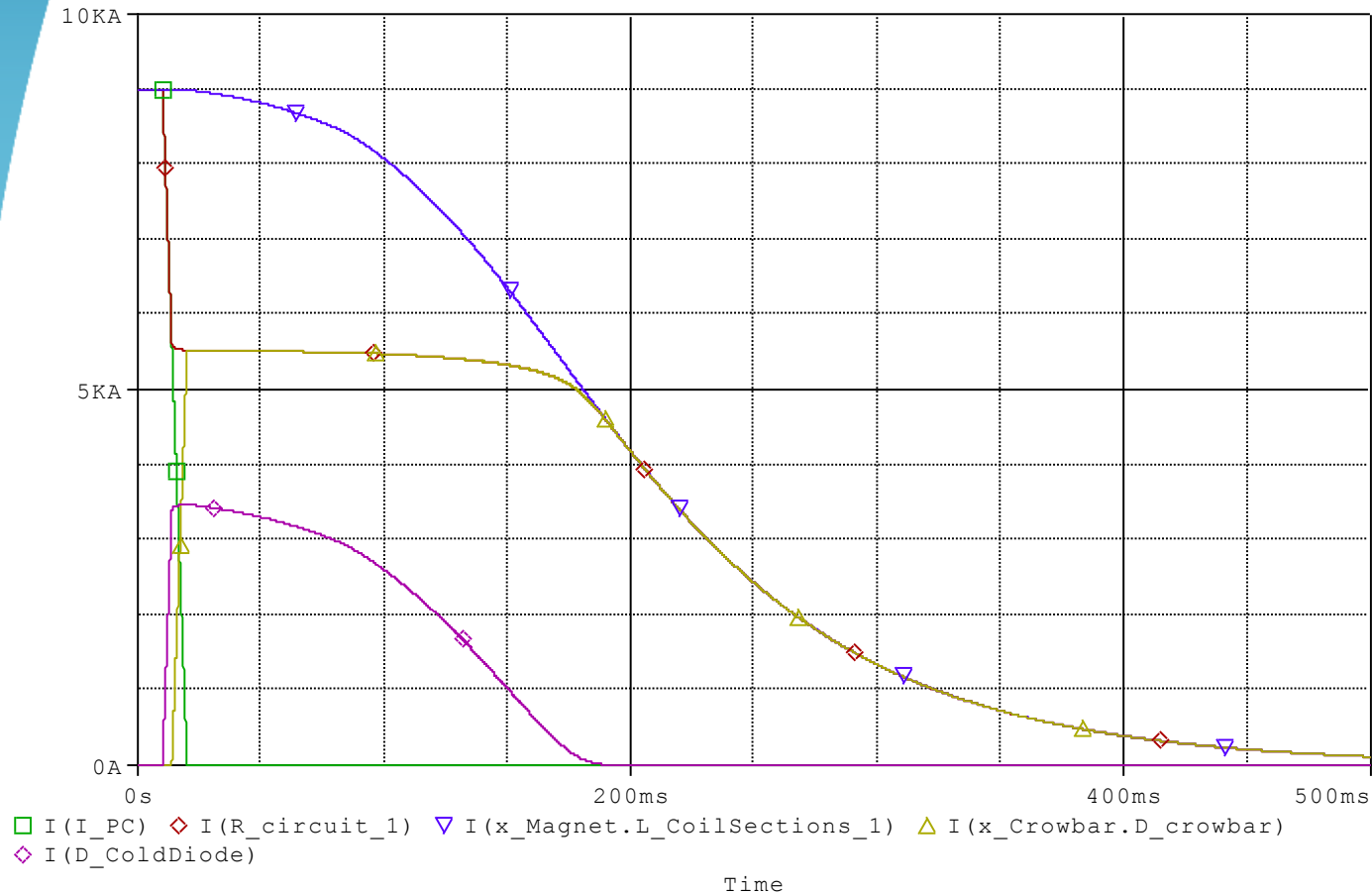
# Proposed test #2 – 9 kA, D1L-QHs delayed by 10 ms



# Proposed test #3 – 6 kA, D1L-QHs delayed by 50 ms

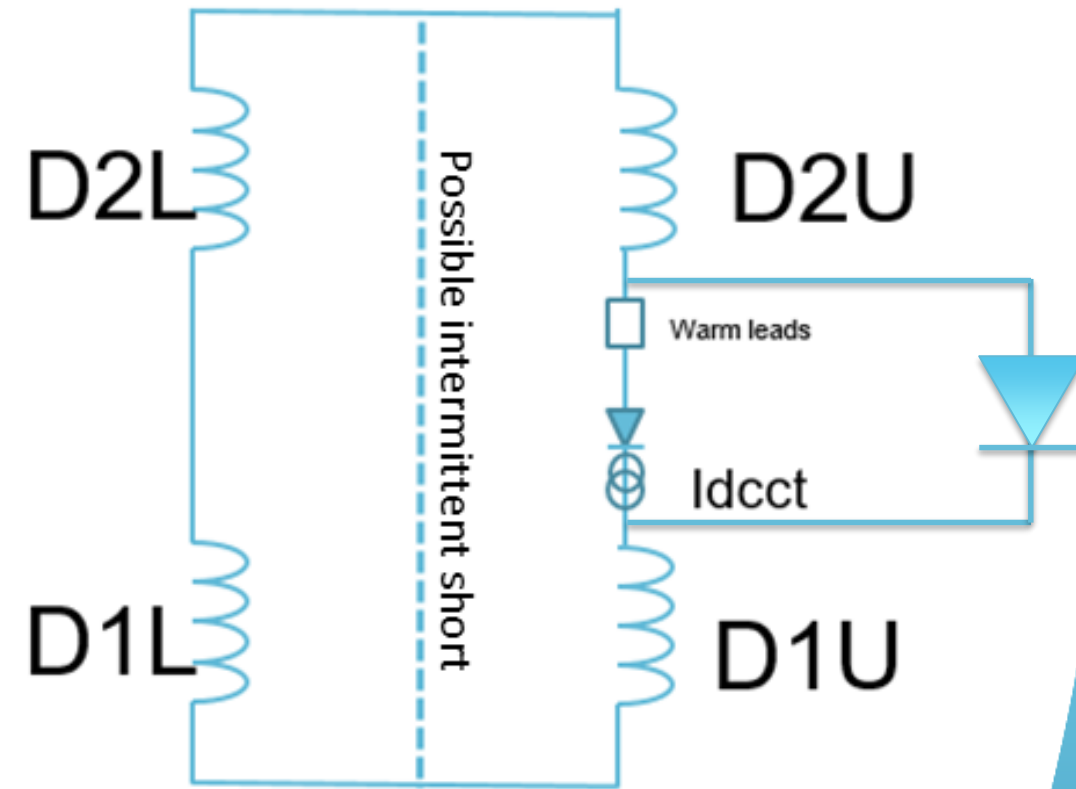
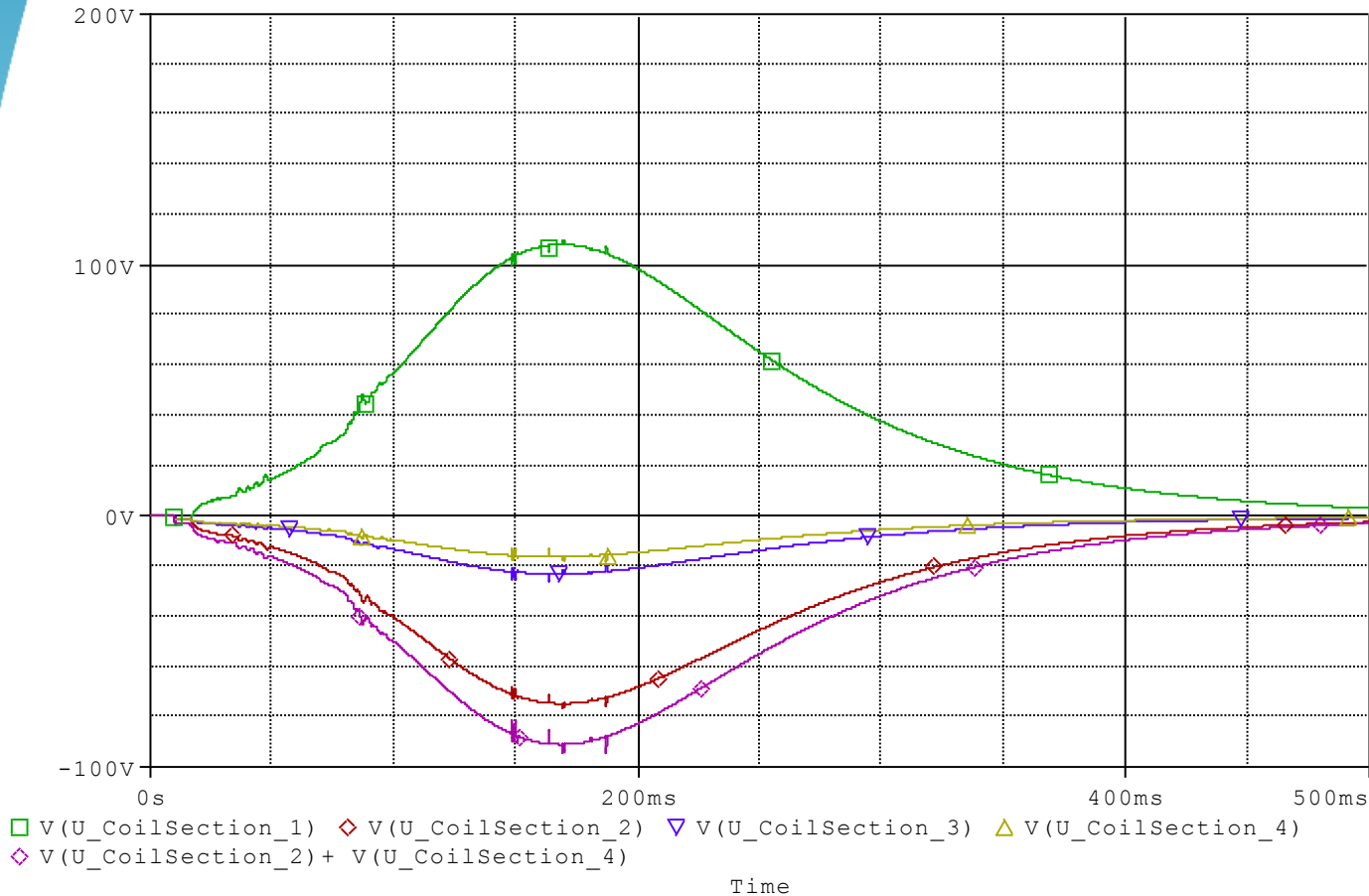


# Proposed test with inverted polarity of the power supply -1



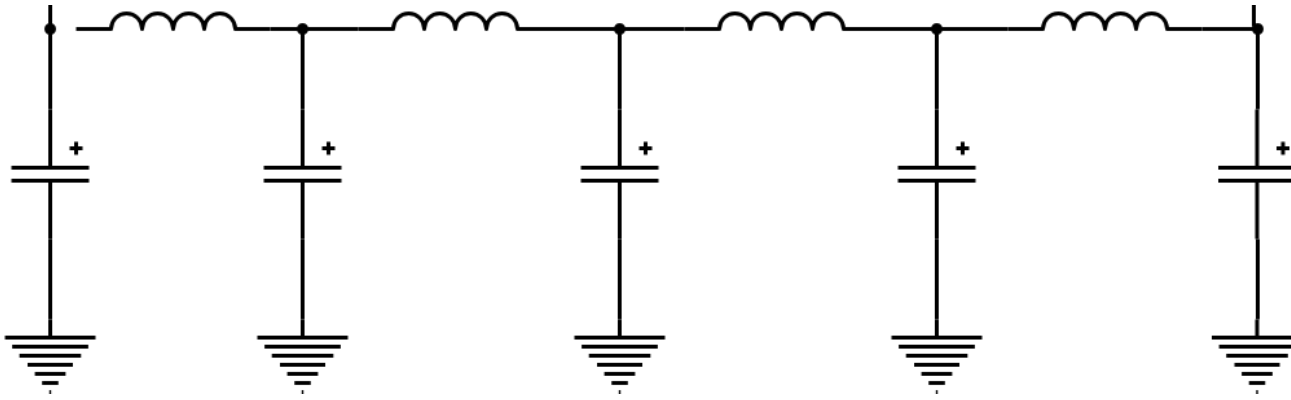
The Cold Diode will conduct. In this simulation, Cold Diode forward voltage remains at 6 V. In reality, it will drop to ~1 V and carry most of the current.  
Current recording will not be available.

# Proposed test with inverted polarity of the power supply -2

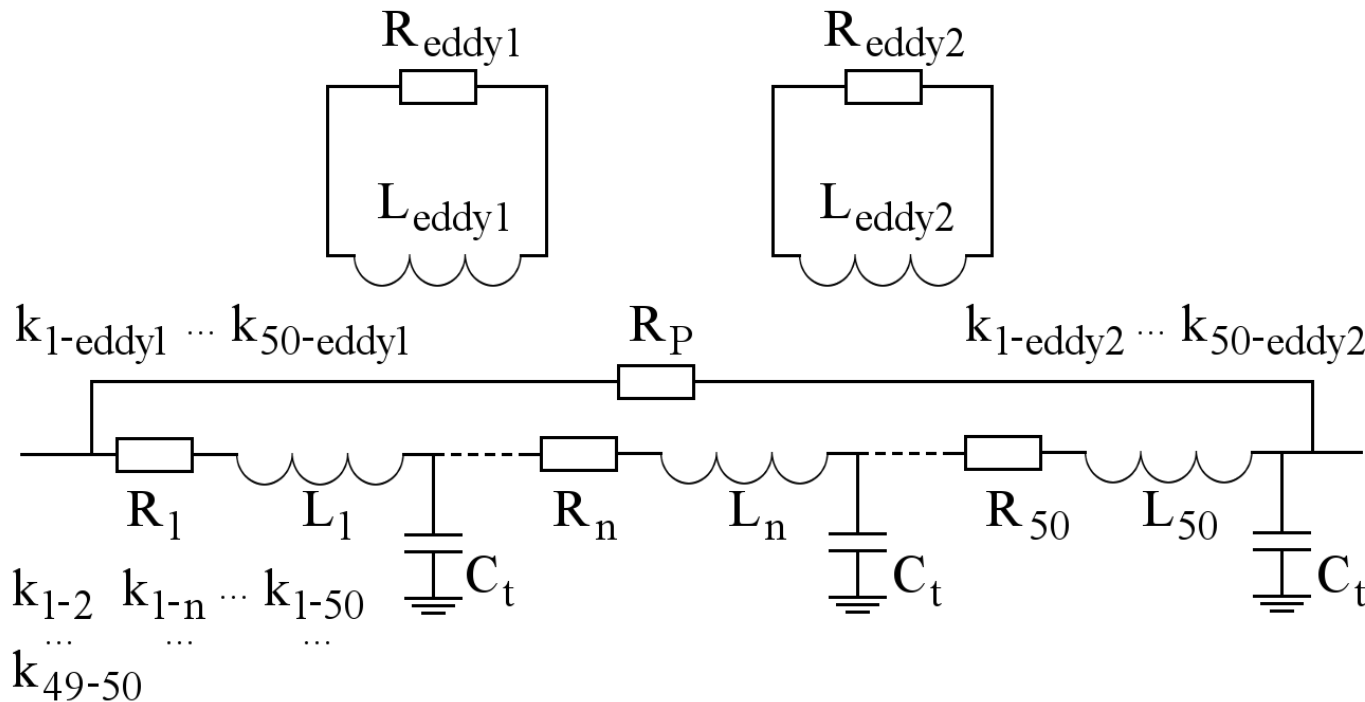


No significant change of the voltages across the four coils

# Frequency-domain model of a magnet



Simplified model



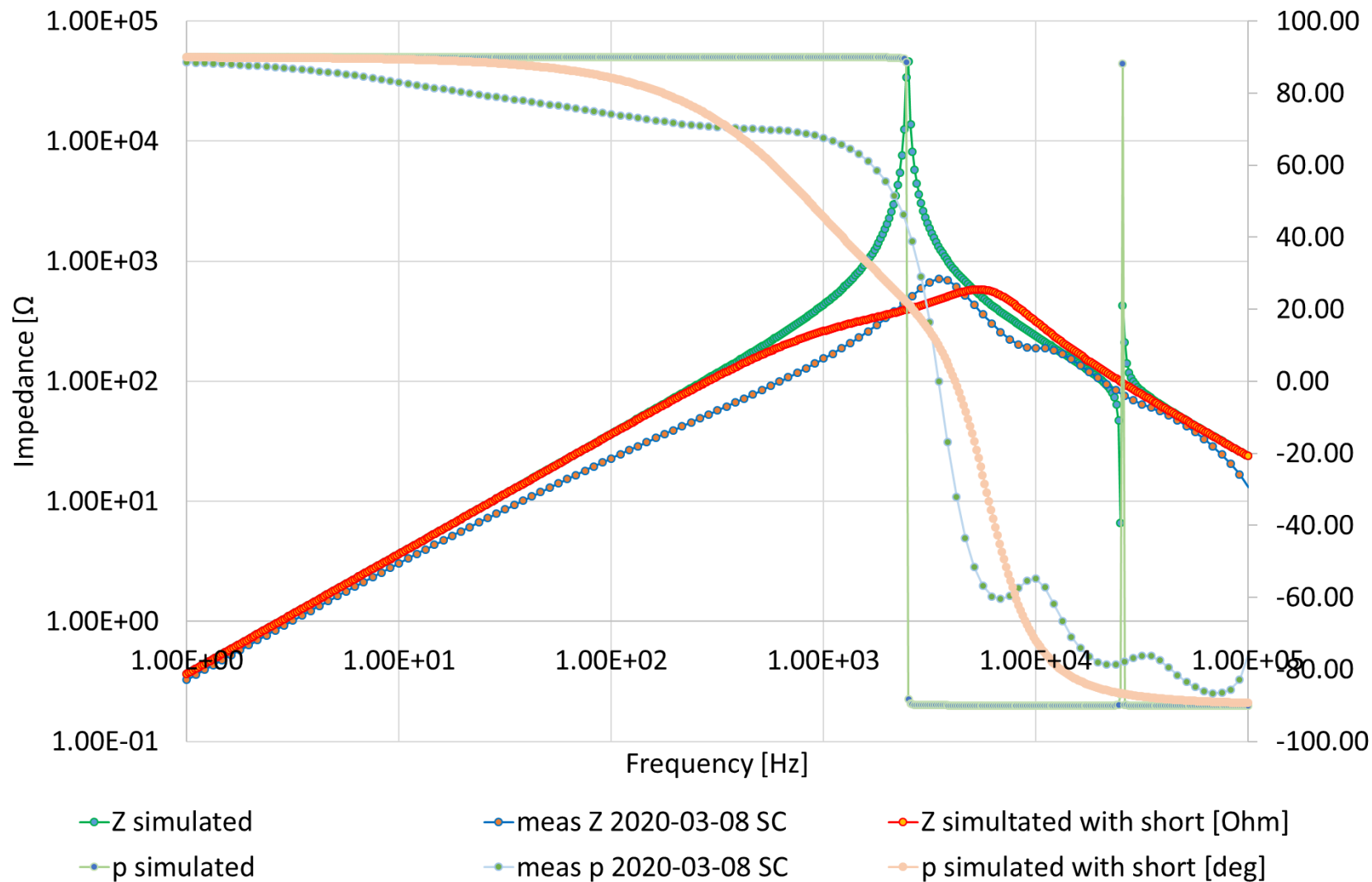
More complex model

- Eddy current effects
- Parasitic resistance effects

These parameters need to be estimated from the measurement of a magnet of the same type without short, or of the same magnet when we know there is no short

# Frequency transfer function

MBHA-001



## Disclaimer

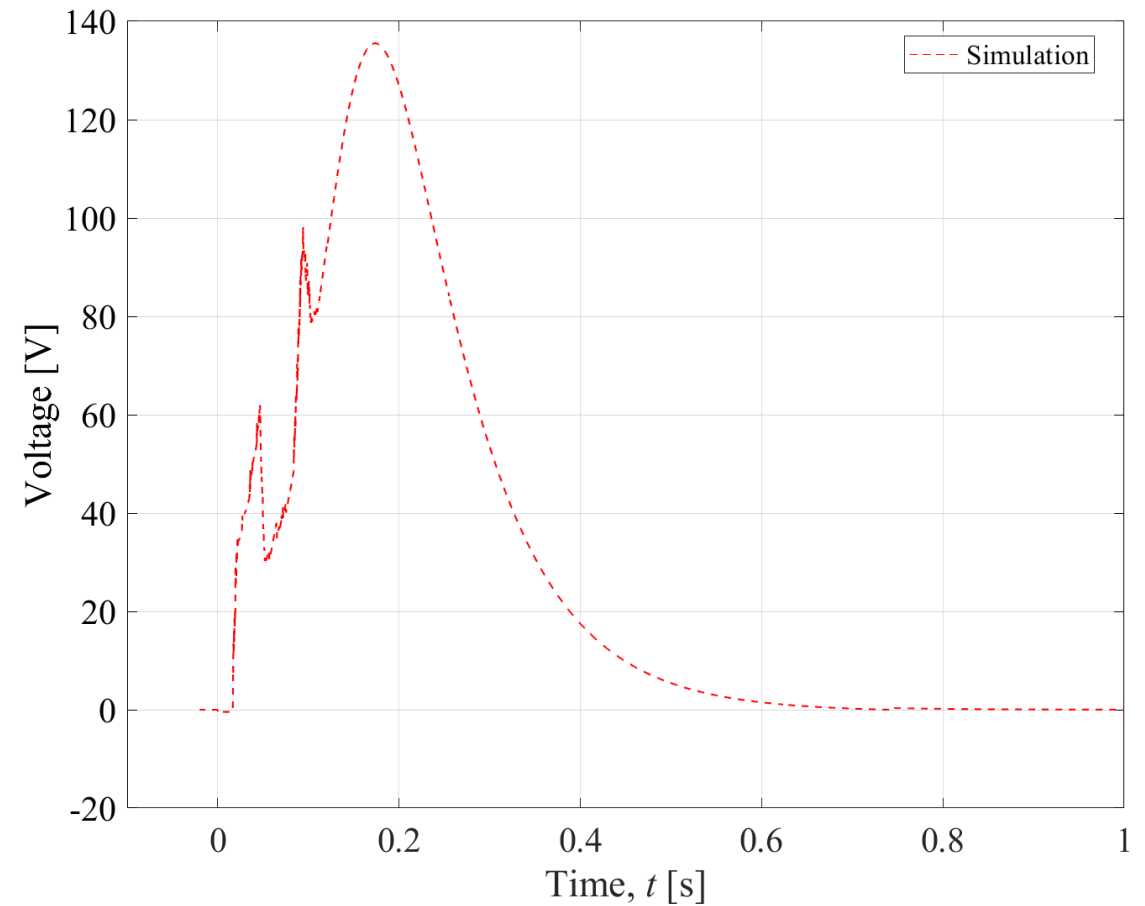
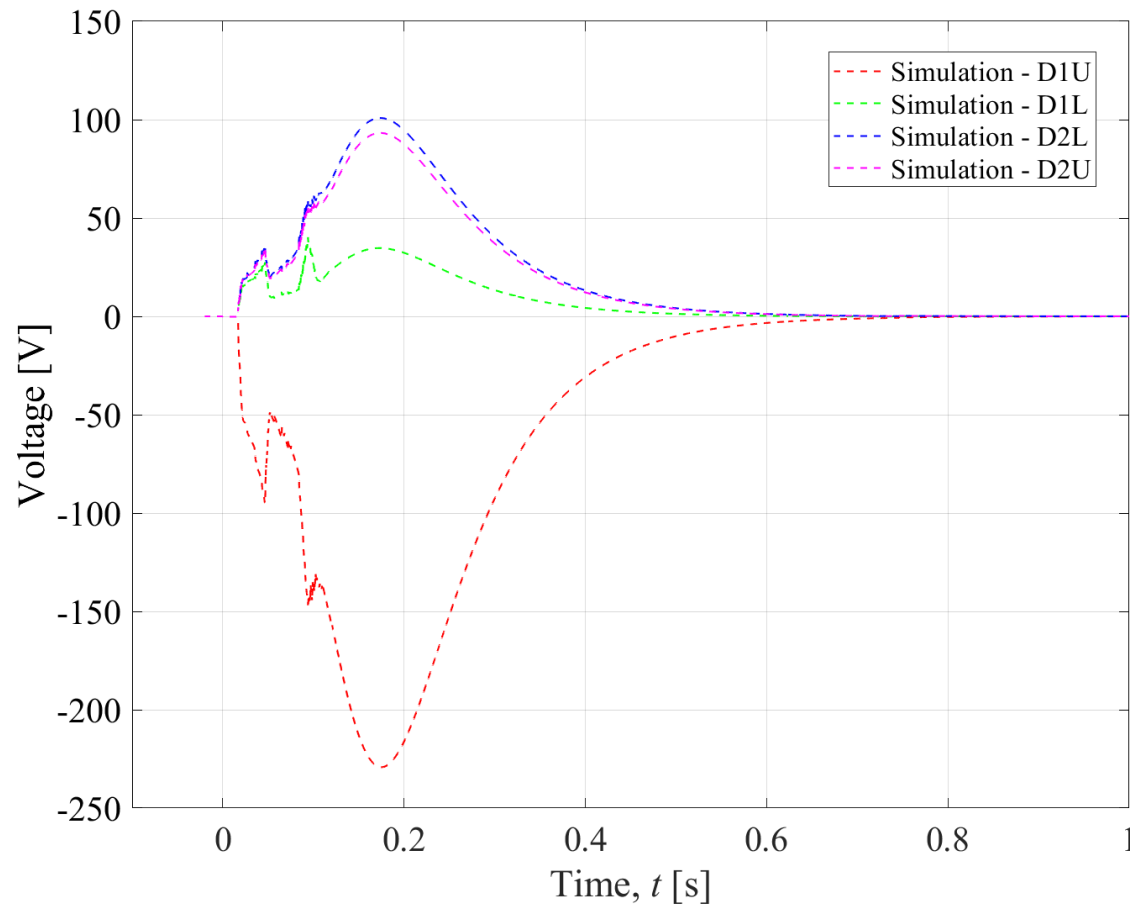
This is a qualitative example.  
The simulation does not necessarily support the short-circuit hypothesis.

After measuring a magnet known to be without shorts, the model can be validated and then used in a predictive way.

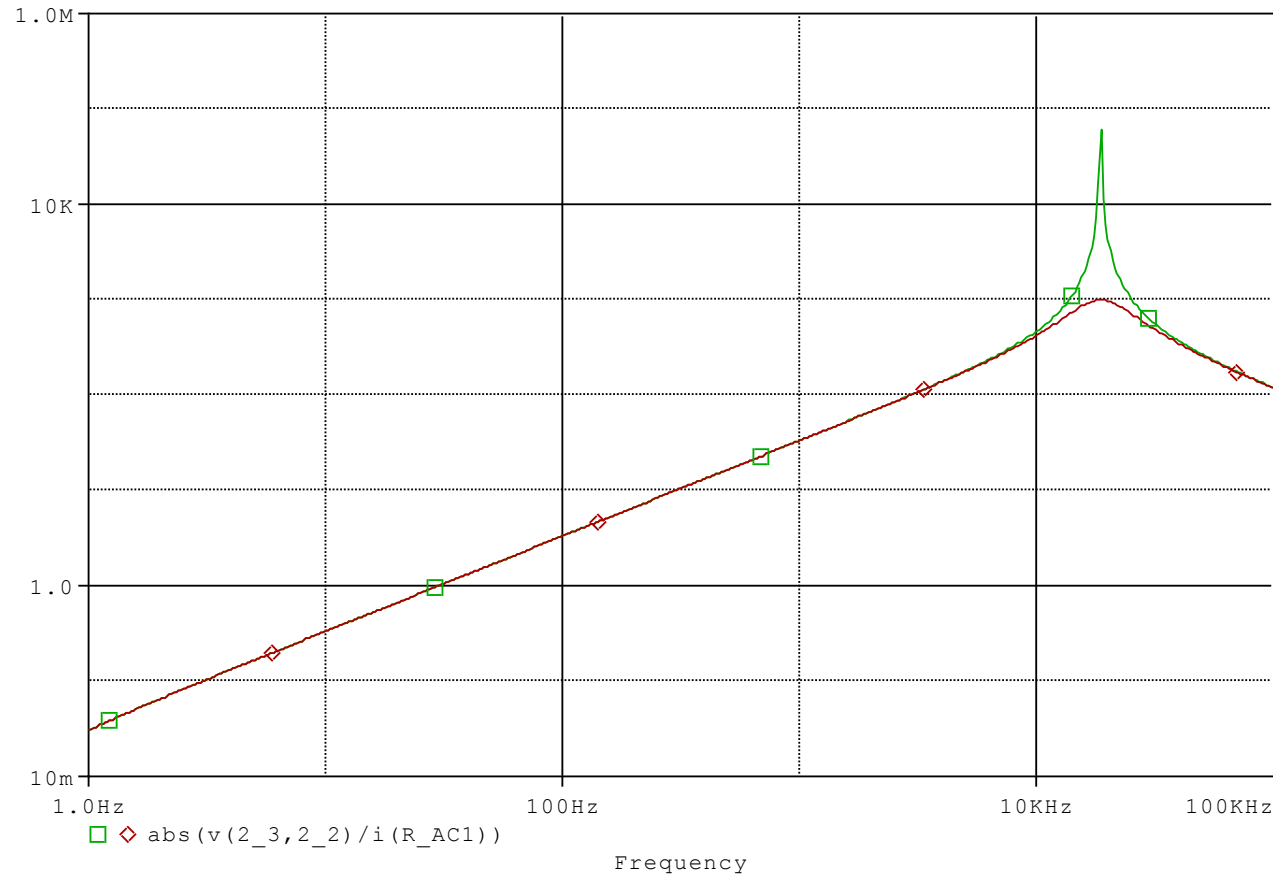
*Measurement data from  
J. Ludwin, M. Bednarek*

# Annex

# Proposed test #2 – 9 kA, D1U-QHs delayed by 30 ms



# Simulation of the proposed measurement of frequency TF

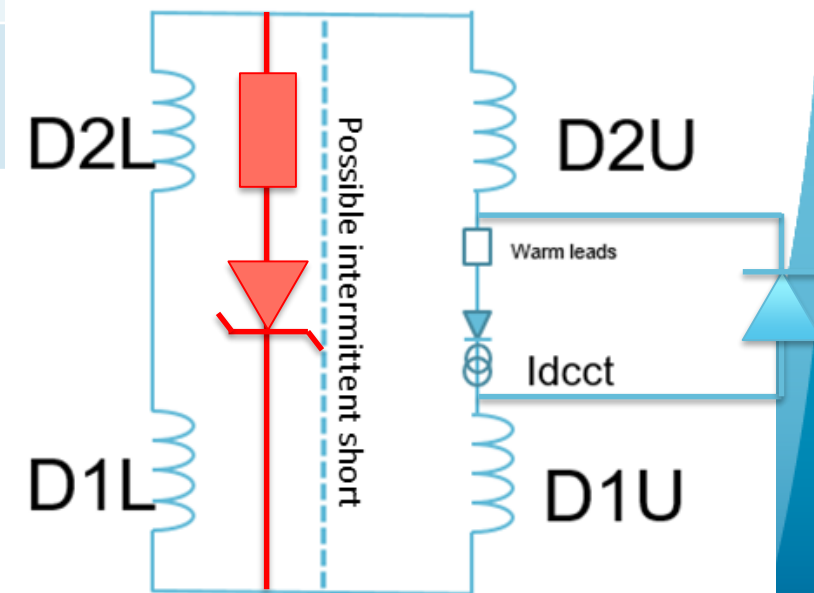


A 1 k $\Omega$  short across the two aperture mid-points would be visible in the frequency range 5 kHz - 50 kHz

These results are only qualitative

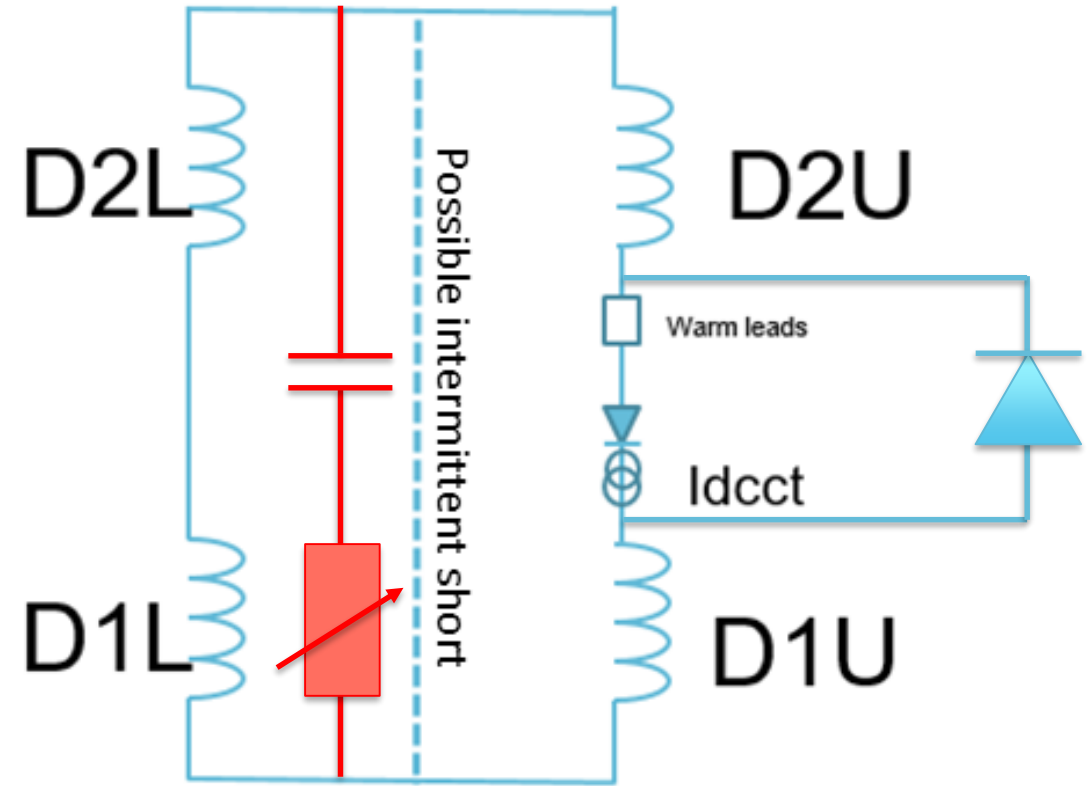
# Simulations of transient after installing a parallel path

Type of parallel path installed	Peak current through the parallel path [A]	Peak voltage across D1L+D2L [V]	We expect to reduce / eliminate spikes
100 $\Omega$ Resistor	0.9 A	90 V	no
10 $\Omega$ Resistor	9 A	90 V	yes
10 V Zener Diode + 0.1 $\Omega$ R	380 A	38 V	yes
10 V Zener Diode + 1 $\Omega$ R	72 A	80 V	yes
10 V Zener Diode + 5 $\Omega$ R	16 A	90 V	yes

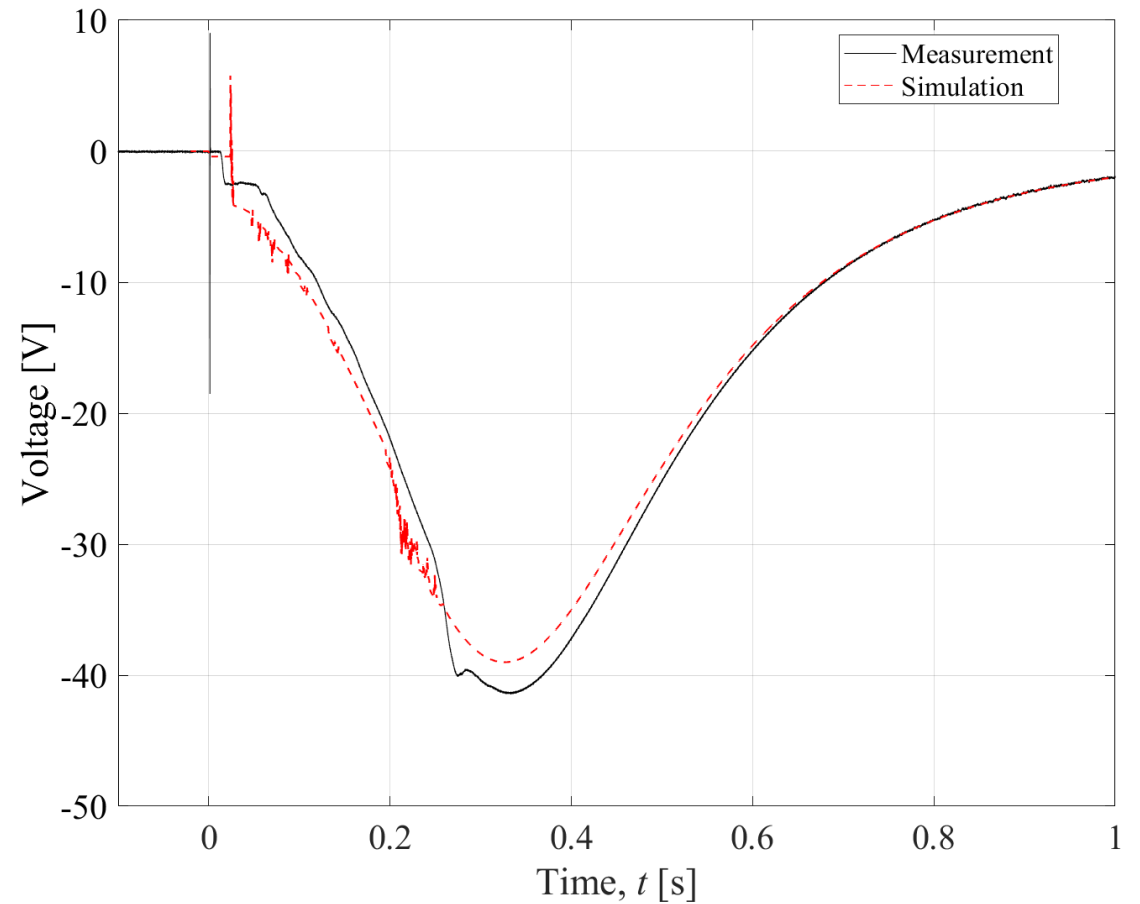
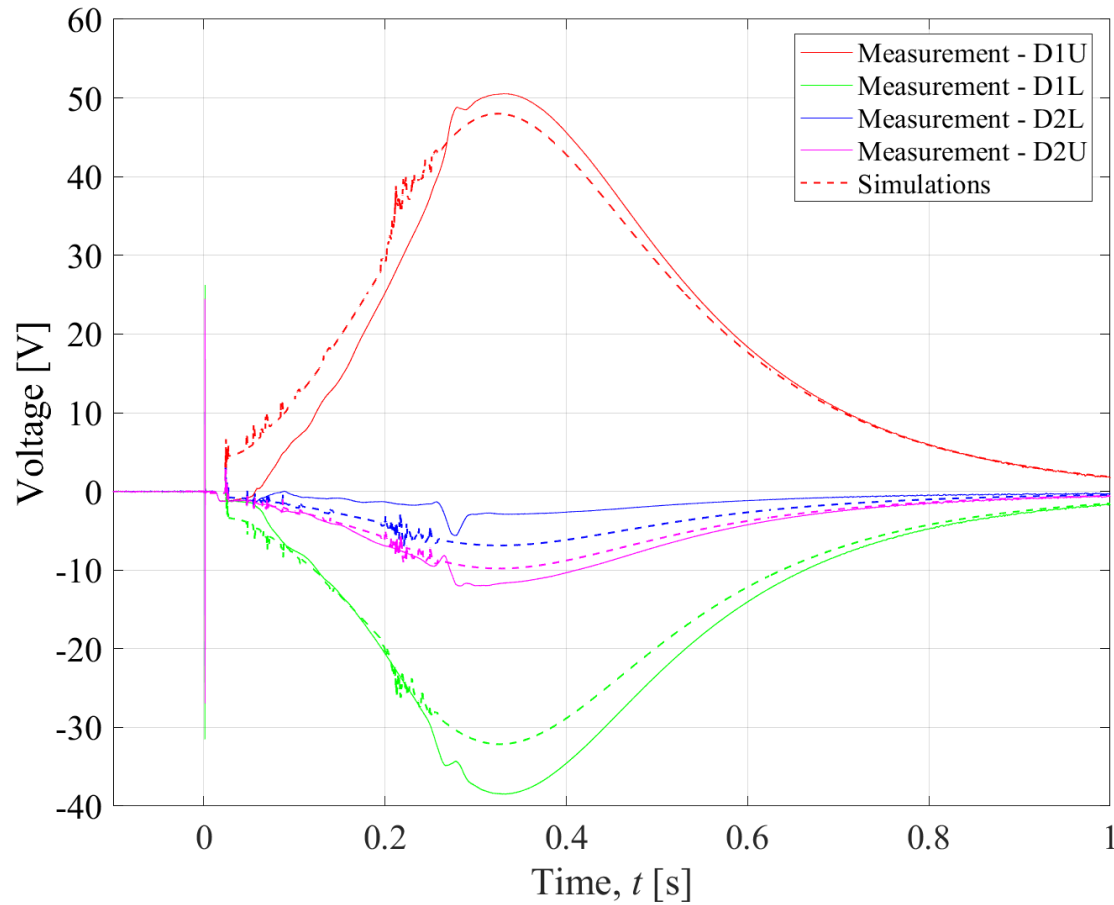


# Simulations of transient in case of capacitive coupling

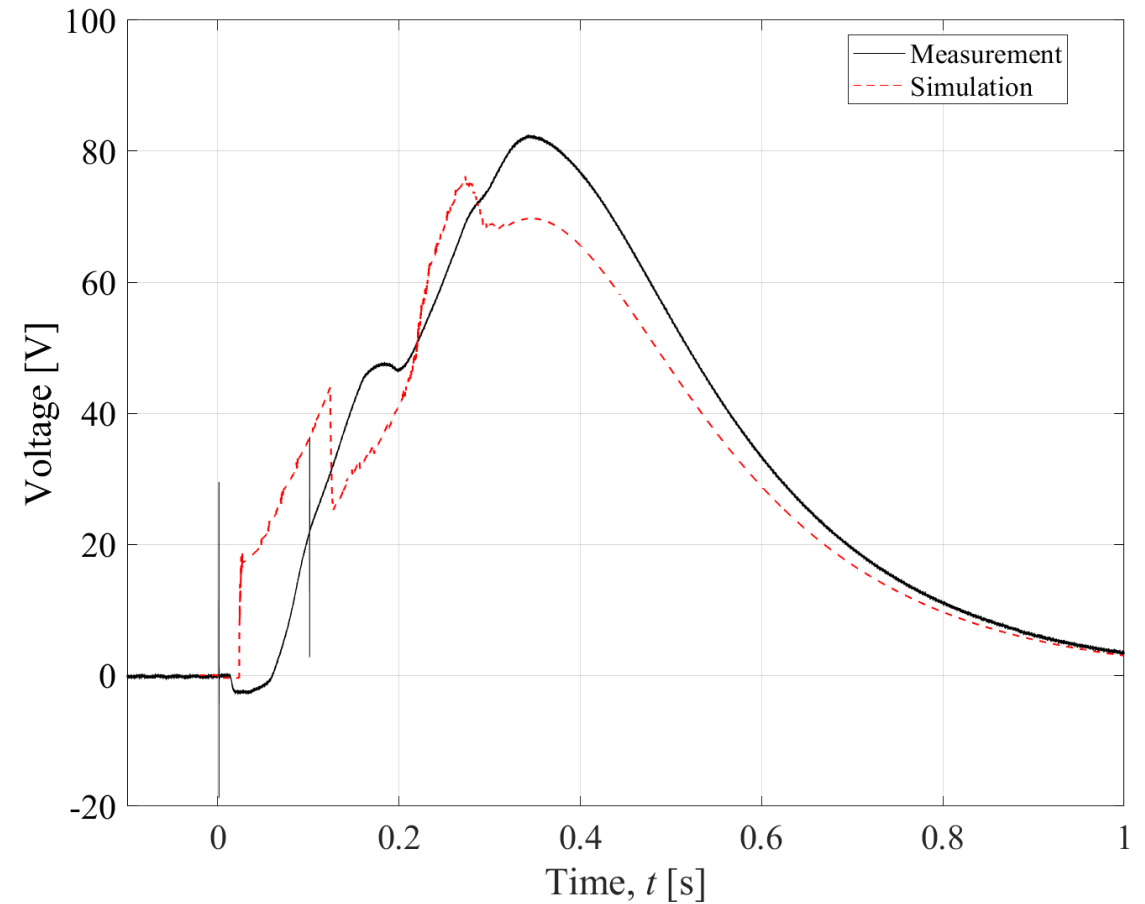
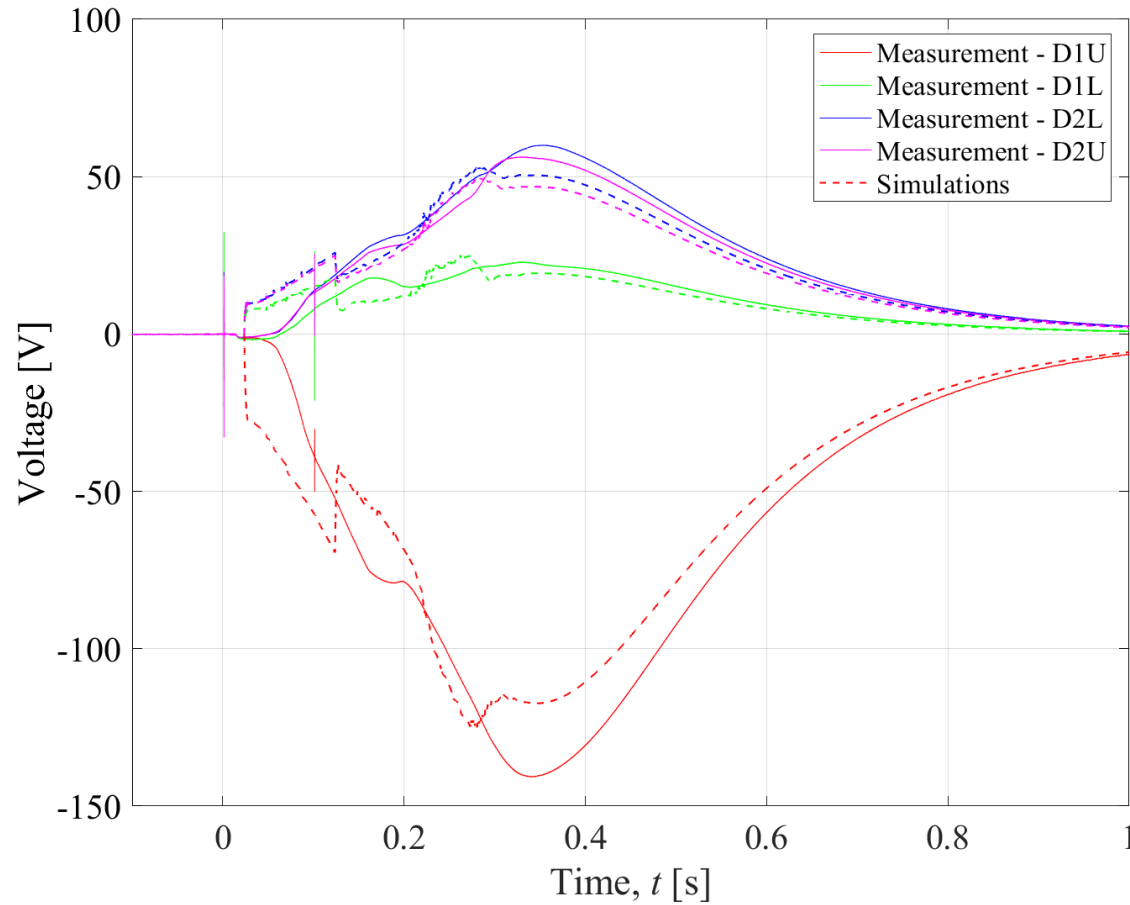
- Idea proposed by Bernardo: not a short, but intermittent capacitive coupling
- I was able to reproduce spikes of a few V across the coils only by assuming a massive capacitance between the mid-point of D1 and D2
  - I used 1  $\mu\text{F}$  and 100  $\mu\text{H}$
- Note: estimated parasitic capacitance for the entire magnet is about 100 nF



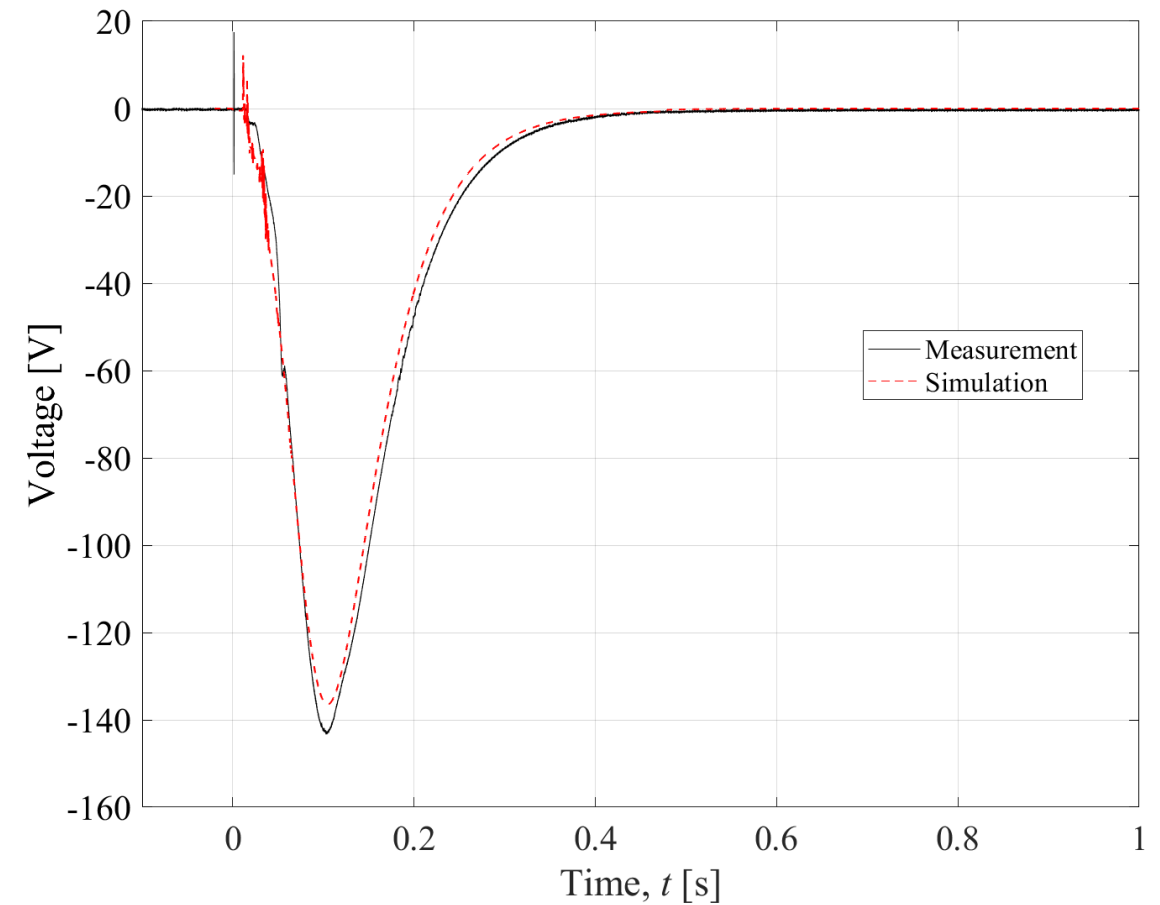
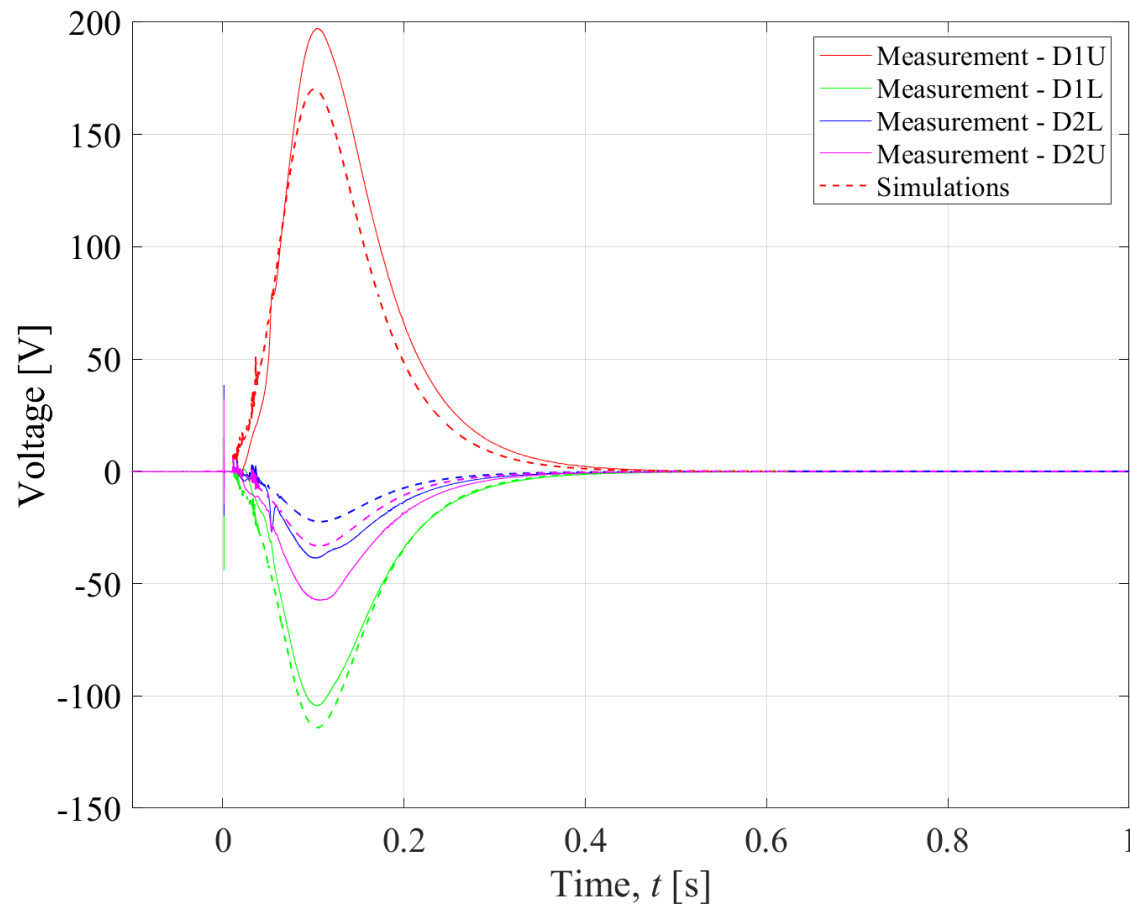
# Simulation cpr Measurement of QH discharge at 6 kA



# Simulation cpr Measurement of discharge at 6 kA with D1U-QH delayed by 100 ms

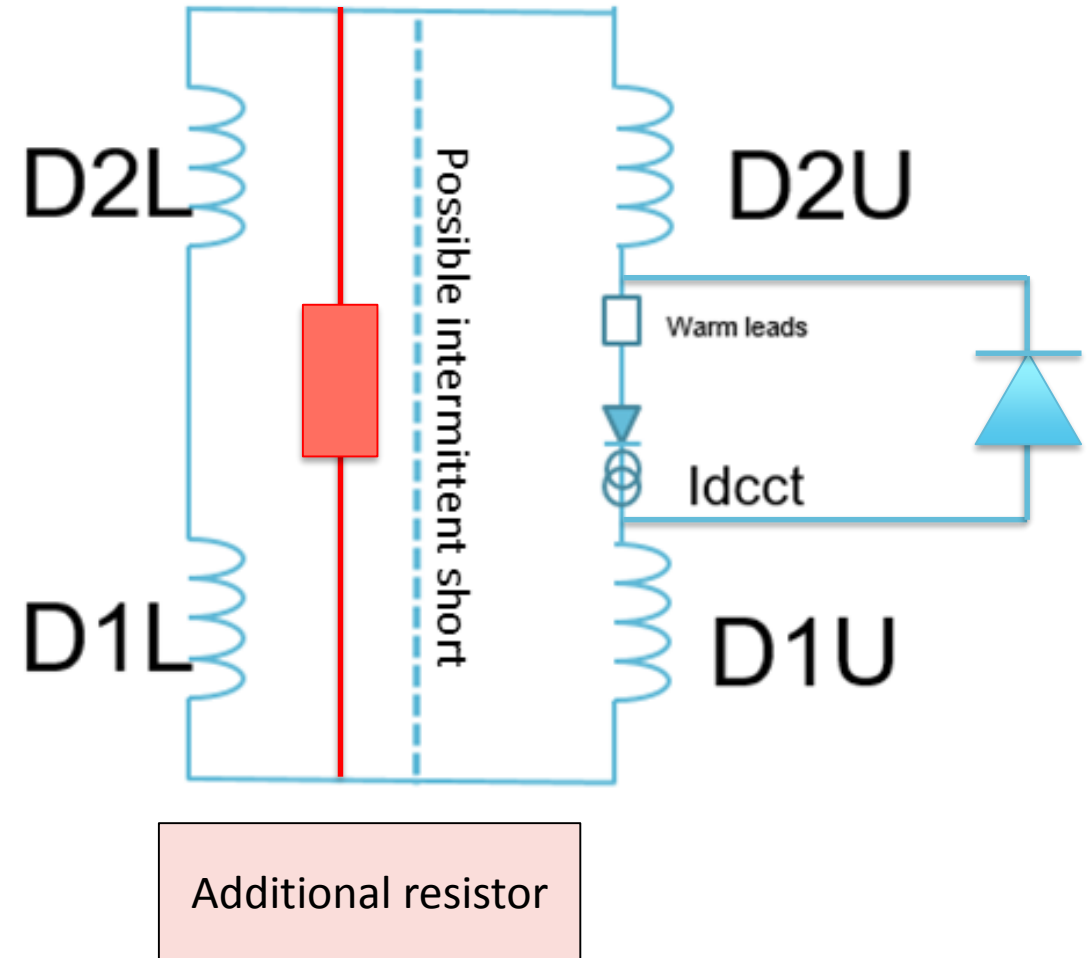


# Simulation cpr Measurement of discharge at 11.85 kA without QH delay



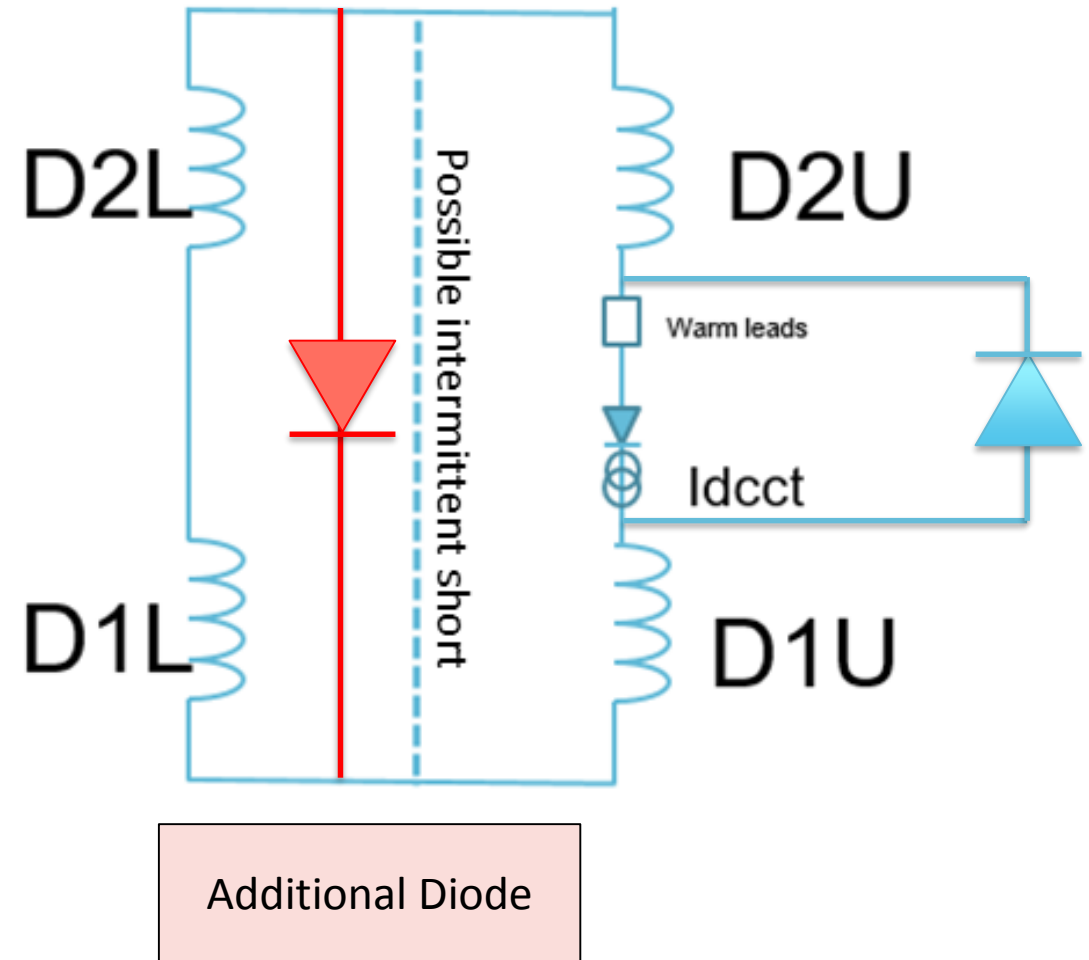
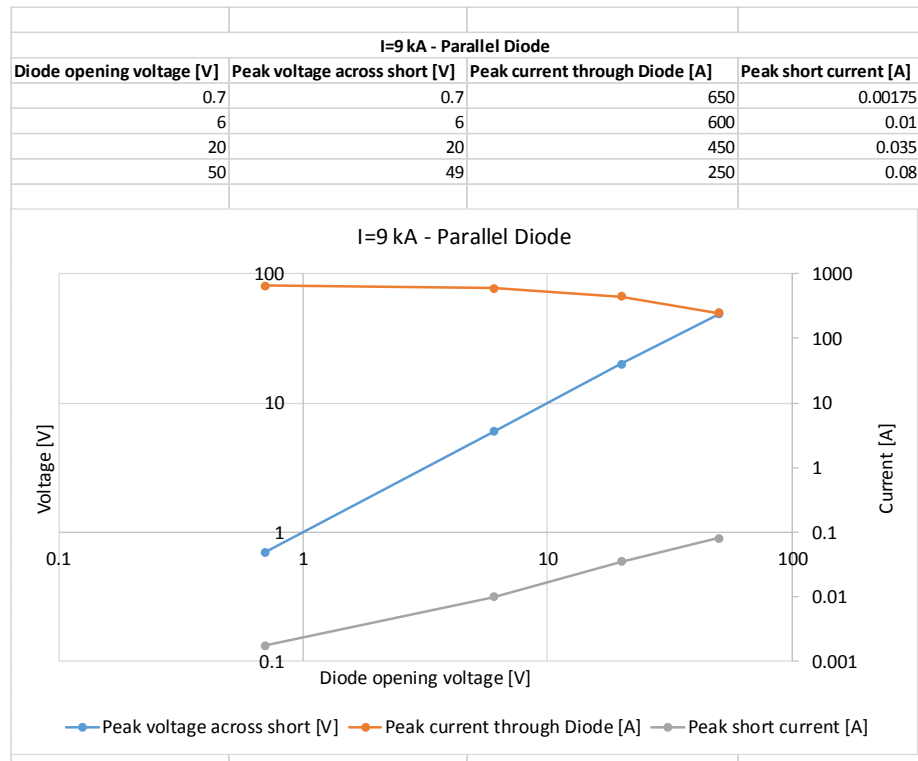
# Option #1: Installing a resistor across the taps

- Installing a resistor across the taps should reduce the spike occurrence (if parallel resistor  $< 10\ \Omega$ )
- The current through the short, nor the power deposited in the short are unchanged
- This is because the presence of the parallel resistor does not change the voltages across the four coils. So the same voltage would be applied across the same changing resistance.
- Same current through the short  $\rightarrow$  Same power deposition, same risk of damage



# Option #2: Installing a resistor + Diode across the presumed short

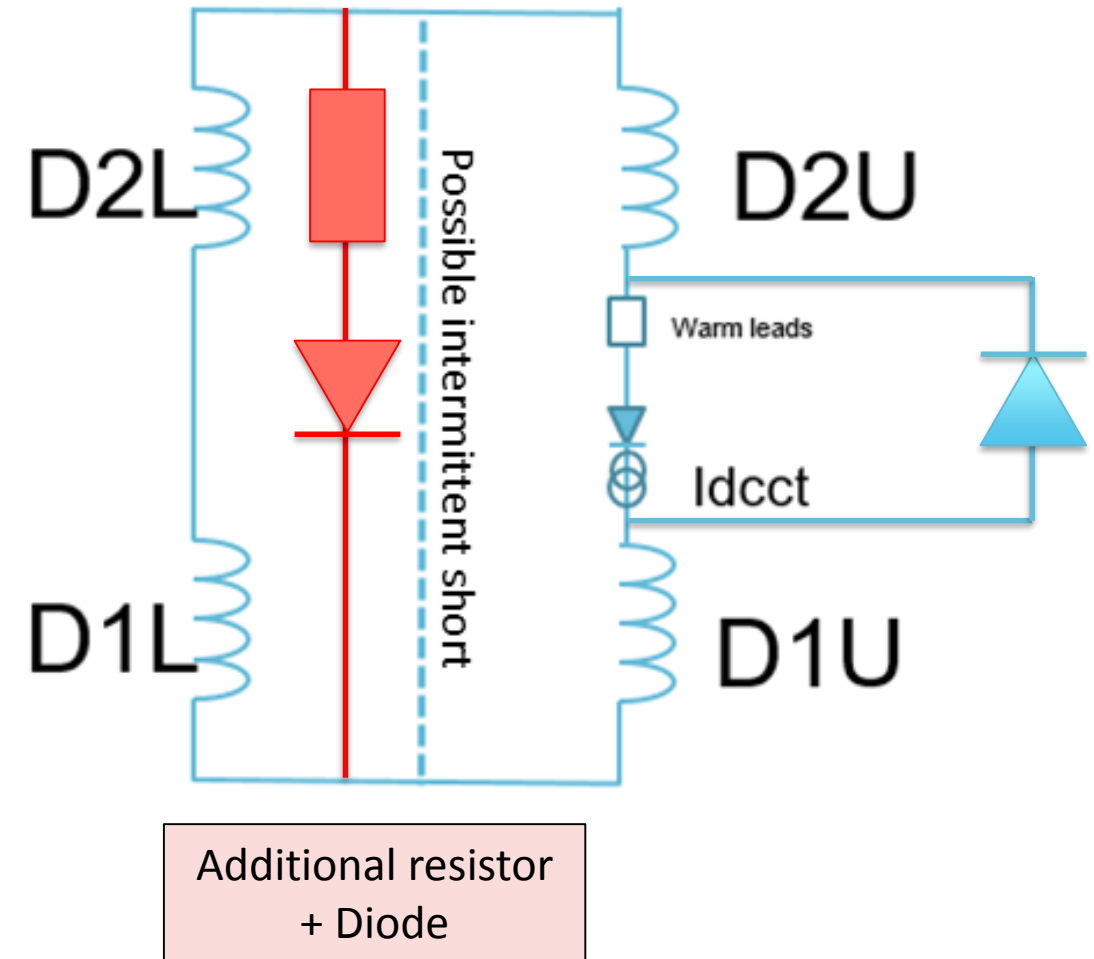
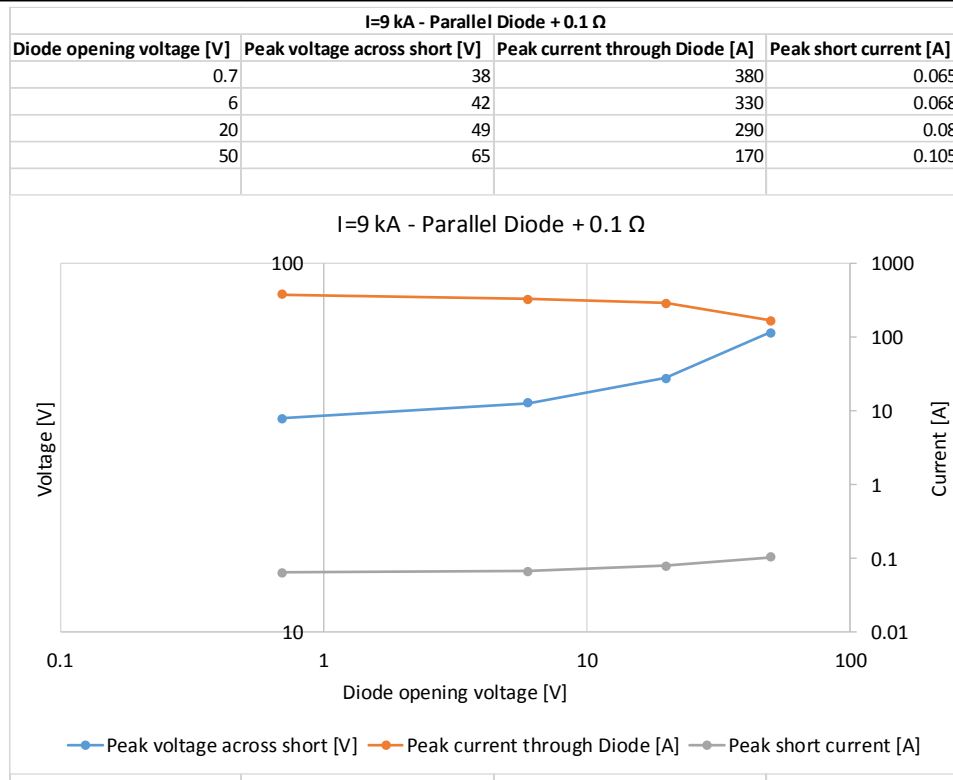
- Installing a Diode across the taps where we believe there is the short
- Polarity is selected to limit the voltage across D1L+D2L [**see diagram for the correct polarity**]
- Voltage across the short effectively suppressed
- But large current (250-650 A) through the Diode
- And hence unbalanced currents in the magnet coils



Courtesy of G. Willering

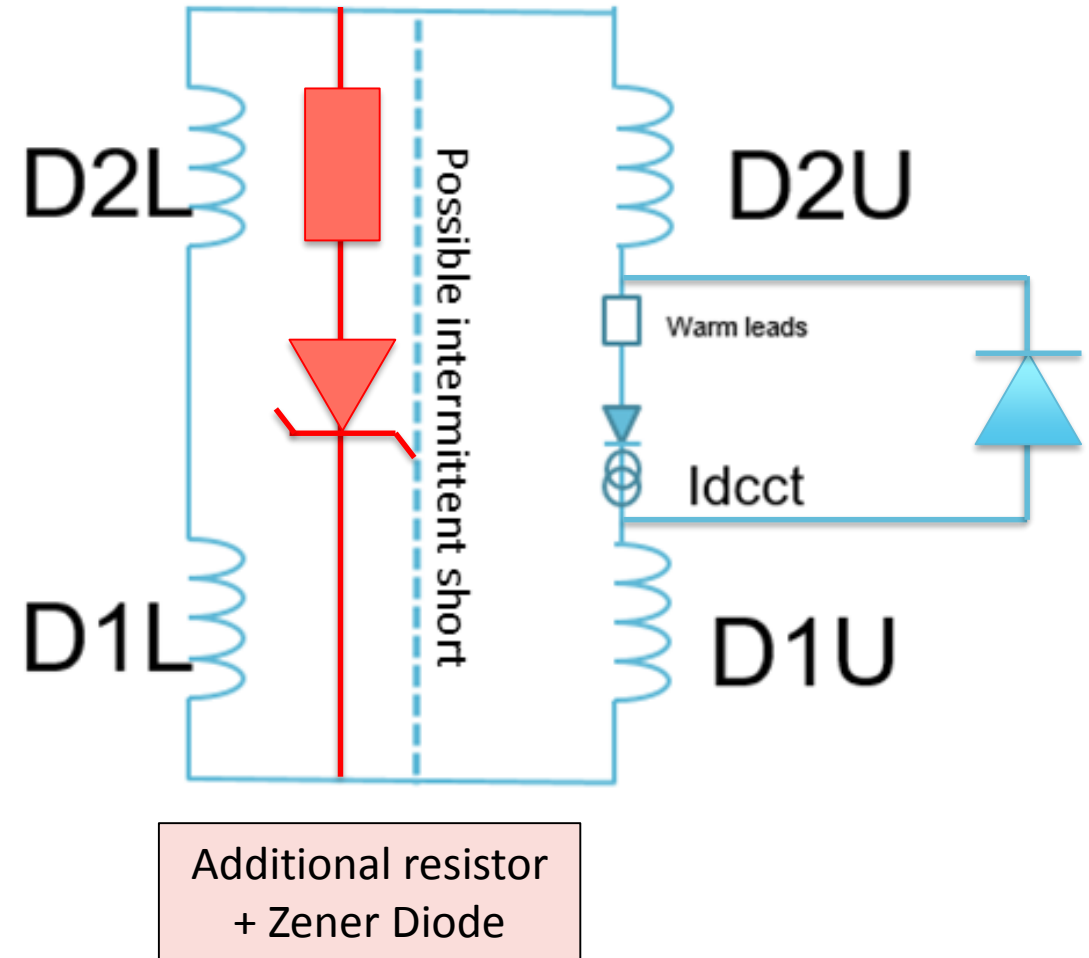
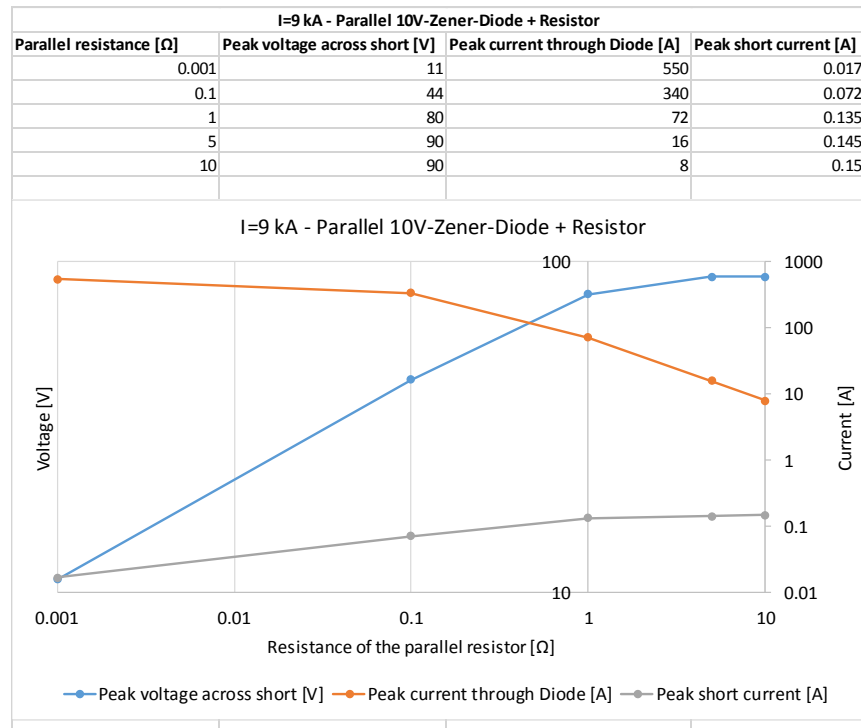
# Option #3: Installing a Resistor+Diode across the presumed short

- Diode polarity is selected to limit the voltage across D1L+D2L [**see diagram for the correct polarity**]
- A small resistor of  $0.1\ \Omega$  has already a significant effect: current through the Diode reduced, but voltage across the short is suppressed less effectively
- For resistance  $\geq 1\ \Omega$ , Diode can't suppress the D1L+D2L voltage effectively



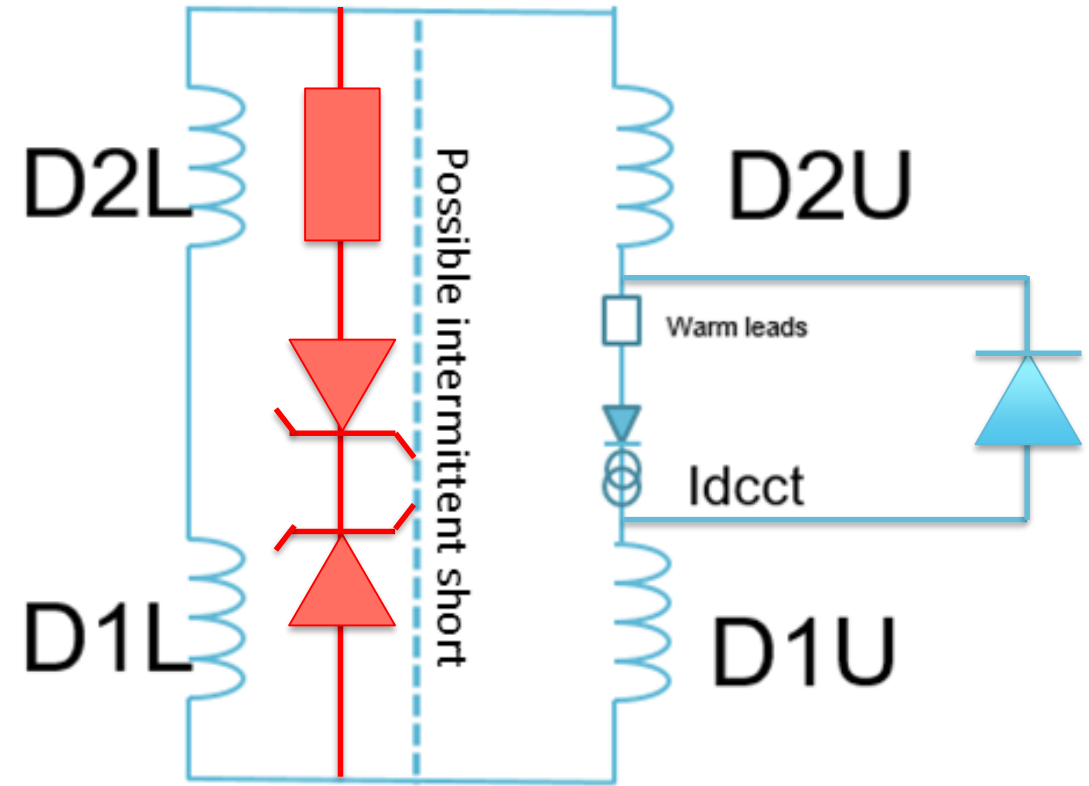
# Option #4: Installing a Resistor+ZenerDiode across the p. short

- Zener Diode [voltage across the Diode clamped between -10 V and +10 V]
- Since during the simulated transient the voltage across D1L+D2L has always the same polarity, using a Zener Diode does not change the results
- However, using a Zener Diode could reduce the peak voltage in other transients [if the internal voltage distribution changes]



# Option #5: Installing a Resistor+2\*ZenerDiode across the p. short

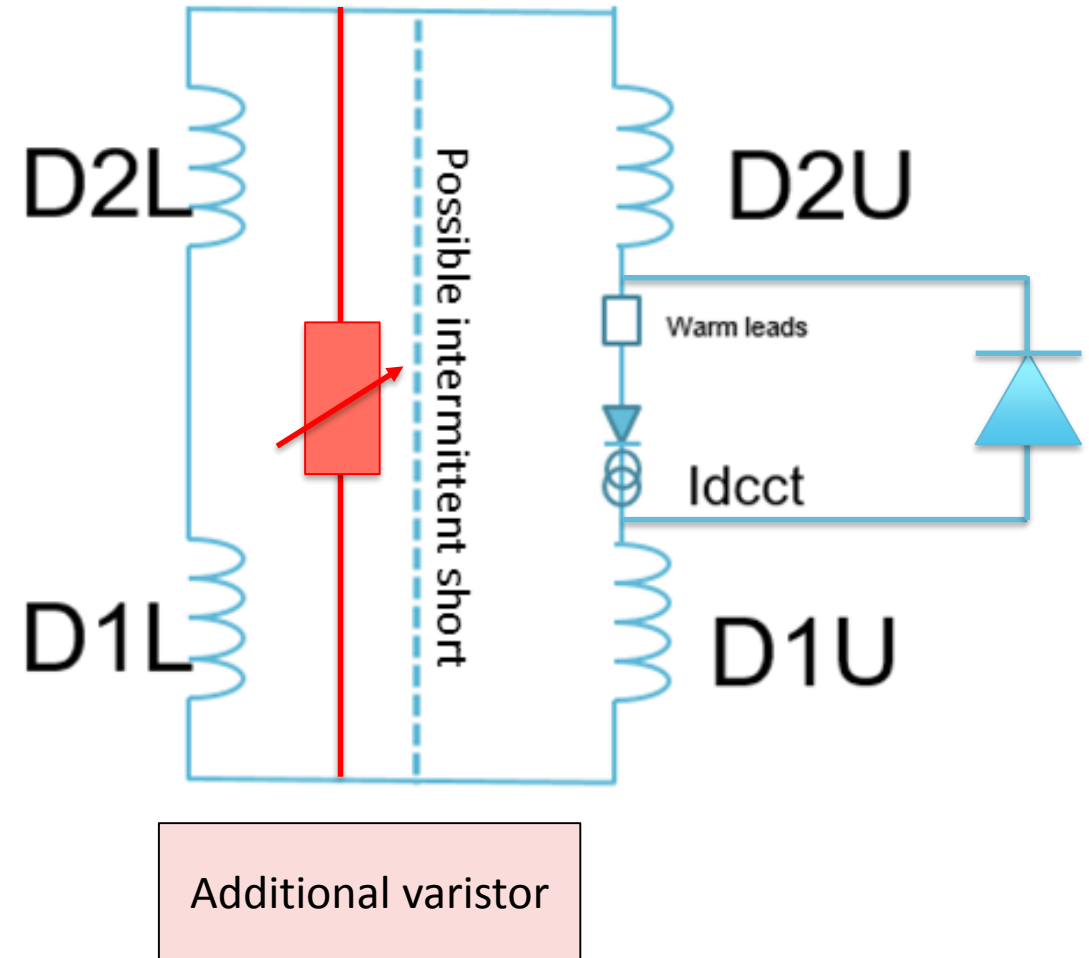
- In this configuration, I don't see any current flowing through the parallel branch during the transient
- So it does not affect the transient



Additional resistor  
+ 2\*Zener Diode

## Option #6: Installing a Varistor across the p. short

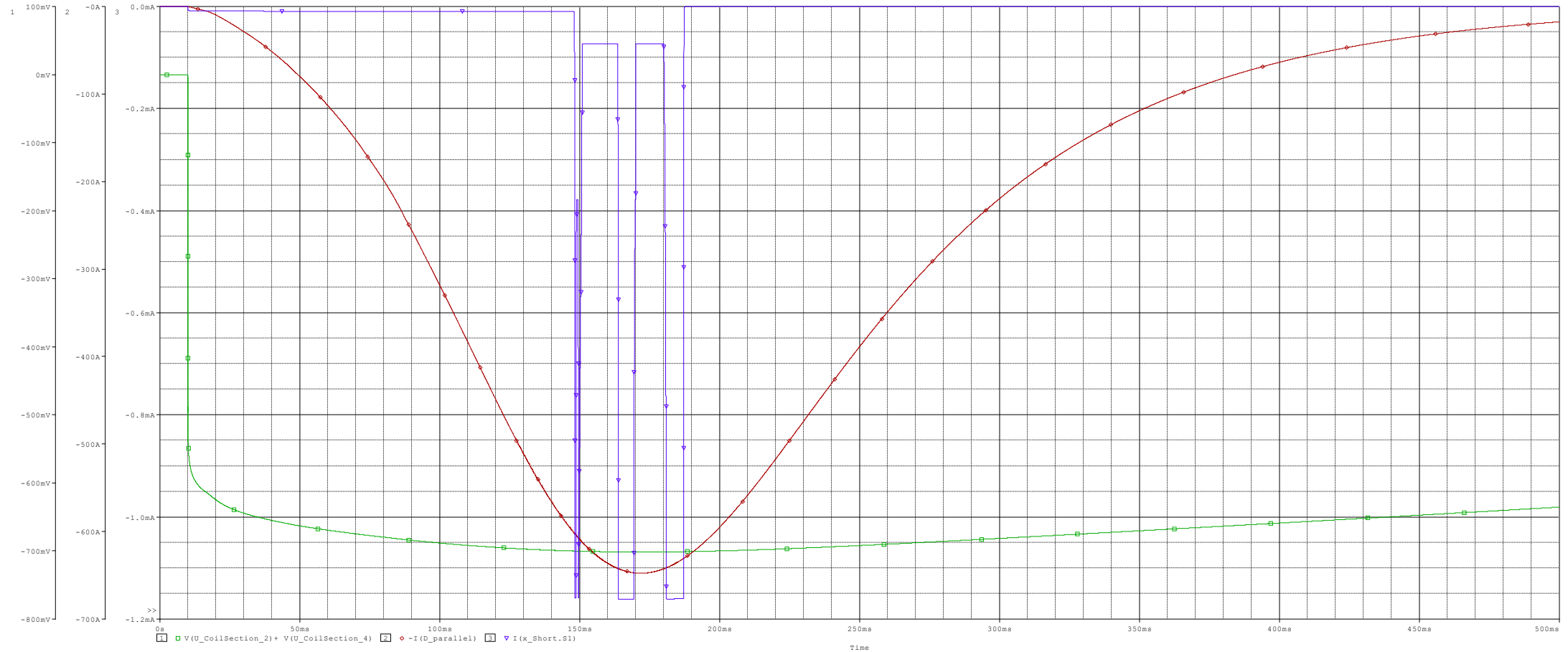
- I didn't run an actual simulation
- Conceptually, it would have a similar effect with respect to the Zener Diode
- However, it would be more complex to analyze/model because of the not very well known characteristics – it would add unknowns



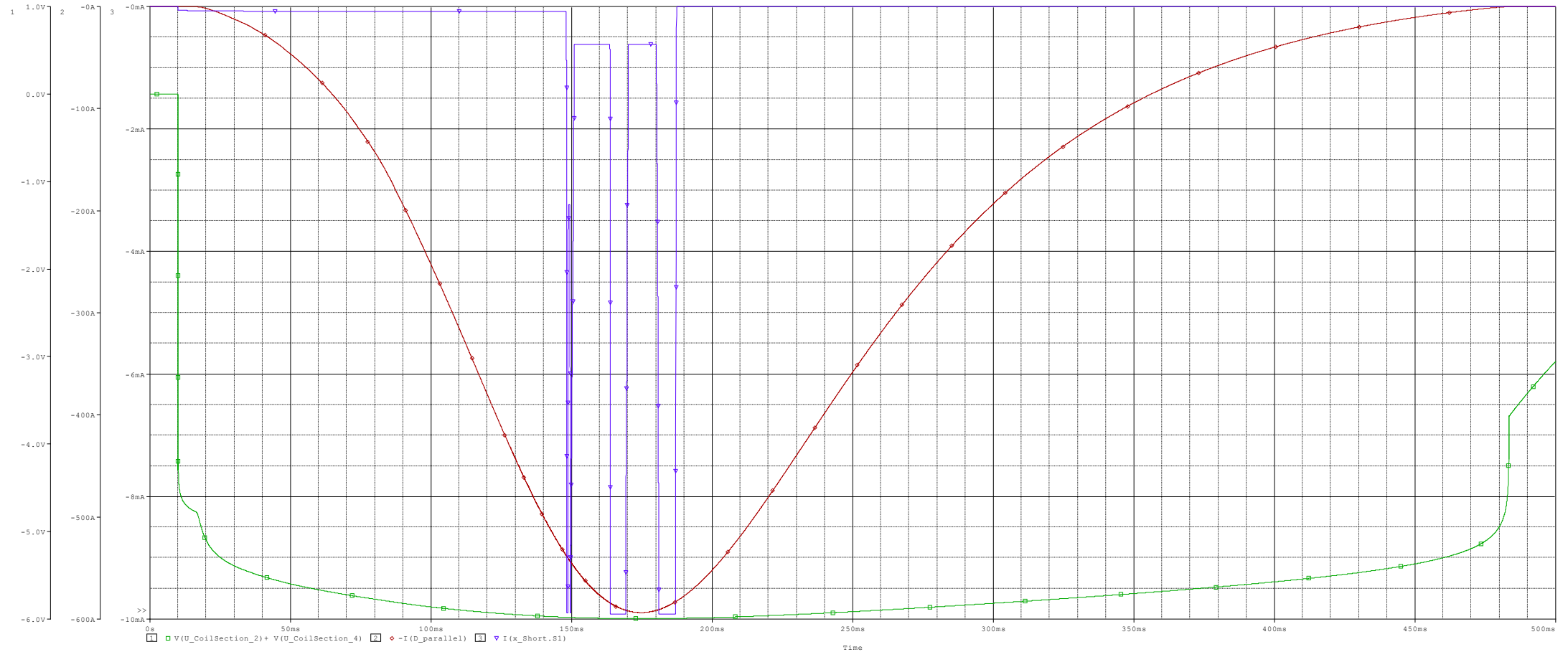
# Conclusion

- Solution with a Diode can effectively limit the voltage across D1L+D2L [presumed short position]
- This should lead to a reduction/elimination of the voltage spikes
- However, to be effective the Diode must carry significant current (250-650 A)
  - This current would pass through taps
  - Also, the currents in the upper/lower coils would be different during the discharge
- A small resistance of  $0.1\ \Omega$  in series to the additional Diode has already a significant effect: current through the Diode reduced, but voltage across the short is suppressed less effectively
- For resistance  $\geq 1\ \Omega$ , Diode cannot suppress the voltage across D1L+D2L because the voltage drop across the resistor is higher than the fixed voltage drop imposed by the Diode
- A solution with a 0.7 V Diode in series to a  $20\ \Omega$  resistor would not limit the voltage across D1L+D2L, nor the current through the short, but could reduce the spikes on the coil voltages

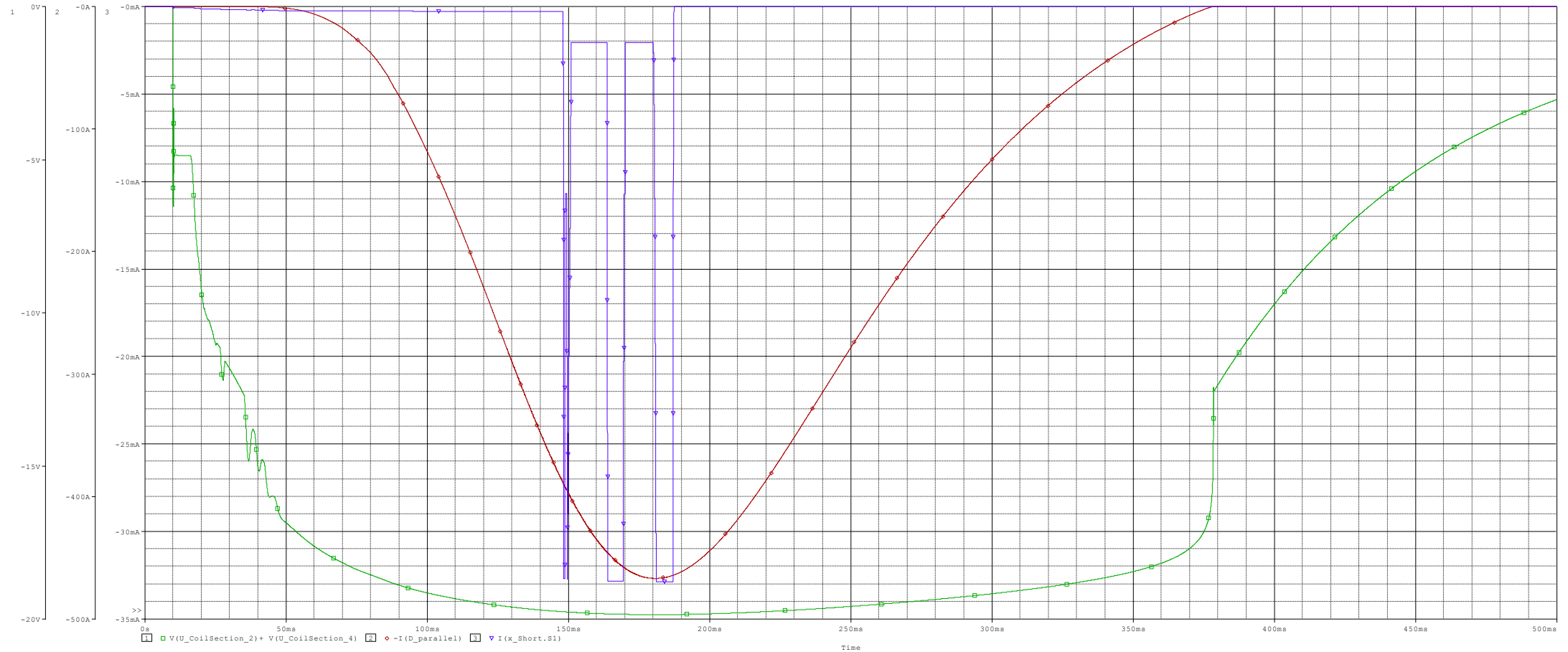
# MBHA001 – D\_parallel – 0.7 V forward voltage



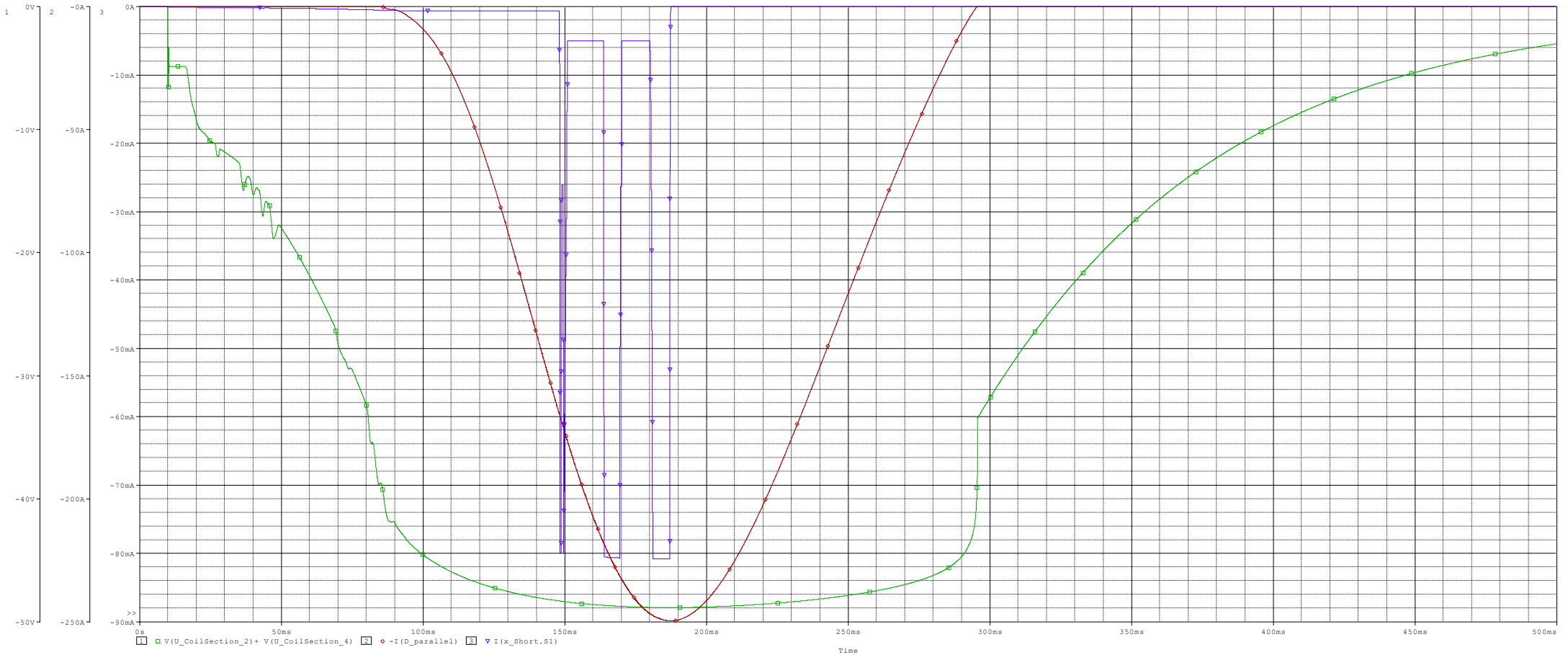
# MBHA001 – D\_parallel – 6 V forward voltage



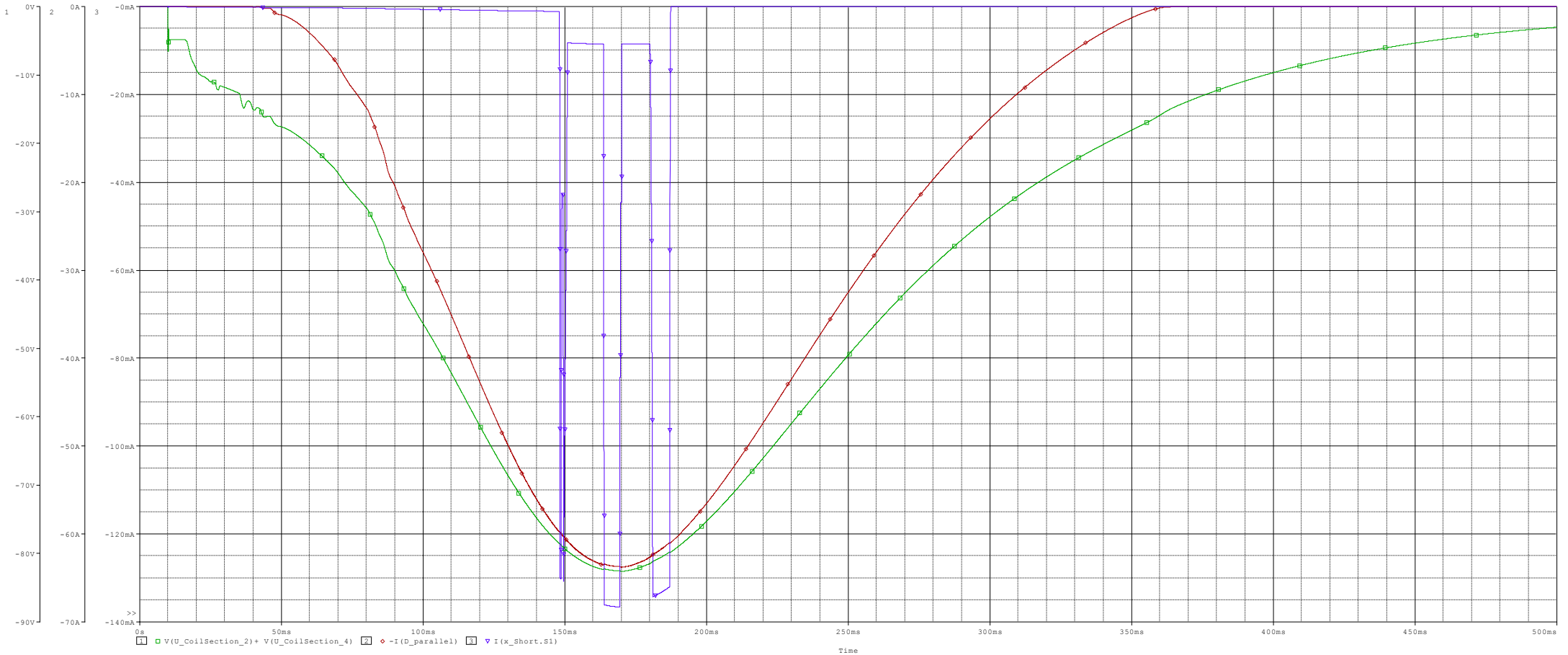
# MBHA001 – D\_parallel – 20 V forward voltage



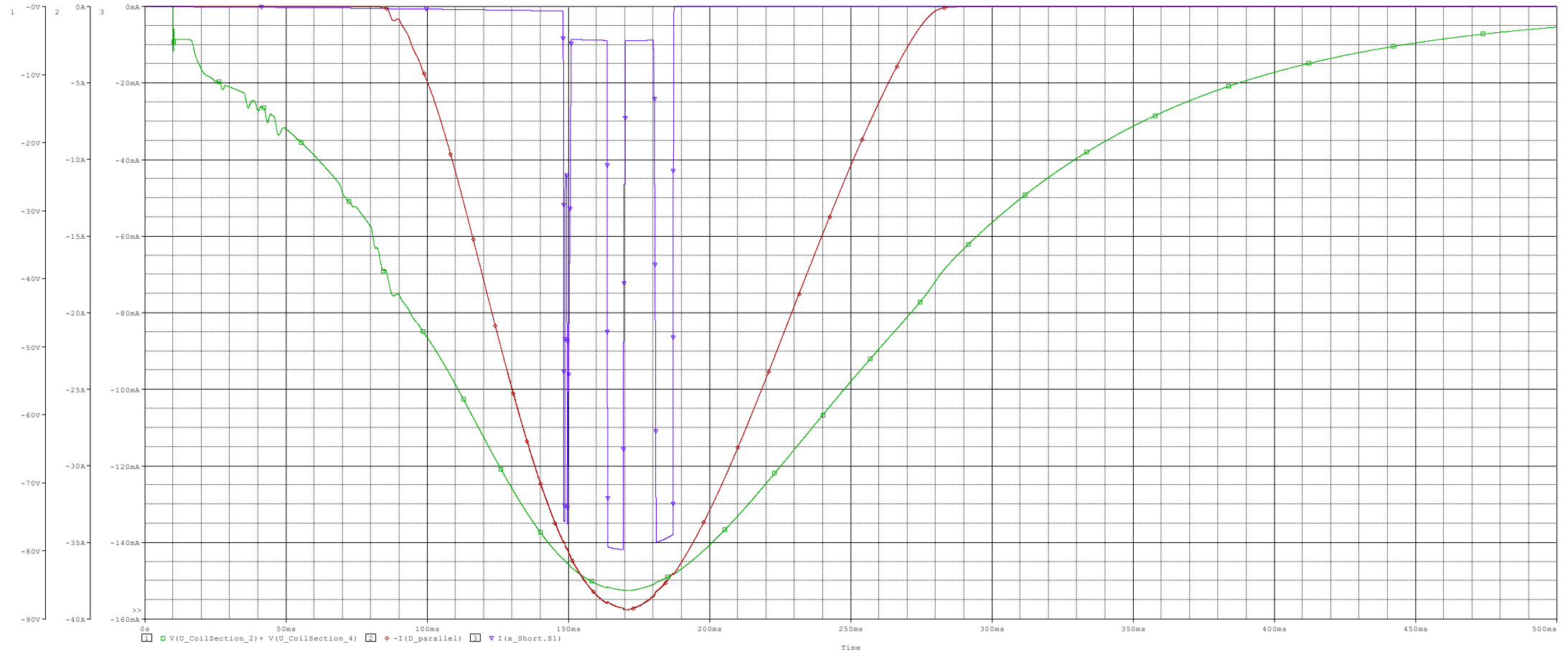
# MBHA001 – D\_parallel – 50 V forward voltage



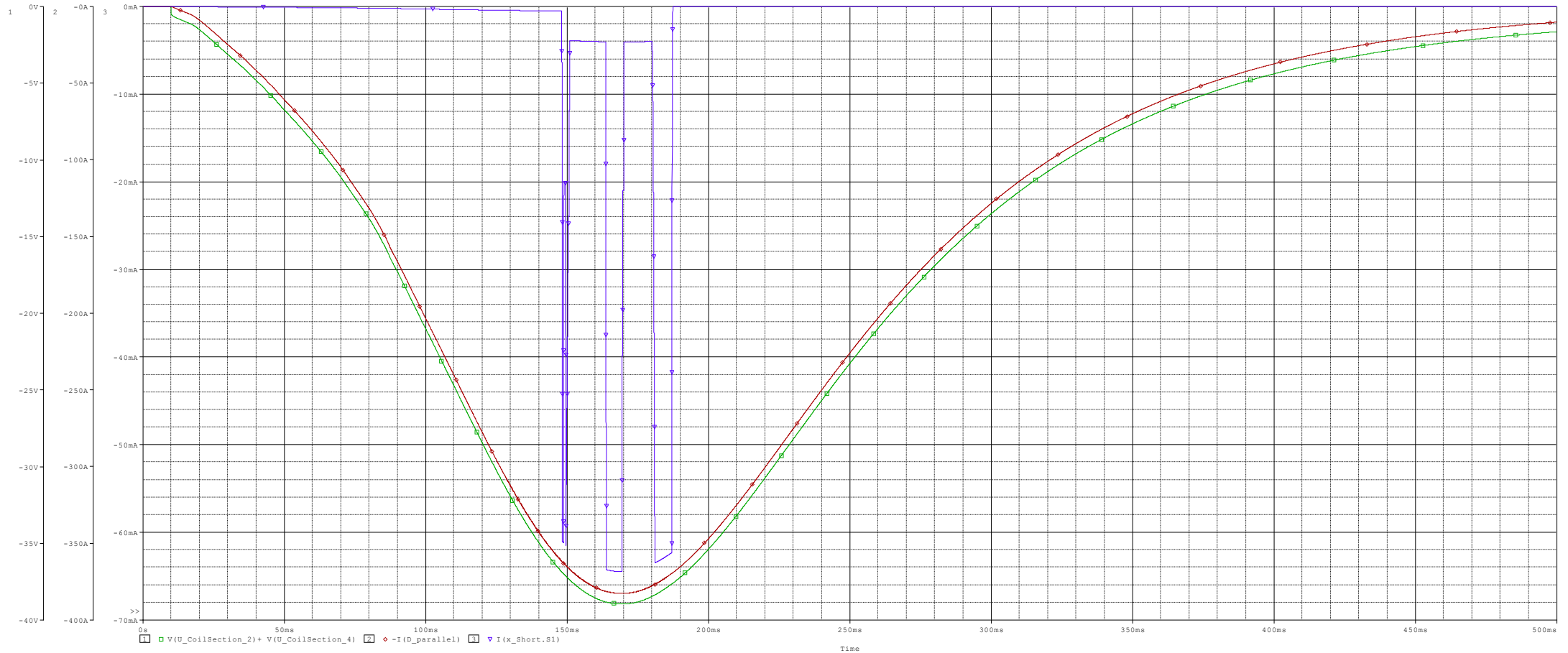
# MBHA001 – D\_parallel + 1 $\Omega$ – 20 V forward voltage



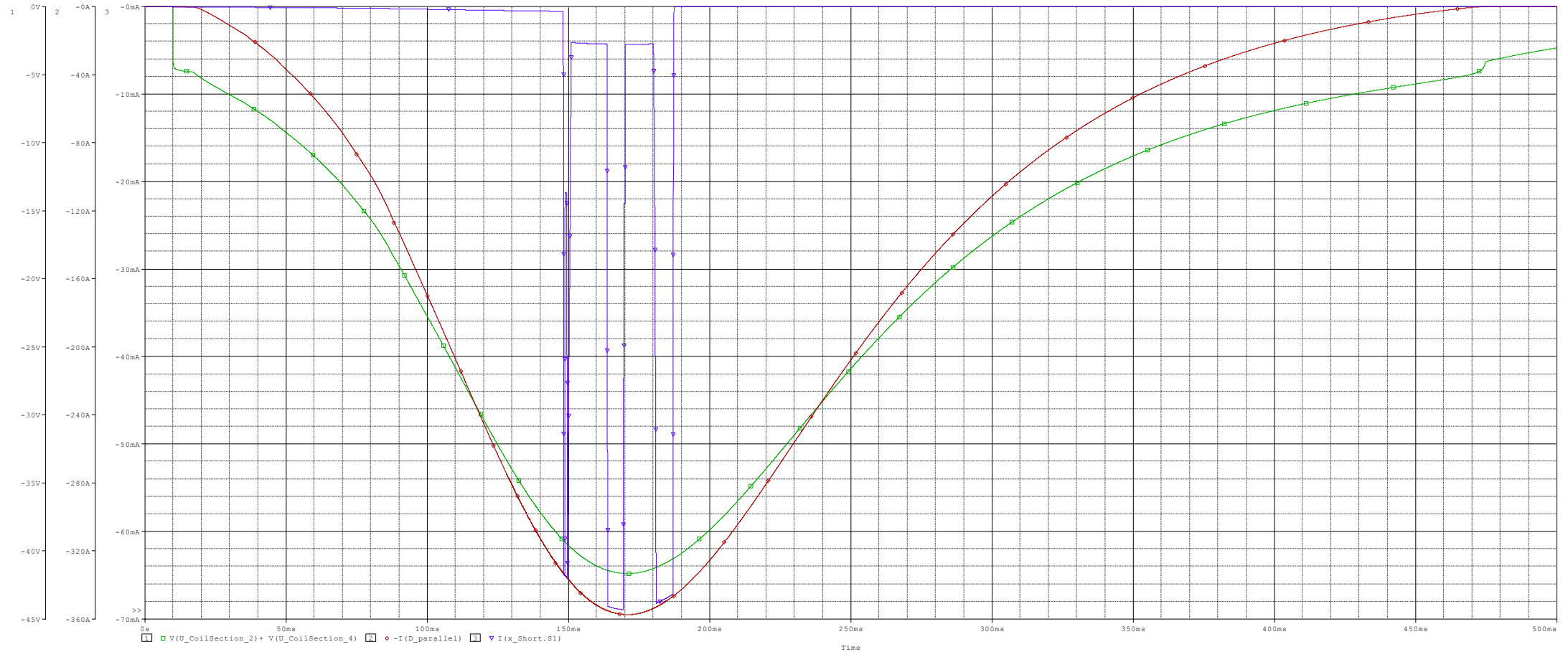
# MBHA001 – D\_parallel + 1 $\Omega$ – 50 V forward voltage



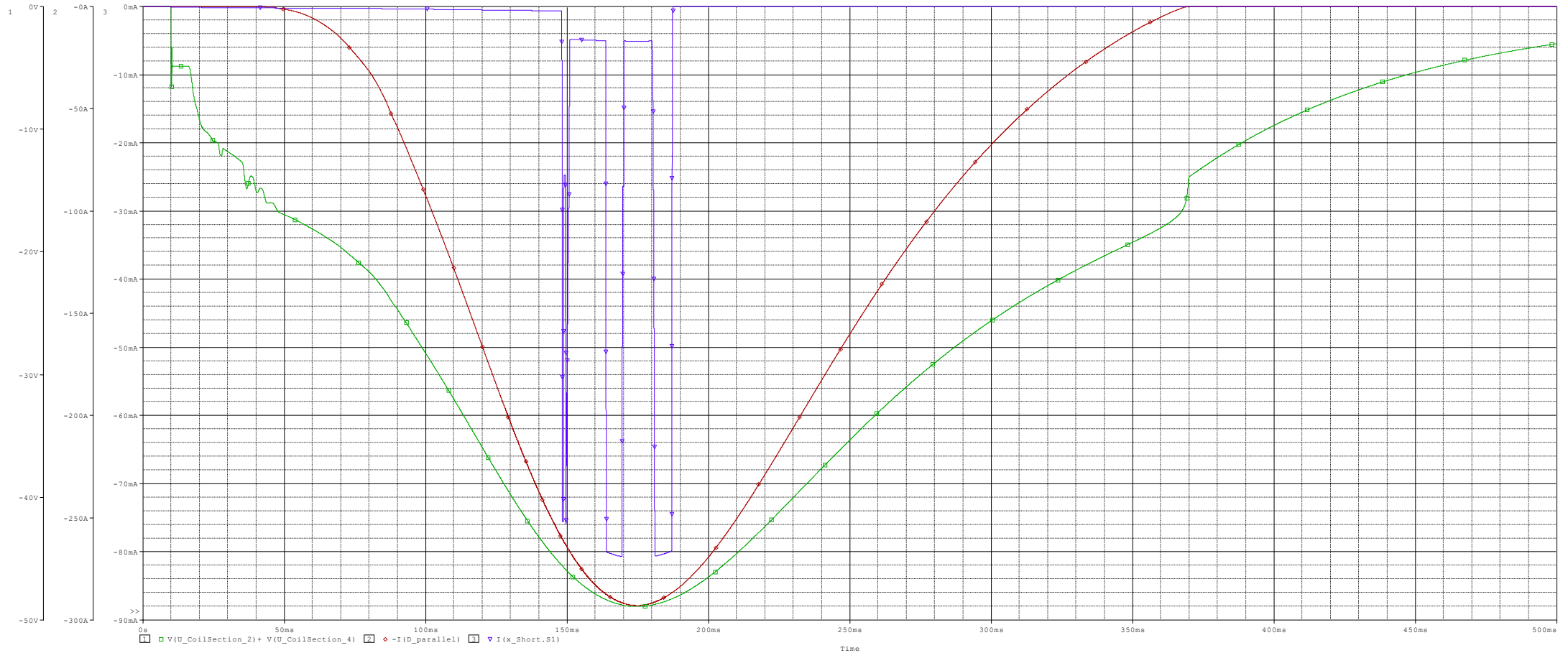
# MBHA001 – D\_parallel + 0.1 $\Omega$ – 0.7 V forward voltage



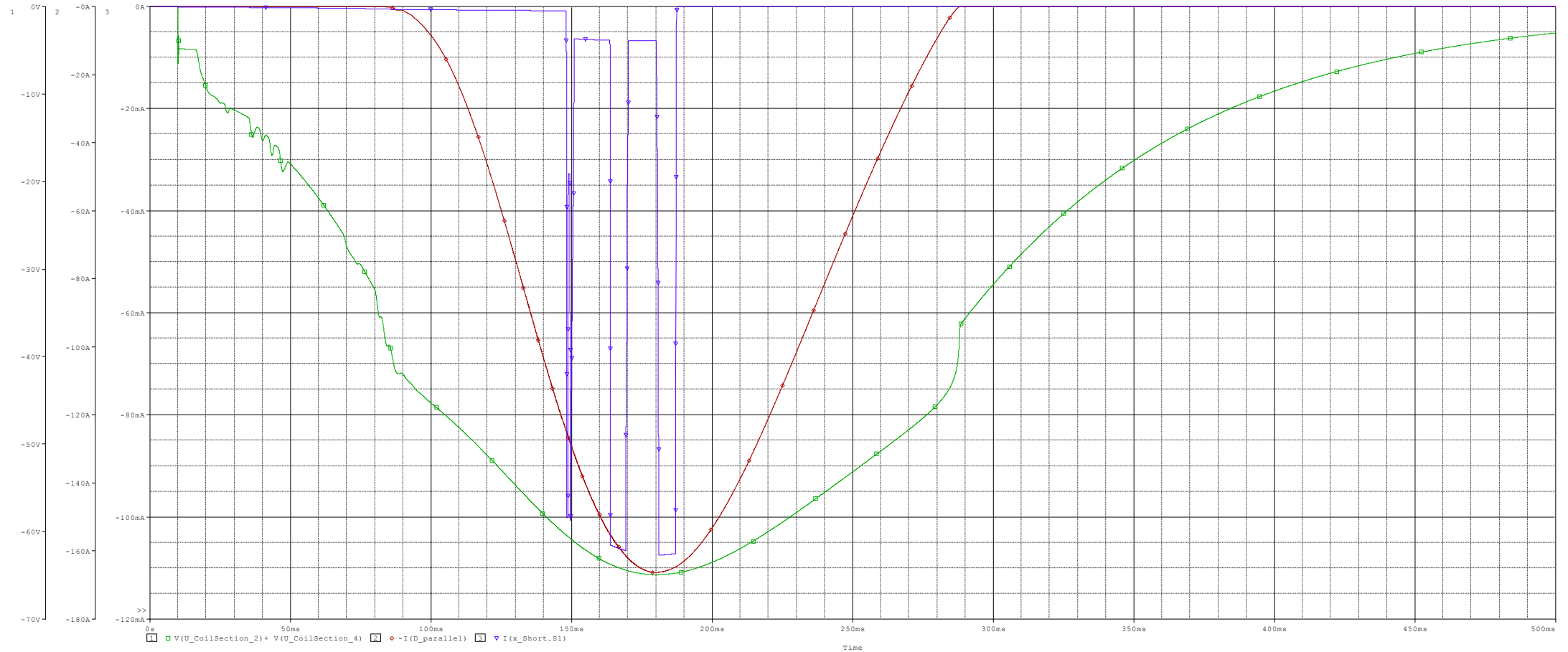
# MBHA001 – D\_parallel + 0.1 $\Omega$ – 6 V forward voltage



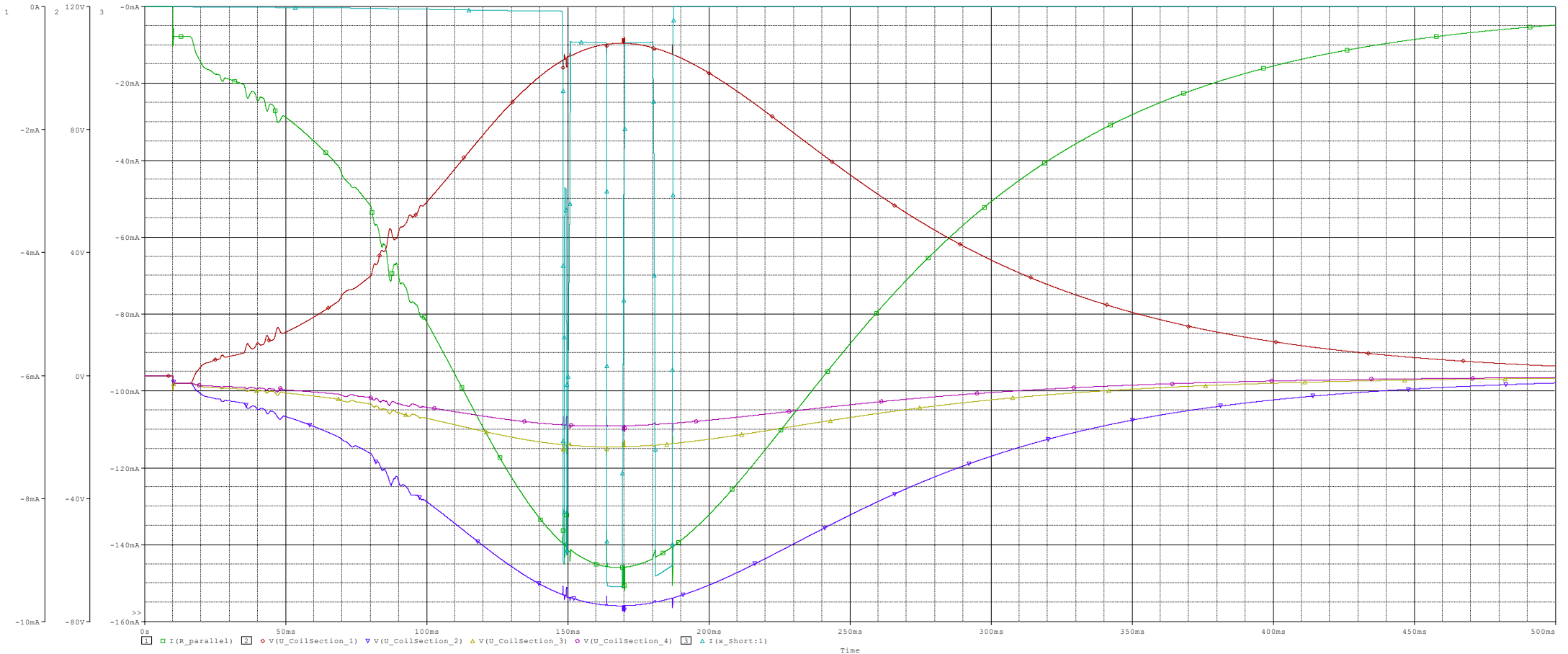
# MBHA001 – D\_parallel + 0.1 $\Omega$ – 20 V forward voltage



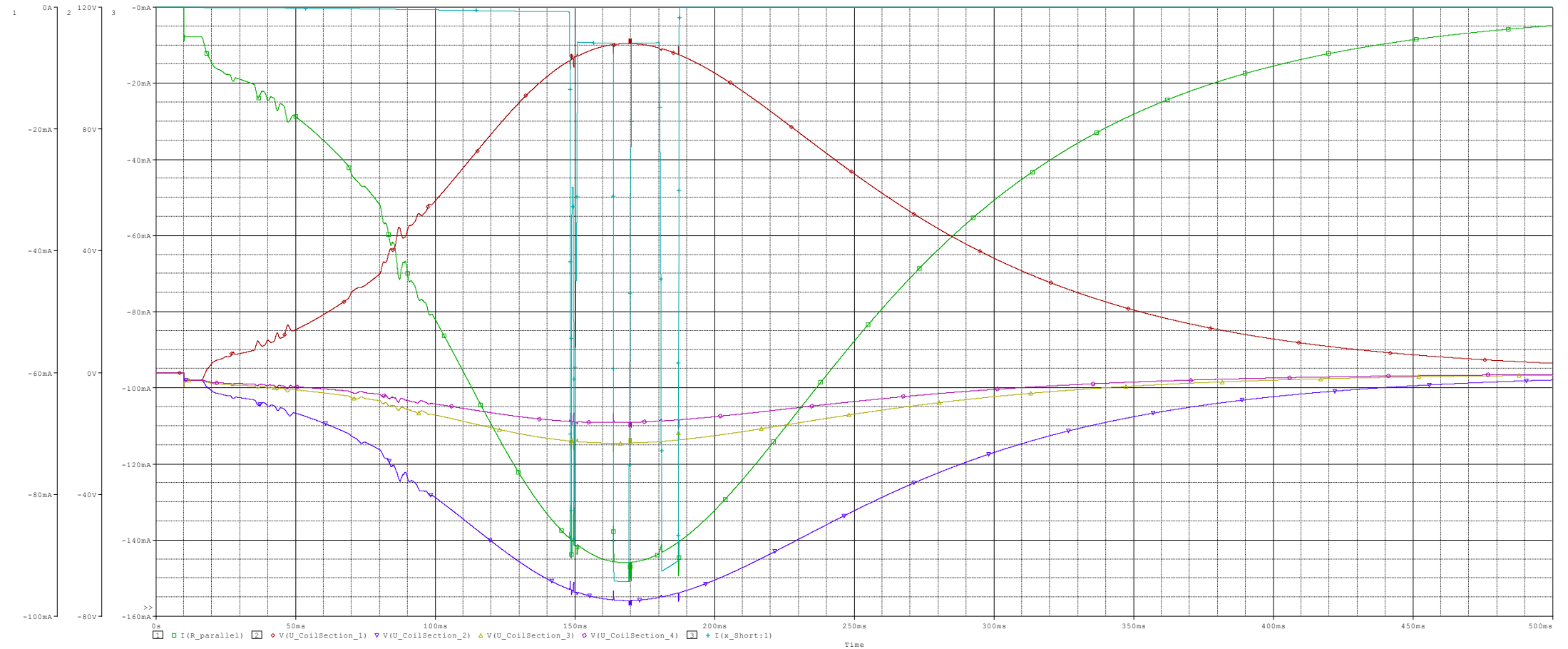
# MBHA001 – D\_parallel + 0.1 $\Omega$ – 50 V forward voltage



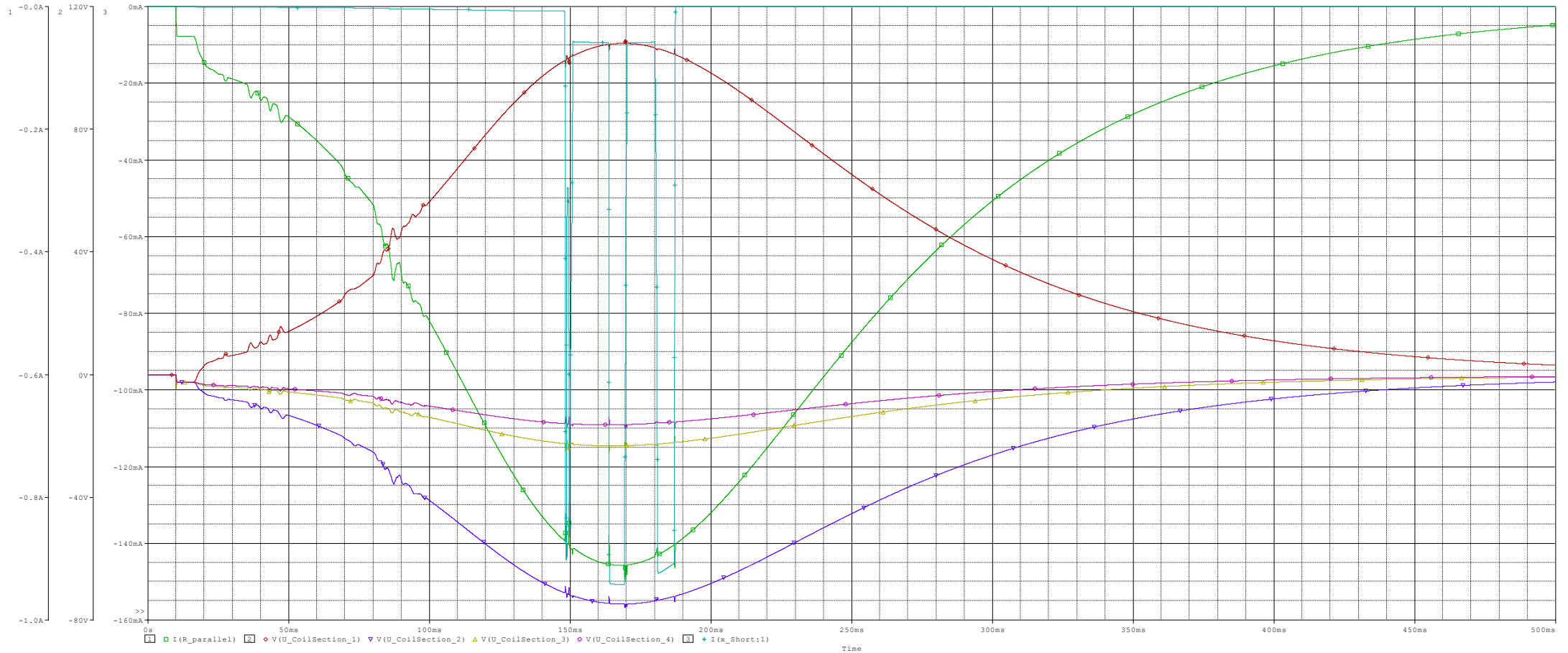
# MBHA001 – R\_parallel=10000 $\Omega$



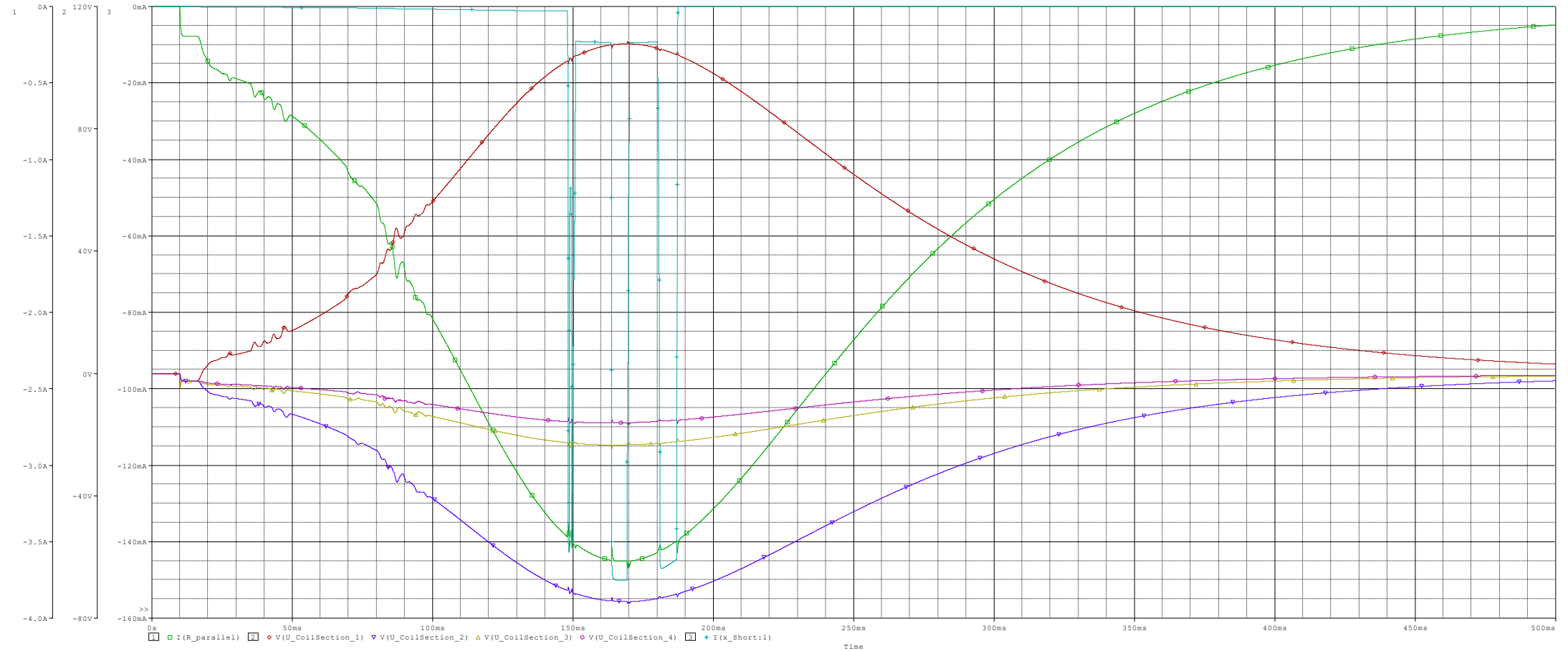
# MBHA001 – R\_parallel=1000 $\Omega$



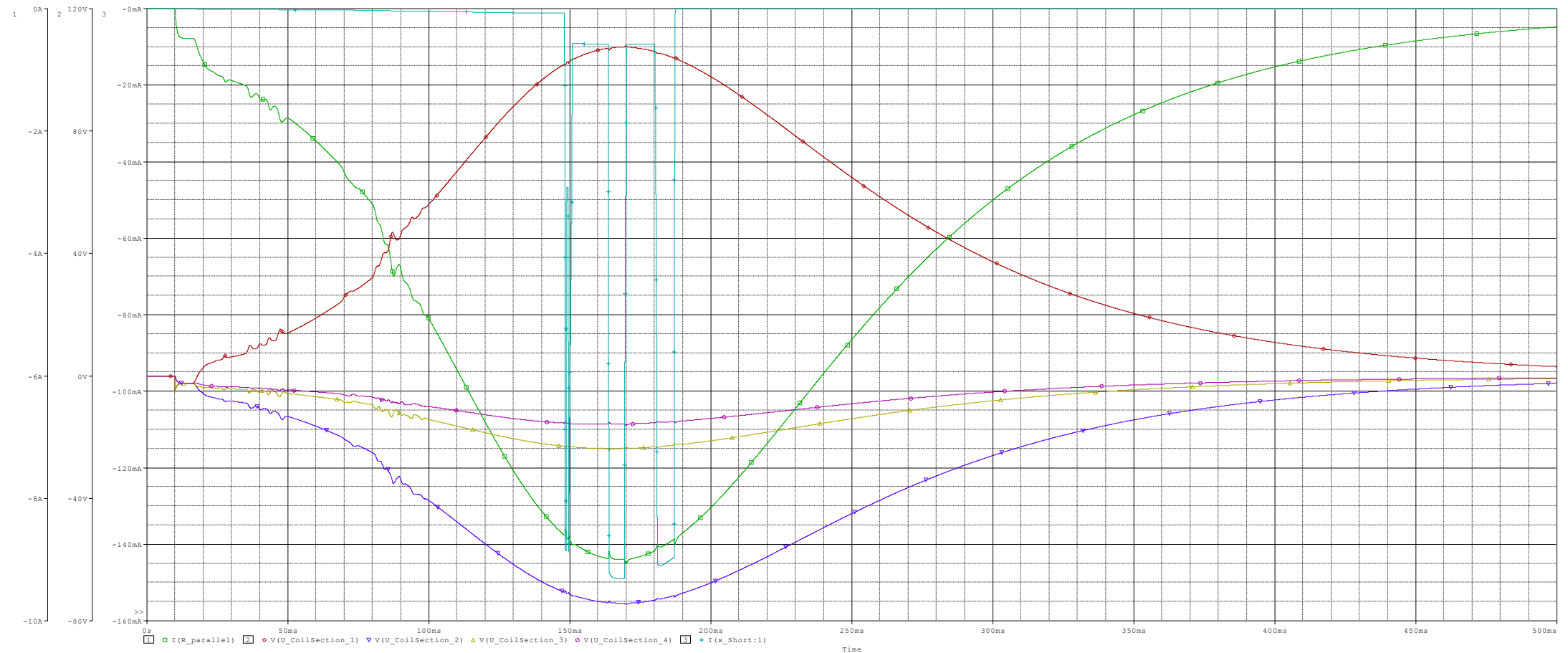
# MBHA001 – R\_parallel=100 $\Omega$



# MBHA001 – R\_parallel=25 $\Omega$



# MBHA001 – R\_parallel=10 $\Omega$



# MBHA001 – R\_parallel=1 $\Omega$

