STATE OF THE ART
UNIVERSAL IMPULSE CURRENT TEST SYSTEMS

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HAEFELY HIPOTRONICS

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OUTLINE

1. ***Overview of Exponential Wave Shapes***
2. **Basic Prinicple of Impulse Current Generation**
3. **Universal Impulse Current Generator for IEC 62305-1**
4. **Universal Impulse Current Generator for IEC 60099-4**
5. **Conclusion**

OVERVIEW EXPONENTIAL WAVE SHAPES

Wave Shape	Specifications and Appearance		
	T_1 *in µs*	T_2 *in µs*	*IEC*
0.25/100	0.25	100	62305-1
1 / ≤ 20	1	≤ 20	60099-4
1/200	1	200	62305-1
2 / 20	2	20	60099-8
4 / 10	4	10	60099-4 60099-8
5 / 300	5	300	61000-4-5 61643-21
6 / 310	6	310	61643-311
8 / 20	8	20	60099-4 60099-8 61000-4-5 61643-11 61643-21 61643-311 61643-331
10 / 250	10	250	61643-21
10 / 350	10	350	61643-11 61643-21 61643-311 61643-331 62305-1
10 / 1000	10	1000	61643-21 61643-311
30 / 60	$30 < T_1 < 100$	$2 \cdot T_1$	60099-4
30 / 80	30	80	60099-4

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10 / 1000	10	1000	61643-21 61643-311
30 / 60	30 < T_1 < 100	2 · T_1	60099-4
30 / 80	30	80	60099-4

8/20		
IEC	*T_1*	*T_2*
62475 61643-21 61000-4-5	8 µs ± 20 %	20 µs ± 20 %
60099-4 60099-8	8 µs ± 1 µs	20 µs ± 2 µs
61643-11 61643-311 61643-331	8 µs ± 10 %	20 µs ± 10 %

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61643-11 61643-311 61643-331	8 µs ± 10 %	20 µs ± 10 %

10/350	
IEC	
62475[a] 61643-21	T_1 = 10 µs ± 30 % T_2 = 350 µs ± 20 % (± 50 %)[a]
61643-11	T_2 T_{peak} ≤ 50 µs (minor interest) $T_{transfer}$ < 5 ms Q = I_{imp}·5·10-4 s – 10/+ 20 % W/R = I_{imp}·2.5·10-4 s -10/+ 45 %
61643-1[b]	T_{peak} ≤ 50 µs (minor interest) $T_{transfer}$ < 10 ms Q = I_{imp}·5·10-4 s ± 20 % W/R = I_{imp}·2.5·10-4 s ± 35 %
62305-1	Δt = 10 µs ± 20 % Q = I_{imp}·5·10-4 s ± 20 % W/R = I_{imp}·2.5·10-4 s ± 35 %

a in case of energy requirement
b replaced by IEC 61643-11

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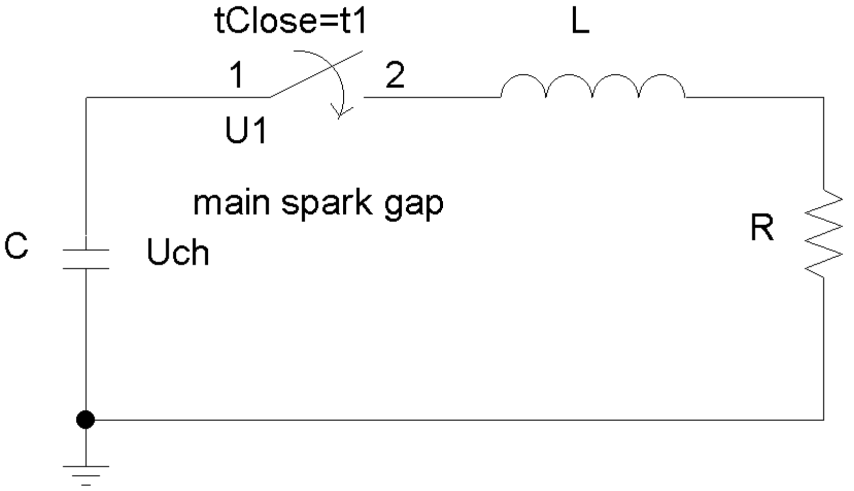
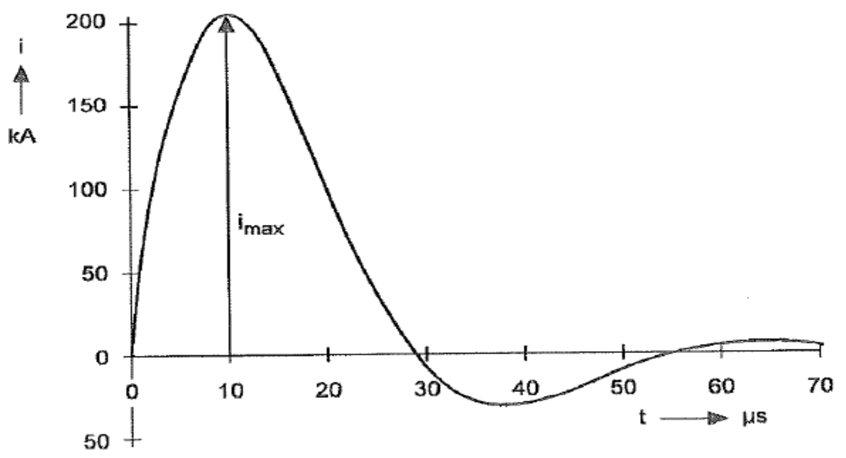
BASIC PRINCIPLE
Periodically Damped Impulse





$$i(t)=\frac{U_{ch}}{\omega\cdot L}\cdot\sin(\omega\cdot t)\cdot e^{-t/\tau};\quad \left(\frac{di}{dt}\right)_{\max}=\frac{U_{ch}}{L}\quad @t_{i_{\max}}=\frac{\arctan(\omega\cdot\tau)}{\omega}$$

$$\tau=\frac{2\cdot L}{R},\quad \omega=\sqrt{\frac{1}{L\cdot C}-\frac{R^2}{4\cdot L^2}},\quad R<2\sqrt{\frac{L}{C}}$$

$$Q=\int_0^\infty |i(t)|\cdot dt=\frac{U_{ch}/L}{\omega^2+1/\tau^2}\cdot\left(\frac{2}{1-e^{-\pi/(\omega\cdot\tau)}}-1\right);\quad \int_0^\infty (i(t))^2\cdot dt=\frac{U_{ch}^2}{4\cdot\omega^2\cdot L^2}\cdot\frac{\tau}{1+1/(\omega\cdot\tau)^2}$$

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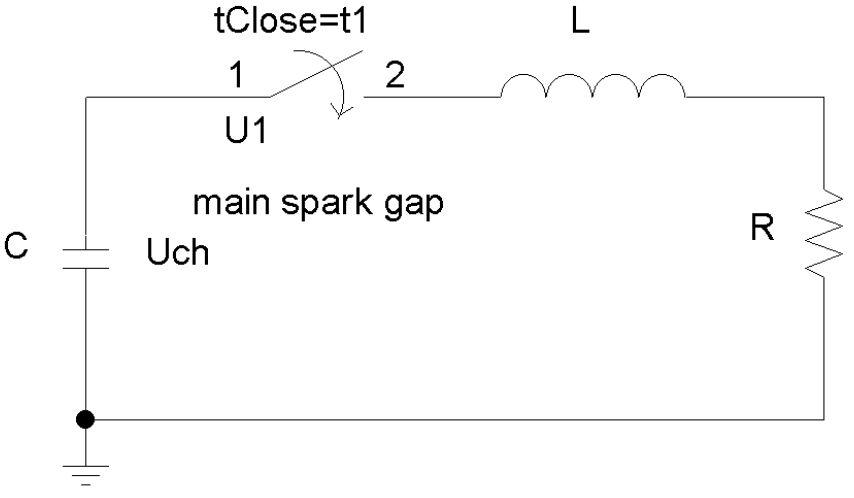
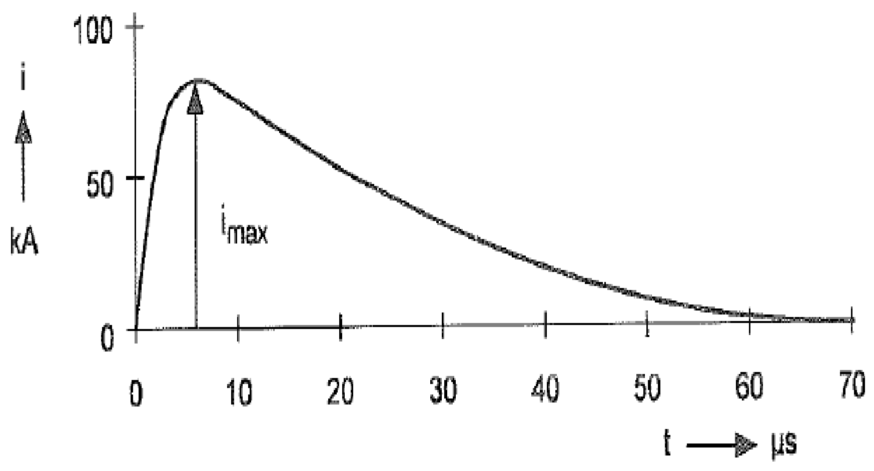
BASIC PRINCIPLE
Aperiodically Damped Impulse - Overdamping





$$i(t)=\frac{U_{ch}}{\sqrt{R^2-4\cdot L/C}}\cdot\left(e^{-t/\tau_1}-e^{-t/\tau_2}\right);\quad \left(\frac{di}{dt}\right)_{\max}=\frac{U_{ch}}{L};\quad t_{i_{\max}}=\frac{\tau_1\cdot\tau_2}{\tau_1-\tau_2}\cdot\ln\frac{\tau_1}{\tau_2}$$

$$\tau_1=\frac{1}{\frac{R}{2\cdot L}-k},\quad \tau_2=\frac{1}{\frac{R}{2\cdot L}+k}\quad,\quad k=\sqrt{\left(\frac{R}{2\cdot L}\right)^2-\frac{1}{L\cdot C}},\qquad R>2\sqrt{\frac{L}{C}}$$

$$Q=\int_0^\infty\left|i(t)\right|\cdot dt=U_{ch}\cdot C;\quad \int_0^\infty\left(i(t)\right)^2\cdot dt=\frac{U_{ch}^2/2}{\left(R^2-4\cdot L/C\right)}\cdot\frac{(\tau_1-\tau_2)^2}{\tau_1+\tau_2}$$

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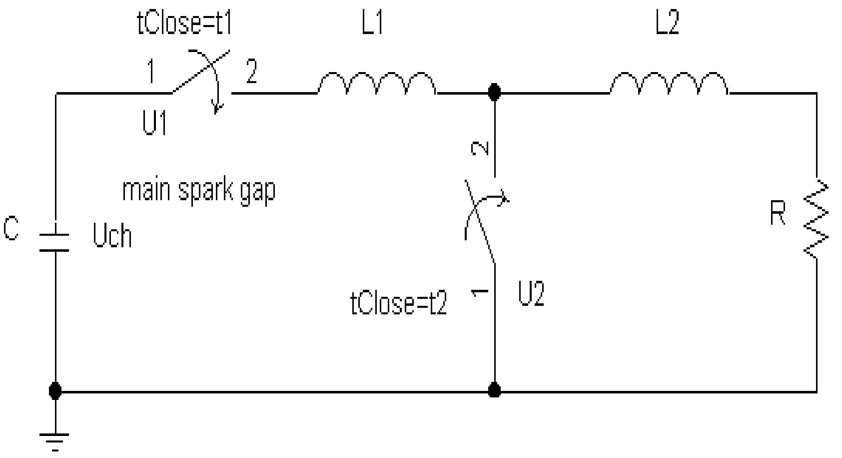
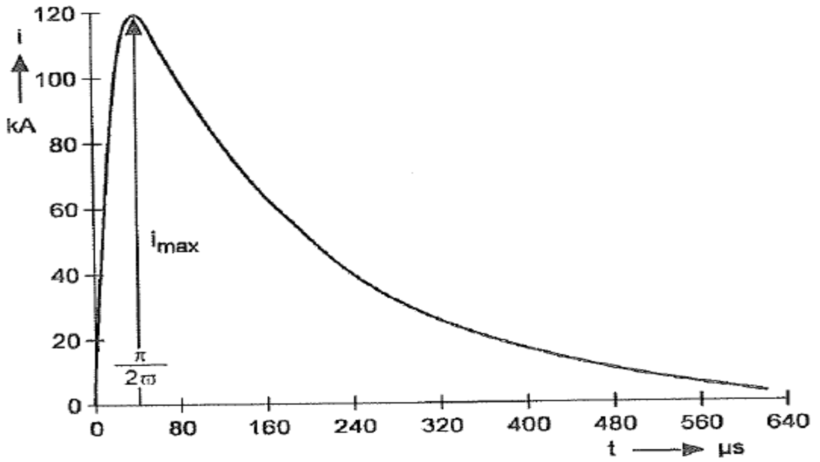
BASIC PRINCIPLE
Aperiodically Damped Impulse - Crowbar





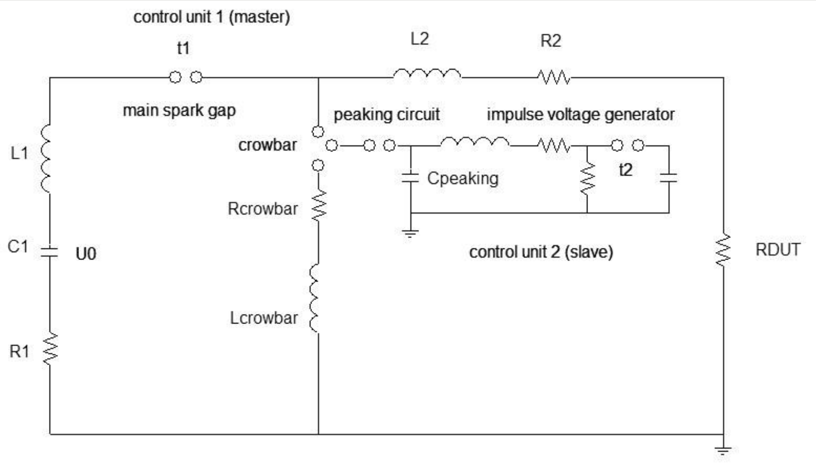
$$i(t) = \frac{U_{ch}}{\omega \cdot (L_1 + L_2)} \cdot \sin(\omega \cdot t) \;\; for\; 0 \le t \le \frac{\pi}{2 \cdot \omega}; \quad i(t) = \frac{U_{ch}}{\omega \cdot (L_1 + L_2)} \cdot e^{-\frac{t}{\tau}} \;\; for\; t \ge \frac{\pi}{2 \cdot \omega}$$

$$\omega = \sqrt{\frac{1}{C \cdot (L_1 + L_2)}}; \qquad \tau = \frac{L_2}{R}, \quad i_{\max} = \frac{U_{ch}}{\omega \cdot (L_1 + L_2)} \; @\, t = \frac{\pi}{2 \cdot \omega}, \quad \left(\frac{di}{dt}\right)_{\max} = \frac{U_{ch}}{(L_1 + L_2)} \; @\, t = 0$$

$$Q = \int_0^\infty |i(t)| \cdot dt = U_{ch} \cdot C + \frac{U_{ch}}{\omega \cdot (L_1 + L_2)} \cdot \tau; \quad \int_0^\infty (i(t))^2 \cdot dt = \frac{U_{ch}^2}{\omega^2 \cdot (L_1 + L_2)^2} \cdot \left(\frac{\pi}{4 \cdot \omega} + \frac{\tau}{2}\right)$$

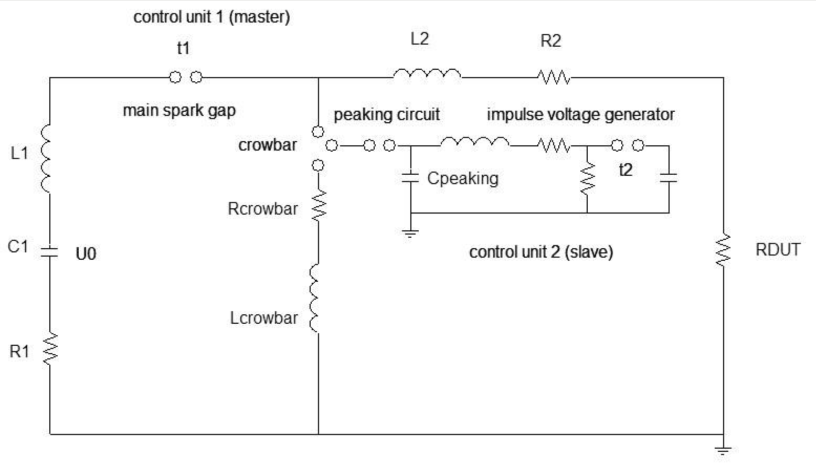
BASIC PRINCIPLE
Aperiodically Damped Impulse - Crowbar Systems

Crowbar with spark gap

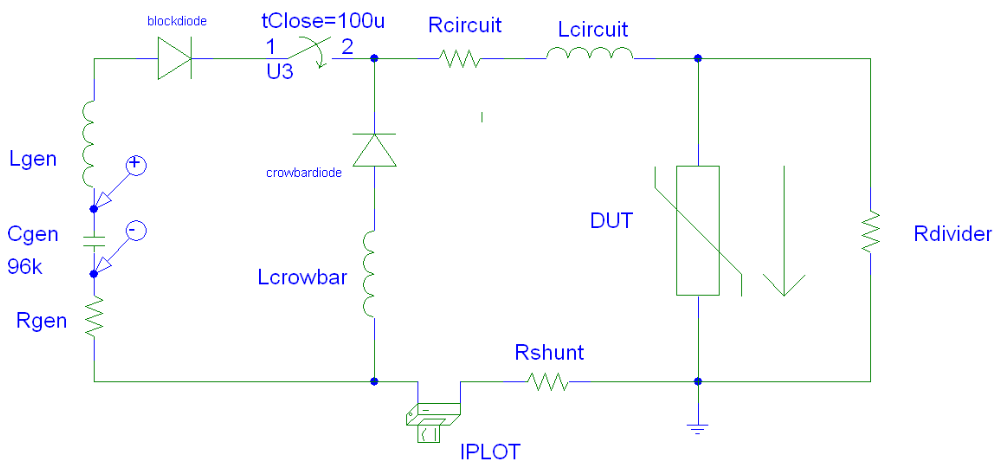


BASIC PRINCIPLE
Aperiodically Damped Impulse - Crowbar Systems

Crowbar with spark gap



Crowbar with diode



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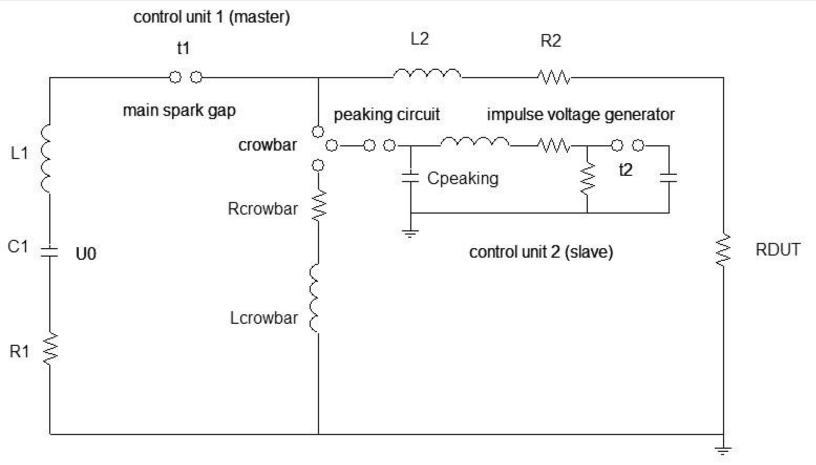
BASIC PRINCIPLE
Aperiodically Damped Impulse - Crowbar Systems

Crowbar with spark gap



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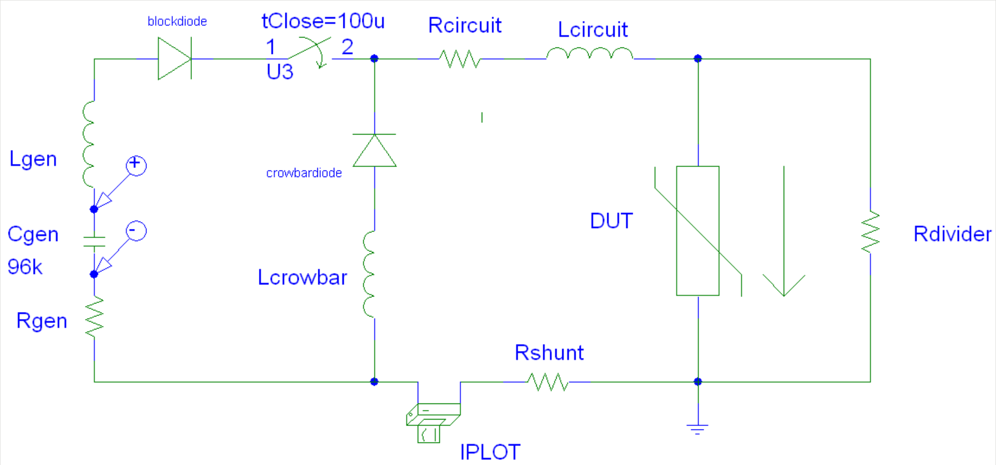

	Crowbar Spark gap	Crowbar Diode	Overdamped
Efficiency	High Resistance .. mΩ	High Resistance .. mΩ	Low Resistance .. Ω
Peak amplitude 10/350	High 250 kA	Medium 50 kA	Low … 10 kA
Back coupling DUT	High	High	Low
Handling	Complicated	Intermediate	Easy
Acoustic noise	High	Low	Low
Electric noise	High	Low	Low
Degree of freedom	High	Low	Low

BASIC PRINCIPLE
Comparison Crowbar / Overdamped Circuit

Identical capacitor bank, time to half value T_2 = 350 μs

		Crowbar	Overdamped
Charging voltage	kV	100	100
Capacitance	μF	30	30
Resistance	Ω	0.036	17
Inductance L_1	μH	1	
Inductance L_2	μH	18	2.1
T_1	μs	29.6	0.83
T_2	μs	350	350
Peak Current	kA	125.7	5.9
	%	100	4.7
Current @ T_2	kA	62.4	3.0

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T_2	μs	350	350
Peak Current	kA	125.7	5.9
	%	100	4.7
Current @ T_2	kA	62.4	3.0

Peak current amplitude approx. 20 x higher for the crowbar arrangement!

BASIC PRINCIPLE
Adjusting exponential impulses

	Charging voltage	Capacitance	Inductance	Resistance
Change	↑	↑	↑	↑
I_{peak}	↑	↑	↓	↓
T_1	–	↑	↑	↓
T_2	–	↑	↑	↑

General guidelines for linear loads without consideration of mutual interactions

Variable impact of parameters depending on load point and mutual interactions

Change in behaviour possible!

Examples:

1. Reduction of capacitors ⇒ increase of generator self inductance; non-linear!
2. Increase of system voltage ⇒ increase of generator self inductance

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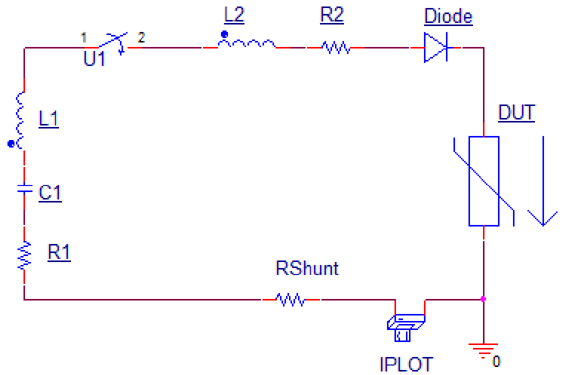
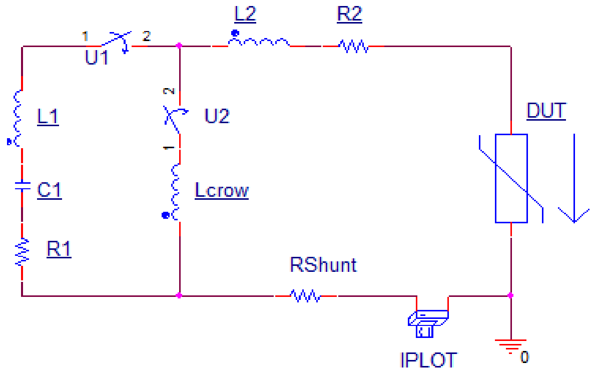
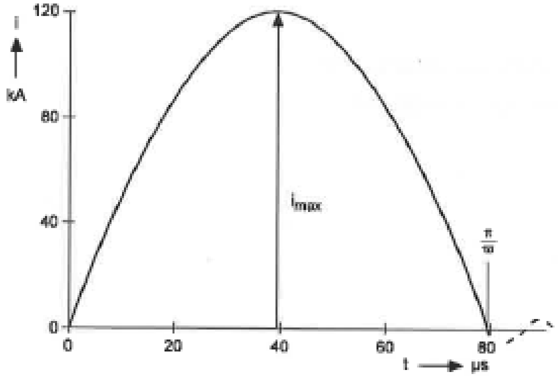
BASIC PRINCIPLE
Sine Half Wave

Diode or crowbar to limit current reversal







$$i(t) = \frac{U_{ch}}{\omega \cdot (L_1 + L_2)} \cdot \sin(\omega \cdot t); \quad 0 \le t \le \frac{\pi}{\omega}; \qquad \omega = \sqrt{\frac{1}{(L_1 + L_2) \cdot C}}$$

Switching @ i(t) = 0; u(t) =-u$_{peak}$

$$i_{\max} = \frac{U_{ch}}{\omega \cdot (L_1 + L_2)} \quad @ \quad t_{i_{\max}} = \frac{\pi}{2 \cdot \omega}; \qquad \left(\frac{di}{dt}\right)_{\max} = \frac{U_{ch}}{(L_1 + L_2)} \quad @ \quad t = 0$$

$$Q = \int_0^{\frac{\pi}{\omega}} i(t) \cdot dt = 2 \cdot U_{ch} \cdot C; \quad \frac{W}{R} = \int_0^{\frac{\pi}{\omega}} i(t)^2 \cdot dt = \frac{U_{ch}^2 \cdot \pi}{2 \cdot \omega^2 \cdot (L_1 + L_2)}$$

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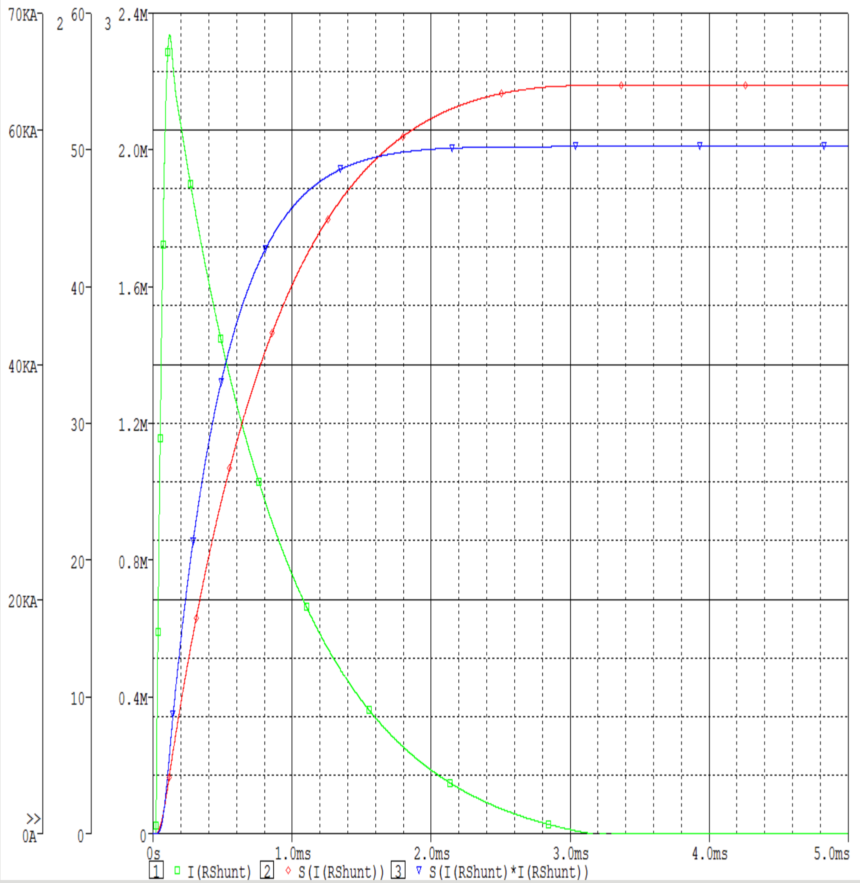
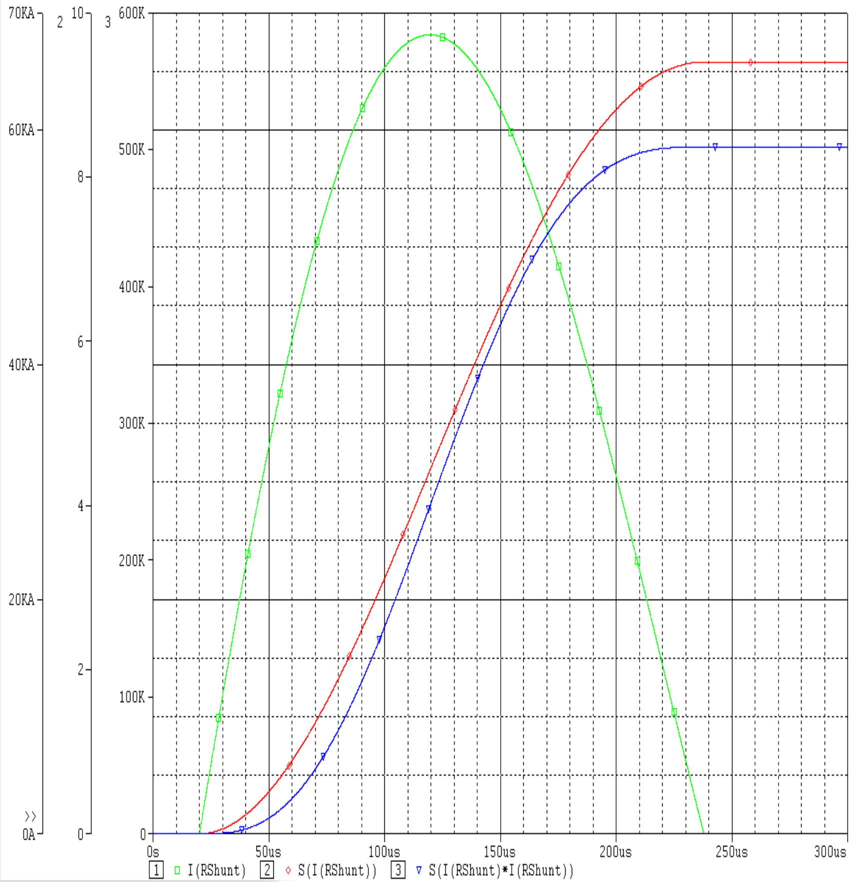
BASIC PRINCIPLE
Comparison Aperiodically Damped / Sine Half Wave

Identical capacitor bank and test object





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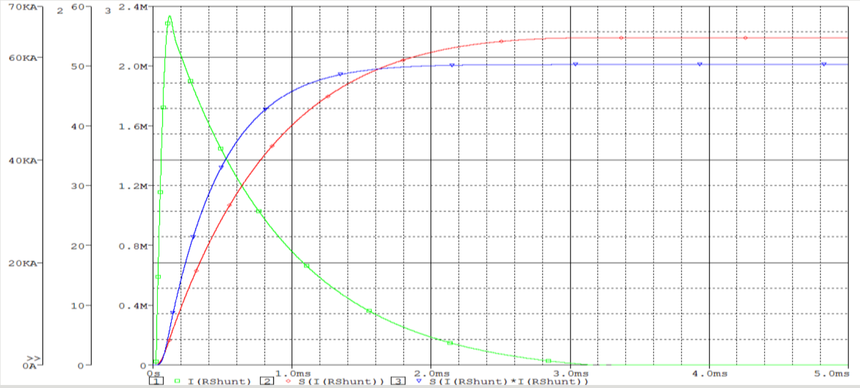

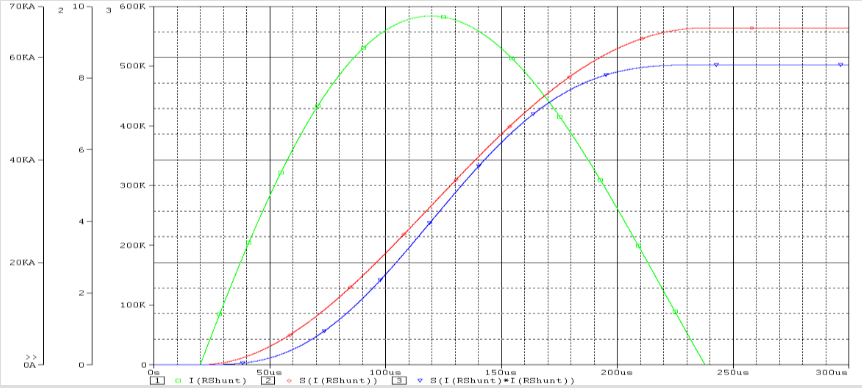

Aperiodically damped with crowbar	Sine half wave
Switching at $I = I_{max}$	Switching at $I = I_{min}$
Switching at $U_{ch} = 0$	Switching at $U_{ch} = - U_{peak}$ (~½ U_{peak})
I_{peak} = 68 kA	I_{peak} = 68 kA
Q = 55 As	Q = 10 As
W/R = 2000 kJ/Ω	W/R = 502 kJ/Ω

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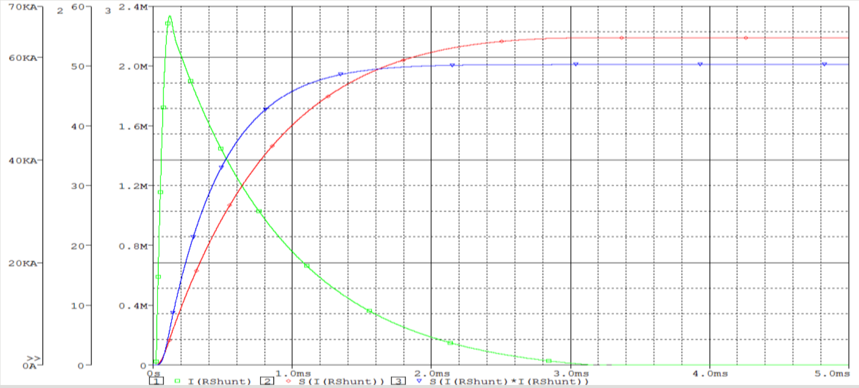
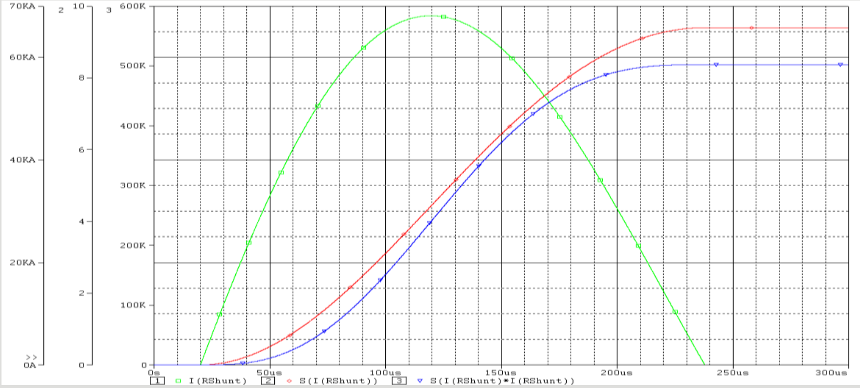
BASIC PRINCIPLE
Comparison Aperiodically Damped / Sine Half Wave

Identical capacitor bank and test object





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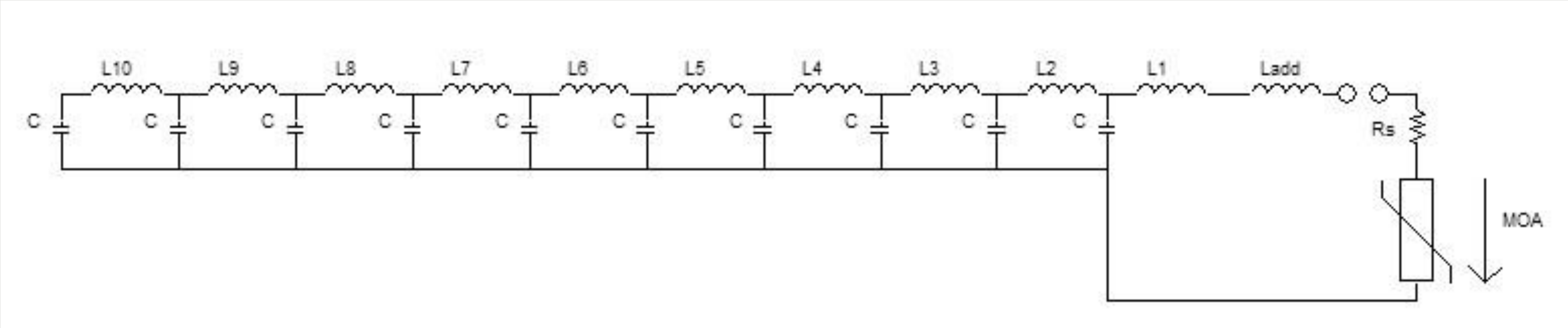
Q = 55 As	Q = 10 As
W/R = 2000 kJ/Ω	W/R = 502 kJ/Ω

Charge Q approx. 5.5 x higher for crowbar arrangement!

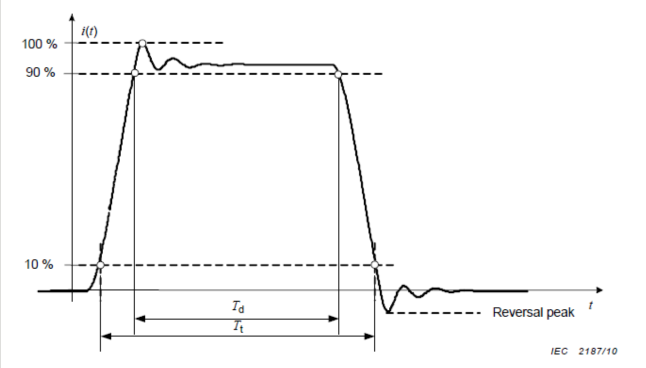
IMPULSE CURRENT GENERATOR
BASIC PRINCIPLE – Rectangular Impulse



$$\frac{n \cdot 1.1 \cdot T_{90\%}}{2 \cdot (n-1)} = \sqrt{L_{tot} \cdot C_{tot}};$$

$$L_{tot} = \sum_{i=1}^{n} L_i, \quad C_{tot} = n \cdot C, \quad n = 8..12$$

$$i_p = \frac{U_0}{R_{tot} + \sqrt{\frac{L_{tot}}{C_{tot}}}}; R_{tot} = R_s + R_{MOA} = \sqrt{\frac{L_{tot}}{C_{tot}}}$$



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ICG FOR IEC 62305-1 Requirements

IEC 62305-1 general wave shapes

	Positive impulse 10/350	First negative impulse 1/200	Subsequent impulse 0.25/100
I_{peak}	200 kA	100 kA	50 kA
di/dt	20 kA/µs	100 kA/µs	200 kA/µs
T_1	10 µs	1 µs	0.25 µs
T_2	350 µs	200 µs	100 µs
Q_{short}	100 C		
W/R	10 MJ/Ω		

IEC 62305-1 wave shapes for test

LPL I	First positive impulse energy 10/350	First positive Impulse 10/350	Subsequent negative impulse 0.25/100
I_{peak}	200 kA		
Q_{short}	100 C		
W/R	10 MJ/Ω		
Δi		200 kA	50 kA
Δt		10 µs	0.25 µs

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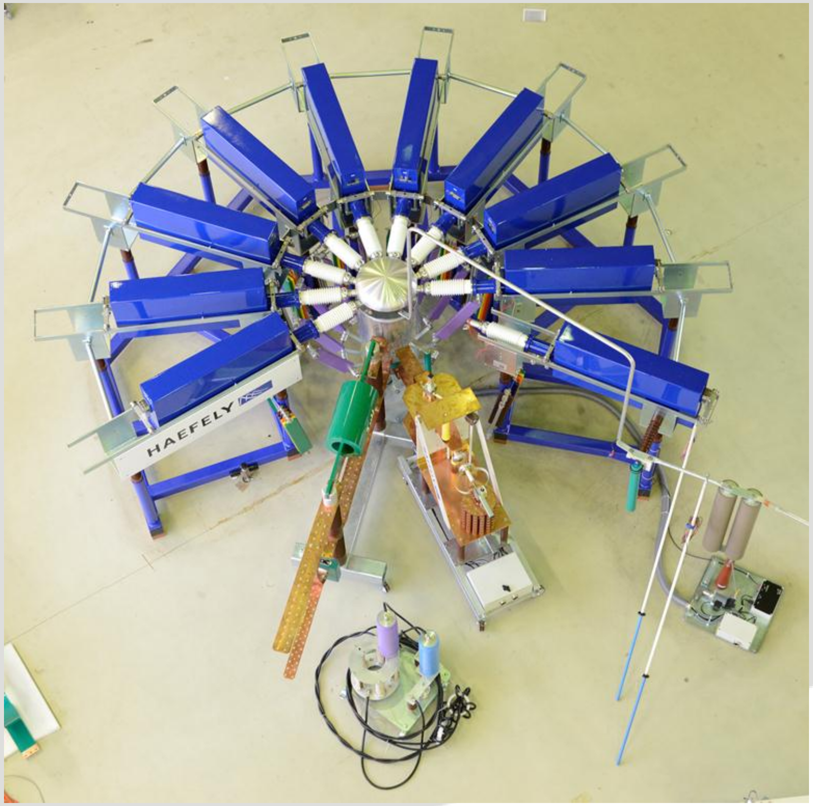
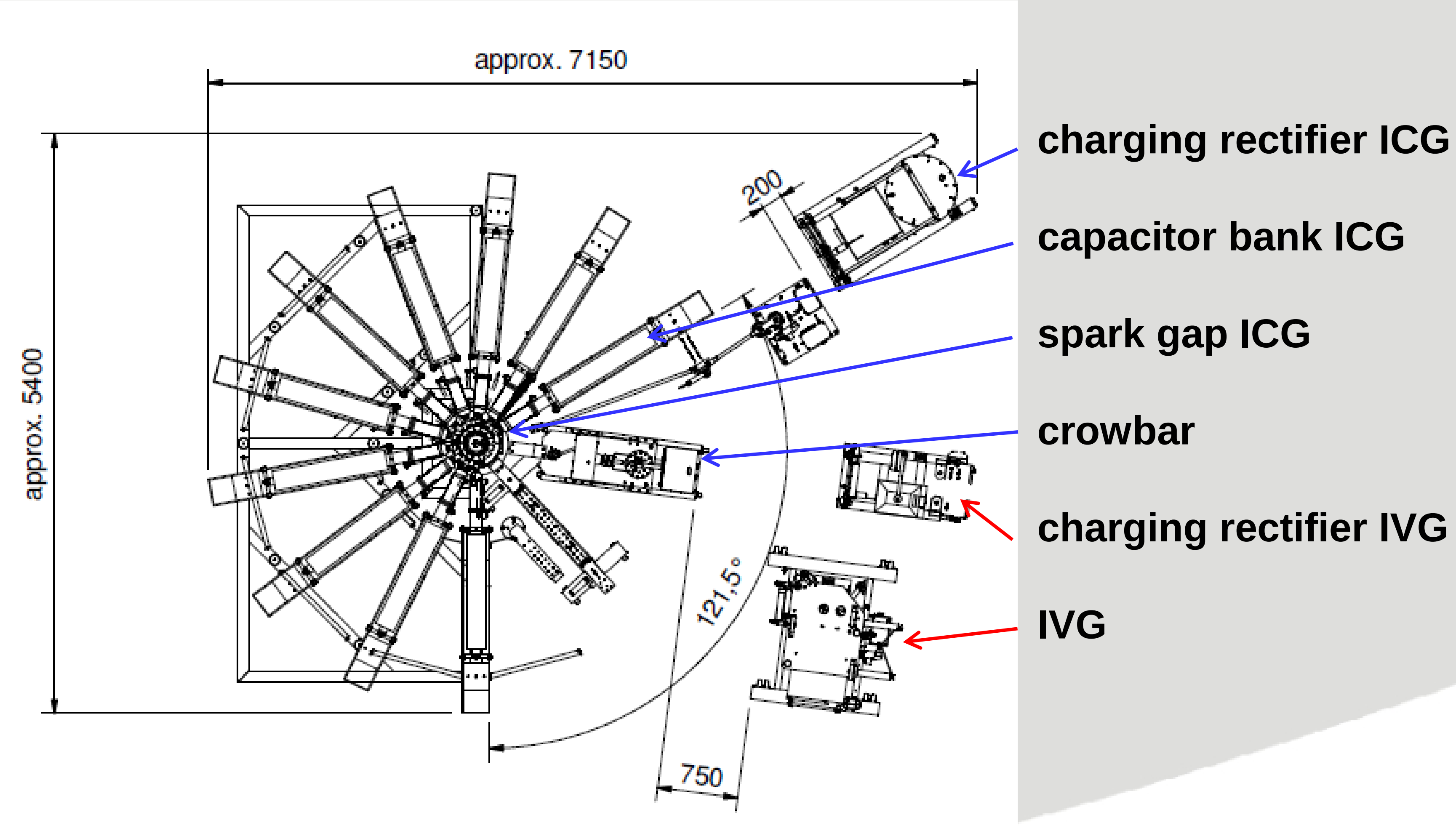
ICG FOR IEC 62305-1
Customer specification

Customer specification

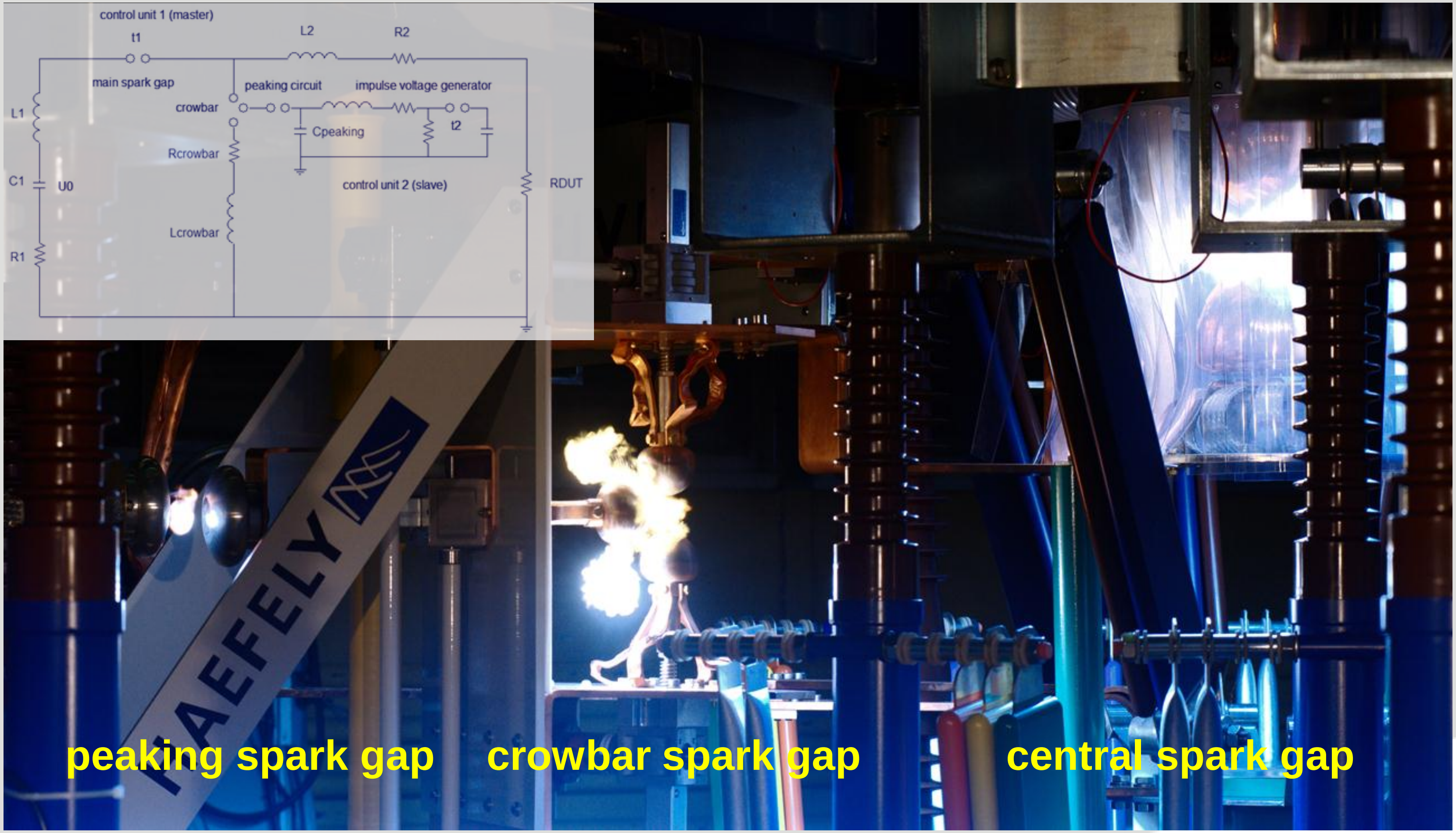
	Positive impulse 10/350	First negative impulse 1/200	Subsequent impulse 0.25/100
I_{peak}	200 kA ± 10 %	100 kA ± 10 %	20 kA ± 10 %
T_1	10 µs ± 10 %	4 µs ± 10 %	0.25 µs ± 20 %
T_2	350 µs ± 10 %	200 µs ± 10 %	100 µs ± 10 %
Q_{short}	100 C ± 20 %		
W/R	10 MJ/Ω ± 35 %		



ICG FOR IEC 62305-1
Layout

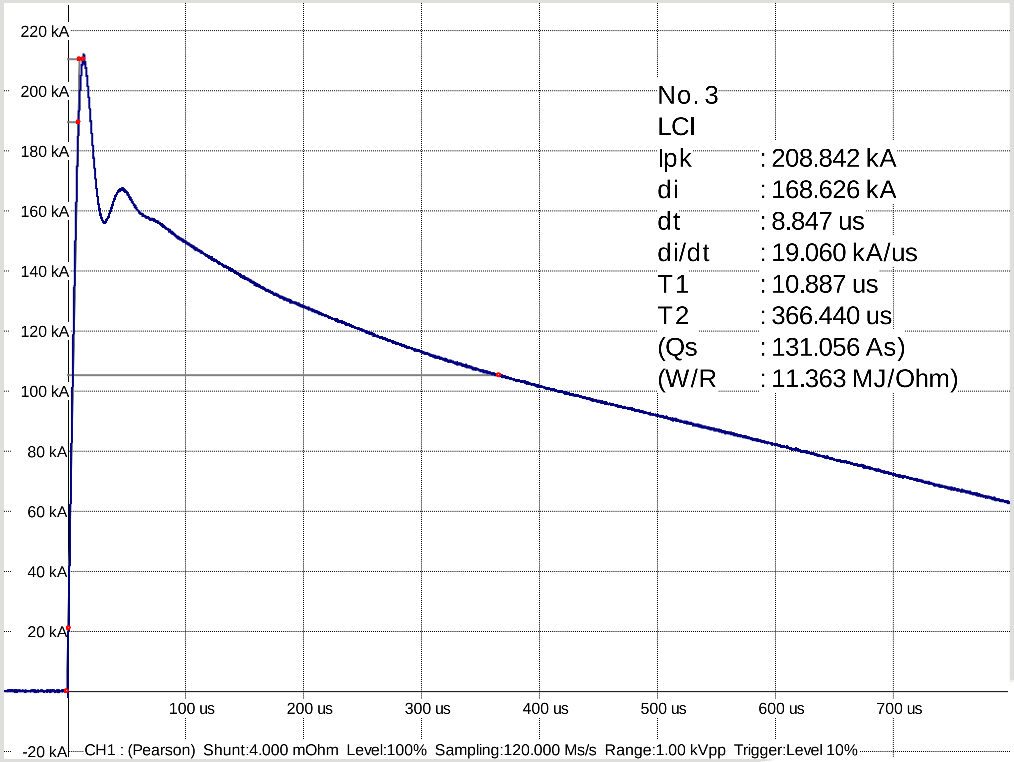


ICG FOR IEC 62305-1
Sphere gaps



ICG FOR IEC 62305-1
Results 10/350

10/350	Positive impulse 10/350
I_{peak}	209 kA
di/dt	19 kA/µs
T_1	10.9 µs
T_2	366 µs
Q_{short}	131 C
W/R	11.4 MJ/Ω



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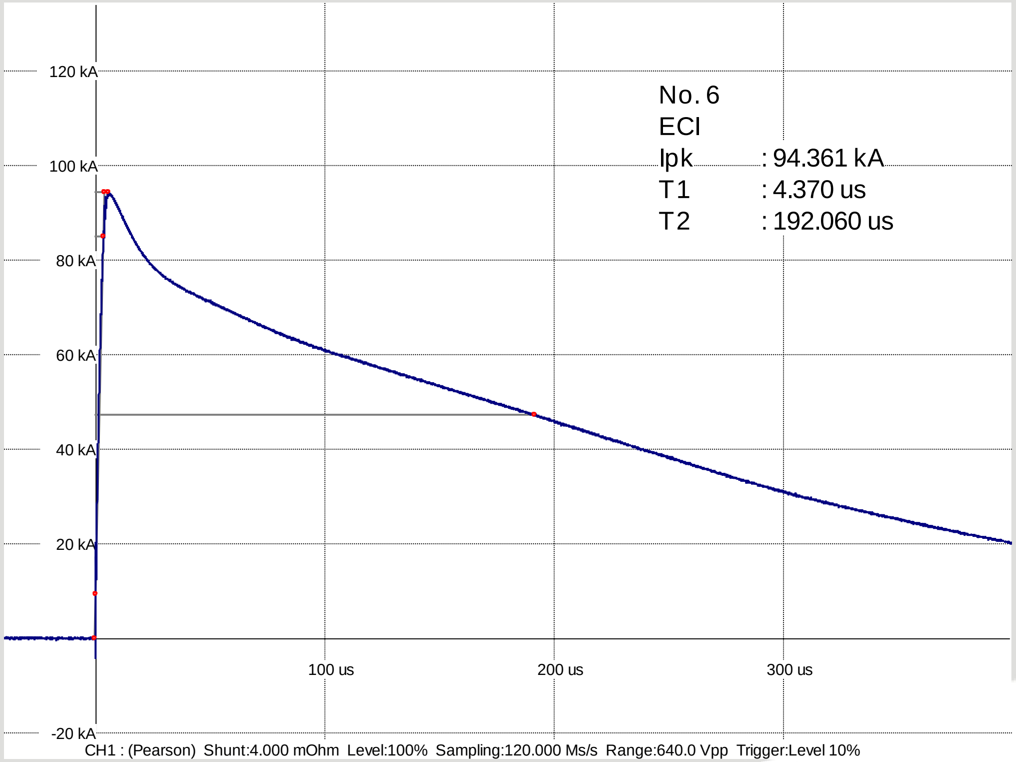
ICG FOR IEC 62305-1
Results 1/200

1/200	T_1/T_2	I_{max}@1 µs	I_{max}
I_{peak}	11.0 kA	53.0 kA	94.4 kA
T_1	1.0 µs	1.0 µs	4.37 µs
T_2	190.0 µs	40.0 µs	192.0 µs
Setup			Crowbar



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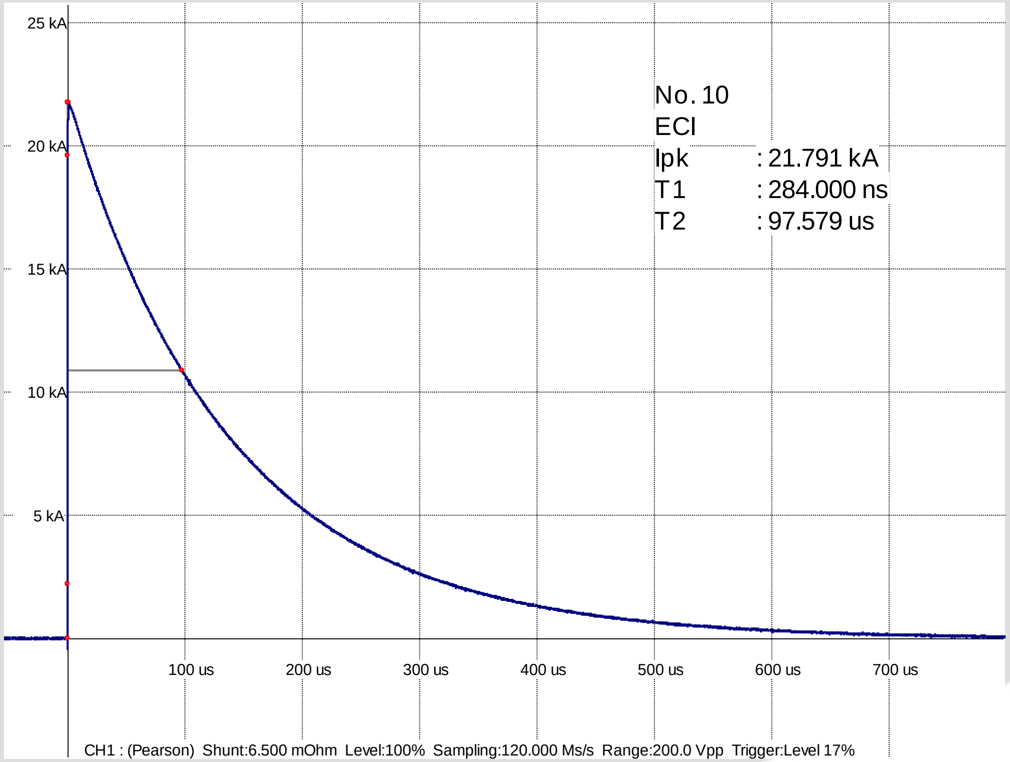
ICG FOR IEC 62305-1
Results 0.25/100

1/100	Subseqeunt impulse 1/100
I_{peak}	21.8 kA
T_1	0.28 ns
T_2	97.6 µs



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OUTLINE

1. **Overview of exponential wave shapes**
2. **Basic Prinicple of Impulse Current Generation**
3. **Universal Impulse Current Generator for IEC 62305-1**
4. ***Universal Impulse Current Generator for IEC 60099-4***
5. **Conclusion**

ICG FOR IEC 60099-4
Customer specification

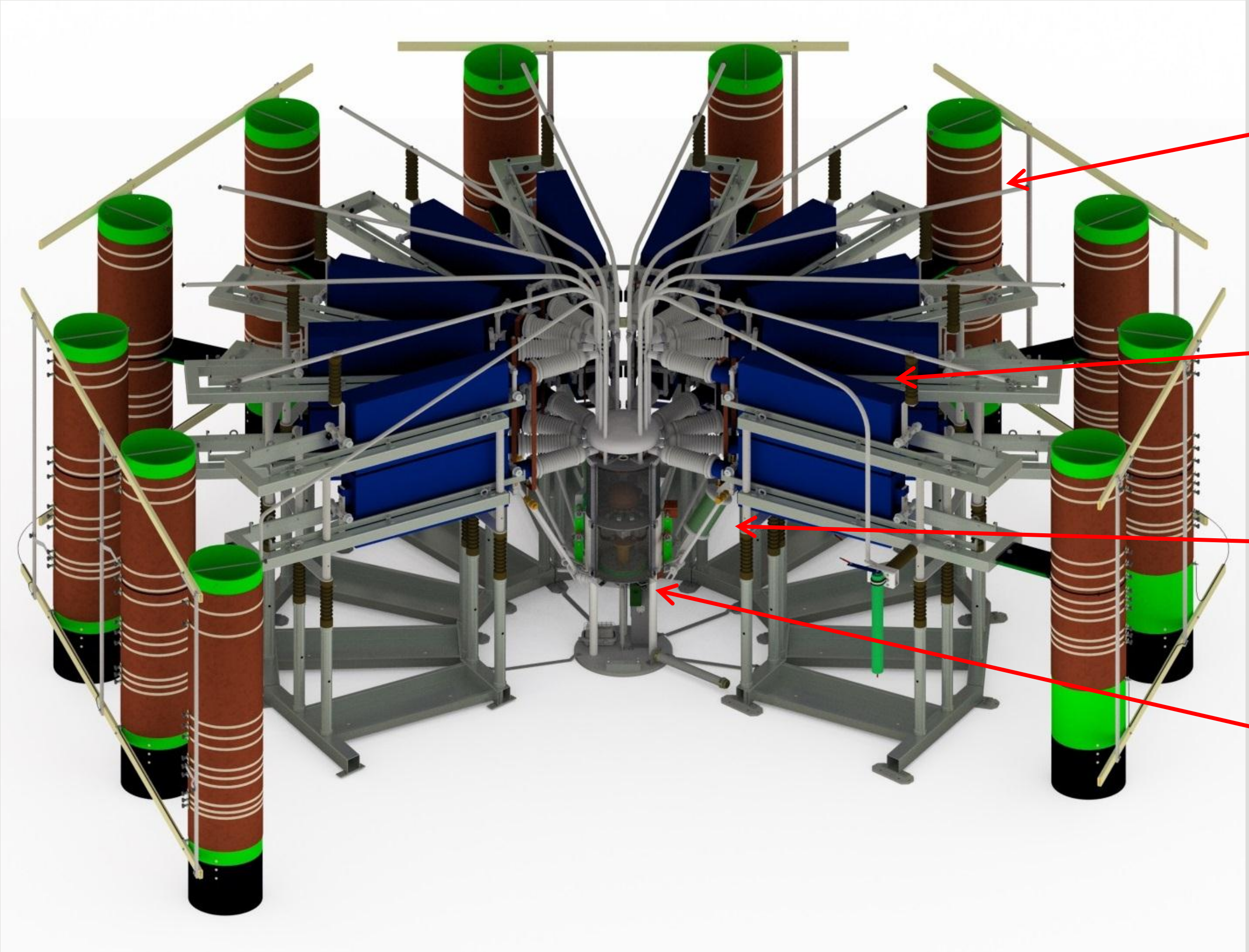
Exponential wave shapes

Impulse	I_{peak} kA	T_1 µs	T_2 µs
0.5/<20	30	0.5	<20
1/<20	50	1	< 20
8/20	75	8	20
4/10	150	4	10
30/80	50	30	80
30/60	45	30	≈ 2x T_1

Sine half wave / rectangular wave

Sine Half Wave	I_{peak} kA	$T_{duration}$ ms
0.2	48	0.2
2	5.8	2
4	3	4
Rectangular	**I_{peak} kA**	**$T_{duration}$ ms**
2	2.8	2
4	1.5	4

ICG FOR IEC 60099-4
Layout



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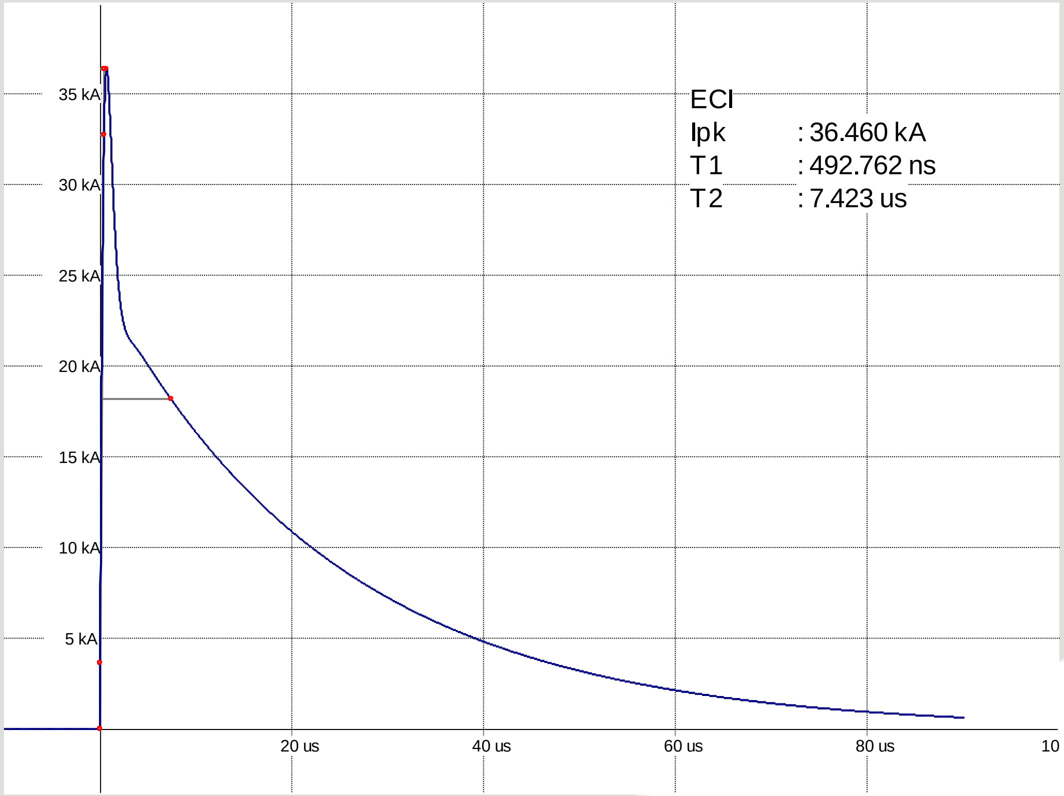
ICG FOR IEC 60099-4
Special Wave Shapes – 0.5/<20

- Combination of capacitors with different capacitance value
- Superposition of currents



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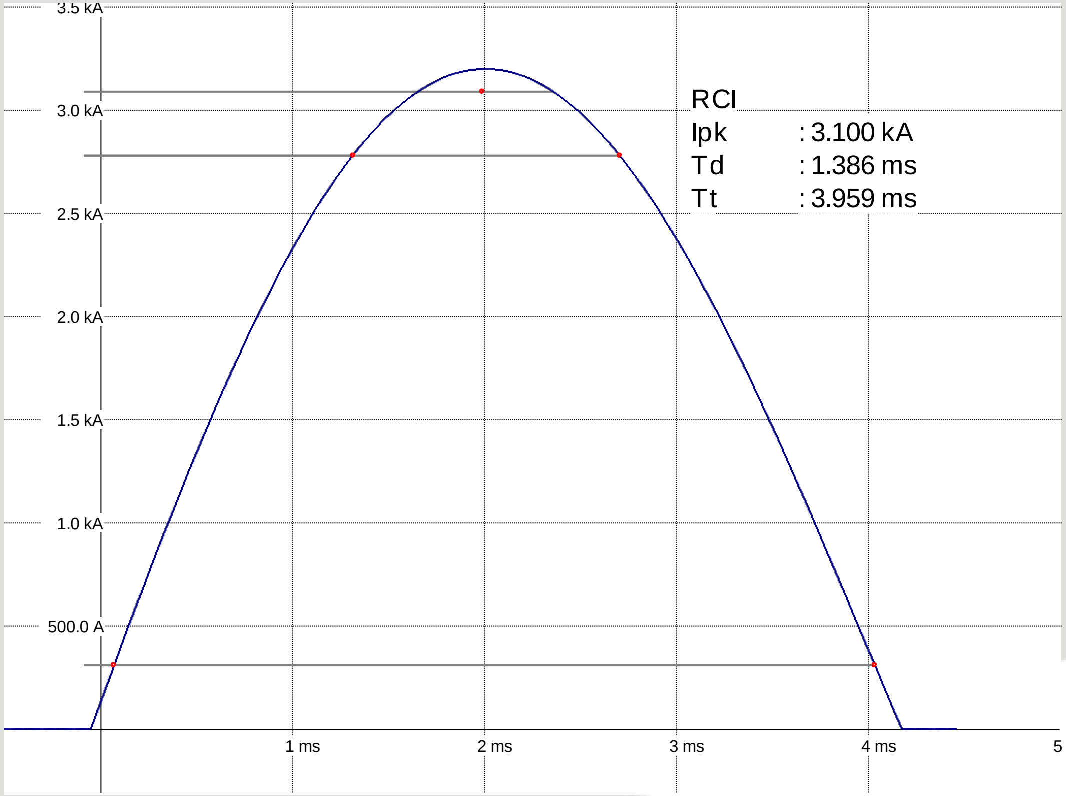
ICG FOR IEC 60099-4
Special Wave Shapes – Sine Half Wave

First time with diode

Up to 50 kA



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Conclusion

- **Universal impulse current generators for almost all waveforms possible with optimally chosen components/extensions**
- **Crowbars can be built for highest current levels up to 250 kA**
- **Aperiodically damped impulses using crowbars beneficial for high energy / charge impulses**
- **Time parameters (especially front times) critical for high energy / charge impulses (10/350) due to necessary inductance values**

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