Switching Capacitor bank Back-to-Back to Underground Cables

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Undergrounding power lines- the great challenge

Calculation of

1. **short-circuit currents.**
2. **temporary overvoltages.**
3. **electromagnetic transients**

→ **To be revised!**

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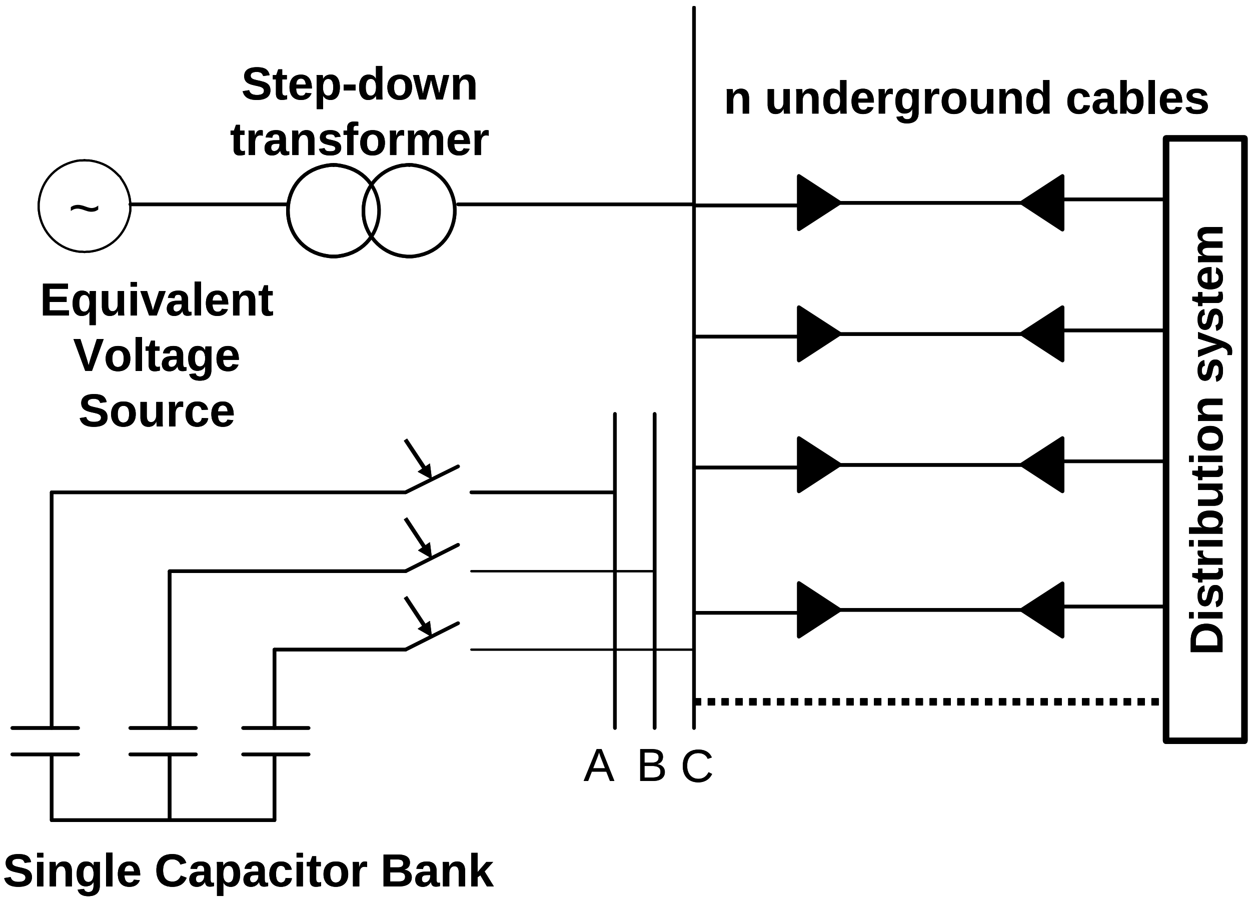
Undergrounding power lines

and the capacitive current switching

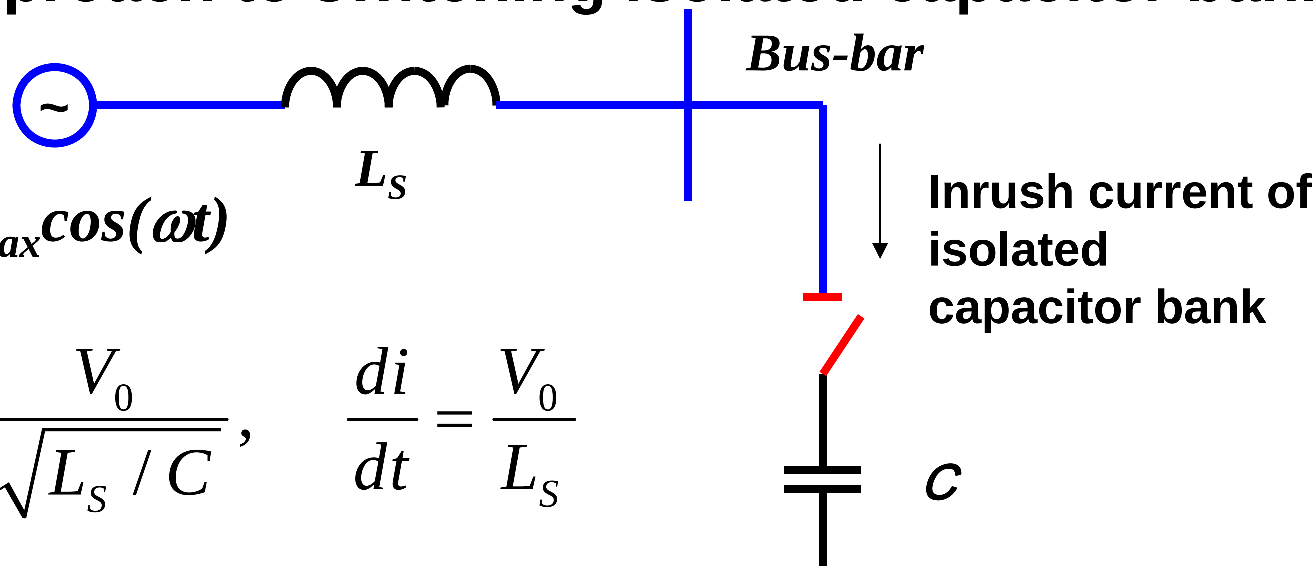


Types of the capacitive switching

Type	Inrush current peak	Inrush current rate of rise	Duty for CBs
Switching lines/cables	Very low	high	Light
Switching single-step capacitor bank	low	low	light
Back-to-back capacitor bank	high	high	Very heavy

Is it true for cable networks?

Traditional approach to switching isolated capacitor bank



$$I_{peak} = \frac{V_0}{\sqrt{L_S / C}}, \qquad \frac{di}{dt} = \frac{V_0}{L_S}$$

Ipeak = 1.6 kA, di/dt = 2.7 kA/ms

Field tests of isolated 24 kV capacitor bank:

I_{peak} = 7 kA, di/dt = 3300 kA/ms

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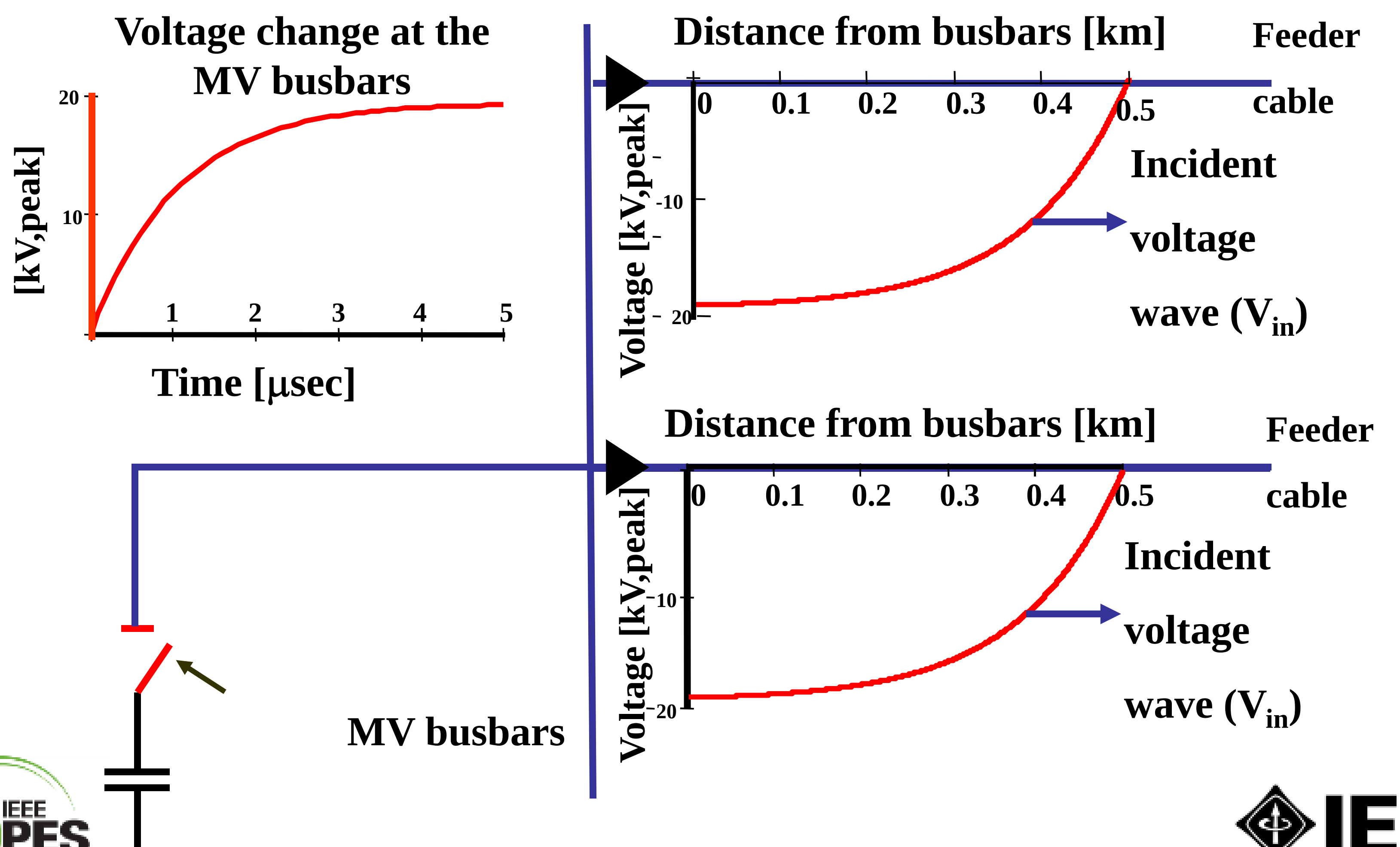
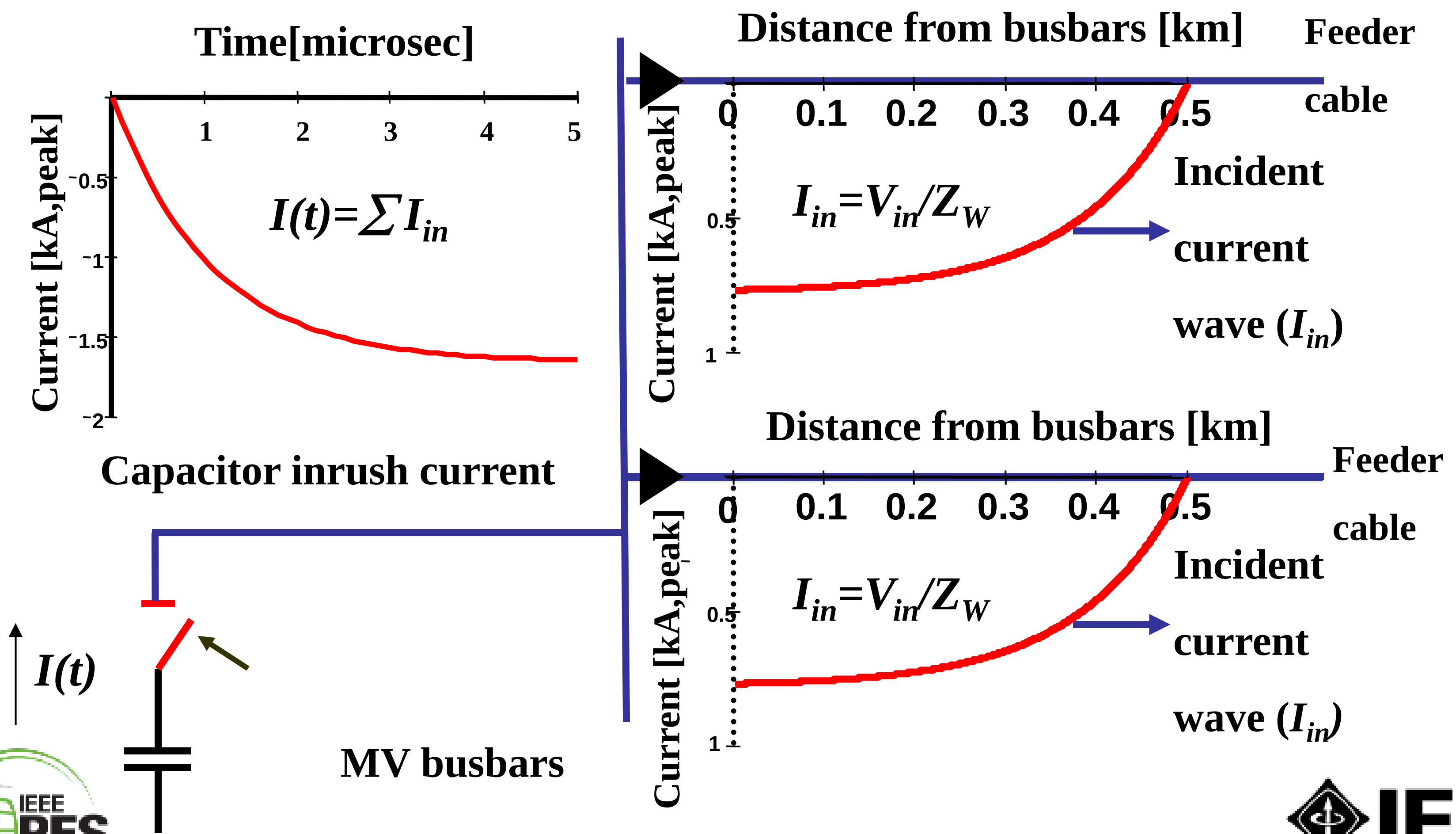
Suggestion: Inrush current is a sum of current surges in the cables



Suggestion: Inrush current is a sum of current surges in the cables



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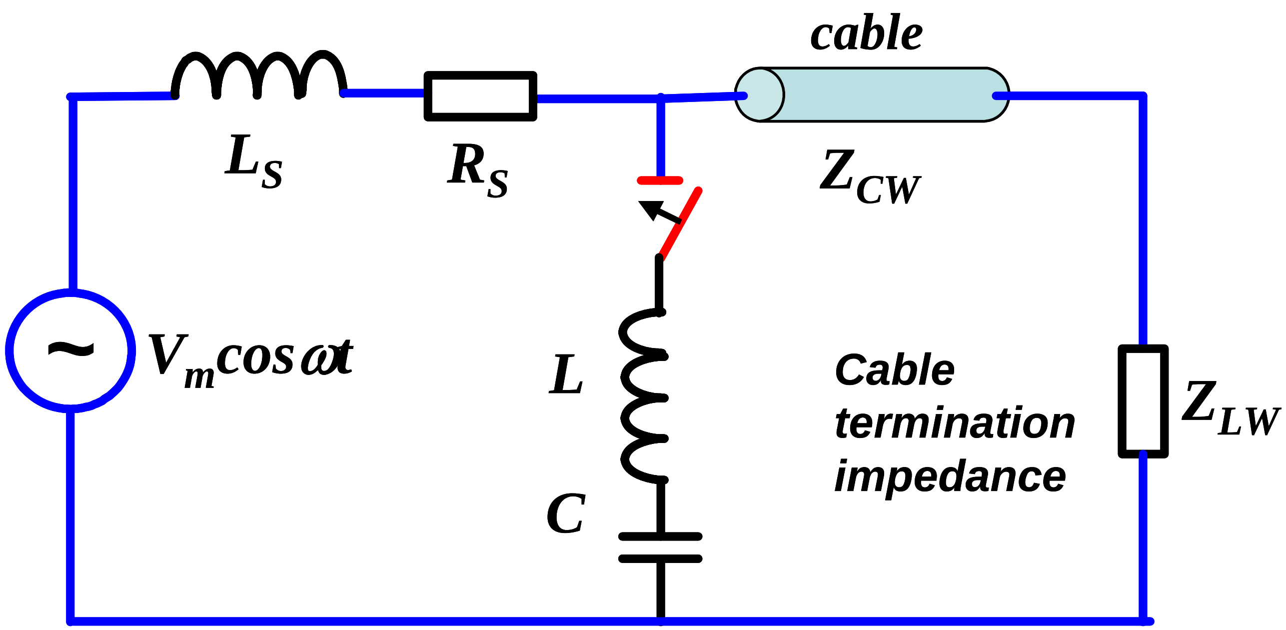
Since measured inrush currents significantly exceed the "inrush current of isolated capacitor bank", their detailed research is necessary for selection of the capacitor bank switchgear.

Main goals of the research:

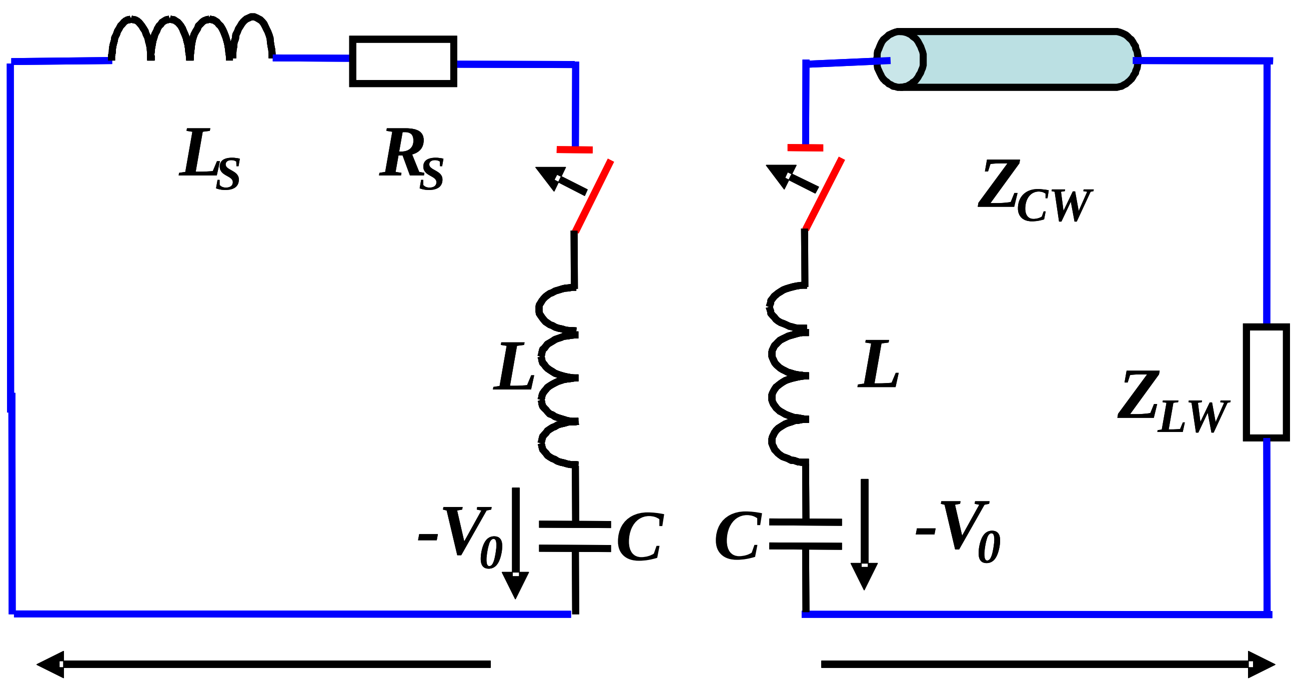
1. **Analytical study of the phenomenon**
2. **Case study of switching 24 kV capacitor banks**

Analytical study



Single phase circuit to analyze the capacitor bank inrush current

Analytical study



Inrush current through the system impedance

Inrush current due to traveling waves in cables

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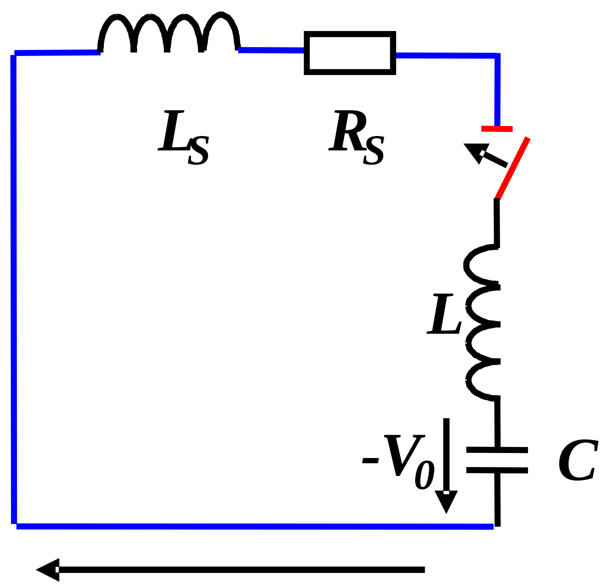
Analytical study: inrush current of isolated capacitor bank



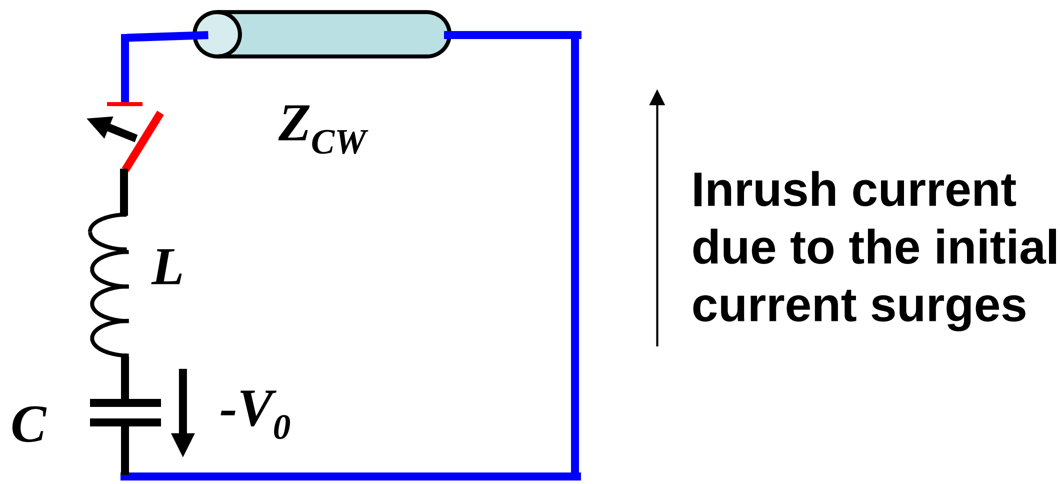
$$i_{tr}(t) = I_{peak} e^{-\frac{R_S}{2L_S}t} \sin \beta t$$

where

$$I_{peak} = \frac{V_0}{\sqrt{L_S / C}}, \qquad \beta = \frac{1}{\sqrt{L_S C}}$$

Analytical study: inrush current due to the traveling waves

General case: underground cables have unequal lengths



$$i(p) = \frac{V_0 C}{LCp^2 + Z_{CW} Cp + 1}$$

Inrush current in the Laplace domain

Analytical study: closed form-expressions of current waveforms

Damping reactor is not applied

$$Z_{CW} \geq 2Z_W$$

$$i(t) = 2Ie^{-\delta t}\sinh \alpha t$$

Damping reactor is applied

$$Z_{CW} \prec 2Z_W$$

$$i(t) = 2Ie^{-\delta t}\sin \alpha t$$

where

$$I = \frac{V_0}{\left|\sqrt{Z_{CW}{}^2 - 4Z_W{}^2}\right|}, \quad \delta = \frac{Z_{CW}}{2L}, \quad \alpha = \frac{\left|\sqrt{Z_{CW}{}^2 - 4Z_W{}^2}\right|}{2L}$$

$$Z_W = \sqrt{\frac{L}{C}}$$ → **Characteristic impedance of the circuit formed by inductance *L* and capacitance C**

$$Z_{CW} = \frac{Z_C}{n}$$ → **Equivalent surge impedance of *n* underground cables**

Analytical study: inrush current peak

$$I_{peak} = \frac{2I\alpha}{\sqrt{\delta^2-\alpha^2}\left(\frac{\sqrt{\delta^2-\alpha^2}}{\delta-\alpha}\right)^{\frac{\delta}{\alpha}}}$$

is reached when

$$t = \frac{1}{2\alpha}\ln\frac{\delta+\alpha}{\delta-\alpha}$$

Limiting case of non-oscillatory inrush current : $\boldsymbol{L} \to 0$

$$I_{peak} = n\frac{V_0}{Z_C}$$

Limiting case of oscillatory inrush current :

$$\sqrt{\frac{\boldsymbol{L}}{\boldsymbol{C}}} \gg \frac{\boldsymbol{Z_C}}{\boldsymbol{n}}$$

$$\boldsymbol{I_{Peak}} = \boldsymbol{V}_0\sqrt{\frac{\boldsymbol{C}}{\boldsymbol{L}}}$$

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Analytical study: maximum value of *di/dt*

$$\frac{di}{dt} = \frac{V_0}{L}$$

The maximum rate of rise of the inrush current is limited only by the equivalent inductance *L*. If *L* includes only stray inductance (damping reactor is not applied) the maximum value of *di/dt* can be extremely high.

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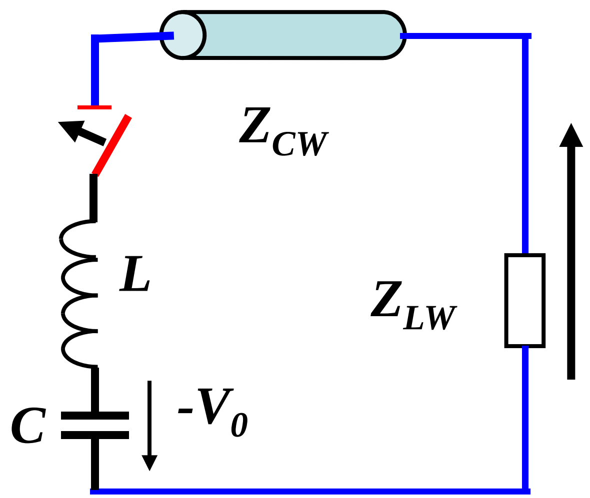
Analytical study: inrush current due to the traveling waves

Particular case: *n* underground cables have equal length



Inrush current due to superposition of the initial current surges and reflected current surges

$$i_S(p) = \frac{V_0 C}{LCp^2 + Z_{CW}Cp + 1} \times$$

$$\times \left[1 - 4\delta \sum_{k=1}^{\infty} \frac{a_L^k [(p+p1)(p+p2)]^{k-1}}{[(p-p1)(p-p2)]^k} \right]$$

Inrush current in the Laplace domain

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Analytical study: closed form-expression of current waveforms when the initial waves and the first 3 reflected waves are considered

$$i_S(t) = i(t) + i_1(t_1) + i_2(t_2) + i_3(t_3)$$

$$i(t) = 2Ie^{-\delta t}\sinh\alpha t$$

$$i_1(t_1) = 2Ie^{-\delta t_1}[a_{11}\sinh(\alpha t_1) + a_{12}\alpha t_1\sinh(\alpha t_1) - a_{12}\delta t_1\cosh(\alpha t_1)]$$

$$i_2(t_2) = 2Ie^{-\delta t_2}[a_{21}\sinh(\alpha t_2) + a_{22}\delta t_2\sinh(\alpha t_2) - a_{21}\alpha t_2\cosh(\alpha t_2)$$
$$+a_{23}\delta^2 t_2{}^2\sinh(\alpha t_2) - a_{24}\delta^2 t_2{}^2\cosh(\alpha t_2)]$$

$$i_3(t_3) = 2Ie^{-\delta t_3}[a_{31}\sinh(\alpha t_3) + a_{32}\delta t_3\sinh(\alpha t_3) - a_{31}\alpha t_3\cosh(\alpha t_3)$$
$$+a_{33}\delta^2 t_3{}^2\sinh(\alpha t_3) - a_{34}\delta^2 t_3{}^2\cosh(\alpha t_3) + a_{35}\delta^3 t_3{}^3\sinh(\alpha t_3) -$$
$$-a_{36}\delta^3 t_3{}^3\cosh(\alpha t_3)]$$

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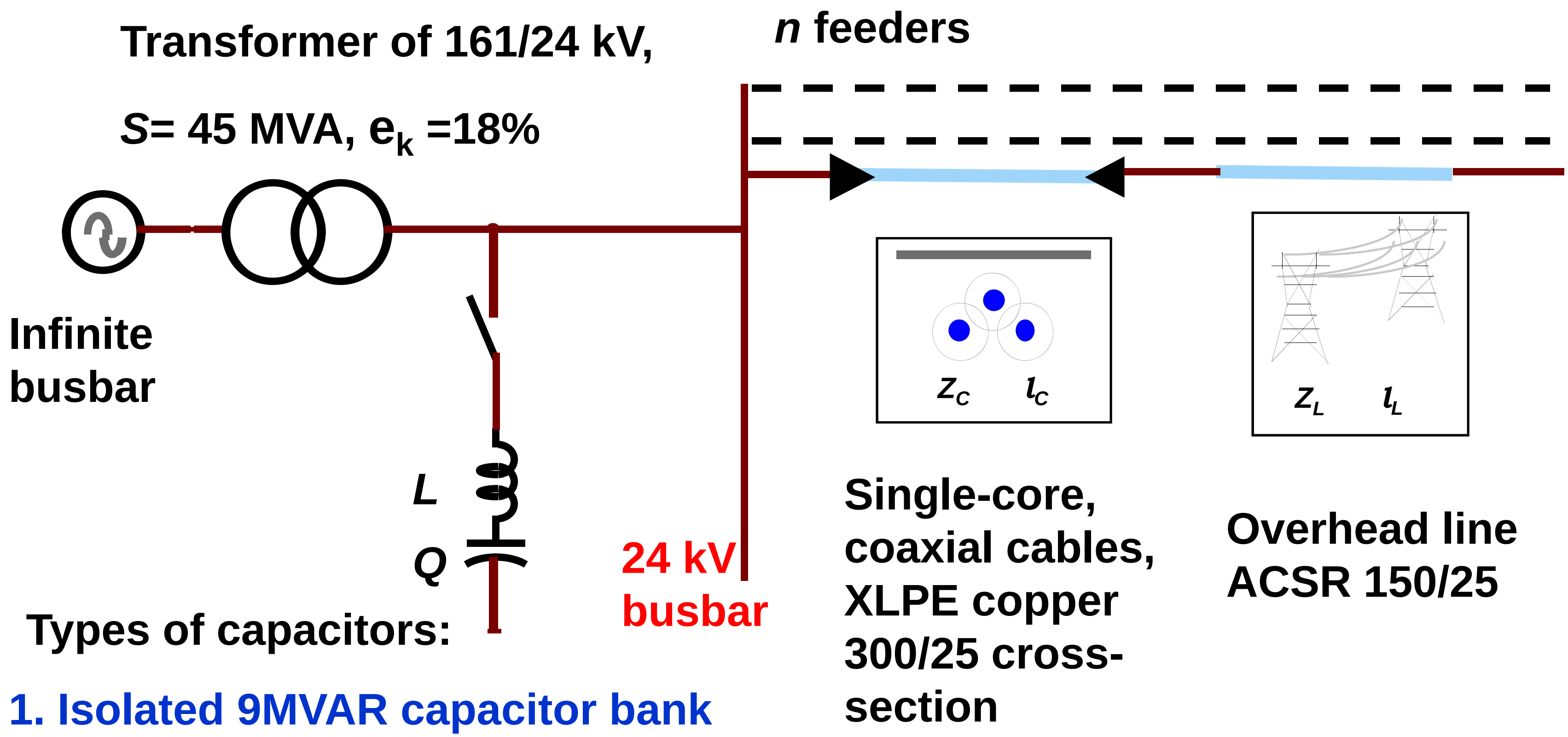
Case study: the circuit description



Types of capacitors:

1. Isolated 9MVAR capacitor bank

2. Multi-step 3×5 MVAR capacitor bank (switching the 1st step)

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Case study: results of the field tests versus EMTP simulation

Switching 9 MVAR, 24 kV capacitor bank

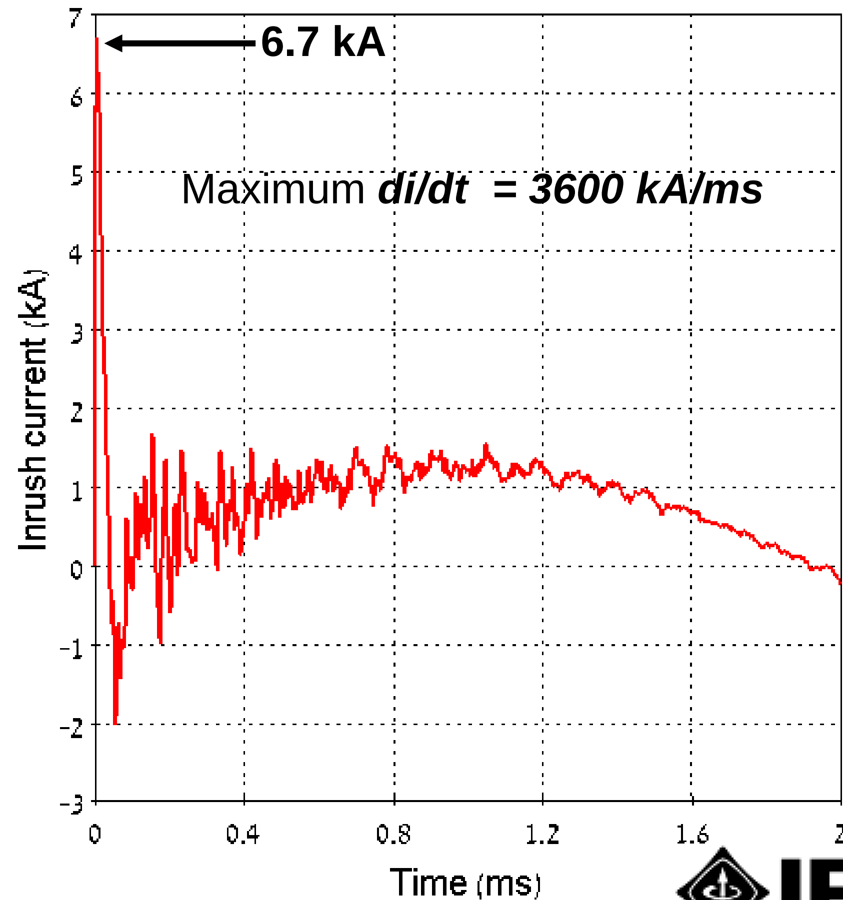
Measured peak inrush currents

Test Number	Peak inrush currents [kA, peak]		
	I_R	I_S	I_T
1	4.8	5.0	5.0
2	5.7	4.6	7.1
3	5.6	4.5	7.2
4	6.1	3.2	6.6

Maximum measured

***di/dt* = 3300 kA/ms**

Result of EMTP simulation



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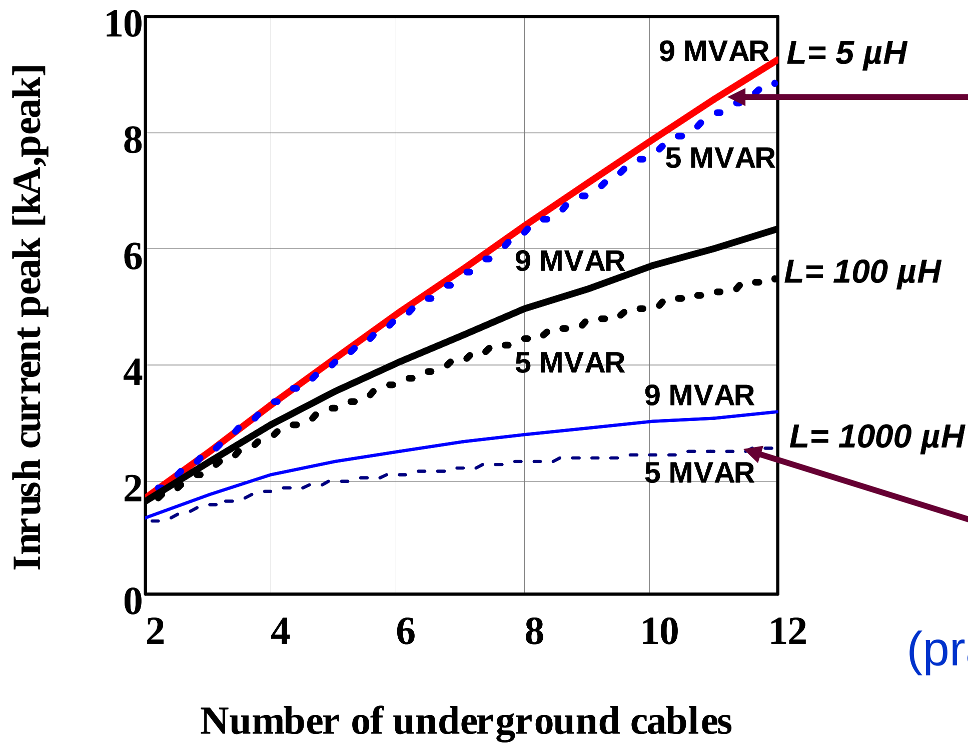
Case study: Parametric study of the inrush current peak

Dependence on the number of underground cables

Ipeak versus number of cables



$$I_{peak} = n\frac{V_0}{Z_C}$$

(proportional to ***n***)

$$\boldsymbol{I_{Peak} = V_0\sqrt{\frac{C}{L}}}$$

(practically independent of ***n***)

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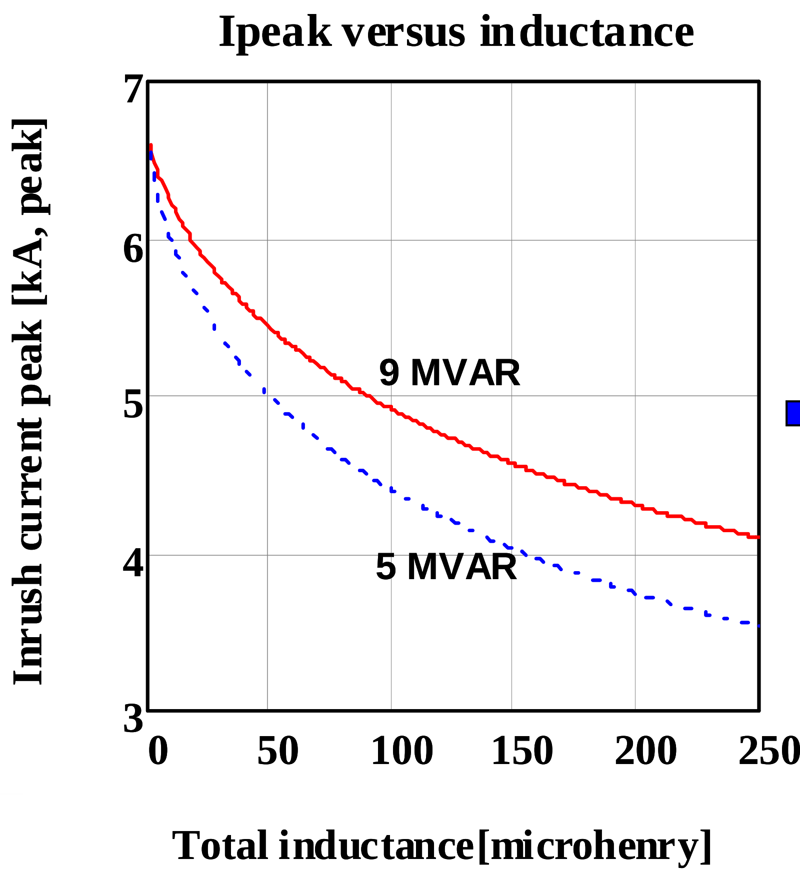
Case study: Parametric study of the inrush current peak

Dependence on the equivalent inductance, *n* =8



Increase of the equivalent inductance ***L*** leads to reduction of the inrush current peak ***Ipeak***

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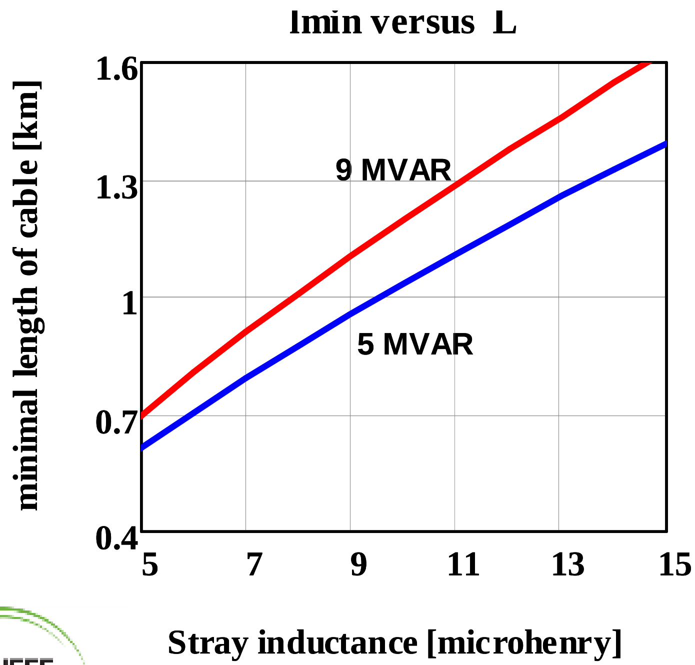
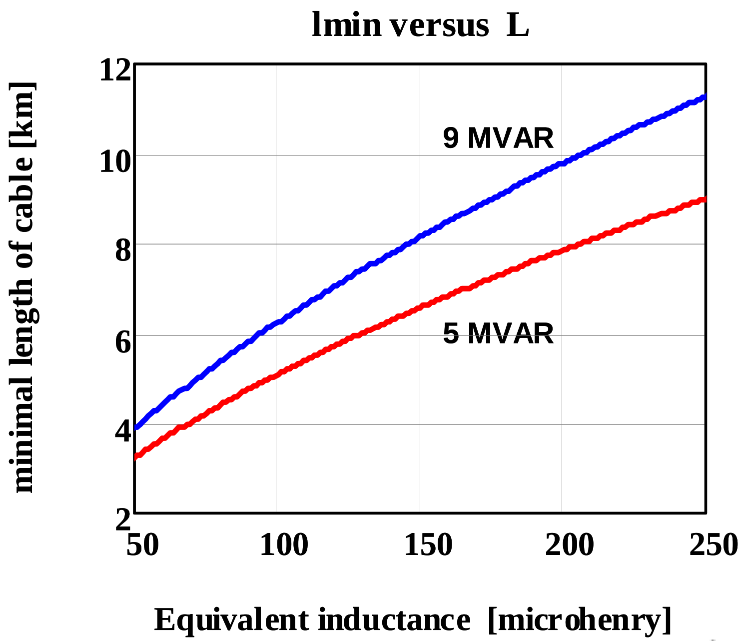
Parametric study of *Ipeak* – Concept of the minimal length of cable

Minimal length of cable ***lmin*** as the shortest cable length among ***n*** cables that makes it possible for the inrush current to reach its peak value ***Ipeak*** before the reflected wave arrives at the substation busbar

For the banks without damping reactor

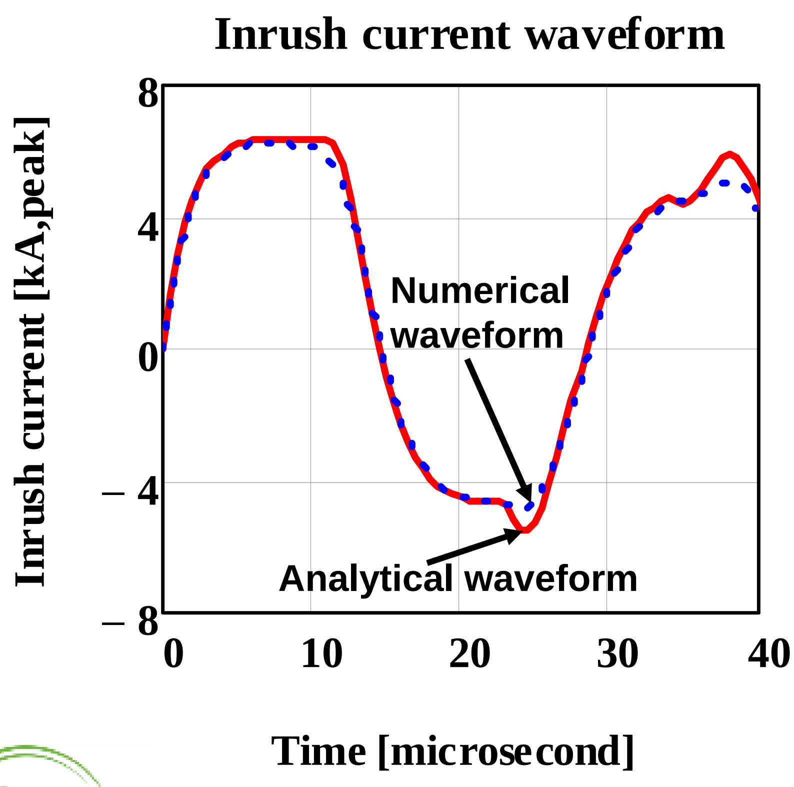


For the banks with damping reactor



Case study: *n* underground cables have equal length

Verification of the derived analytical expressions: *lc*= 1km, *Q*=9 MVAR, *L* = 5μH, *n* =8



Very good agreement between the analytical waveforms and the EMTP waveforms enables to accept the hypothesis that the inrush currents occur due to the traveling waves in the alongside underground cables!

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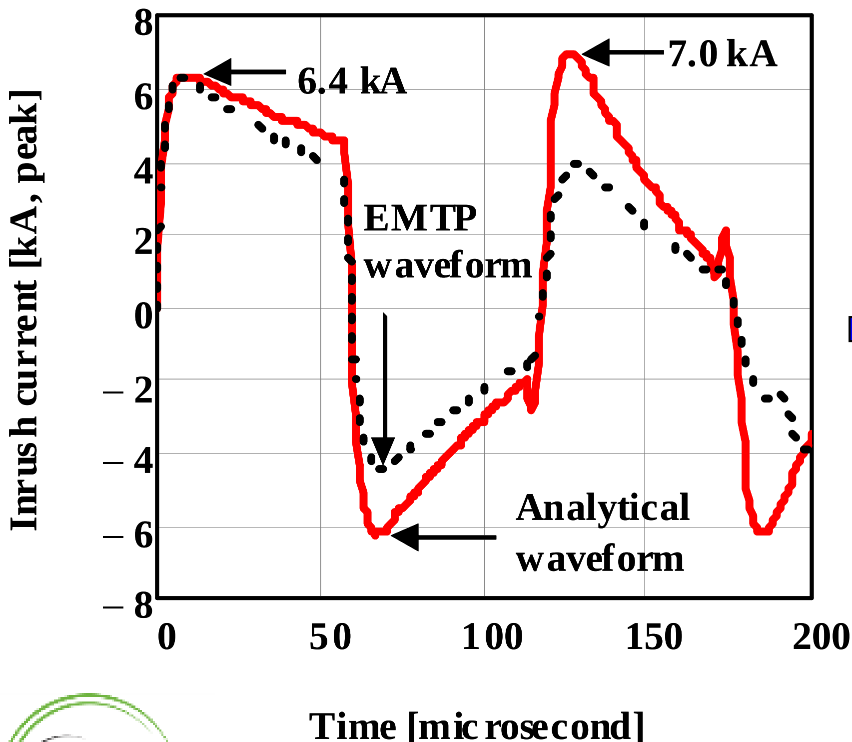
Case study: *n* underground cables have equal length

Verification of the derived analytical expressions: *lc*= 5 km, *Q*=9 MVAR, *L* = 5μH, *n* =8

Inrush current waveform

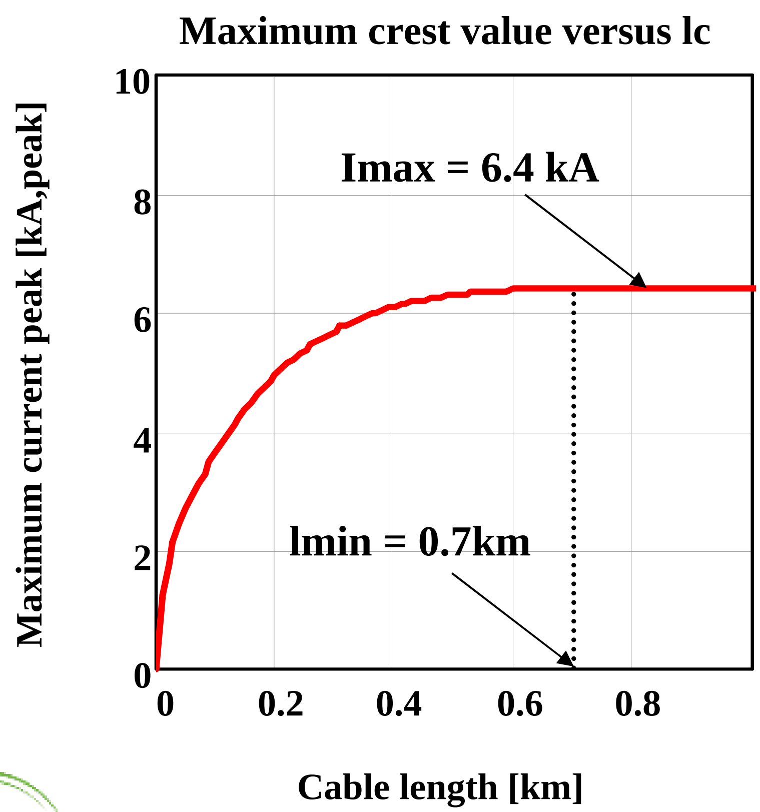


For *n* identical long cables the maximum value of the inrush current is always achieved at the first peak of the current waveform.

The following crest values of the current waveform are smaller than the 1st peak because of the attenuation of the traveling waves.

Case study: Parametric study of the inrush current peak

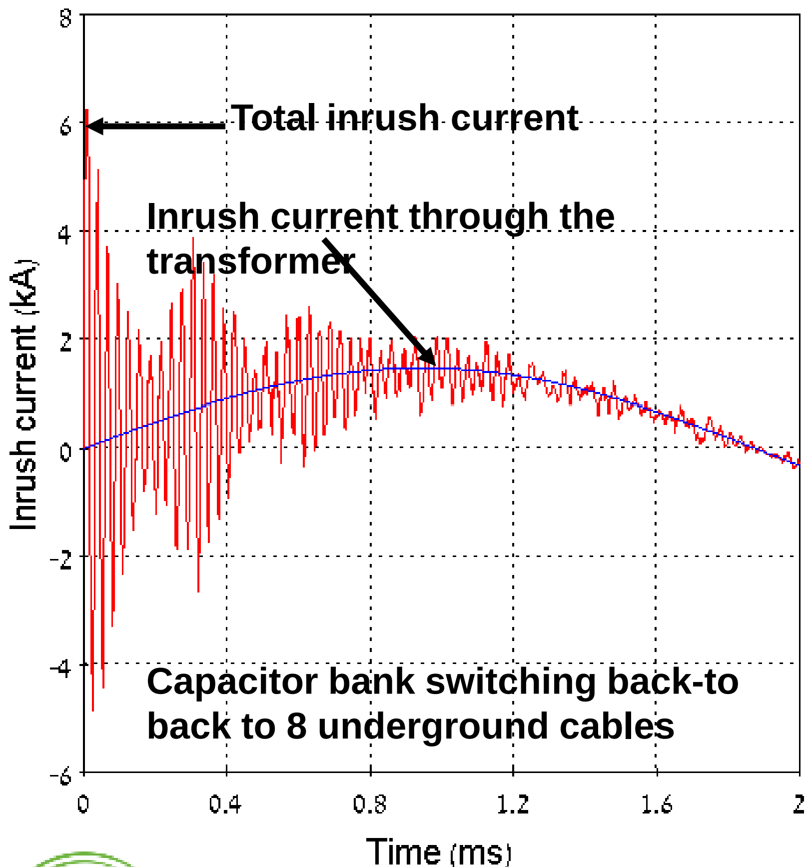
Dependence on the cable length: Q=9 MVAR, $L = 5\mu H$, $n = 8$

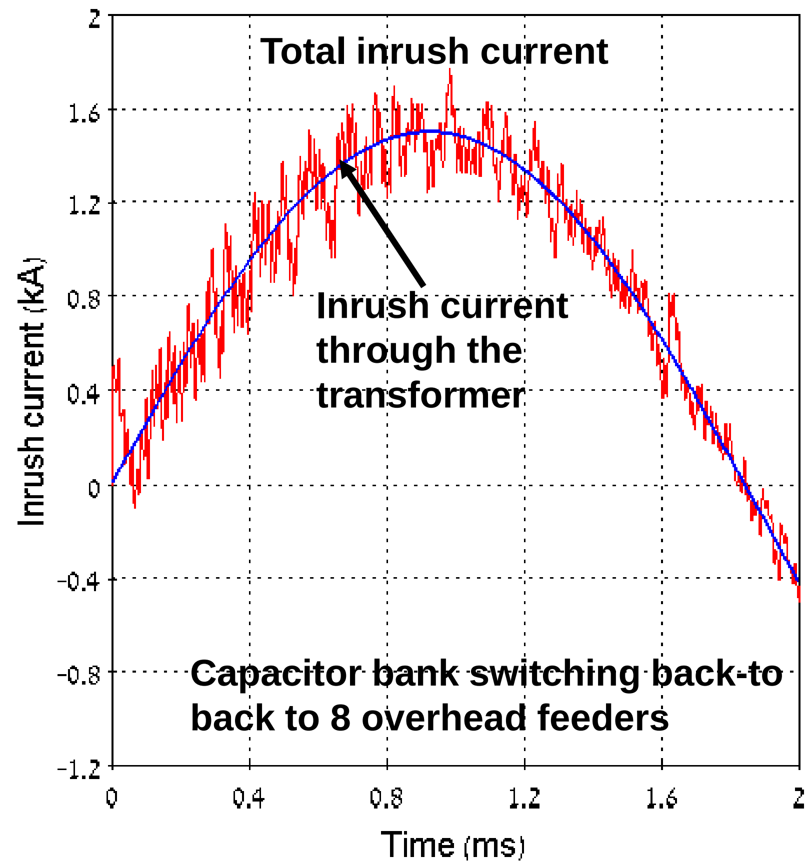


Variation of the cable length from 0 to *lmin* results in increase of the maximum current peak from zero to the inrush current peak *Ipeak*.

The following growth of the cable length does not cause increase of the maximum current peak because of the attenuation of the traveling waves in the cables.

Case study: Undergrounding the distribution power lines and the inrush current





Switching 170 kV, 200 MVAR capacitor bank back-to-back to underground cables (damping reactor is not applied)

Calculation method	*Ipeak* [kA, peak]	*di/dt* [kA/ms]
"inrush current of isolated capacitor bank"	6.8	20
Switching back-to-back to 6 underground cables	32	9000

Operational experience: Analysis of failures of 24 kV, minimum-oil circuit breakers used for switching isolated capacitor banks

Handling capacitor inrush currents (Ipeak = 4-6 kA, di/dt = 1000-3000 kA/ms)

↓

Quick oil deterioration; problems with CB mechanical system

↓

Restrikes during opening CB, Inrush currents having Ipeak = 8-12 kA

↓

Explosions of CB breaking unit accompanied by a short circuit on the substation busbar

Conclusions

1. **Since the inrush current during the capacitor bank switching back-to-back to the underground cables significantly exceeds the "inrush current of isolated capacitor bank" it should taken into account in the selection of the capacitor bank switchgear.**

2. **It seems that switching capacitor bank back-to-back to the underground cables should be addressed in the standards concerning the capacitive current switching**