Application of Power Circuit Breakers for Switching Capacitive and Light Inductive Currents

IEEE Circuit Breaker Tutorial

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Fellow

Nature of Capacitive and Small Inductive Currents

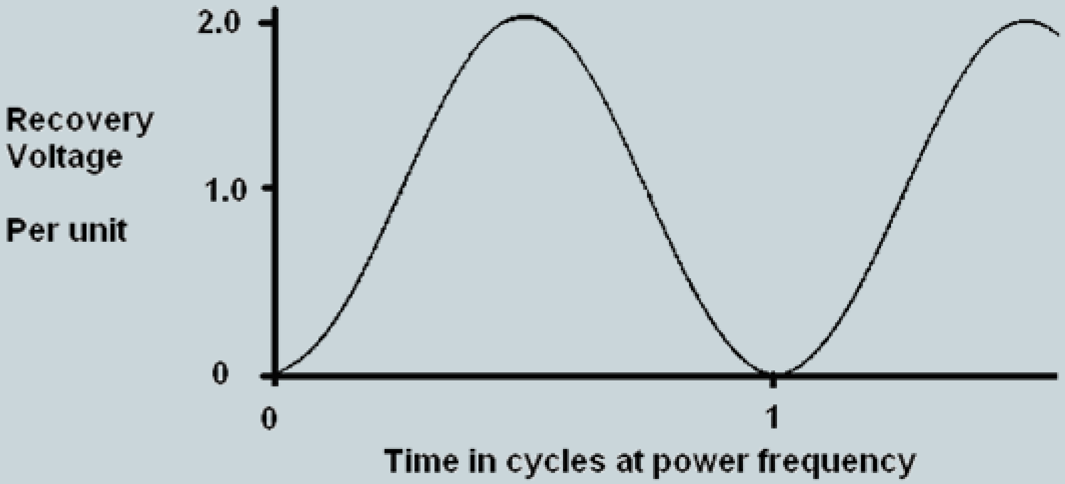
- Small in magnitude
  - Some technologies use current to assist in interruption
- Current and voltage 90 degrees out of phase
- Circuit breakers frequently called upon to deal with switching these currents
- Switching can result in extreme magnitudes of currents and extreme rates of change of voltage

- This presentation is based on C37.012 and C37.015, the application guides for switching these currents. It is impossible to cover all the material in these in detail, and there are other important issues with switching these currents that are not covered in the application guides. This presentation is intended to provide an overview of all the issues associated with switching these currents.

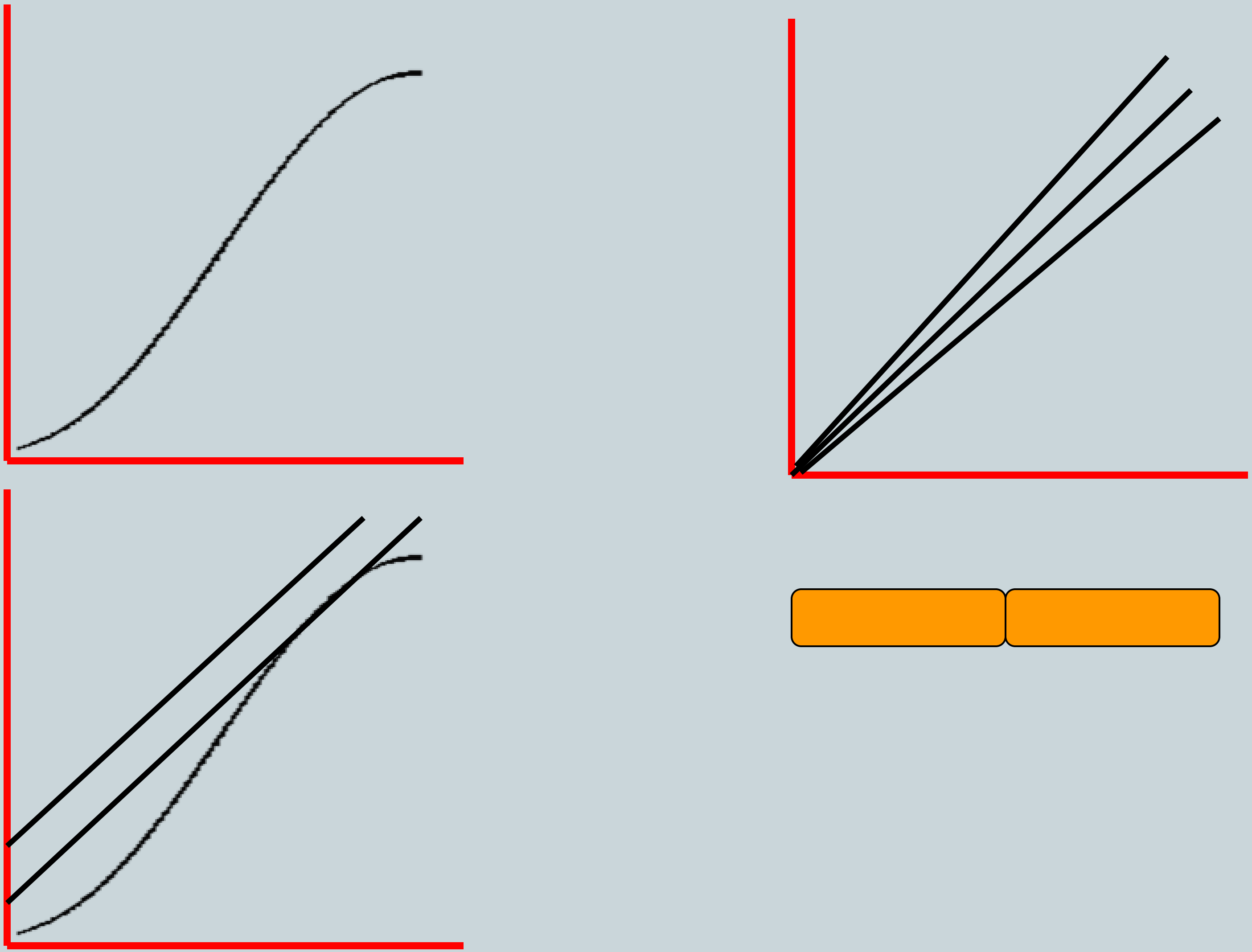
Shunt Capacitor Bank Switching

- Continuous Current
  - Margins for capacitor tolerance
  - Margins for harmonic current
  - Margin of 35% typical

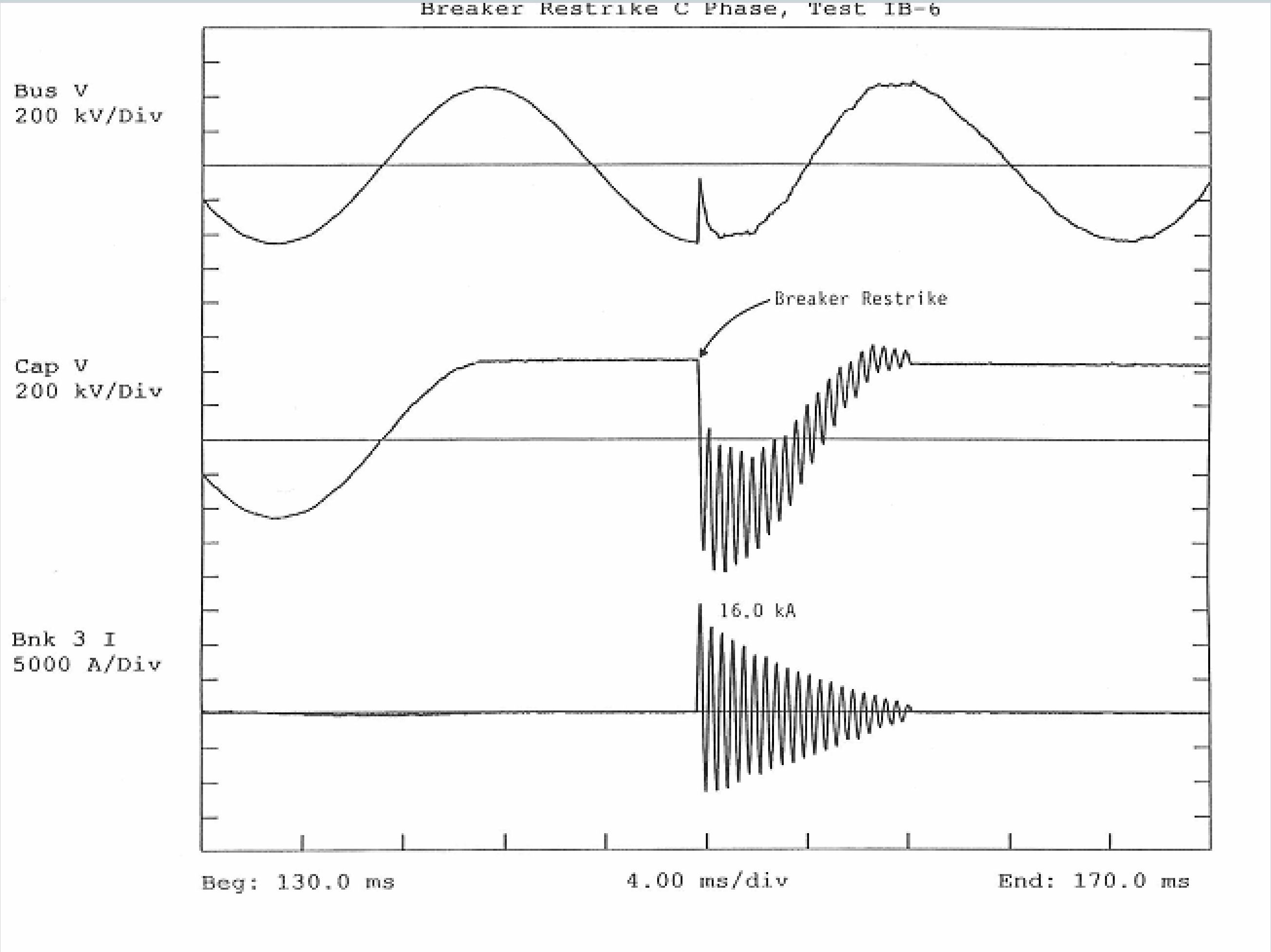
- Interrupting shunt capacitor bank current



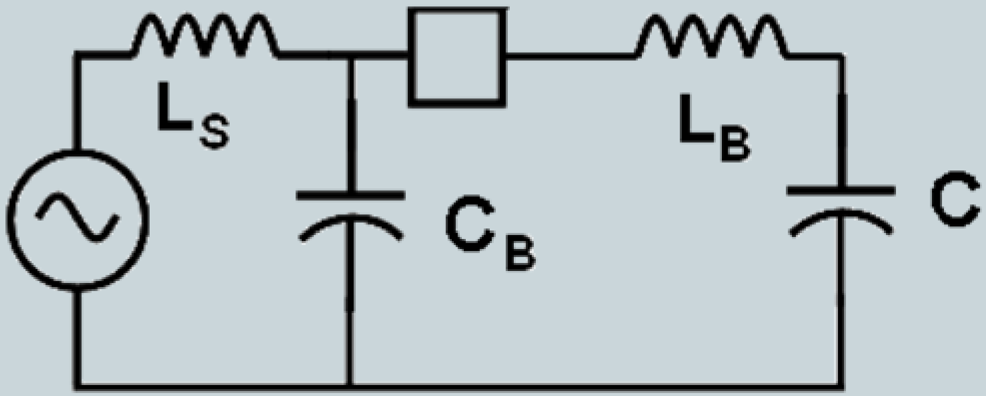
What is a Restrike?



Restrike, Back to Back with CLR's



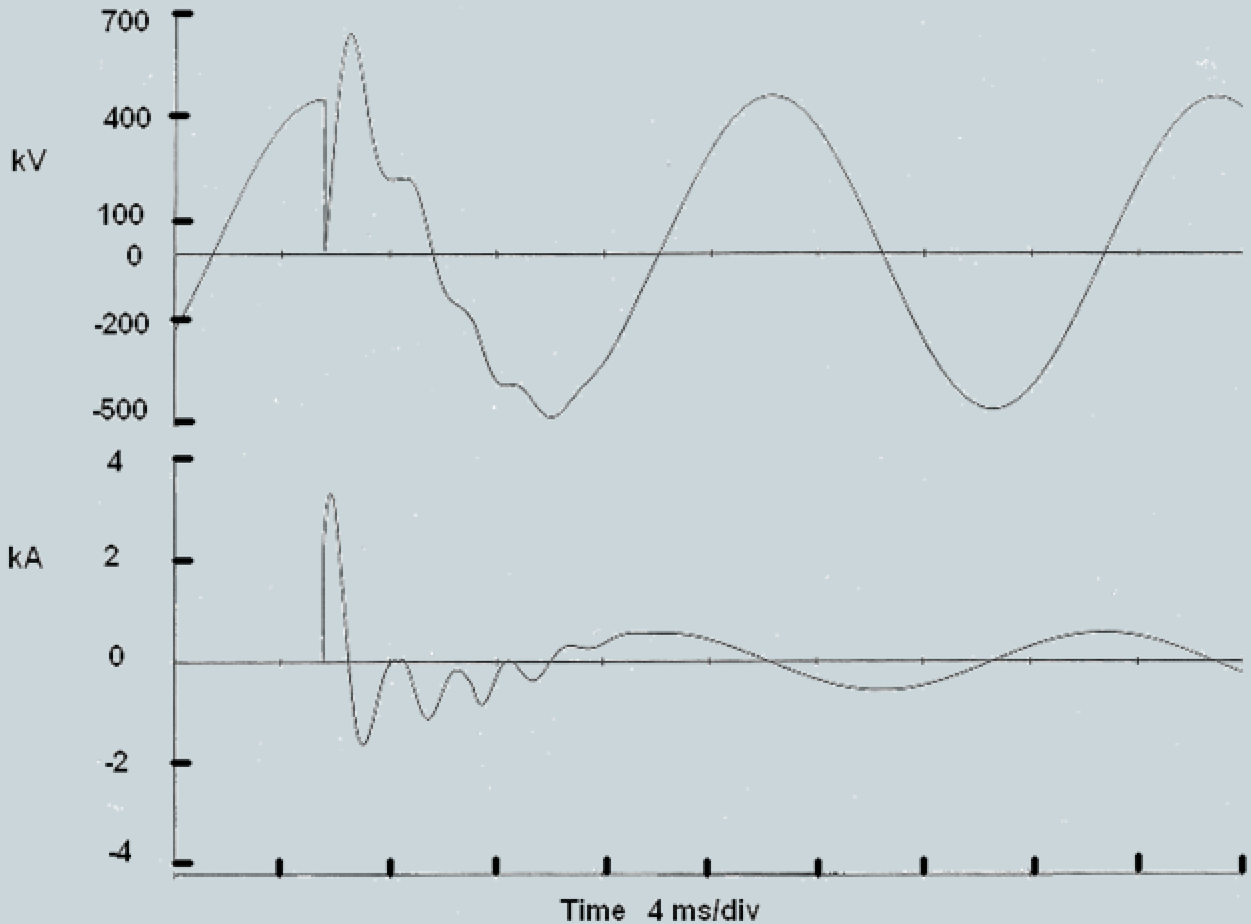
Energizing Shunt Capacitor Banks



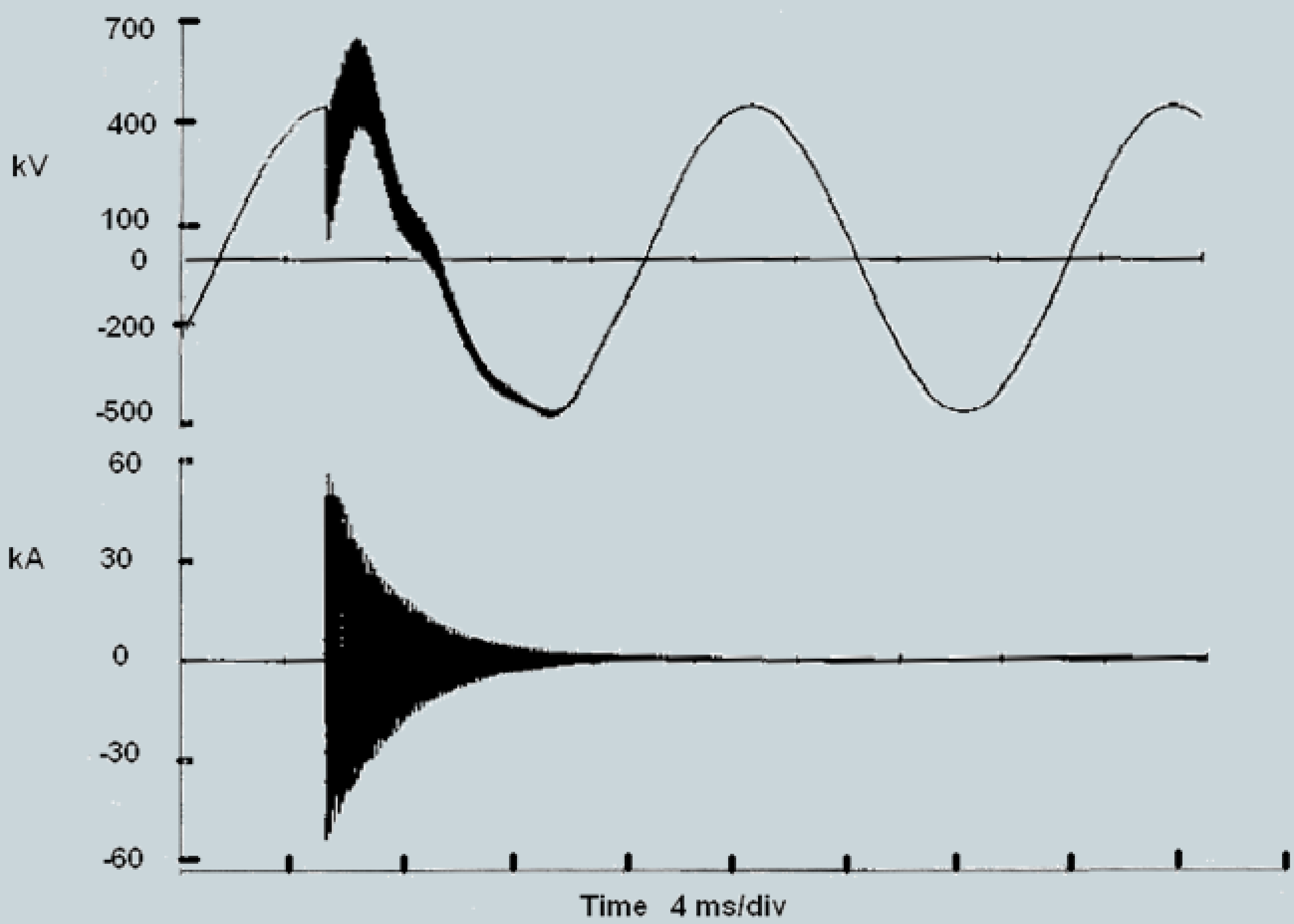
Single or isolated bank

Back to back

500 kV Single Bank Energization



500 kV Back to Back Energization



Consequences of Capacitor Inrush Transients

- Dip to zero voltage
  - Interference with devices that use zero crossing detectors

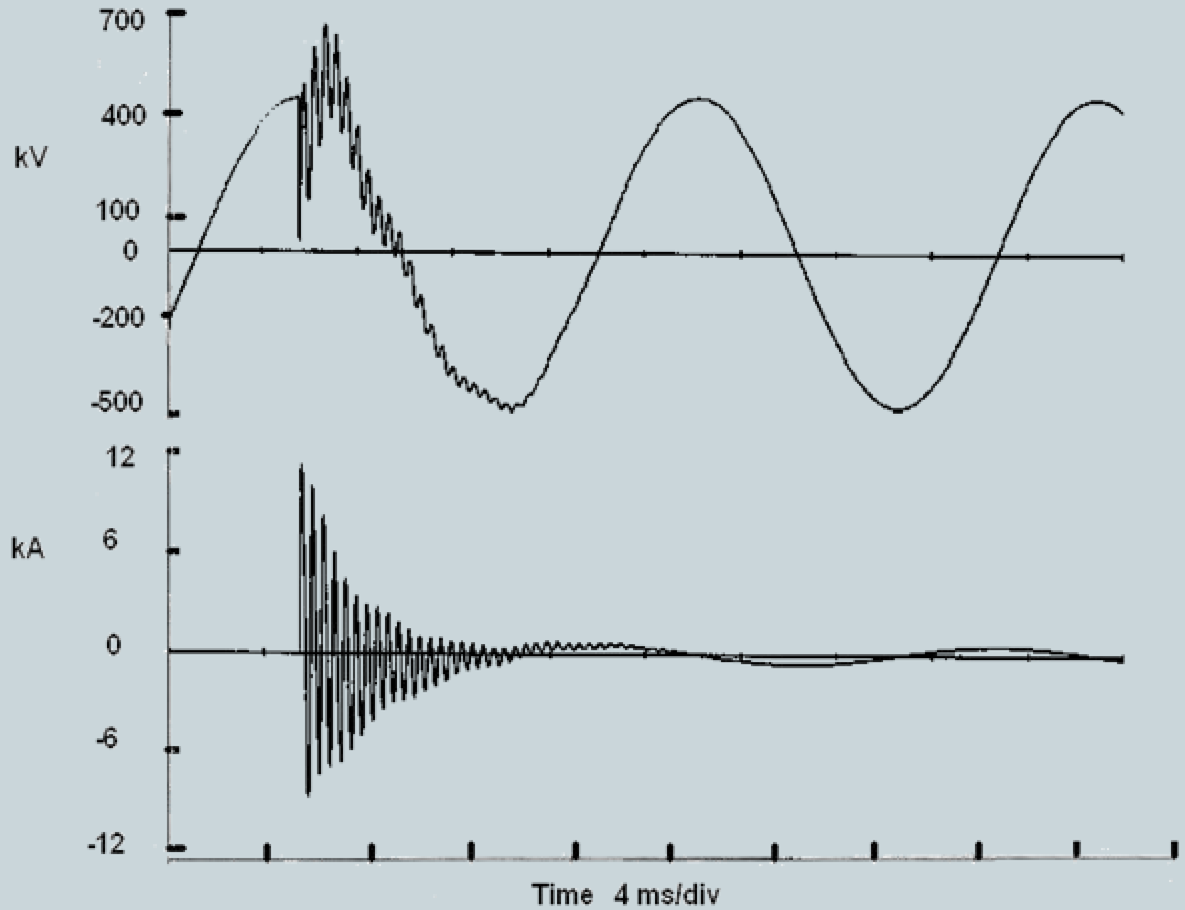
- Back to back results in extremely high currents
  - Damage to primary and secondary equipment
  - Safety

- Restrike (trapped charge)
  - 2 X the voltage, effects 2 X

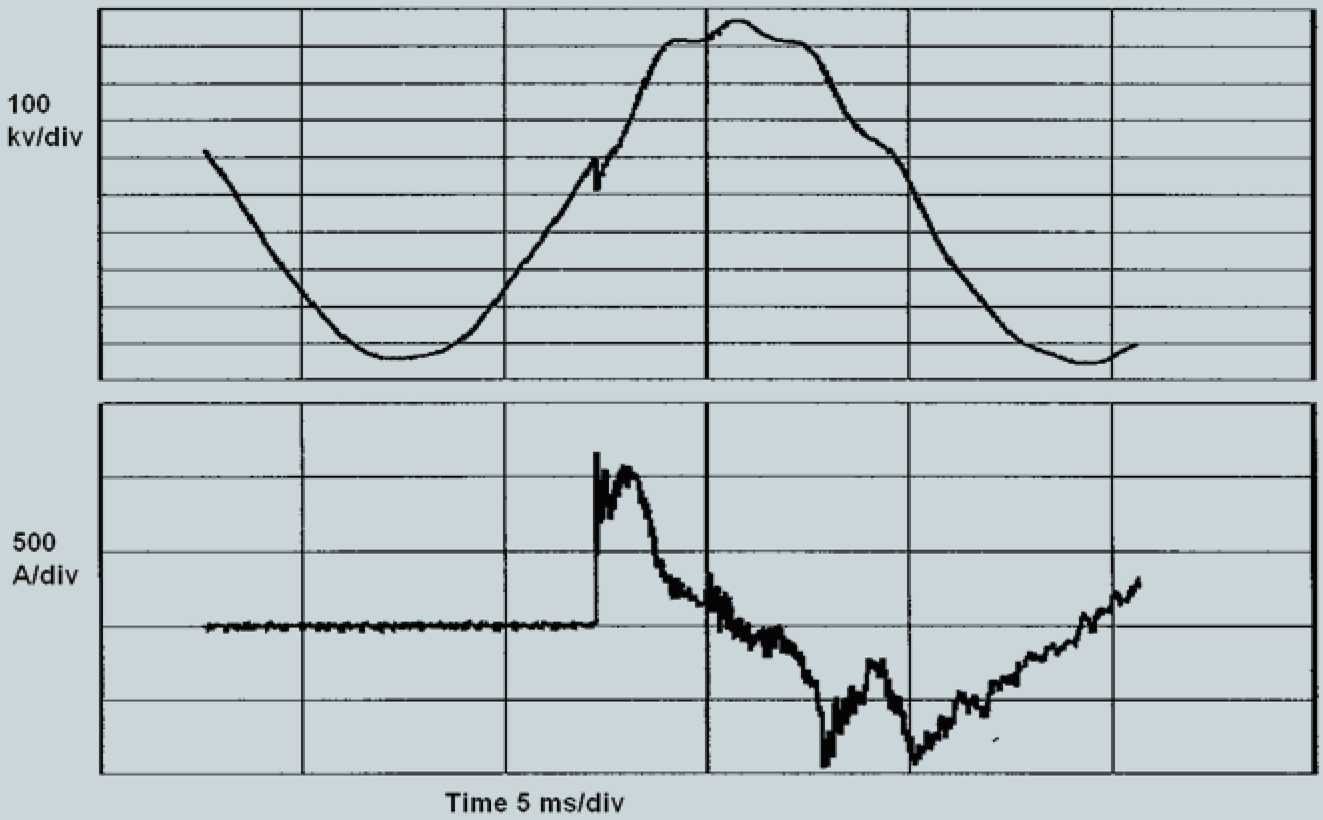
Mitigation of Closing Transients

- Closing Resistor or Reactor
- Fixed Current Limiting Reactor
- Controlled closing

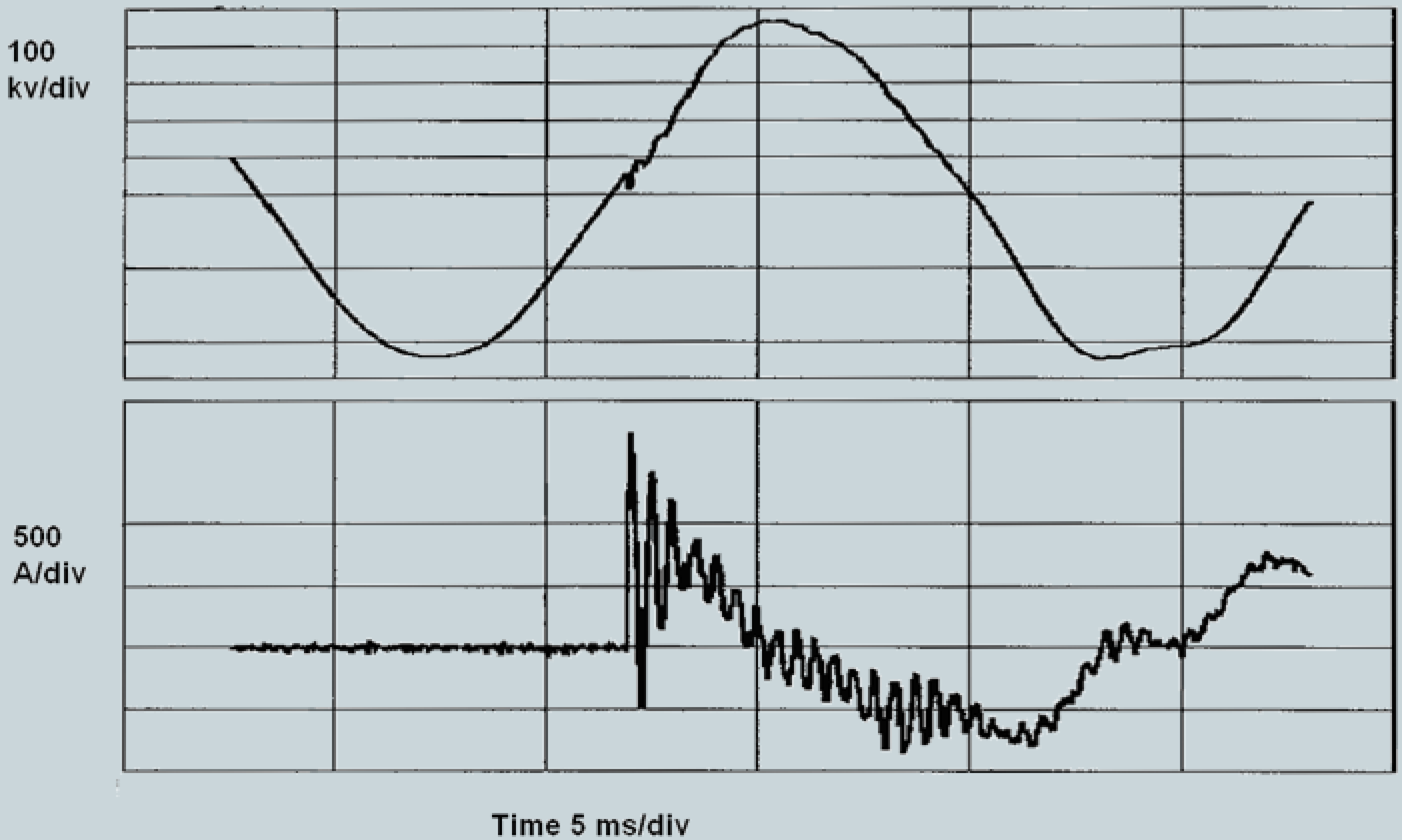
500 kV Back to Back Energization with CLR



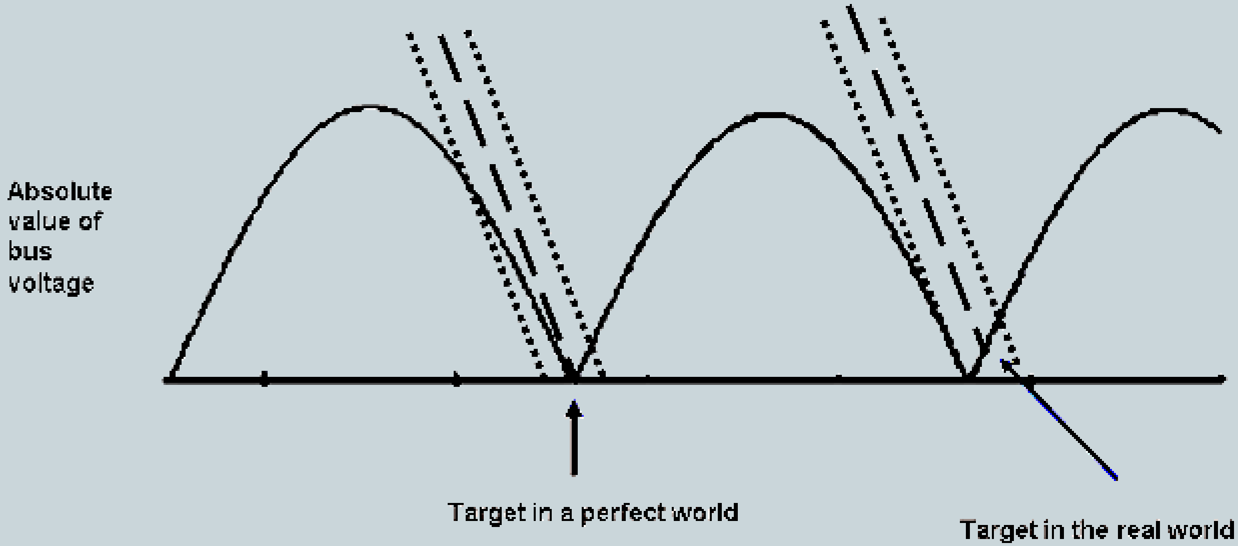
Controlled Closing, Single Bank



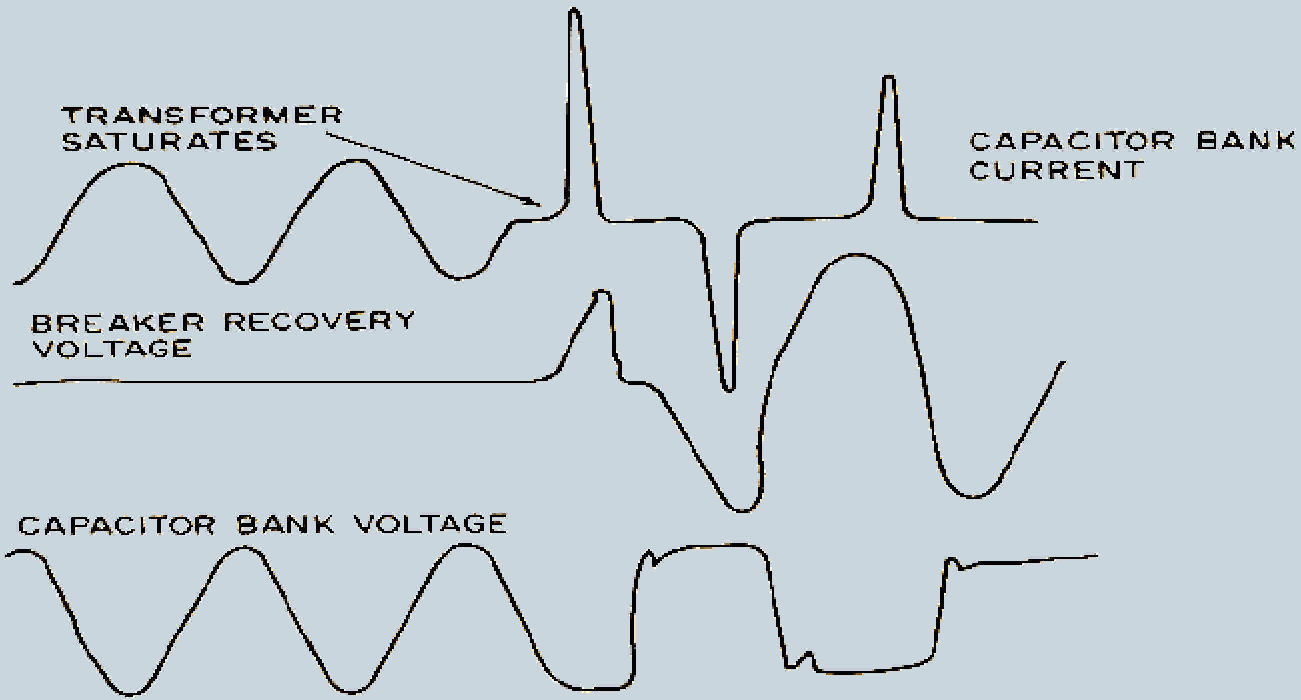
Controlled Closing, Back to Back



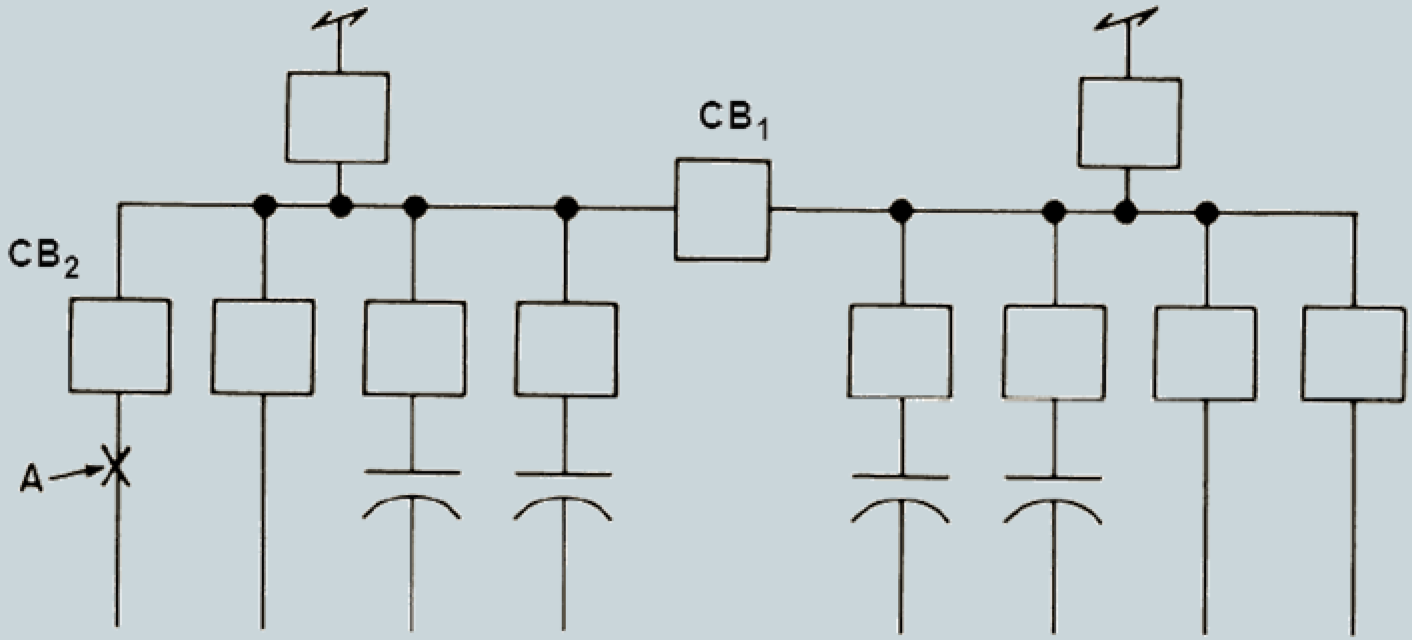
Controlled Closing, Capacitor Banks, targeting



Switching Capacitor Through a Transformer

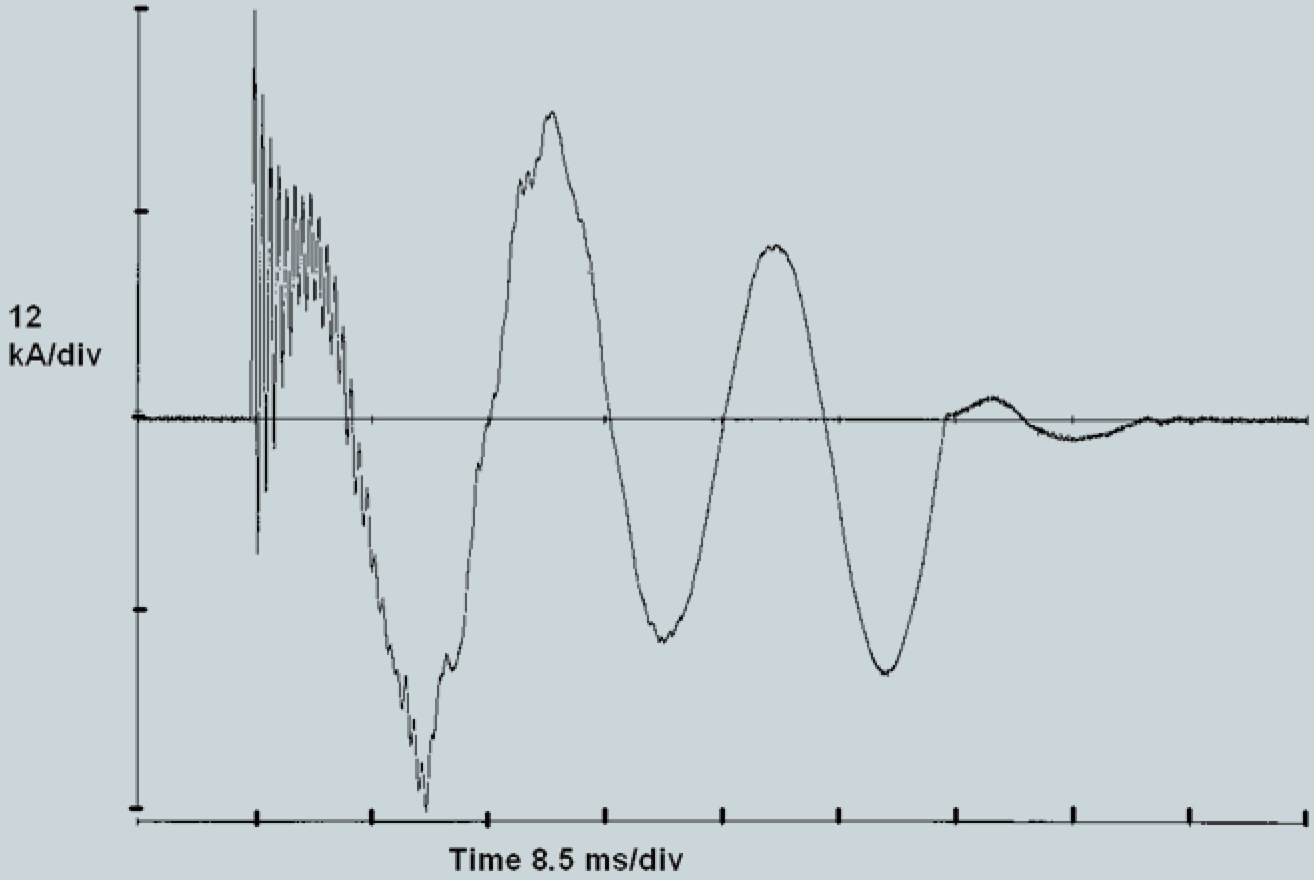


Faults Near Capacitor Banks



•Outrush, TRV effects, high source impedance voltage rises (or long lining), etc.

Line Fault, 500 kV system, with 430 Mvar of Connected Capacitors



Circuit Breaker Standards

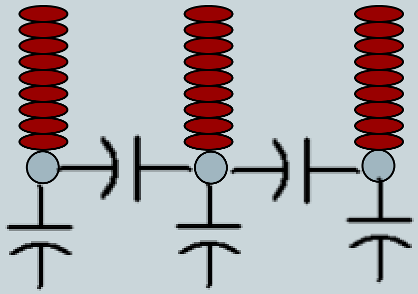
Restrike probability: C0, no rating, C1, ~ 1 restrike in 50 operations, C2, ~ 1 restrike in 300 operations

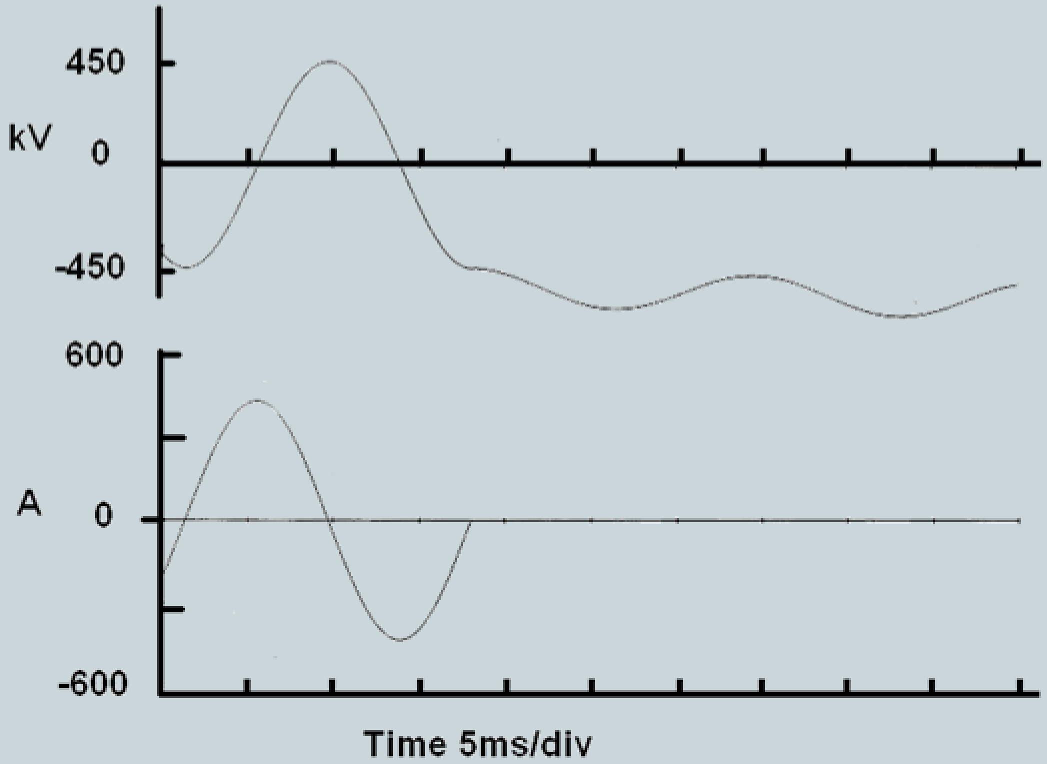
Line No.	Rated Maximum Voltage kV, rms	Rated Continuous Current A, rms	Class C0 Circuit Breakers (1) (2)		Class C1 or Class C2 (2) (4)	
					Isolated Capacitor Bank Switching	
			Rated Overhead Line Current A, rms	Rated Isolated Capacitor Bank or Cable current (6) A, rms	Rated Capacitor Bank Current (6) A, rms	Rated Overhead Line Current A, rms
	Col 1	Col 2	Col 3	Col 4	Col 5	Col 6
1	123	< 2000	50	50	1200	160
2	123	≥2000	50	50	1200	160
3	145	< 2000	80	80	1200	160
4	145	≥2000	80	80	1200	160
5	170	< 2000	100	100	1200	160
6	170	≥2000	100	100	1200	160
7	245	< 2000	160	160	1200	200
8	245	≥2000	160	160	1200	200
9	362	< 2000	250	250	1200	315
10	362	≥2000	250	250	900	315
11	550	≤ 4000	400	400	900	500
12	800	≤ 4000	900	500	900	900

Circuit Breaker Standards

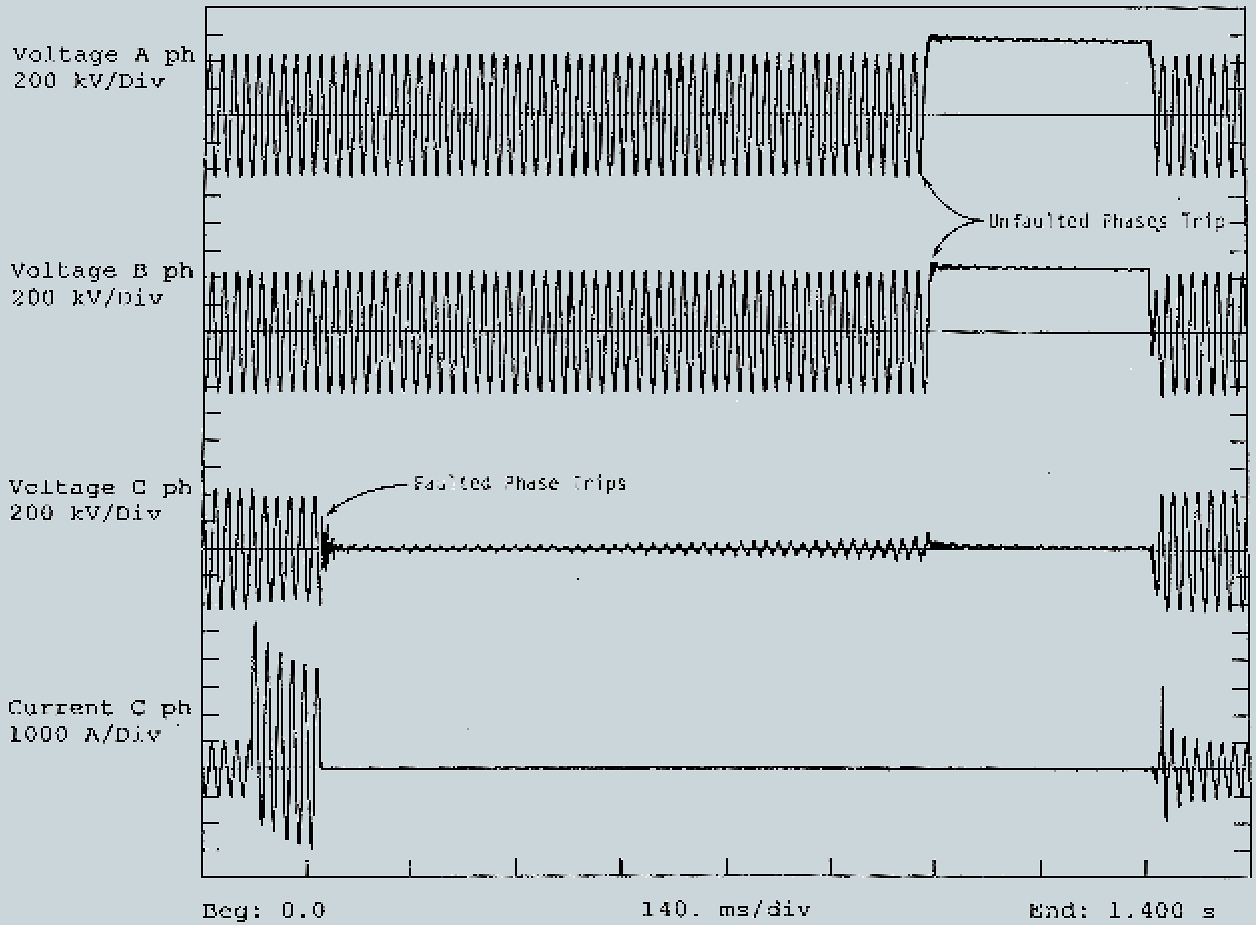
Line No.	Rated Maximum Voltage	Rated Continuous Current	Class C1 or Class C2 Circuit Breakers (2) (4)						
			Back to back Capacitor Bank Switching						
			Rated Capacitor Bank Current (6)	Rated Inrush Current (3) (5)					
				Alternate 1 (7)		Alternate 2 (7)		Alternate 3 (7)	
				Peak Value	Frequency	Peak Value	Frequency	Peak Value	Frequency
	kV, rms	A, rms	A, rms	kA, Peak	kHz	kA, Peak	kHz	kA, Peak	kHz
	Col 1	Col 2	Col 3	Col 4	Col 5	Col 6	Col 7	Col 8	Col 9
13	123	< 2000	700	16	4.3	6	2	25	13
14	123	≥2000	700	16	4.3	6	2	60	8.5
15	145	< 2000	700	16	4.3	6	2	25	13
16	145	≥2000	700	16	4.3	6	2	60	8.5
17	170	< 2000	700	20	4.3	6	2	25	13
18	170	≥2000	700	20	4.3	6	2	60	8.5
19	245	< 2000	700	20	4.3	6	2	25	13
20	245	≥2000	700	20	4.3	6	2	60	8.5
21	362	< 2000	700	25	4.3	6	2	20	21
22	262	≥2000	800	25	4.3	6	2	65	8.5
23	550	< 4000	800	25	4.3	6	2	20	21
24	550	≥4000	800	25	4.3	6	2	65	8.5
25	800	< 4000	800	25	4.3	6	2	20	21
26	800	≥4000	800	25	4.3	6	2	65	8.5

Switching Overhead Transmission Lines - Interruption

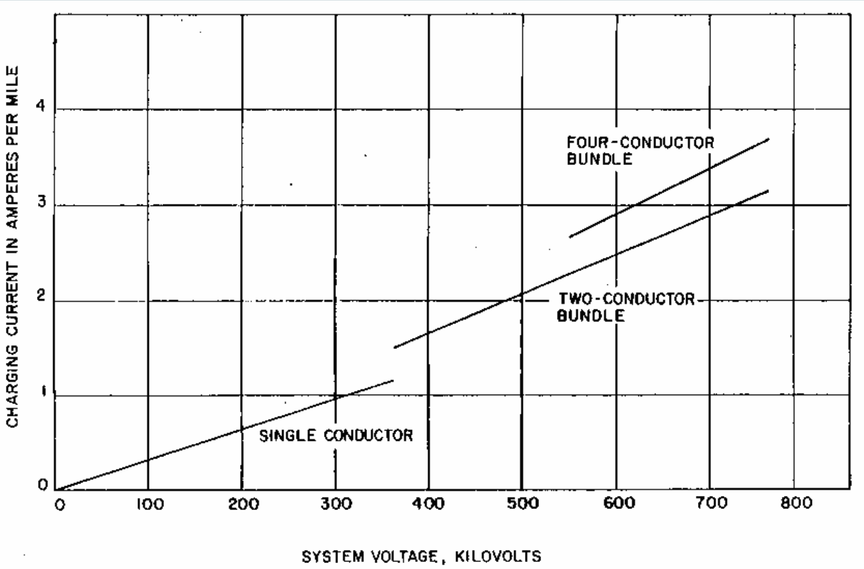


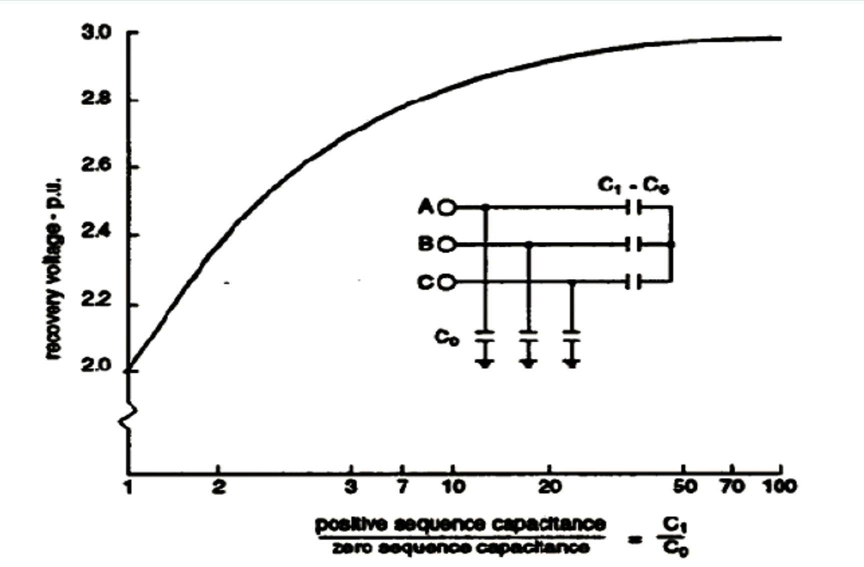


Switching Overhead Transmission Lines

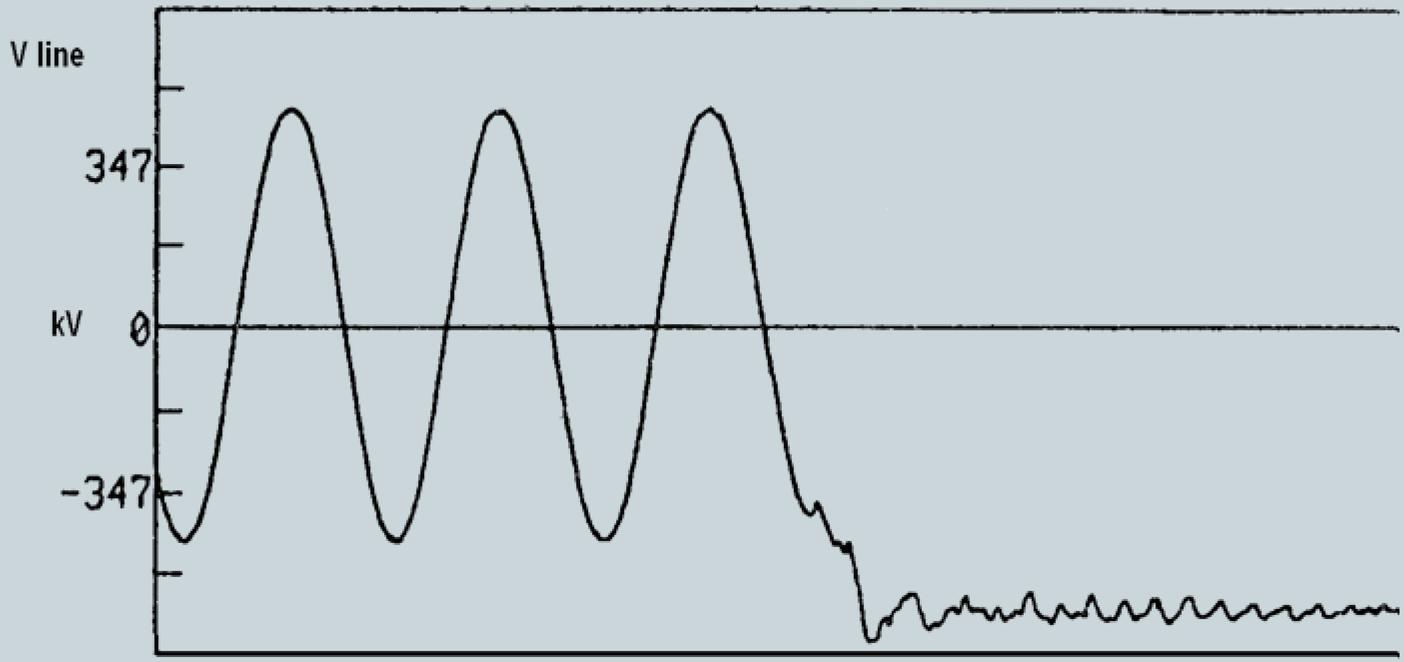


Charging Current and Recovery Voltage



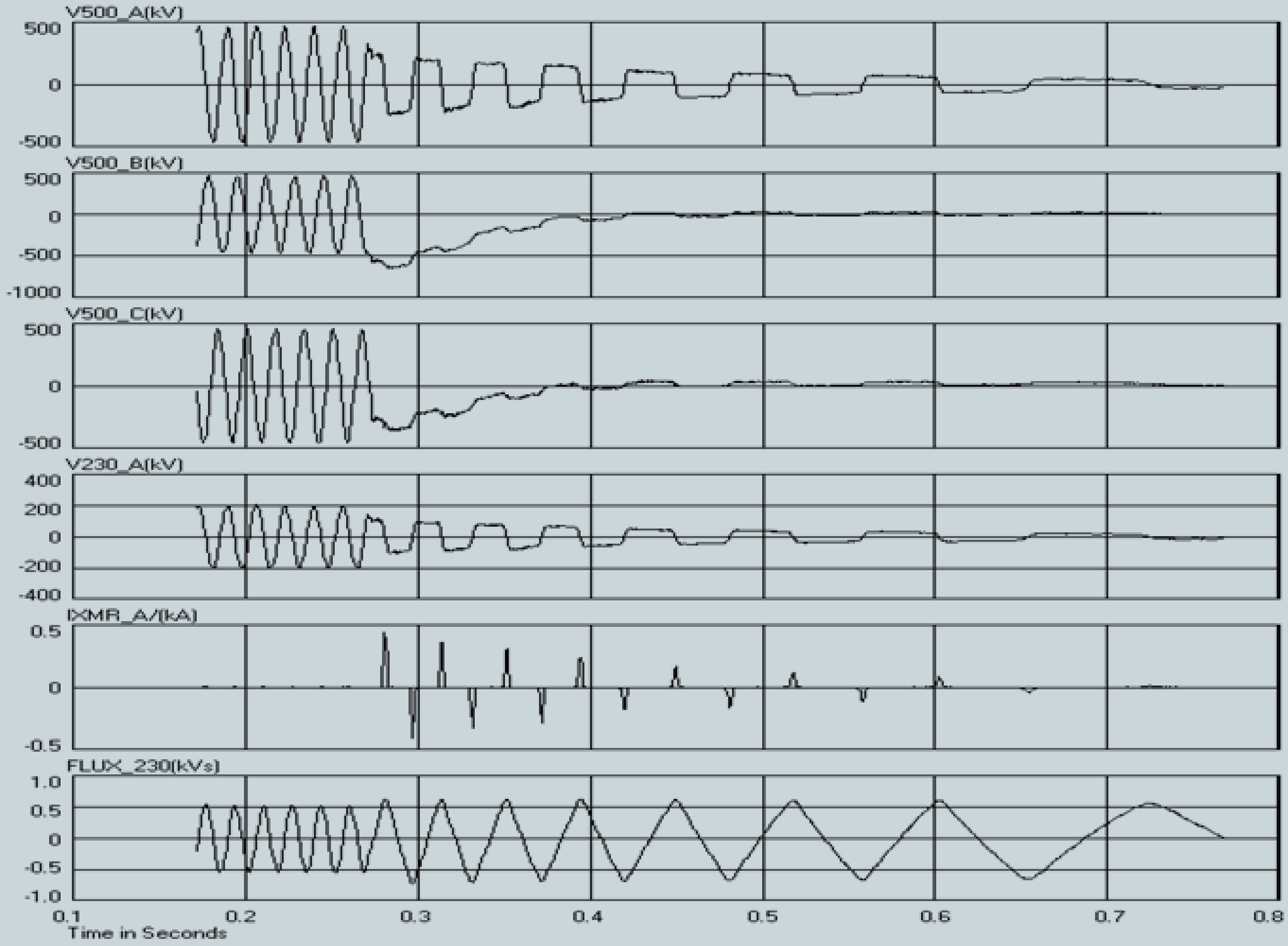


Recovery Voltage on Unfaulted Phases

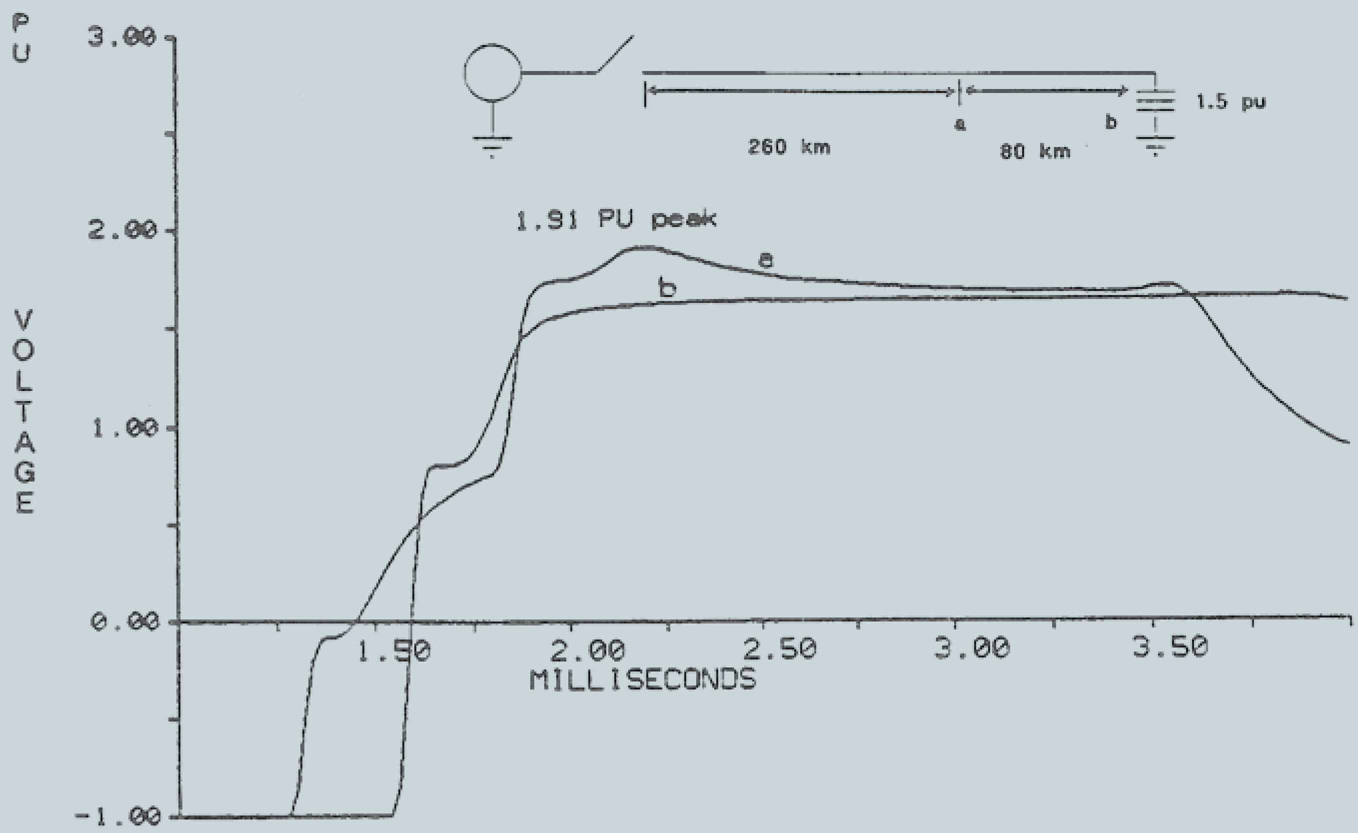


Neutral shift, coupling of transients

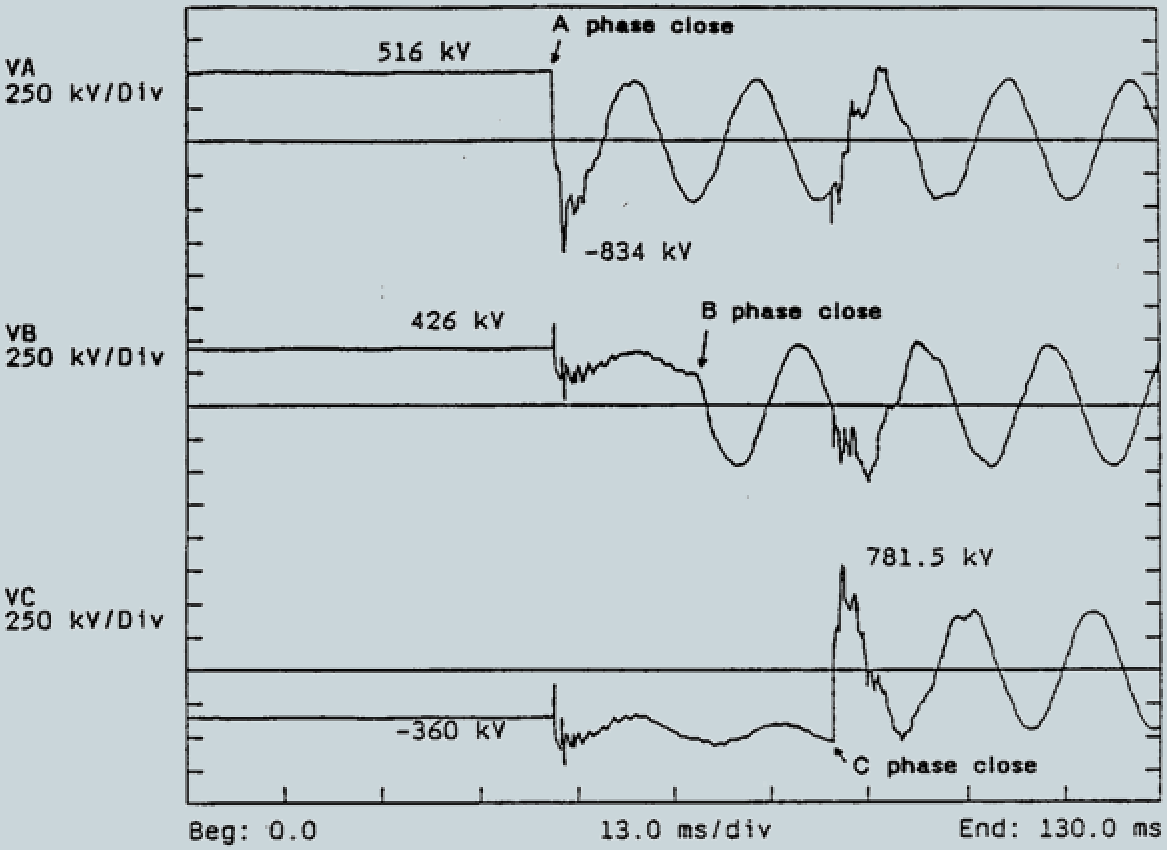
De-energization of a Line with Connected Transformer



Energization of Transmission Lines, Switching Surges



Switching Surge Overvoltages

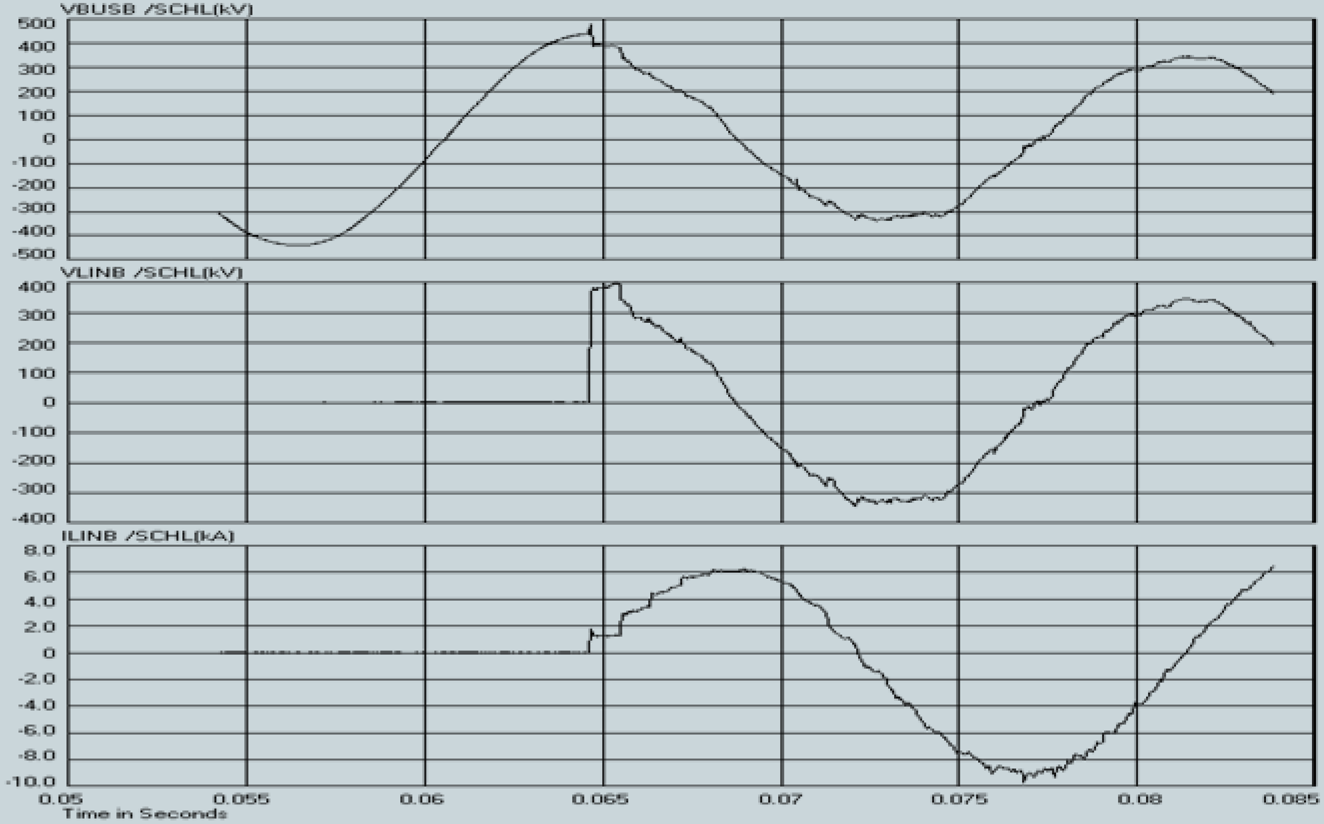


Switching Surge Mitigation

- Only needed above 245 kV (rarely at 245 kV)

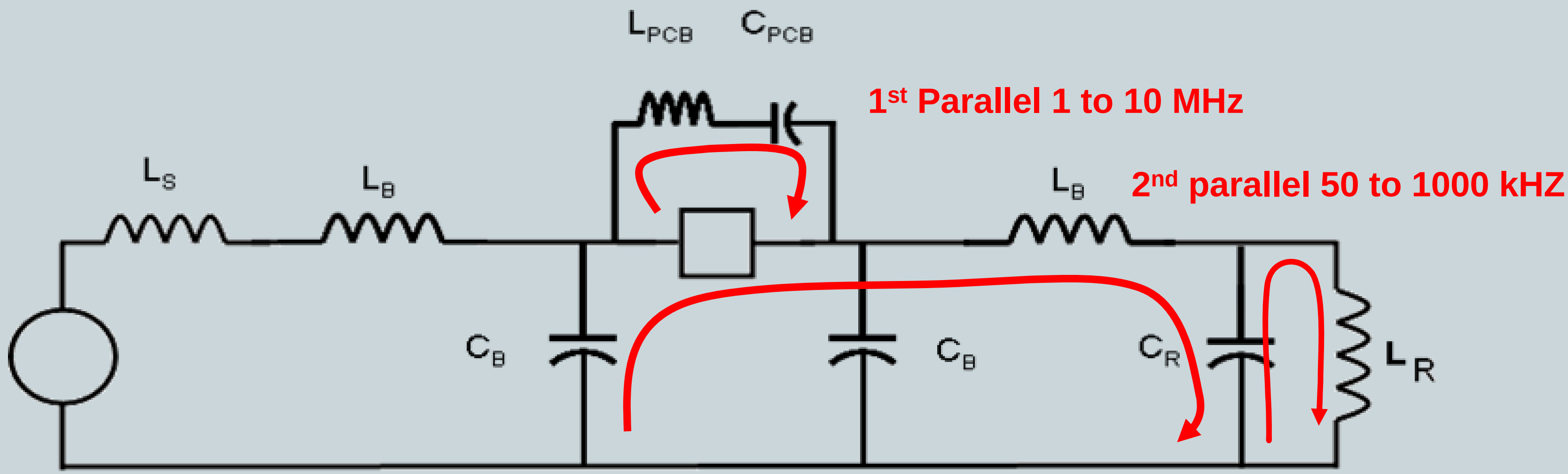
- Closing resistors
- Line connected surge arresters
- Controlled closing
- Trapped charge reduction (line connected PT's – caution)
- Single pole reclosing (limited due to secondary arc)
- Controlled closing
- Staggered pole closing

Traveling Waves Present on Most Line Phenomena



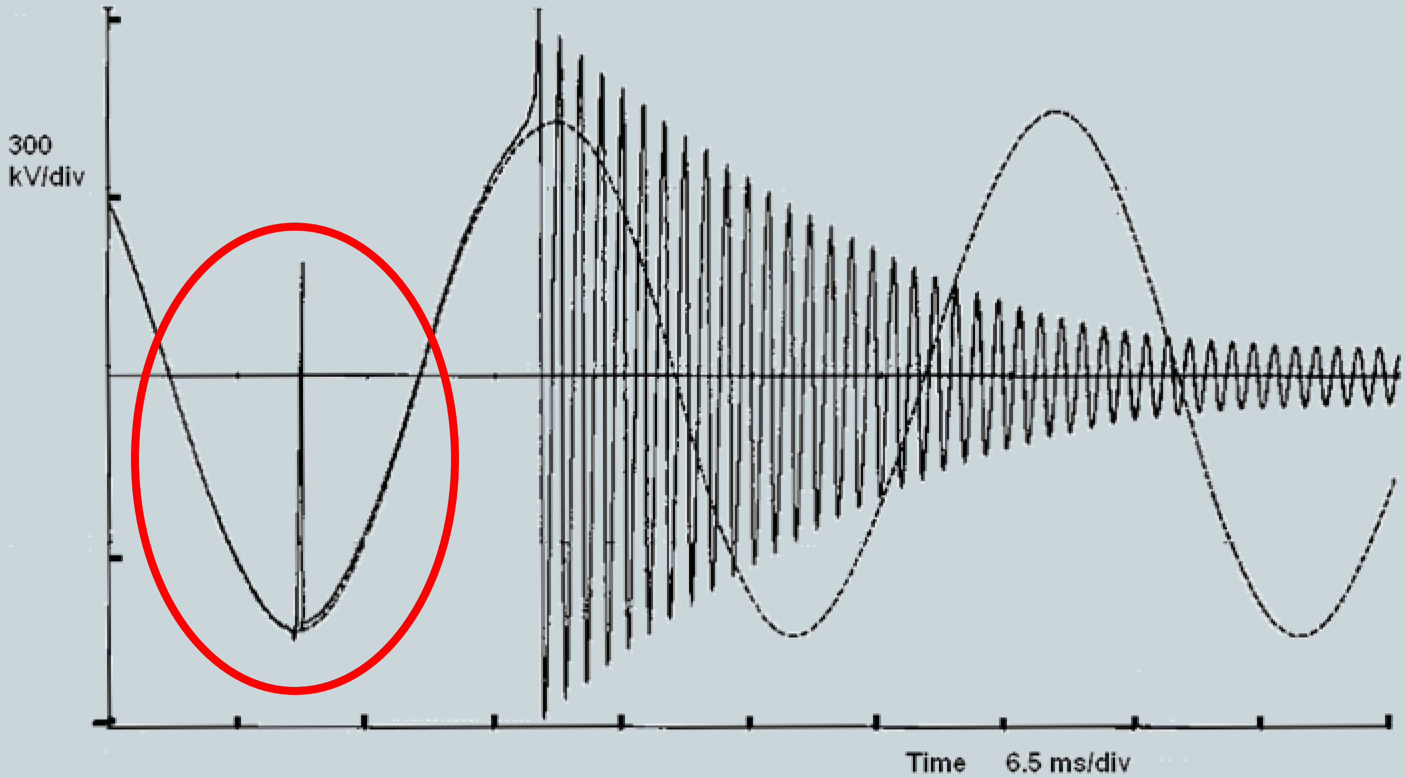
Closing into a fault, 500 kV field test data.

Shunt Reactor Switching



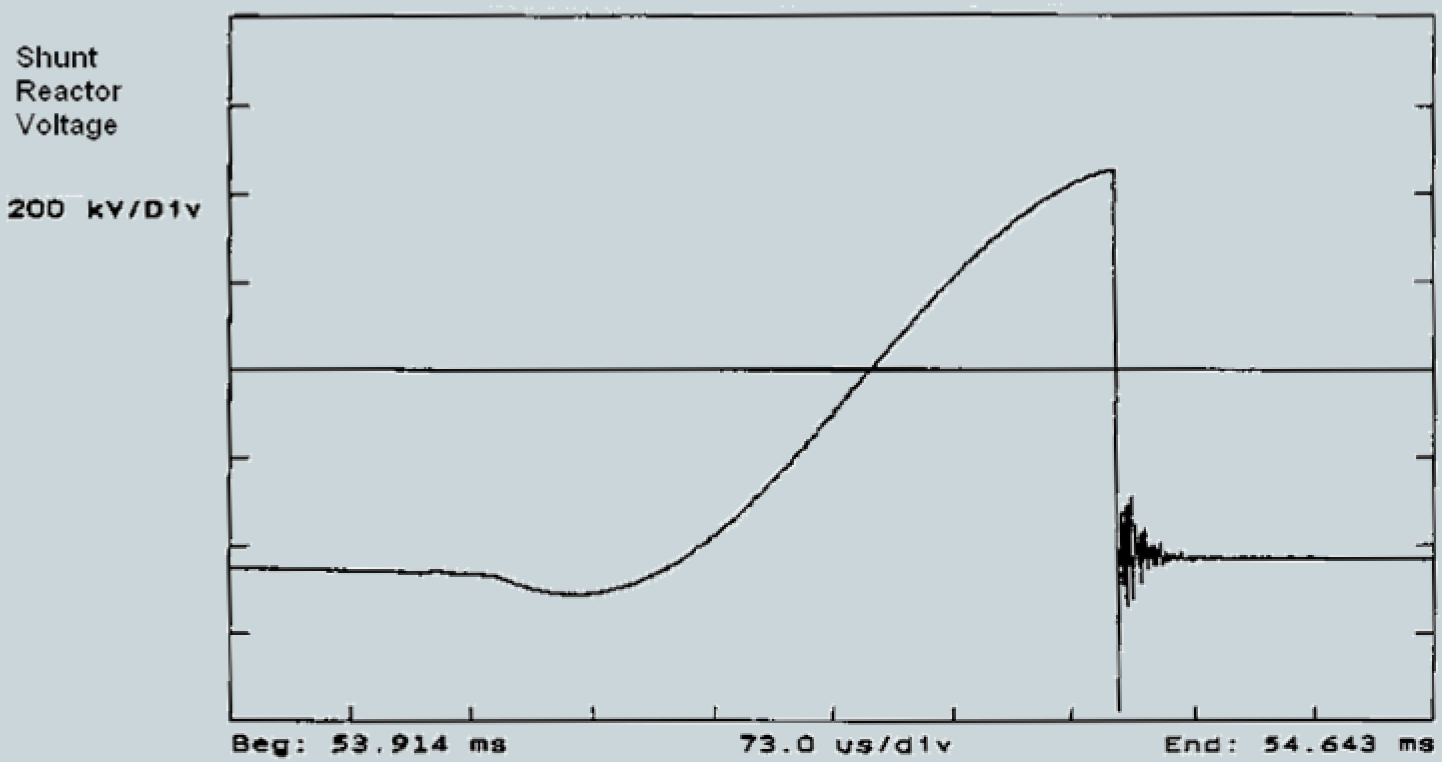
Load oscillation 1 to 5 kHz

225 Mvar Shunt Reactor Interruption

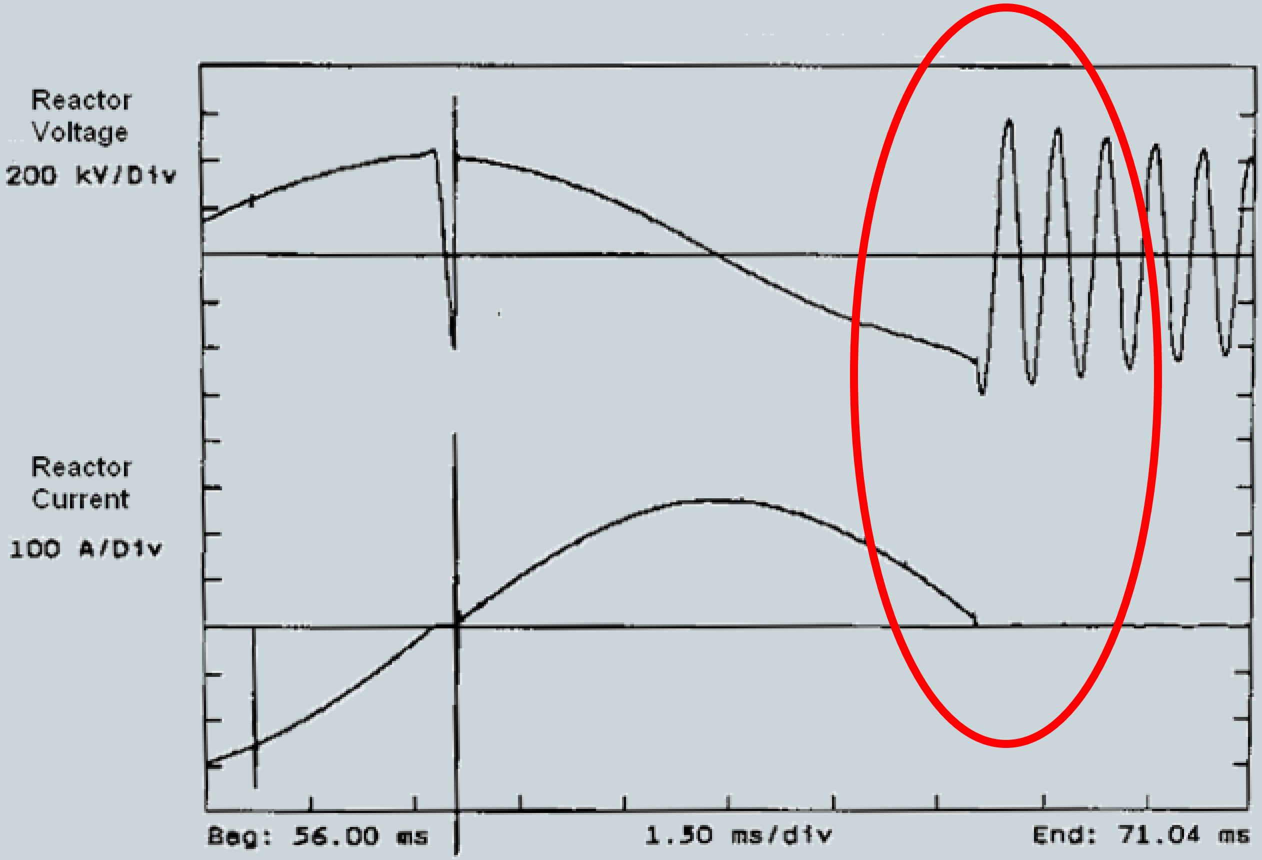


500 kV bus and reactor voltages, field test data

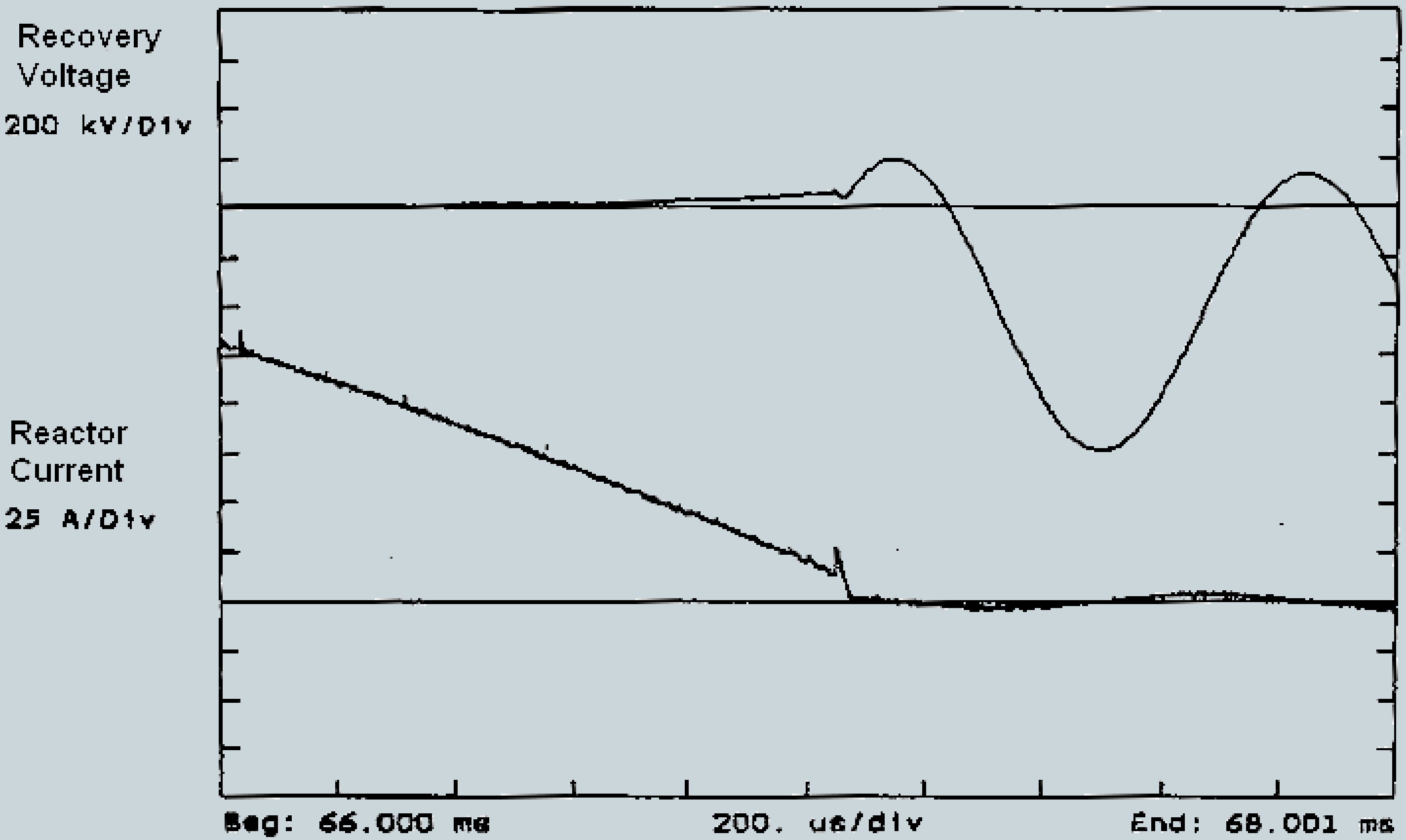
Time Expansion of Previous Slide



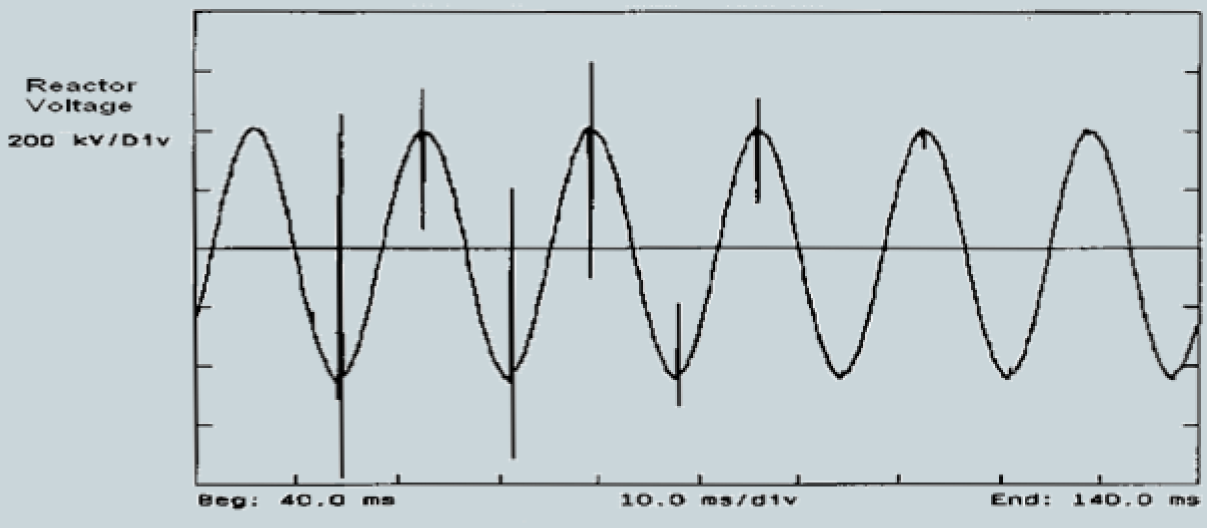
Re-ignition and Current Chopping



Time Expansion of Previous Slide

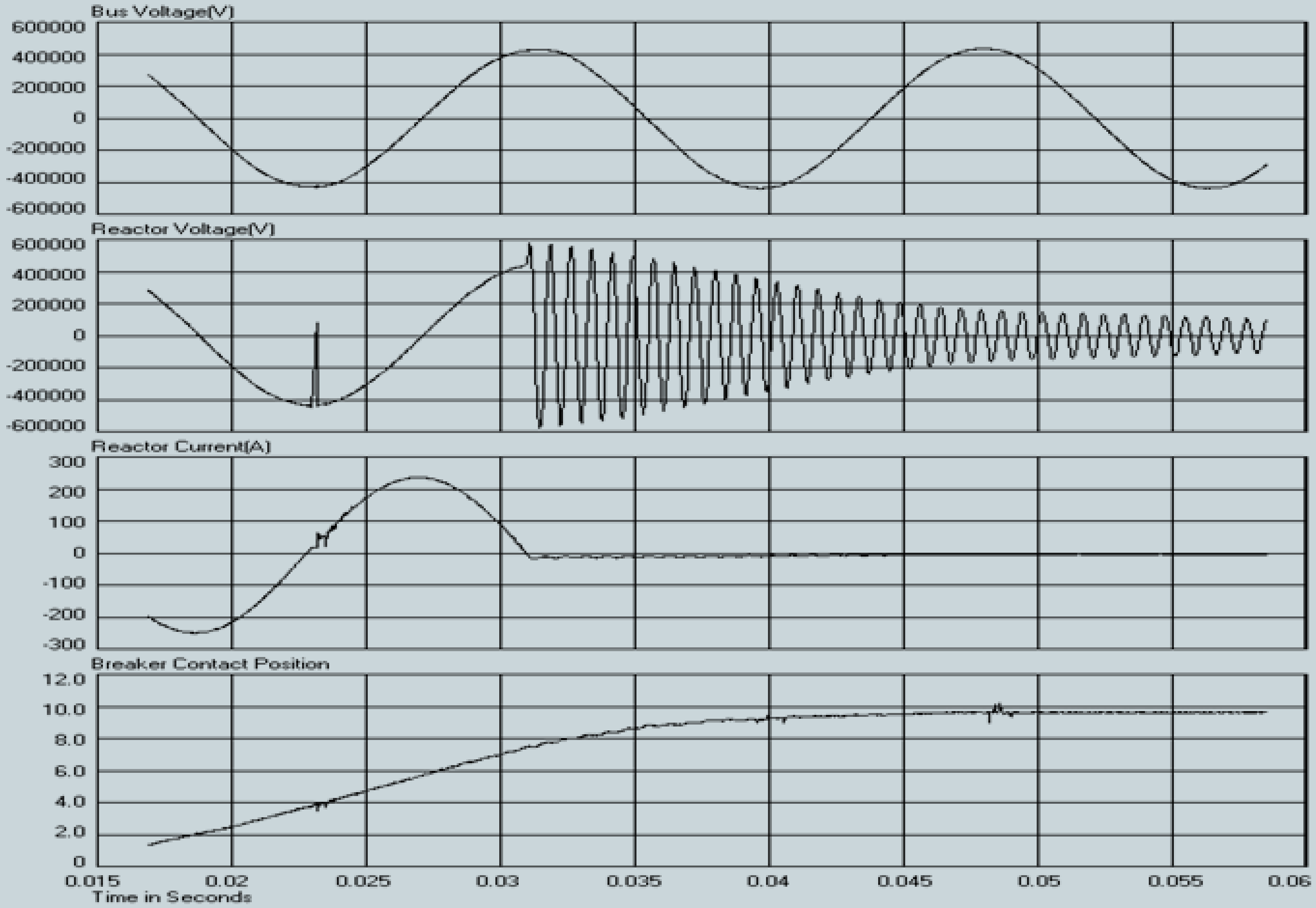


Reactor Current Interruption Failure

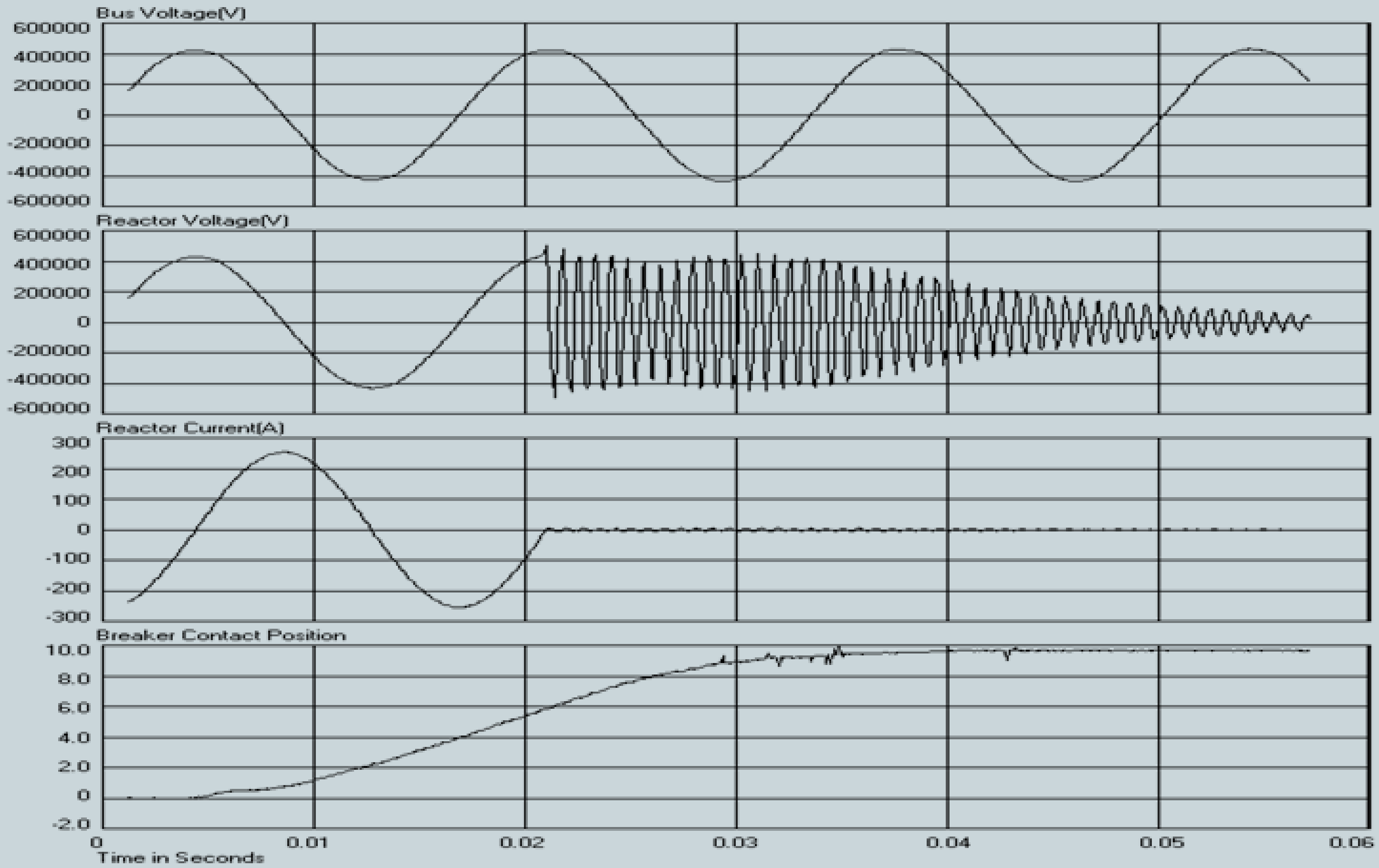


- Interruption still a difficult duty for circuit breakers
- Differences in the parameters make a standard test nearly impossible

Shunt Reactor Current Interruption w/o Controlled Opening



Shunt Reactor Current Interruption with Controlled Opening



Energizing Shunt Reactors

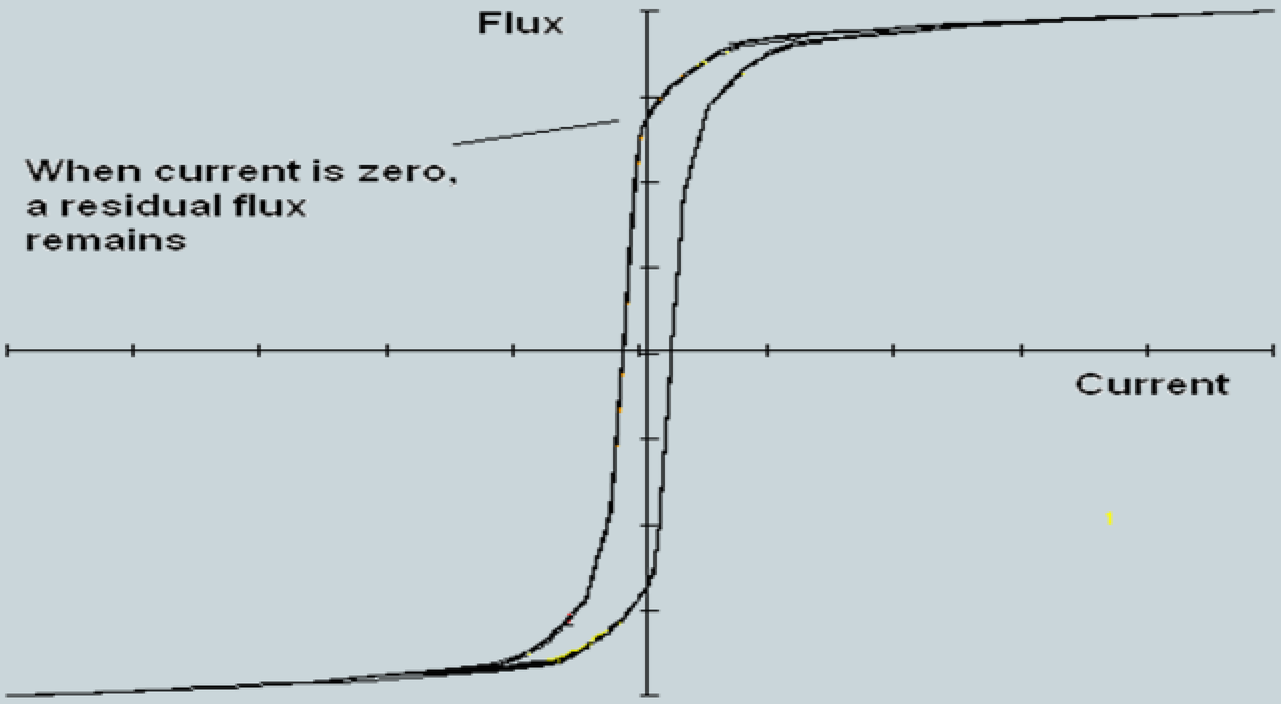
- Inrush currents smaller than for power transformers (to be discussed next), and not generally considered a problem

- Can cause sympathetic inrush in nearby power transformers

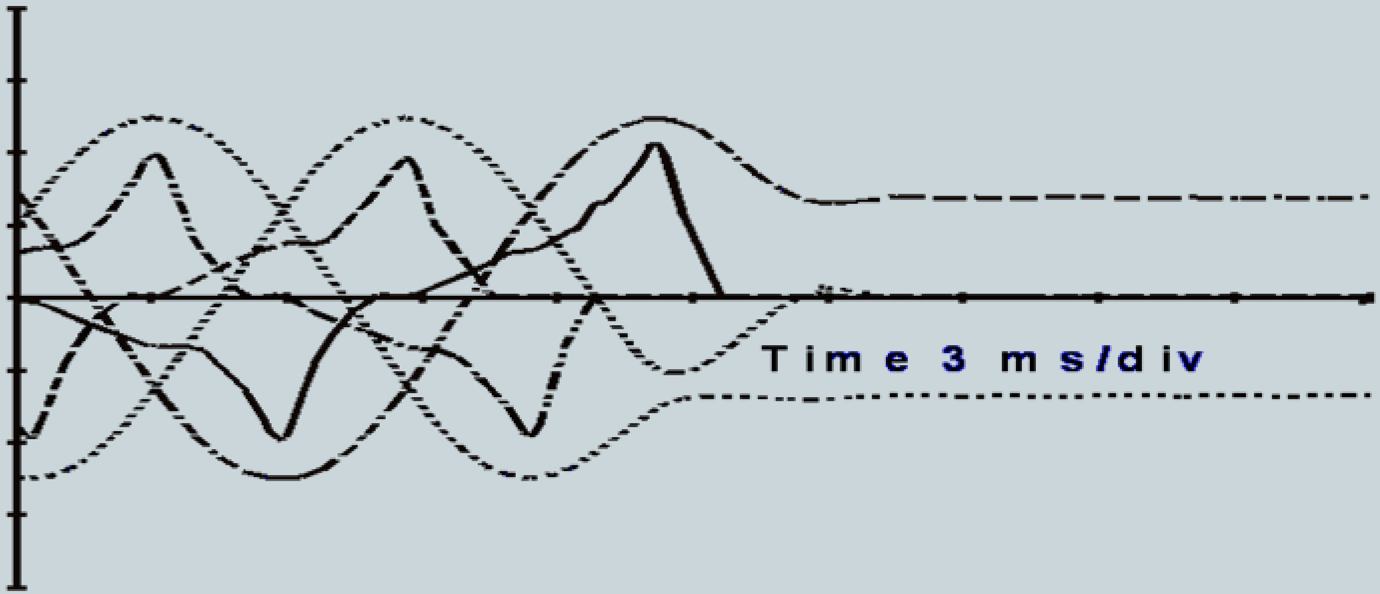
- Problems have only been observed in certain configurations

Switching Transformer Magnetizing Currents

Transformer Core Characteristic



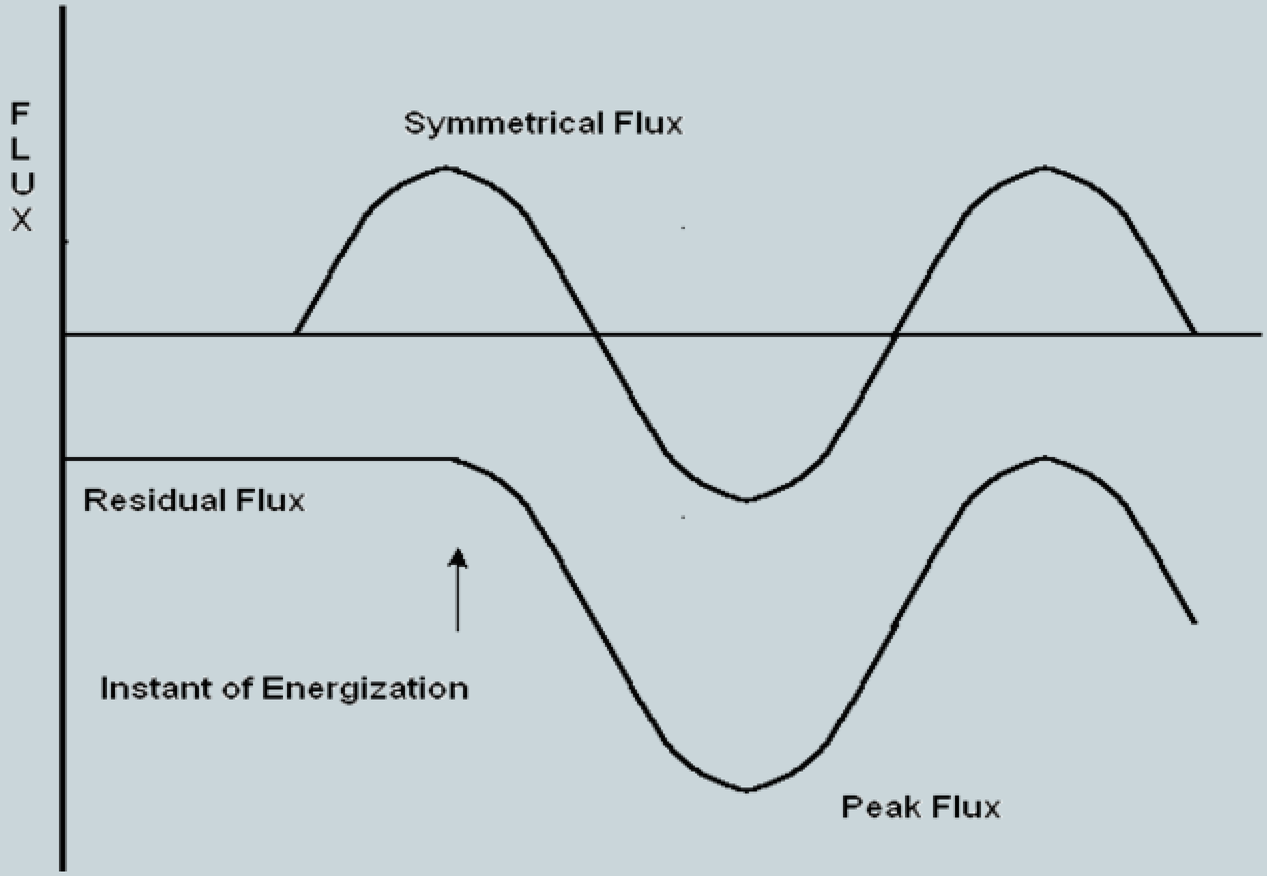
Magnetizing Current Interruption



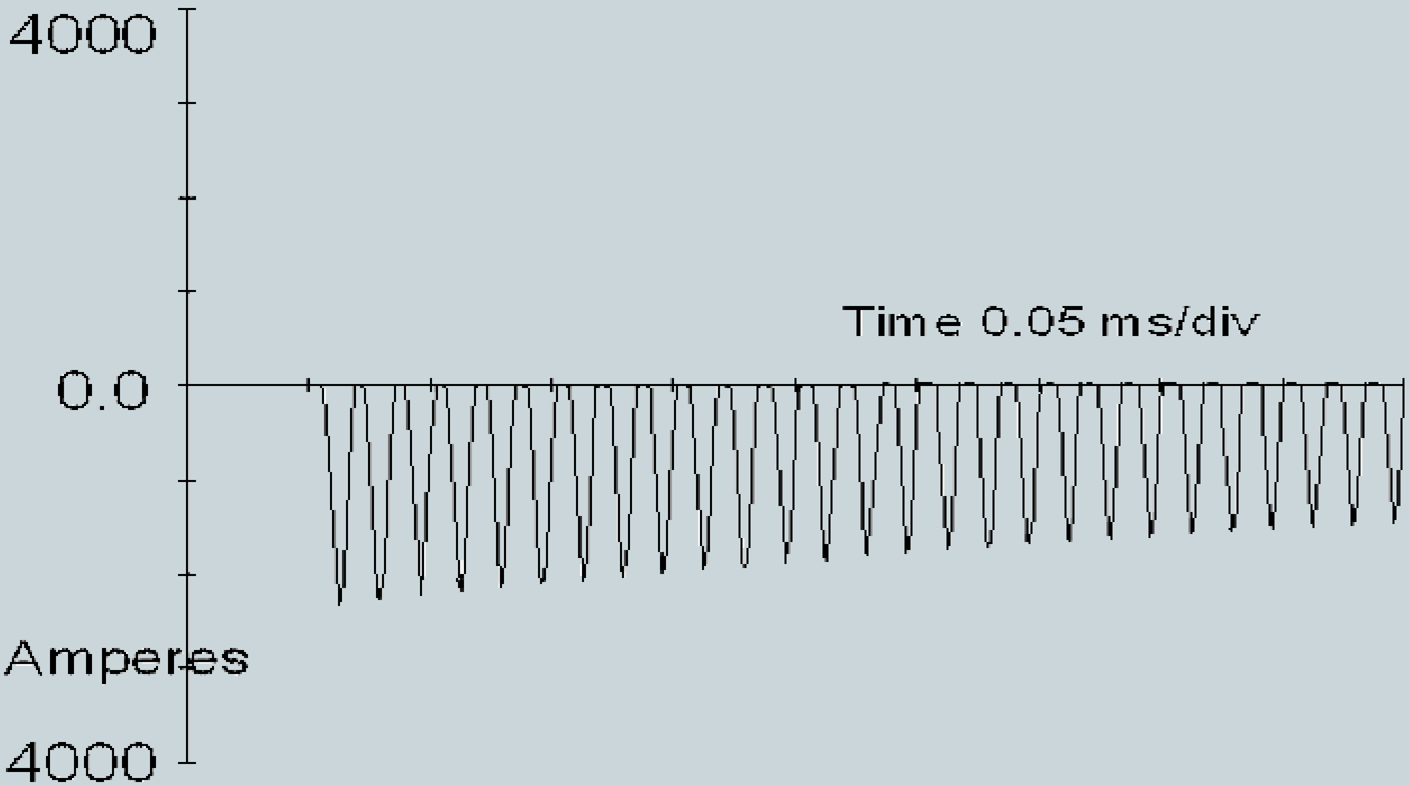
Magnetizing current interruption also showing core flux

Residual core flux remains (typical pattern)

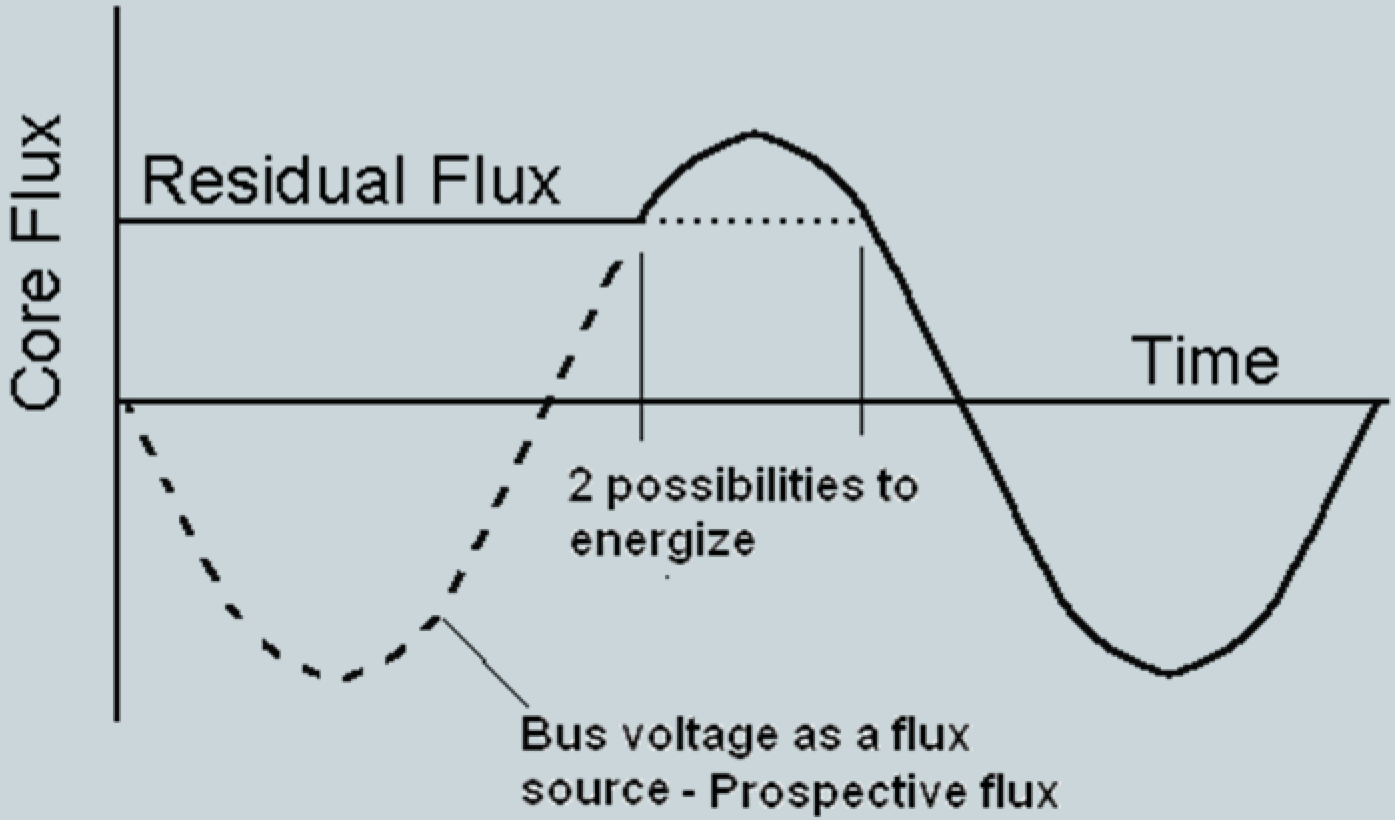
Energizing a Transformer



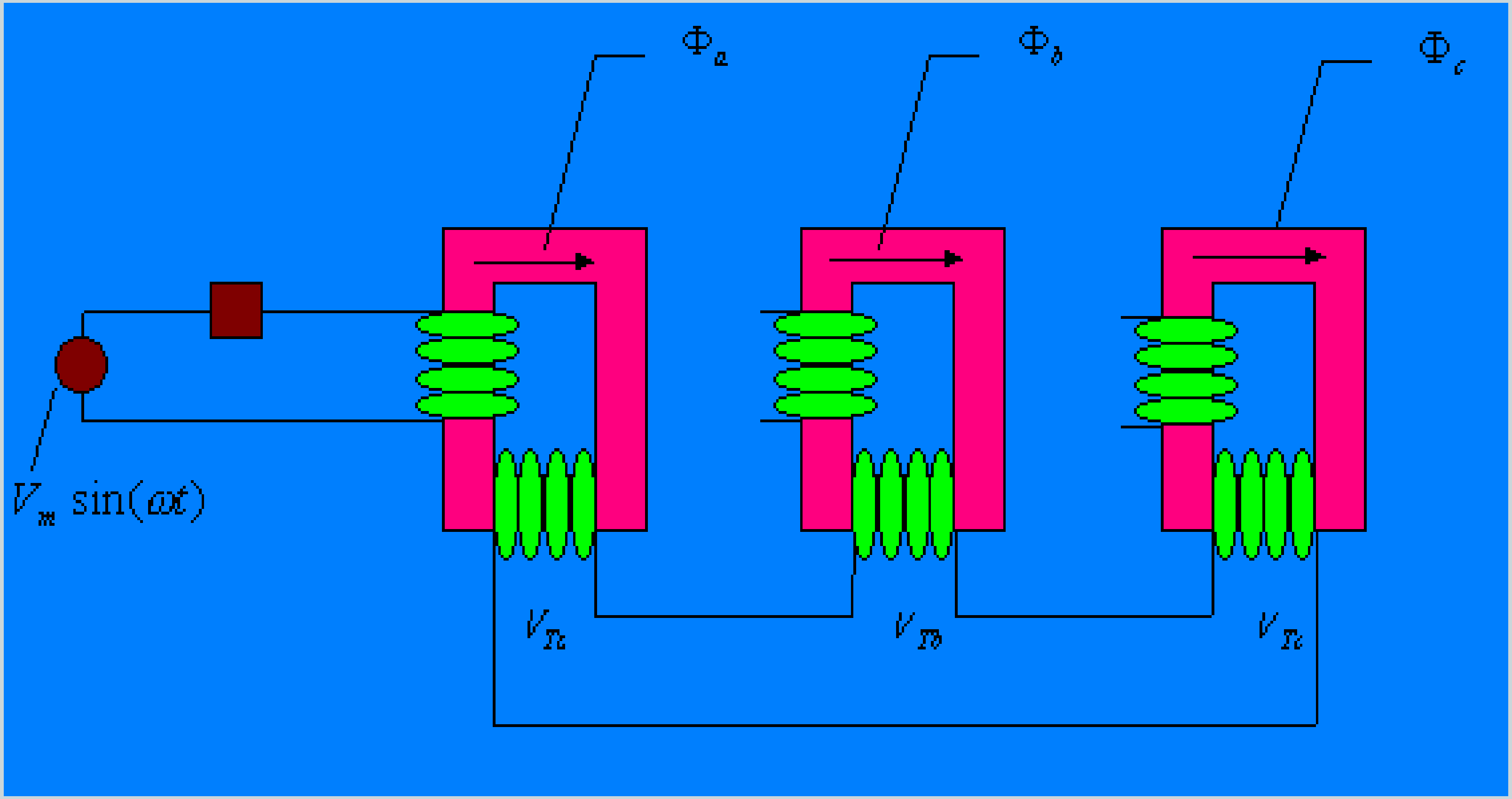
Inrush Current



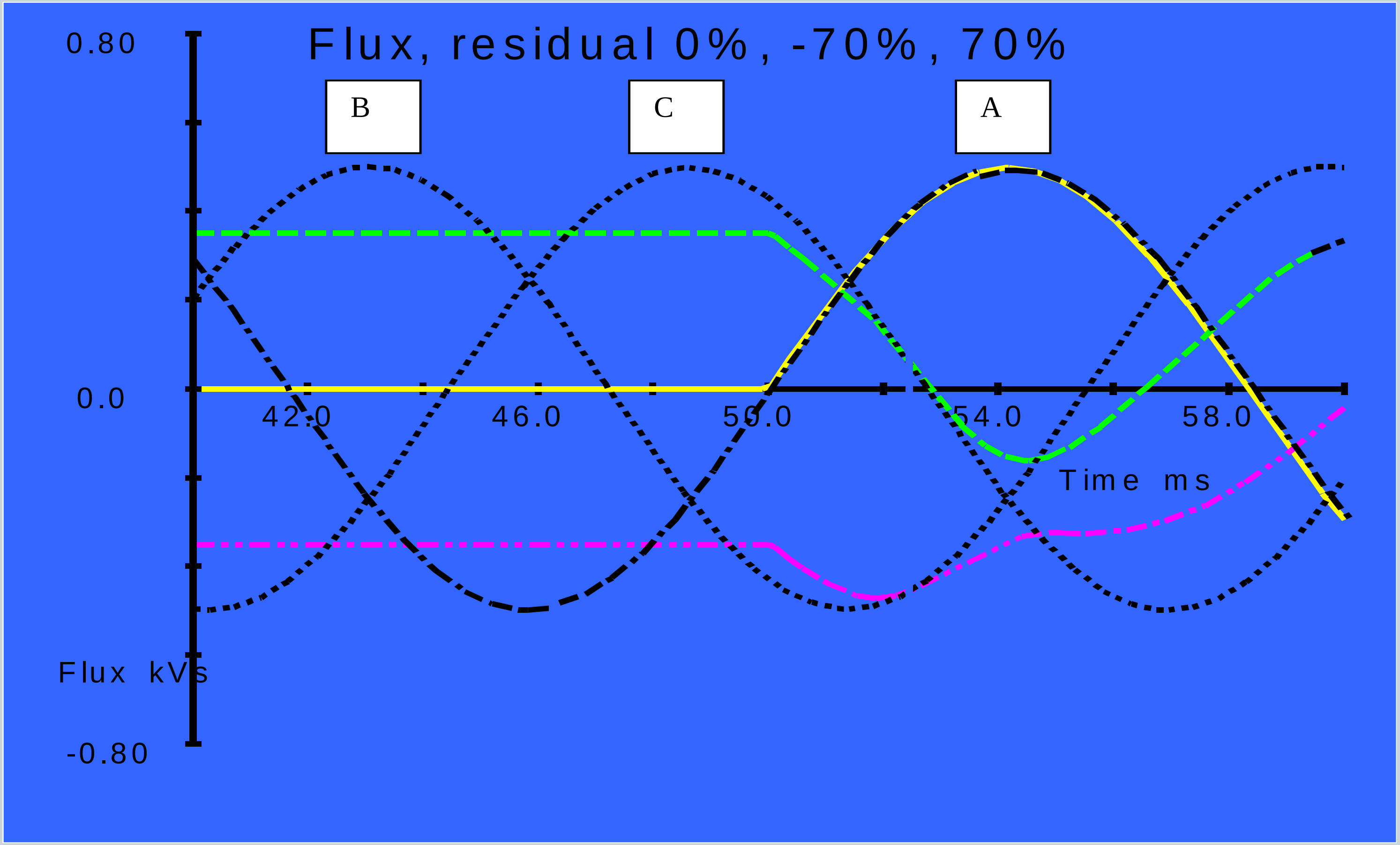
Controlled Closing Applied to Transformers



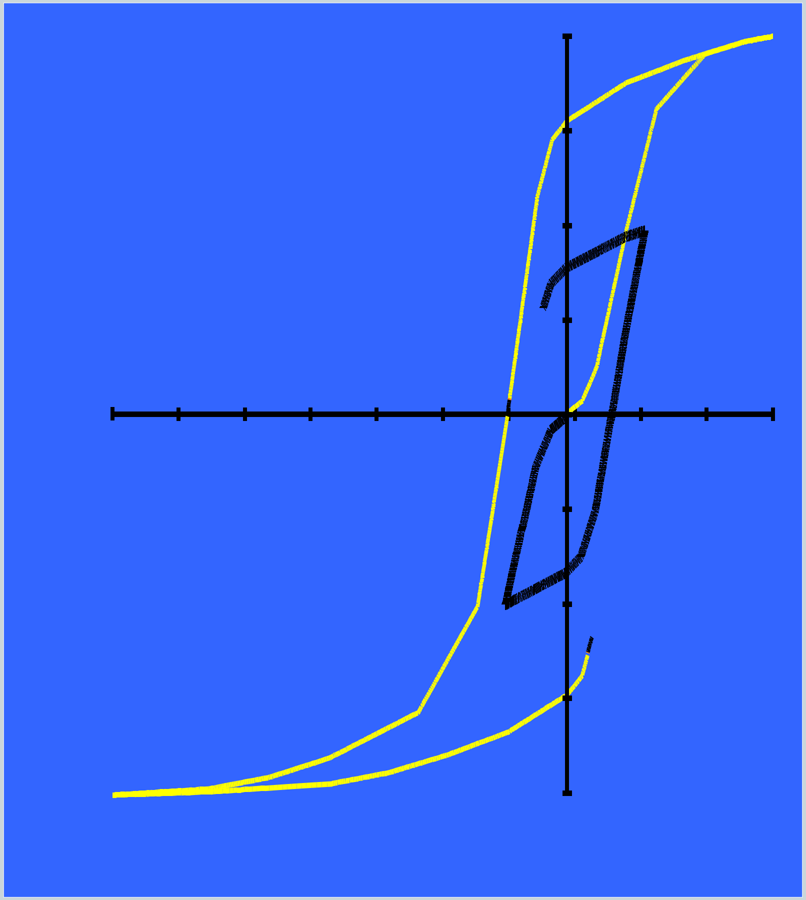
Three Phase Transformers

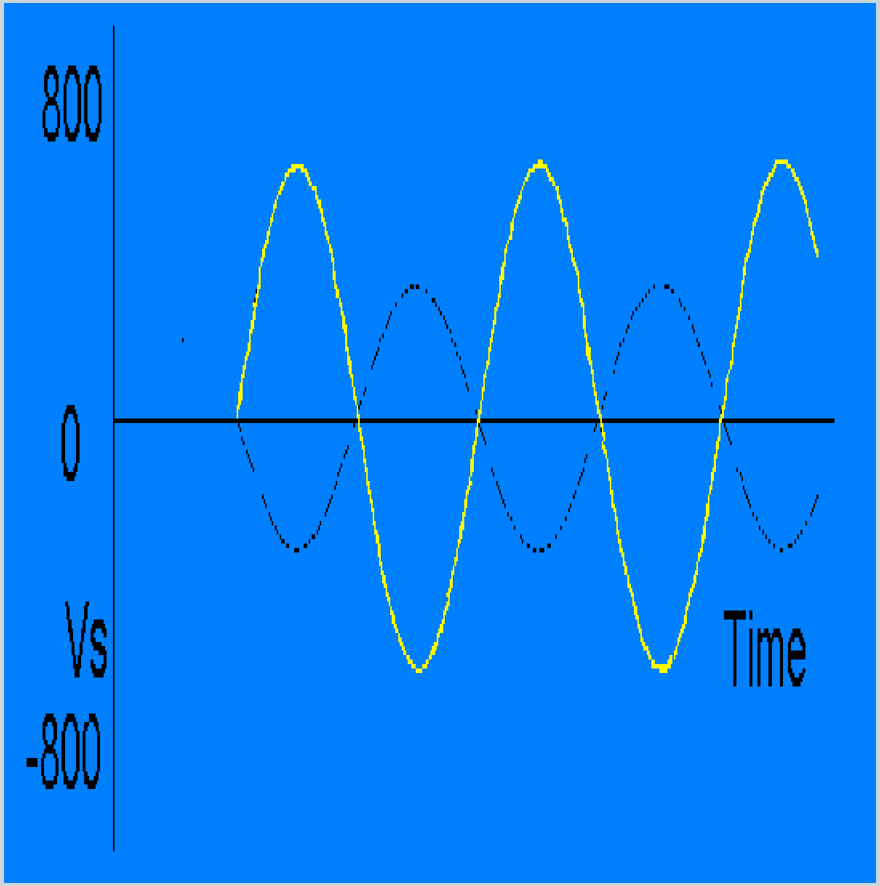


Prospective and Dynamic Flux

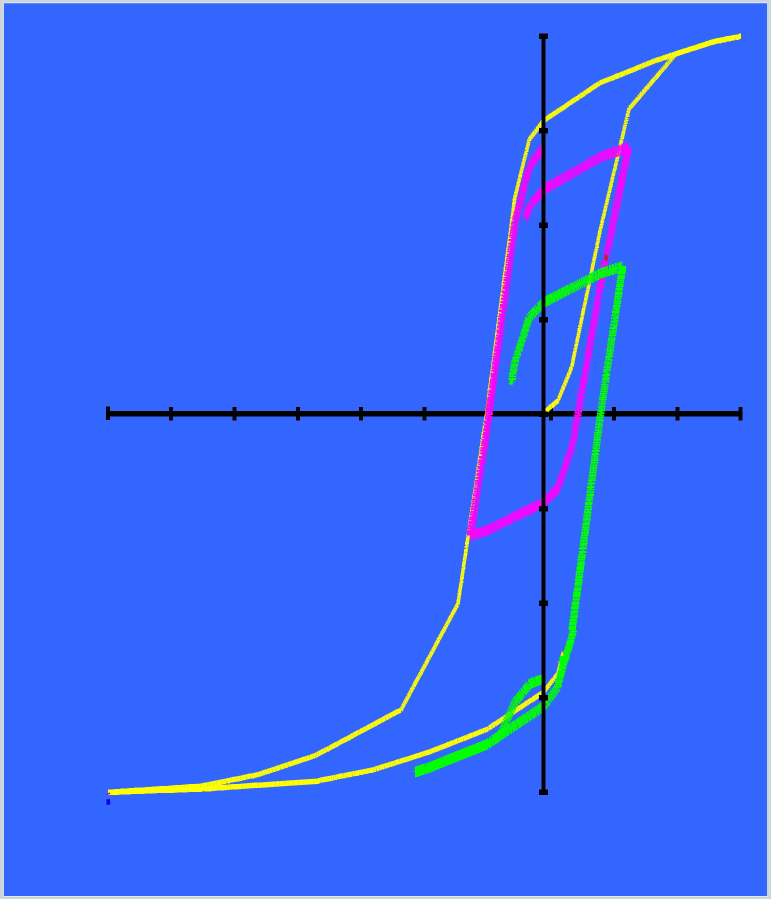


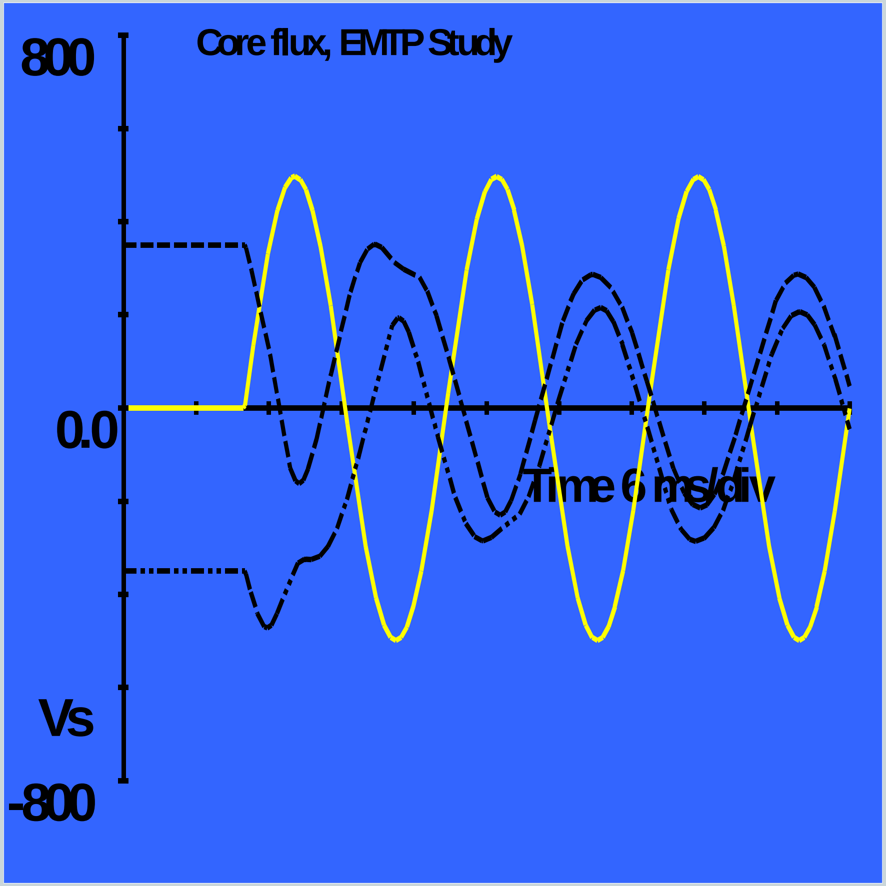
Core Flux - No residual





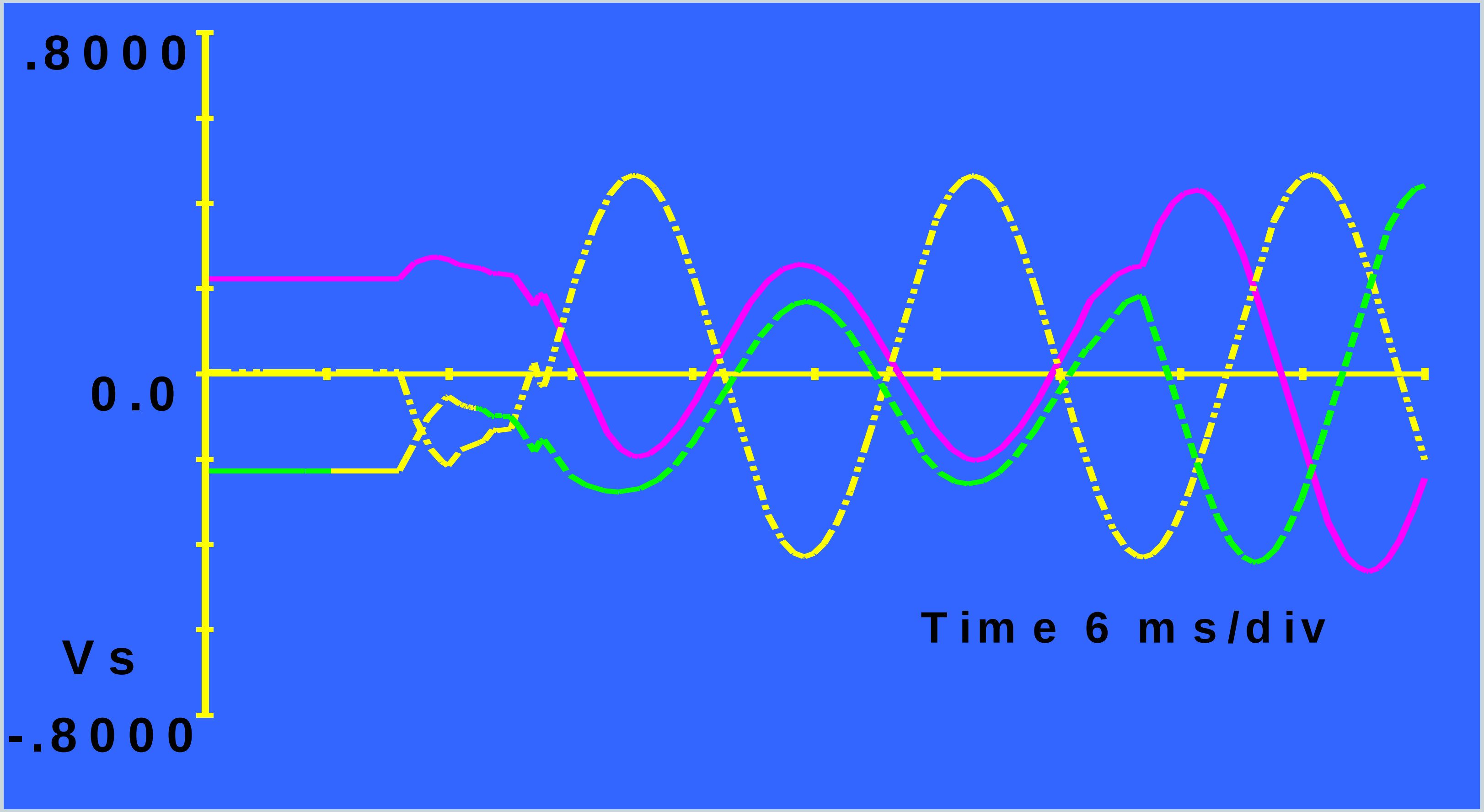
Core flux with residual flux



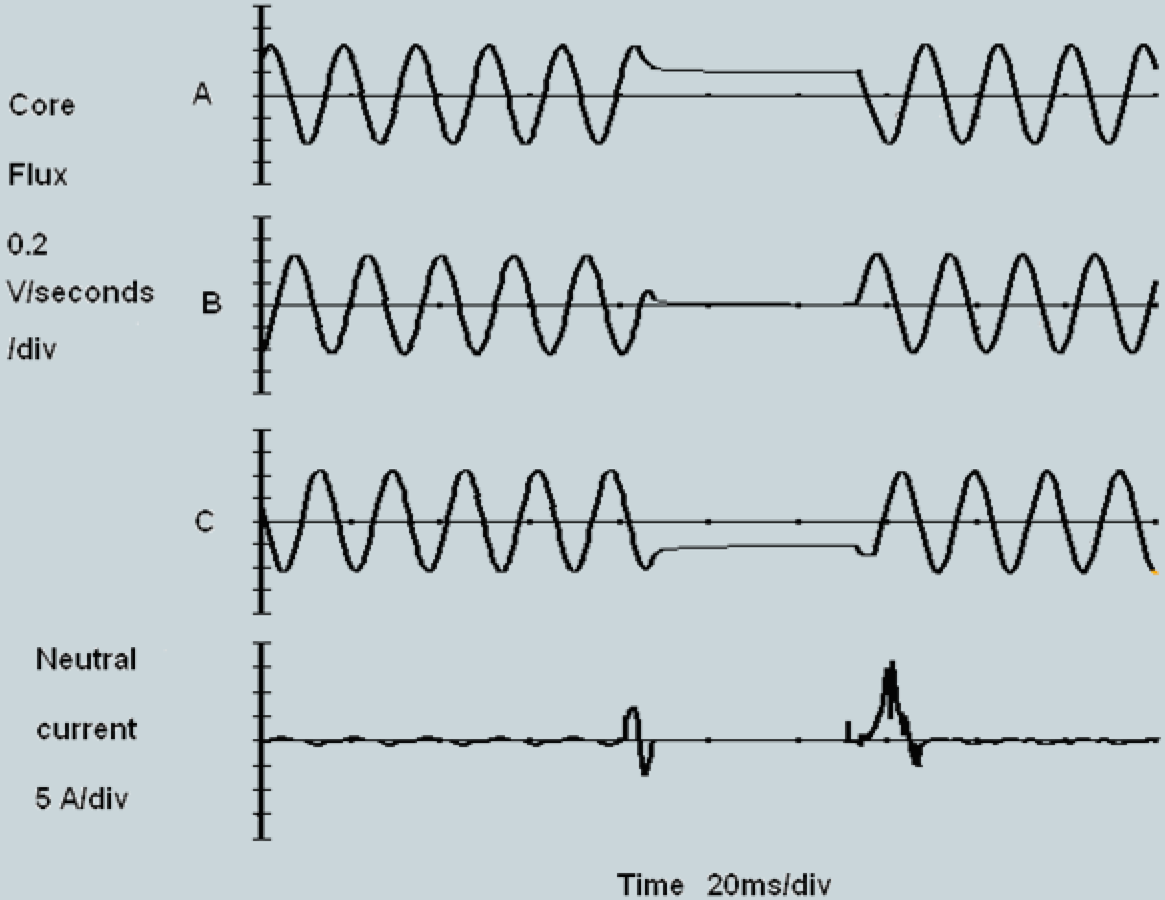


Verification - Laboratory Tests

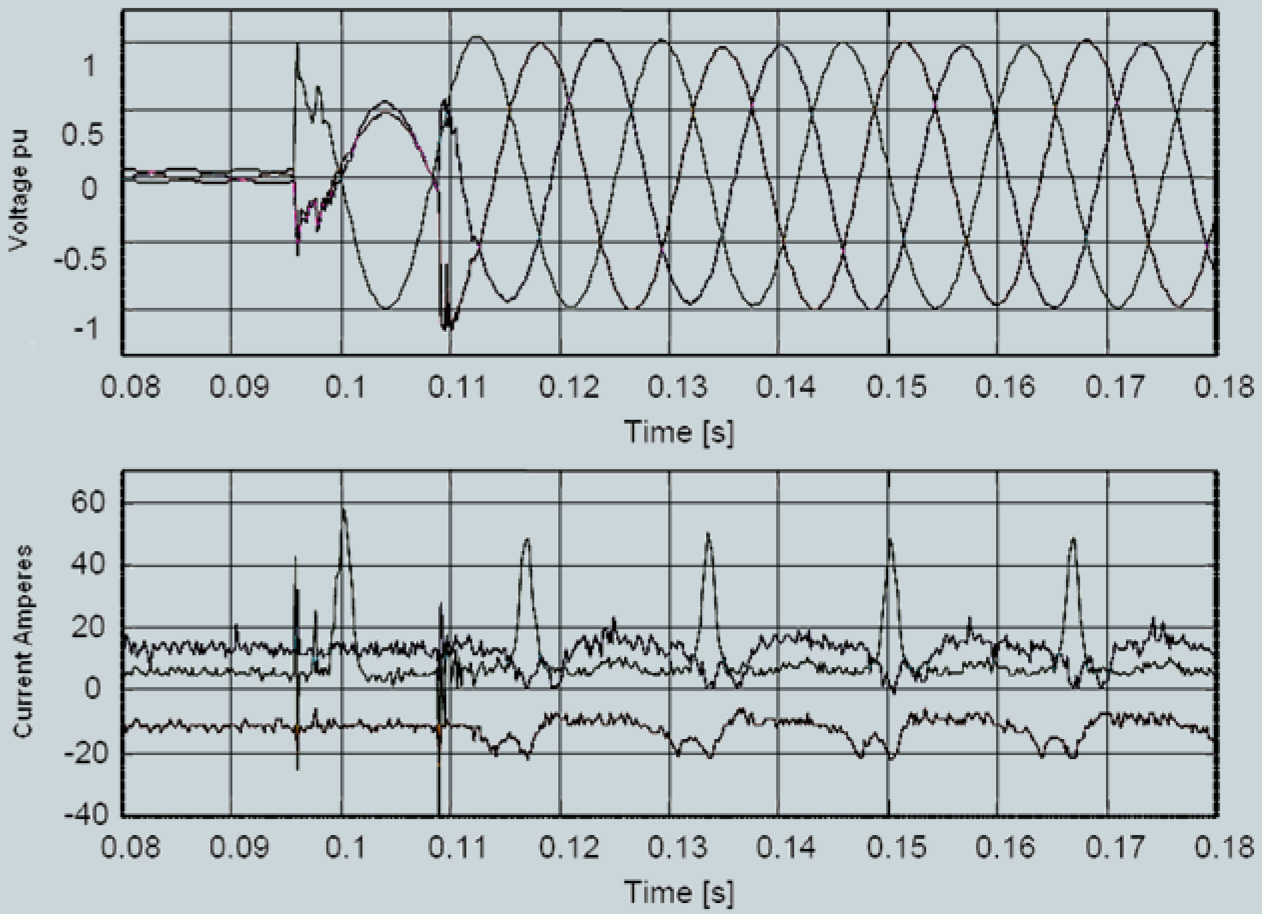
Delayed Closing Strategy



Test on Laboratory Transformer



Controlled Closing on 500 kV Transformer



Summary

- Capacitive and light reactive currents are frequently seen and may be the most difficult duties for a circuit breaker
- Switching surge/transient problems are typically associated with switching shunt capacitor banks, shunt reactors, transformers, cables, and lines (capacitive and light reactive currents).
- Due to the complexity, correct application for these duties can be among the most difficult application issues
- Today solutions are available which were not in the past (modern circuit breaker technologies, controlled switching, MOSA's, etc.)

- Questions?