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Switching Surges

IEEE PES Lecturer Program (DLP)
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Presentation Outline

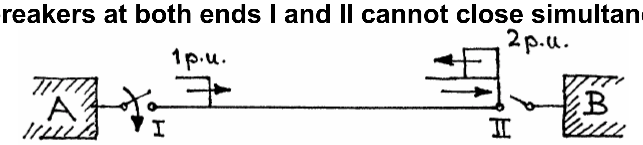
- Closing and re-closing operations on transmission lines (line energization)
- Reduction of overvoltages in closing and re-closing operations on transmission lines
- Computer models for closing and re-closing operations on transmission lines
- Examples for closing and re-closing operations on transmission lines
- Example for temporary overvoltages
- Examples for subsynchronous resonance
- Example for single-line-to-ground fault on transmission lines
- Example for transient recovery voltage

Presentation Outline

- Example for linear resonance after opening a transmission line in parallel with another line
- Examples for steady-state coupling between parallel transmission lines
- Capacitor switching
- Inrush Currents
- Interruption of small inductive currents
- References
- General references

Closing & Re-closing Operations on Transmission Lines

- **Circuit breakers at both ends I and II cannot close simultaneously.**

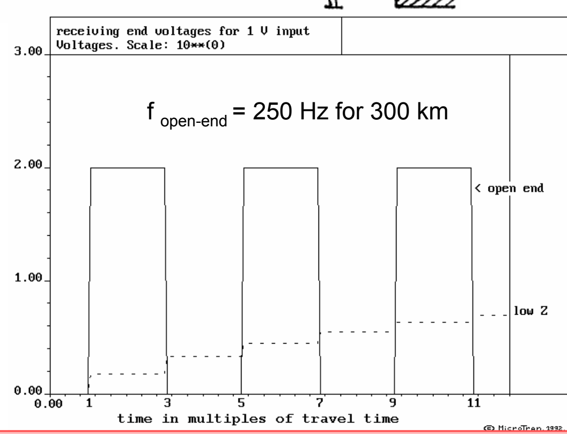


- Therefore, the voltage surge travelling down the line doubles at the open end.

$$f_{open-end} = \frac{1}{4\tau}$$

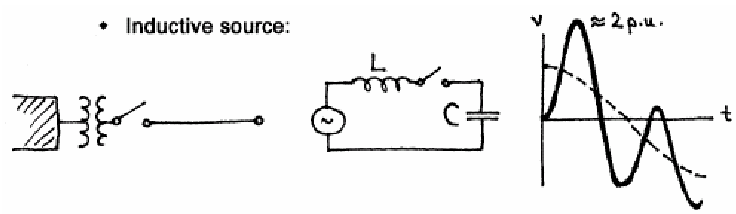
- Low impedance termination (dotted).

$$f_{low-Z} = \frac{1}{2\tau}$$

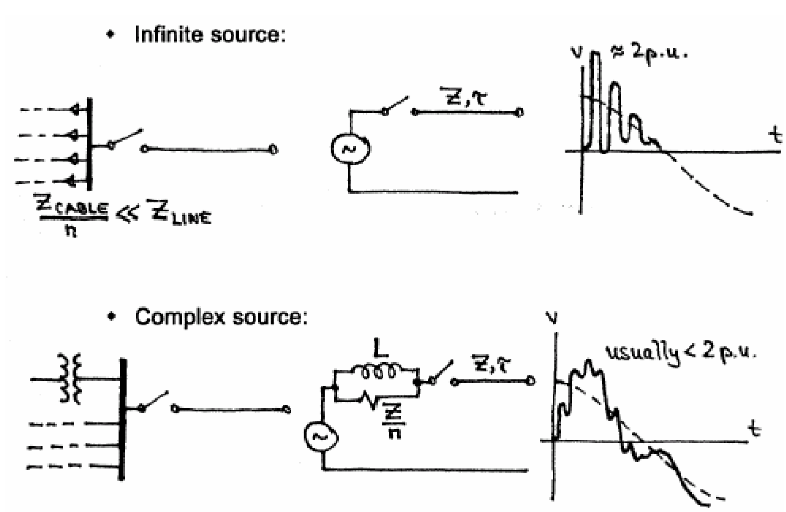


Closing & Re-closing Operations on Transmission Lines

- **In reality, overvoltage can be >2.0 p.u. because:**
  - not infinite source in A (therefore reflections),
  - line may have "trapped charge" from preceding opening operation,
  - three poles do not close simultaneously,
  - there are multi-velocity waves on a three-phase line (zero-sequence wave speed is slower than positive sequence wave speed),
  - etc.
- **Approximate classification (from a paper by M. Erche [1]):**



Closing & Re-closing Operations on Transmission Lines



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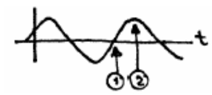
- **Statistical distribution**
  - Overvoltage is not a single value, but statistically distributed because overvoltage depends on V_{source} at instant of closing,



  - three poles do not close simultaneously.

- **Closing times**
  - Many cases must be run with different circuit breaker closing times, that are either varied
    - statistically,
    - or systematically.

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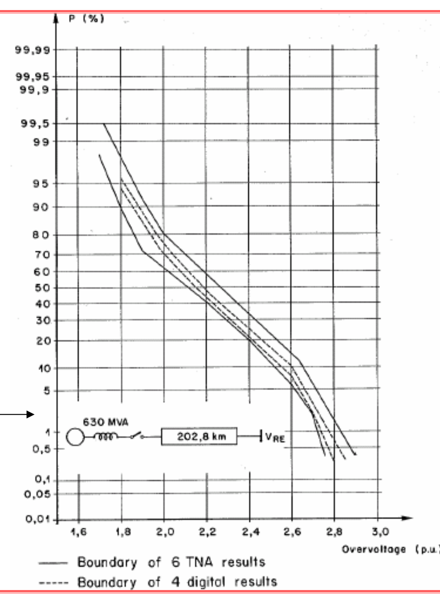
- Cumulative frequency distribution from 100 closing operations on digital computers and transient network analyzers (TNA's).

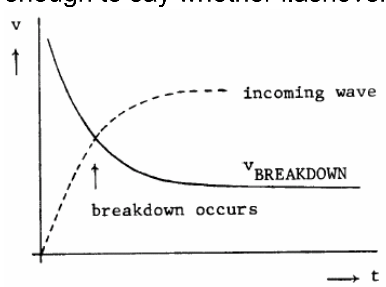
- 2 % value is often used to define overvoltage with one number



- If insulation can withstand the 2 % overvoltage value, then 98 % of switching operations will statistically be successful.
- 2 % of switching operations may statistically cause insulator flashover.
- By opening circuit breaker and re-closing again, arc will be extinguished (self-restoring insulation).

Voltage/time curves

- Peak instantaneous overvoltage is not enough to say whether flashover across insulator occurs.
- Waveshape is also determining factor.
- For nice laboratory impulses, voltage/time curves can be obtained.



- Actual waveshapes are much more complicated, but standard impulse waveshapes are needed for laboratory testing, to meet impulse test standards.
- There are flashover models, such as the integral method, but rarely used:

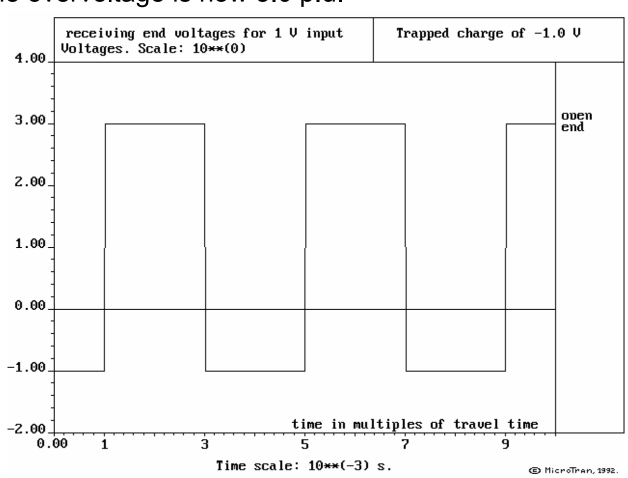
$$\int_{t_1}^{t_2} \left(v(t) - v_0\right) dt = F$$

Closing & Re-closing Operations on Transmission Lines

- **Events in re-closing operations**
  - A fault occurs, usually in one phase.
  - The transmission line is de-energized (switched off at one end, then on other end).
  - On unfaulted phases, the current is capacitive when remote end is already switched off. Therefore, current and voltage are 90 ° out of phase.
  - When current interrupts at current zero, voltage on line is at its maximum (say, at -1.0 p.u.).
  - If circuit breaker re-closes when source voltage is at its opposite maximum (say, at +1.0 p.u.), there is a voltage change of 2.0 p.u.
  - This re-closing operation with "trapped" charge produces the highest overvoltages.

Closing & Re-closing Operations on Transmission Lines

- **Events in re-closing operations**
  - The overvoltage is now 3.0 p.u.



Reduction of Overvoltages in Closing and Re-Closing Operations on Transmission Lines

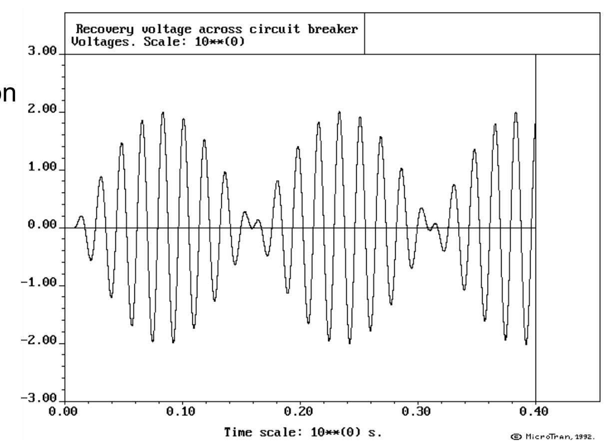
1. Controlled closing

- Contacts close at instant when voltage is close to zero across the contacts.
- Requires some prediction of voltage across contacts.
- Prediction is easy with a sinusoidal voltage on the source side, and
  - zero voltage on the line side,
  - or dc voltage on the line side with trapped charge.
- Prediction is more complicated when re-closing into trapped charge on a line with shunt reactors.

Reduction of Overvoltages in Closing and Re-Closing Operations on Transmission Lines

1. Controlled closing

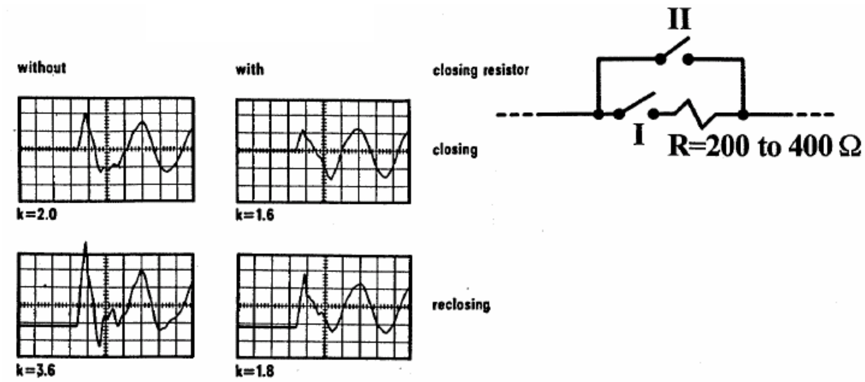
- Re-closing into trapped charge on a line with shunt reactors:
- In this case, there is a beat phenomenon in voltage across contacts.
- Resonance between shunt reactors and line capacitance usually somewhat below 50 or 60 Hz).



Reduction of Overvoltages in Closing and Re-closing Operations on Transmission Lines

2. Closing (pre-insertion) resistors

- Close contact I first, then II after 8 to 10 ms.
- From [1]:



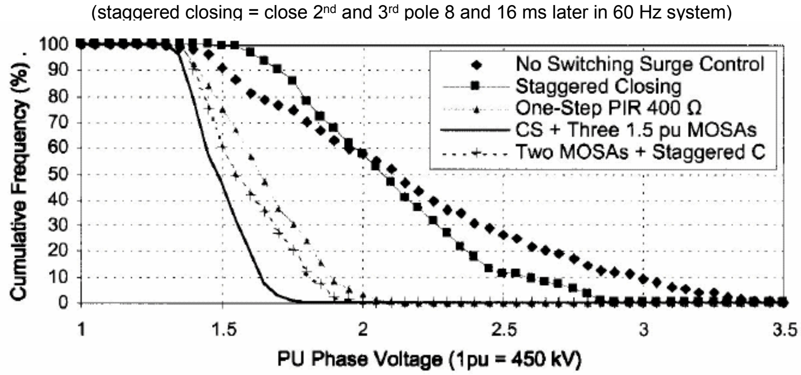
Reduction of Overvoltages in Closing and Re-closing Operations on Transmission Lines

3. Metal oxide surge arresters

- At both ends
- At both ends and middle.

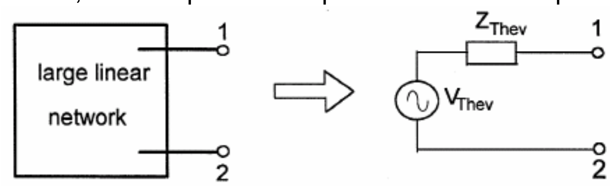
4. Comparison from [2] & [3] **(re-closing into trapped charge with shunt reactors)**:

(staggered closing = close 2nd and 3rd pole 8 and 16 ms later in 60 Hz system)

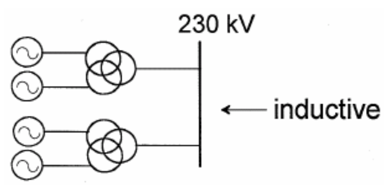


Computer Models for Closing and Re-closing Operations on Transmission Lines

- **Feeding network**
  - Simplest model is voltage source behind 50 Hz or 60 Hz “short-circuit impedance”, both for positive sequence and zero sequence.



  - This simple model is reasonable if the feeding network is mostly inductive, as in the case of switching from a power plant:

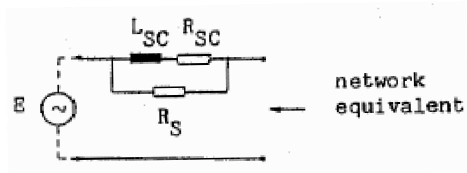


Computer Models for Closing and Re-closing Operations on Transmission Lines

- **Feeding network**
  - If the feeding network is more complicated, CIGRE recommends to represent the lines in detail one or two substations away from the substation where switching is done.
  - Beyond the one or two substations away, use the short-circuit impedances to represent the rest.
  - Some utilities prefer to represent the large system completely in detail (Hydro-Quebec?).

Computer Models for Closing and Re-closing Operations on Transmission Lines

- **Feeding network as equivalent network**
  - A simplified version of an equivalent network recommended by CIGRE uses the short-circuit impedance (resistance R_{SC} and inductance L_{SC}) in parallel with the surge impedance of the connected lines, divided by the number of lines, $R_S = Z_{surge}/n$ [4]:



  - Frequency dependent network equivalent ("FDNE") creates an R-L-C network that has more or less the same frequency response as the complete network, over the frequency range of interest. Starts from frequency scan of complete network.

Computer Models for Closing and Re-closing Operations on Transmission Lines

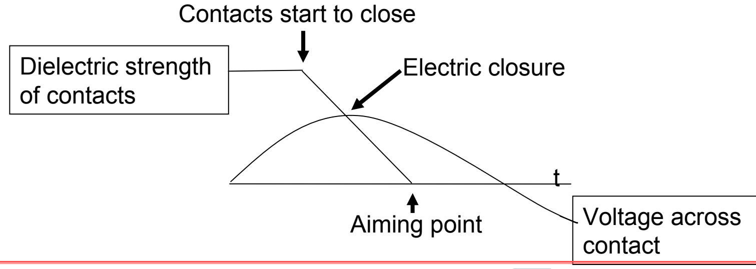
- **Feeding network as equivalent network**
  - H. Singh and A. Abur developed a time domain model that reaches back more in history [5]:

$$i(t) = g_0 v(t) + g_1 v(t - \Delta t) + g_2 v(t - 2\Delta t) + \ldots$$

  - This can handle travel time delays on transmission lines more easily.
  - Both FDNE and the time domain model are developed from the full system.
  - If the equivalent is not used very often, it may be best to work directly with the full system.

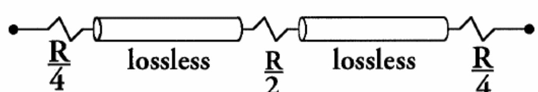
Computer Models for Closing and Re-closing Operations on Transmission Lines

- **Circuit breaker**
  - Normally, the circuit breaker is represented as an ideal switch,
    - with closing time specified,
    - and closing taking place at the next time step $n \cdot \Delta t \geq t_{close}$, or in some versions at $n \cdot \Delta t$ closest to t_{close}.
    - For slow circuit breakers or circuit switchers, prestrike may have to be taken into account.



Computer Models for Closing and Re-closing Operations on Transmission Lines

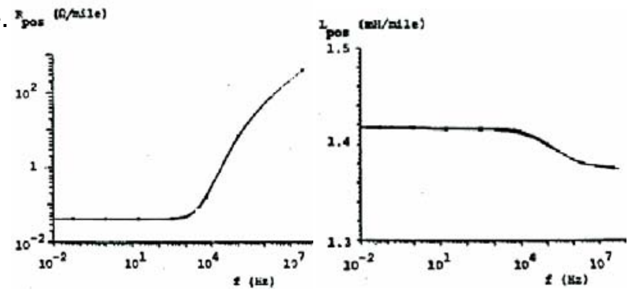
- **Transmission line; constant parameter model**
  - The simplest model is the constant parameter model with constant per-unit length parameters R', L', C', both in positive sequence and zero sequence.
    - In EMTP version that I am familiar with, R' is not really distributed, but lumped at both ends and the middle.



    - Total resistance $R = R' \cdot length$ must be much less than characteristic impedance Z_{char} .
    - A truly distributed resistance is a special case of line models with frequency dependent parameters, because Z becomes frequency dependent: $Z_{char} = \sqrt{\dfrac{R' + j\omega L'}{j\omega C'}}$

Computer Models for Closing and Re-closing Operations on Transmission Lines

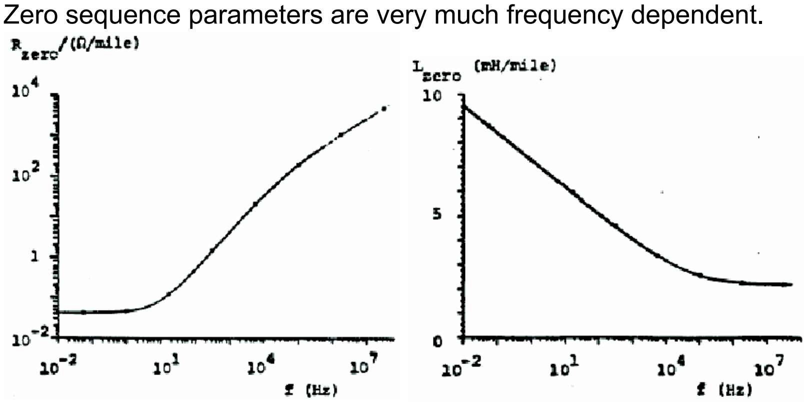
- **Transmission line; constant parameter model**
  - This model is often accurate enough for switching studies because
    - frequencies are not very high (maybe to 10 kHz),
    - positive sequence parameters are more or less constant in that range.



    - Zero seq. parameters are frequency dependent, but if three poles close simultaneously, then there are no zero sequence surges.

Computer Models for Closing and Re-closing Operations on Transmission Lines

- **Transmission line, frequency-dependent parameter models**
  - Zero sequence parameters are very much frequency dependent.



  - This dependence must be taken into account if there are noticeable zero sequence currents and voltages in the transients.

Computer Models for Closing and Re-closing Operations on Transmission Lines

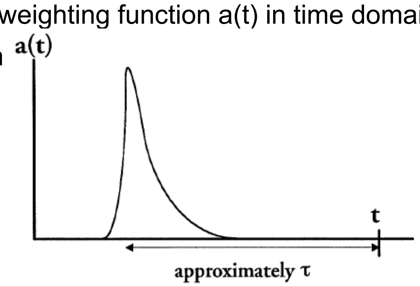
- **Transmission line, frequency-dependent parameter models**
  - F. Castellanos and J. R. Marti [6] developed a frequency-dependent line model by lumping $R(\omega) + j\omega L_{internal}(\omega)$ in many more places along lossless line sections, and taking the frequency dependence of these lumped impedances into account.
    - $R(\omega) + j\omega L_{internal}(\omega)$ represents the resistances and internal inductances of the conductors and of earth return.
    - For three-phase lines, these impedances are 3*3 matrices.
    - It works directly in the phase domain, without having to go through transformation between phase and mode quantities.
    - Well suited for un-transposed lines.
    - This approach works for underground cables as well, with minor modifications [7].

Computer Models for Closing and Re-closing Operations on Transmission Lines

- **Transmission line, frequency-dependent parameter models**
  - Most EMTP models are based on fitting propagation factor $e^{-\gamma l}$ and characteristic impedance $Z_{char}(\omega)$ in the frequency domain.
  - For both positive and zero sequence, find propagation constant

$$\gamma = \sqrt{(R'(\omega) + j\omega L'(\omega)) \cdot j\omega C'}$$

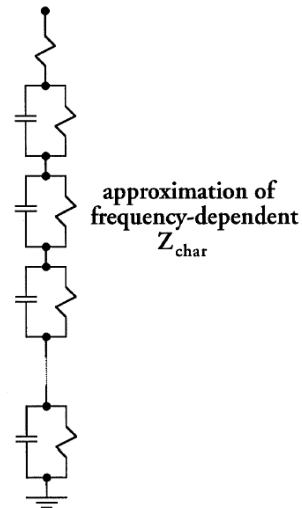
  - With approach of J. R. Martí [8], calculate propagation factor $A(\omega) = e^{-\gamma l}$ in frequency domain, & convert to weighting function a(t) in time domain.
  - Before, we picked one history term going back τ. Now we pick more, using a weighting function a(t).
  - For efficiency, recursive convolution is used to sum history points with a(t).



Computer Models for Closing and Re-closing Operations on Transmission Lines

- **Transmission line, frequency-dependent parameter models**
  - The characteristic impedance was a pure shunt resistance Z before. Now it is frequency- dependent.
  - Approximate $Z(\omega)=\sqrt{\dfrac{R'(\omega)+j\omega L'(\omega)}{j\omega C'}}$

    with an R-C circuit, as shown at right.
  - Straightforward for "balanced" (perfectly transposed) lines.
  - On un-transposed lines, transformation matrix approximated as real and constant (not good for double-circuit lines).



Computer Models for Closing and Re-closing Operations on Transmission Lines

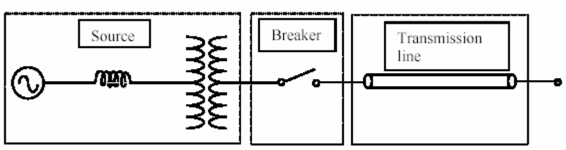
- **Transmission line, frequency-dependent parameter models**
  - Much progress has been made, particularly for un-transposed lines, mostly with phase domain based models:
    - T. Noda, N. Nagaoka and A. Ametani [9] developed the ARMA model (auto-regressive moving average).
    - A. Morched, B. Gustavsen and M. Tartibi [10] developed the universal model with vector fitting.
    - B. Gustavsen [11] added many refinements.
    - A. B. Fernandes and W. L. A. Neves included effects of shunt conductance [14, 15].
    - Etc.

Computer Models for Closing and Re-closing Operations on Transmission Lines

- **Trapped charge**
  - There are various ways to represent it, depending on EMTP version.
    - Simulate the line opening, wait for trapped charge to settle to dc after some oscillations, then close again. May require long simulation time.
    - In version which I use, initial conditions can be read in, which override the ac steady-state solution values. Example for line from 1 to 2 with phases A, B, C, read in initial voltages in 1A, 1B, 1C, 2A, 2B, 2C, and read in zero initial currents in 1A-2A, 1B-2B, 1C-2C.
    - In older versions of EMTP, and maybe ATP, you can connect special voltage sources $V_{max}\cos(\omega t)$ with a frequency of 0.001 Hz, (Tstart = 5432.0?), to approximate dc (solving directly for dc requires extensive code changes to handle $\omega L = 0$ and $1/\omega C = \infty$).

Examples for Closing and Re-closing Operations on Transmission Lines

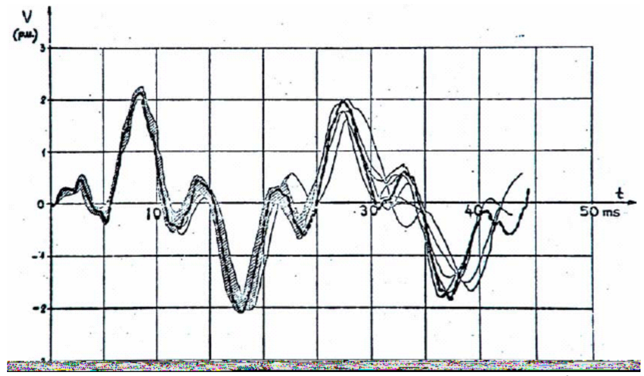
- **CIGRE test case for energization of 202.8 km long line from inductive source [12]**



  - Source impedance (generator + transformer):
    $R_{pos} = R_{zero} = 6.75\ \Omega$; $X_{pos} = X_{zero} = 127\ \Omega$ at 50 Hz.
  - Line: $Z'_{pos} = 0.04 + j\ 0.318\ \Omega$/km at 50 Hz, $C'_{pos} = 11.86$ nF/km;
    $Z'_{zero} = 0.26 + j\ 1.015\ \Omega$/km at 50 Hz, $C'_{zero} = 7.66$ nF/km;
    length = 202.8 km. Constant R', L', C' assumed.
  - Circuit breaker: closing times, with respect to instant when voltage in phase A goes through zero from positive to negative;
    $T_{CLOSE-A} = 3.05$ ms, $T_{CLOSE-B} = 8.05$ ms, $T_{CLOSE-C} = 5.55$ ms.

Examples for Closing and Re-closing Operations on Transmission Lines

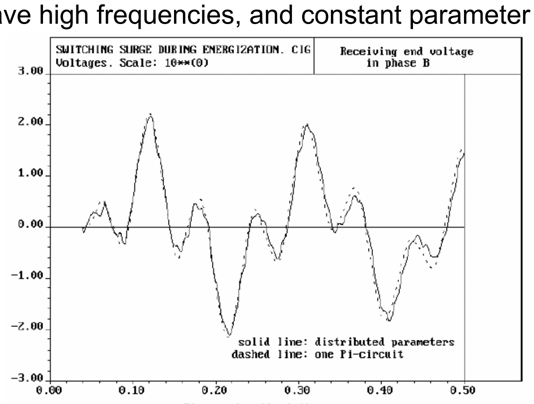
- **CIGRE test case for energization of 202.8 km long line from inductive source [12]**



  - Overvoltage at receiving end in phase B; computer results (dashed line) superimposed on family of curves from transient network analyzer results; time count starts when wave arrives at receiving end

Examples for Closing and Re-closing Operations on Transmission Lines

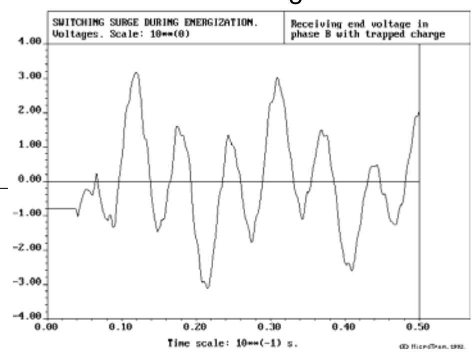
- **CIGRE test case for energization of 202.8 km long line from inductive source [12]**
  - This case did not have high frequencies, and constant parameter line model and single Π-circuit gave almost identical results.
  - In general, I would not recommend Π-circuits (on transient network analyzers, switched line was typically represented by cascade connection of 10 Π-circuits).



Examples for Closing and Re-closing Operations on Transmission Lines

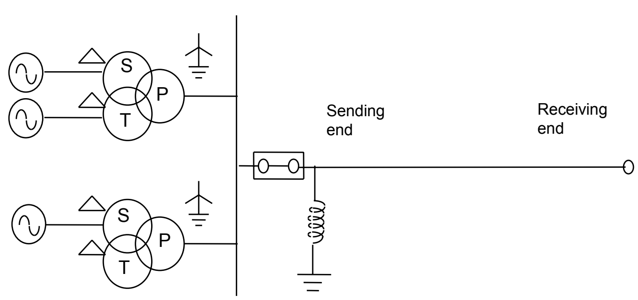
- **CIGRE test case for energization of 202.8 km long line from inductive source [12]**
  - Trapped charge can increase or decrease the overvoltages.
  - Depends on polarity of trapped voltage.

Trapped charge (p.u.)			Overvoltages (p.u.)		
A	B	C	A	B	C
0.0	0.0	0.0	2.068	2.166	2.287
0.9	0.8	-0.8	1.368	1.538	1.342
-0.9	-0.8	0.8	3.086	3.172	3.469



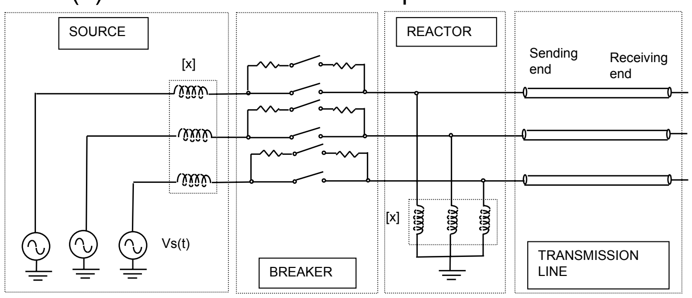
Examples for Closing and Re-closing Operations on Transmission Lines

- **Energization of 400 km long line through closing resistors [13]**
  - This was a field test by CEMIG in Brazil.
  - Line was switched from a power plant. No other lines were connected.
  - Line had a three-phase shunt reactor at sending end.



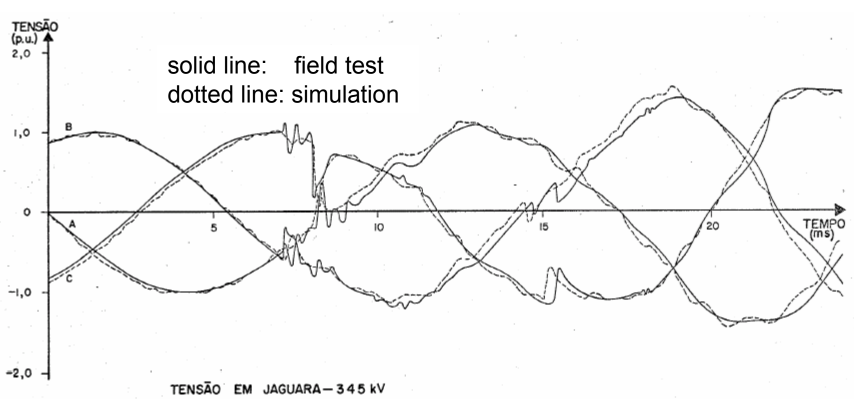
Examples for Closing and Re-closing Operations on Transmission Lines

- **Energization of 400 km long line through closing resistors [13]**
  - Modelling: (1) Find positive and zero sequence impedances looking into power plant (generator with X_d") , and then model as 3 coupled impedances.
    (2) Model shunt reactor as 3 coupled impedances.
    (3) Model line with constant parameters.



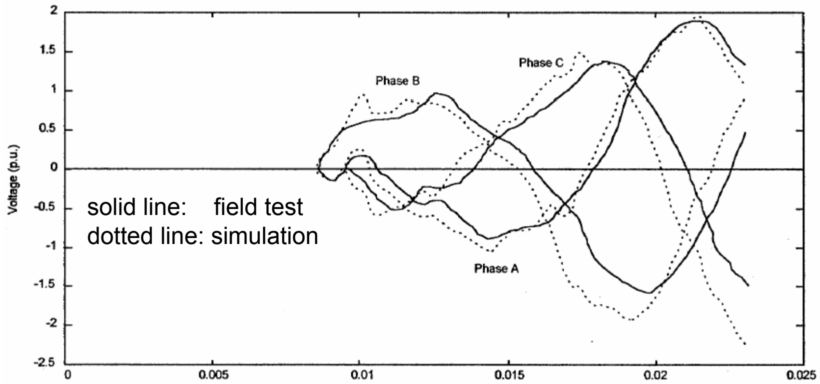
Examples for Closing and Re-closing Operations on Transmission Lines

- **Energization of 400 km long line through closing resistors [13]**
  - Voltages at sending end.



Examples for Closing and Re-closing Operations on Transmission Lines

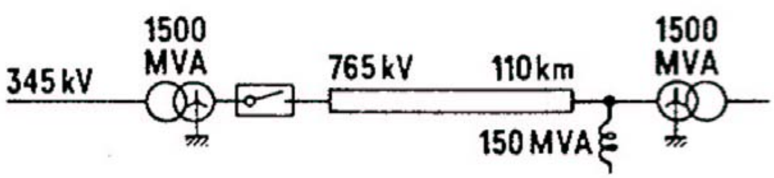
- **Energization of 400 km long line through closing resistors [13]**
  - Voltages at receiving end.



  - Going from constant to frequency-dependent parameter models did not improve results much.

Example for Temporary Overvoltages

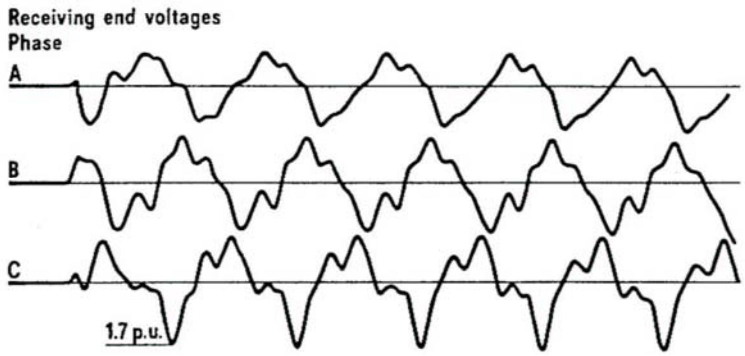
- **Energization of a line terminated with transformer or shunt reactor**
  - Example from M. Erche [1]:



  - This case is probably from American Electric Power Corp.
  - Caused by resonances between harmonics from transformer saturation and line capacitance.

Example for Temporary Overvoltages

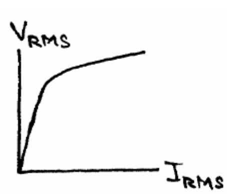
- **Energization of a line terminated with transformer or shunt reactor**

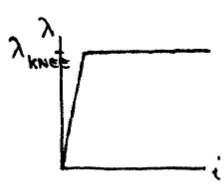


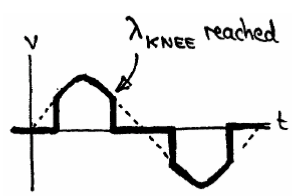
  - Overvoltages can last a long time.

Example for Temporary Overvoltages

- **Energization of a line terminated with transformer or shunt reactor**
  - Nonlinear inductances do not keep peak voltages down.
  - Part of the voltage around voltage zero is "cut out", because of 90° phase shift between flux and voltage.
  - $V_{RMS} = f(I_{RMS})$ must be converted to flux linkage = f (current) (simplified as 2-slope nonlinearity here)







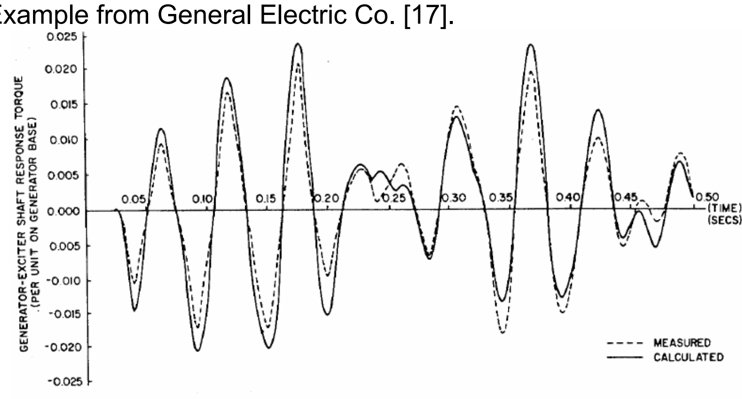
  - This "cut out" produces the harmonics.

Examples for Subsynchronous Resonance

- **Interaction between mechanical resonances on turbine-generator shaft system and on electric network side**
  - Occurs at frequencies below power frequency.
  - Most likely to occur on steam turbines, if a transmission line with series capacitors is switched.
  - Unlikely to occur on hydro turbines because "stiffer" with higher resonance frequencies.
  - Can also be caused by control modes in nearby HVDC terminal.

Examples for Subsynchronous Resonance

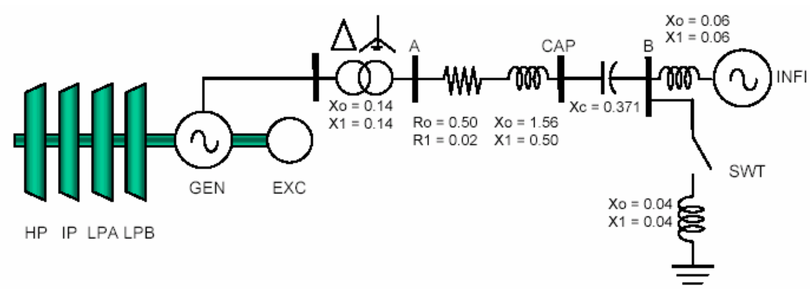
- **Interaction between mechanical resonances on turbine-generator shaft system and on electric network side**
  - Example from General Electric Co. [17].



Shaft Torque Comparison of Calculated Results to Actual Test Measurements for Out-Of-Phase Synchronization

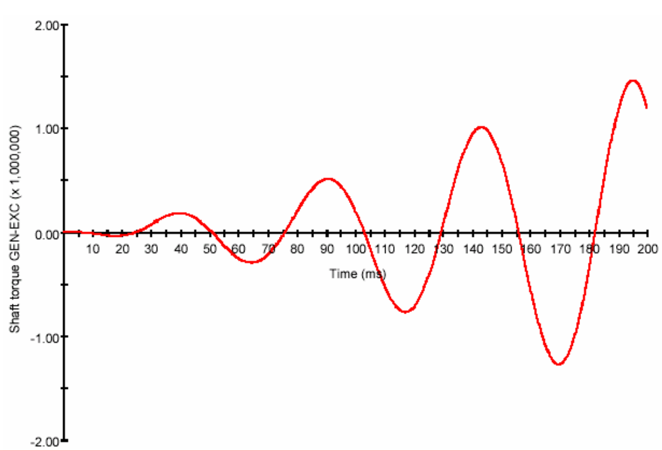
Examples for Subsynchronous Resonance

- First IEEE benchmark model [18, 20].



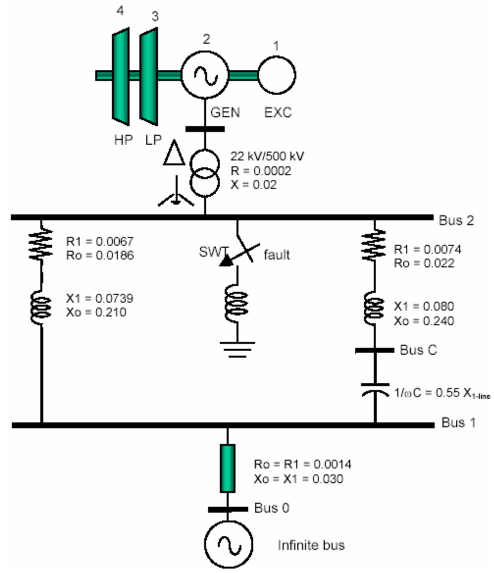
Examples for Subsynchronous Resonance

- First IEEE benchmark model, torque between generator & exciter.



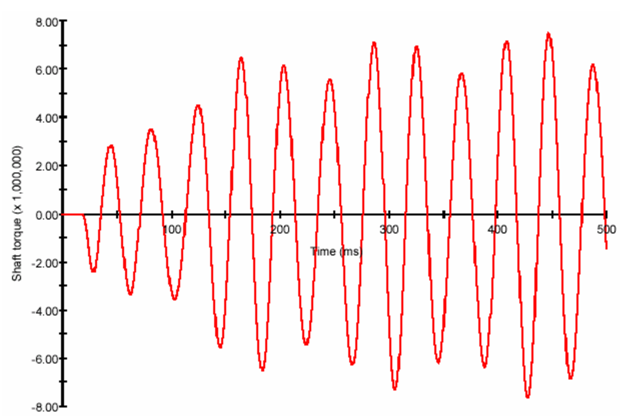
Examples for Subsynchronous Resonance

- Second IEEE benchmark model [19, 21].



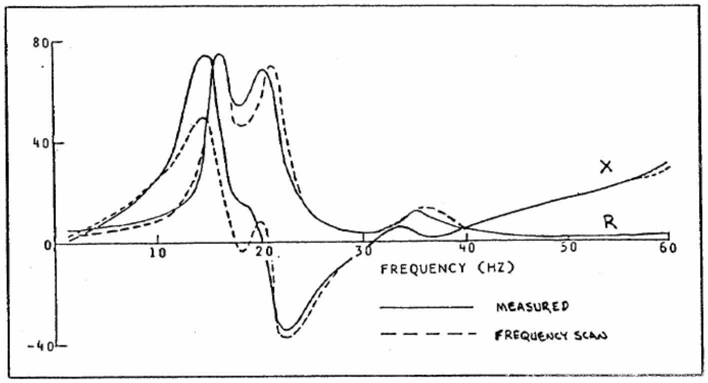
Examples for Subsynchronous Resonance

- Second IEEE benchmark model, shaft between generator and low pressure steam turbine.



Examples for Subsynchronous Resonance

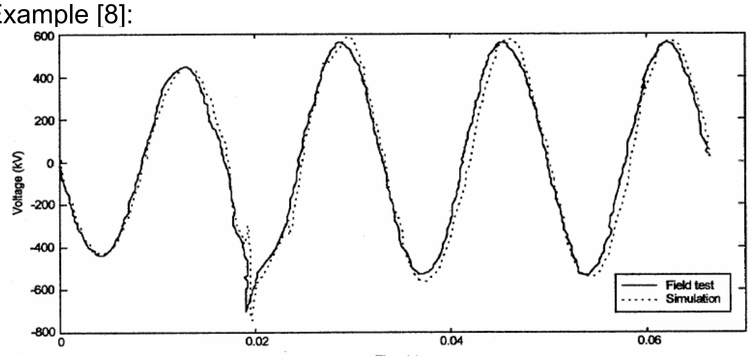
- **Frequency-scan for impedance seen from power plant**
  - Helps to see whether potential for subsynchronous resonance exists.
  - Example from [26]:



  - Measured: Short circuit was applied for a few cycles. Change in Δv, Δi transformed from time domain to frequency domain, to obtain Z(ω).

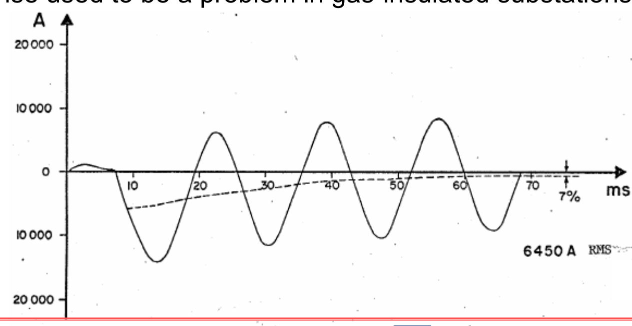
Example for Single-Line-to-Ground Fault on Transmission Lines

- **When a single-line-to-ground fault occurs on a transmission line, there will be overvoltages on the unfaulted phases (typically 1.6 p.u.)**
  - Frequency dependent line model is necessary, because there are large zero sequence currents ($I_{zero} = I_{pos} = I_{neg}$ in fault current).
  - Example [8]:



Example for Transient Recovery Voltage

- **When circuit breaker opens to remove the fault, a "transient recovery voltage" appears across the contacts.**
  - If rate of rise is too steep or amplitude is too high, circuit breaker may restrike or re-ignite.
  - Important to include stray capacitances of transformers, busbars, etc.
  - Initial rate of rise used to be a problem in gas-insulated substations.
  - Example from [13, 25].
  - Fault current:



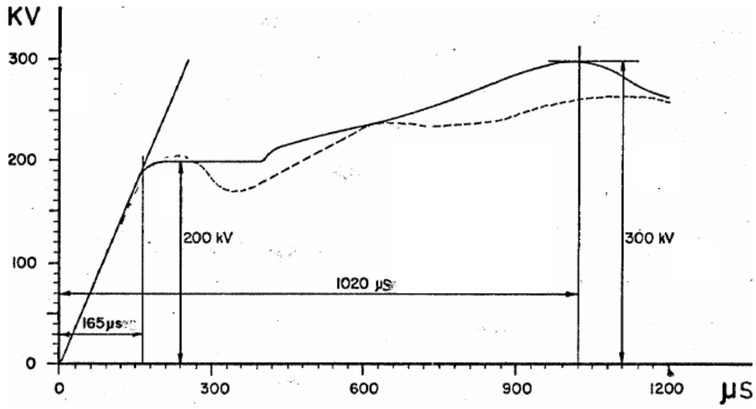
Example for Transient Recovery Voltage

- For simulation, one can either simulate complete event (fault initiation, fault clearing).

- I prefer "cancellation method", whereby a current is injected across circuit breaker contacts that cancels the fault current.
  - Starts from zero initial conditions.
  - Network need only be represented to distance away where total travel time > t_{max} (no reflections coming back beyond that point).

Example for Transient Recovery Voltage

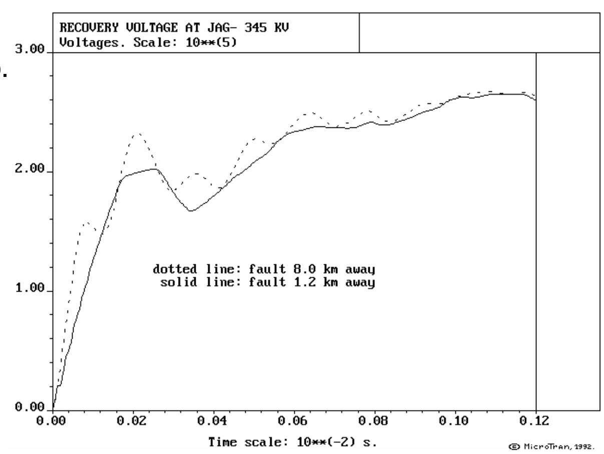
- Results for fault at 1.2 km from substation:



Solid line = field test; dotted line = simulation.

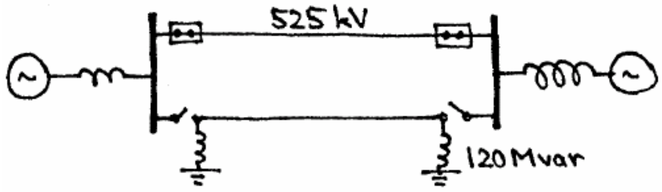
Example for Transient Recovery Voltage

- Initial rate of rise becomes worse if fault farther away from substation ("short-line fault" or "kilometric fault").
- Fault moved from 1.2 km to 8.0 km:
- Fault current decreases 13.7%.
- Initial rate of rise increases.



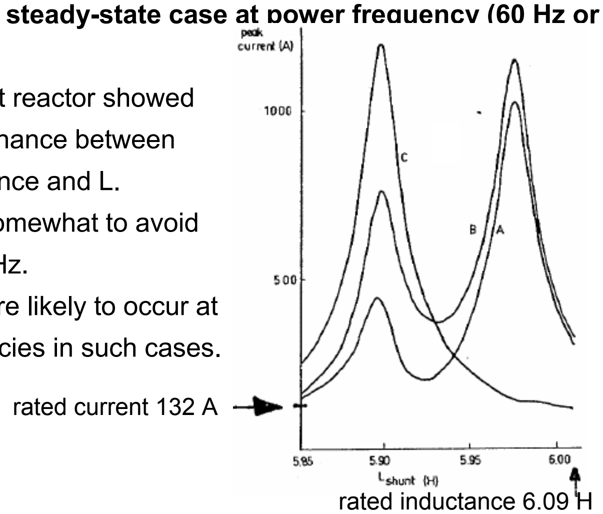
Example for Linear Resonance after Opening a Transmission Line in Parallel with another Line

- **Can be studied as a steady-state case at power frequency (60 Hz or 50 Hz)**
  - Best transmission line model is Π-circuit.
  - For complicated transposition schemes, use one Π-circuit for each section.
  - Example from planning study at Bonneville Power Administration:



Example for Linear Resonance after Opening a Transmission Line in Parallel with another Line

- **Can be studied as a steady-state case at power frequency (60 Hz or 50 Hz)**
  - Varying L of shunt reactor showed possibility of resonance between coupling capacitance and L.
  - L was changed somewhat to avoid resonance at 60 Hz.
  - Resonance is more likely to occur at harmonic frequencies in such cases.



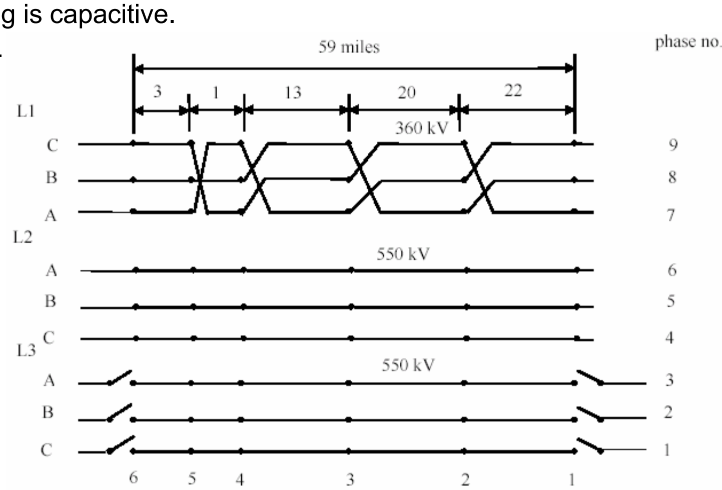
Example for Linear Resonance after Opening a Transmission Line in Parallel with another Line

- **A similar case that actually happened on a 345 kV line that was close to an energized 138 kV line is reported in [31] and [32].**

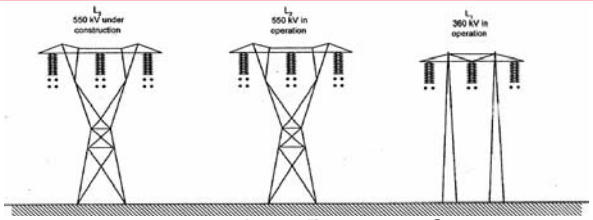
- **A case of what might happen on a 765 kV line close to an energized 345 kV line is discussed in [33] for these situations:**
  - No transpositions on both lines.
  - 345 kV line transposed.
  - 765 kV line transposed.
  - Both lines transposed.

Example 1 for Coupling between Parallel Transmission Lines

- **Three circuits in parallel are modelled as five nine-phase Π-circuits**
  - Coupling is capacitive.
  - Steady-state case.



Example 1 for Coupling between Parallel Transmission Lines

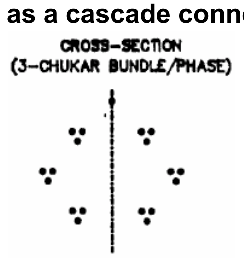


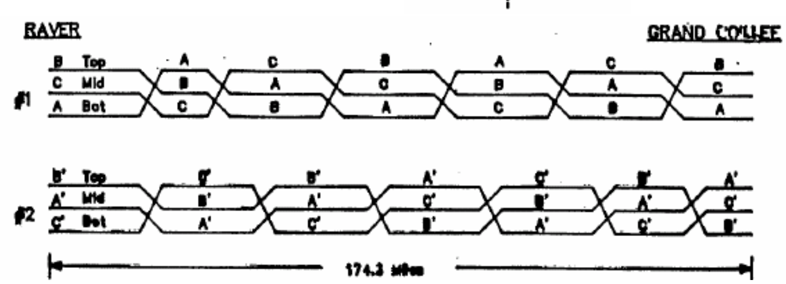
Electrostatic coupling at power frequency

	line	phase	simulation	measurement
Voltages on lines in operation	L1		360 kV	372 kV
	L2		550 kV	535 kV
Induced voltages on open line	L3	A	28.20 kV	30 kV
		B	14.19 kV	15 kV
		C	8.04 kV	10 kV
Grounding currents when line is grounded	L3	A	10.78 A	11 A
		B	3.26 A	5 A
		C	1.53 A	1 A

Example 2 for Coupling between Parallel Transmission Lines

- **A double-circuit line is modelled as a cascade connection of twelve six-phase Π-circuits.**
  - Coupling is inductive [23].
  - Steady-state case.





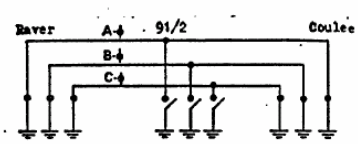
Example 2 for Coupling between Parallel Transmission Lines

- Results from one of many tests.

LOAD = 840 MW
VOLTAGE IN kV, CURRENT IN AMPS

	COULEE		91/2		RAVER	
	EMTP	TEST	EMTP	TEST	EMTP	TEST
V_A =	0	-	0.8	0.6	0	-
V_B =	0	-	2.0	2.1	0	-
V_C =	0	-	1.0	0.8	0	-
I_A =	49	42	-	-	47	39
I_B =	31	25	-	-	32	27
I_C =	49	44	-	-	49	43

Energized circuit of double-circuit line not shown

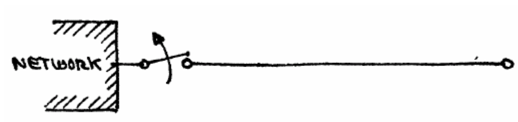


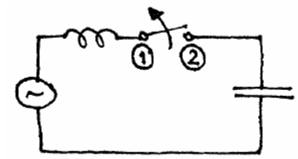
Example 3 for Coupling between Parallel Transmission Lines

- **From B. C. Hydro and Power Authority [24]**
  - Steady-state case.
  - A large zero sequence voltage was induced into a 138 kV line from adjacent 500 kV lines.
  - It distorted the 2½-element revenue metering schemes of two large industrial customers supplied from the 138 kV line.
  - The two customers were overcharged 3.5% for 15 years.
  - They received refunds of Can. $ 4 million.
  - The metering scheme was changed.

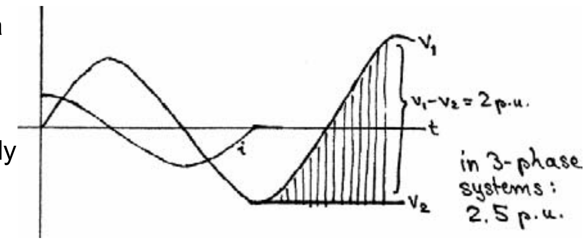
Capacitor switching

- **Switching capacitances off**
  - When switching a capacitor or unloaded transmission line off, the capacitance remains charged up.





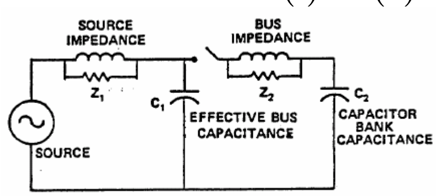
  - 2.0 p.u. overvoltage across contacts half a cycle after opening.
  - Modern SF_6 circuit breakers are less likely to restrike than older circuit breakers.



Capacitor switching

- **Energization of capacitors**
  - Voltage on capacitor cannot change instantaneously, because it is determined by integral:

$$v(t) = v(0) + \frac{1}{C}\int_0^t i \cdot du$$

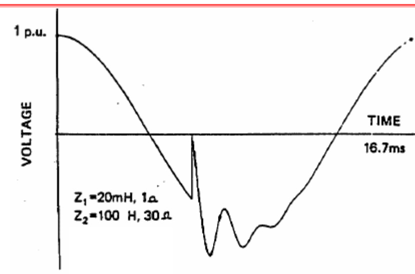


Equivalent circuit for EMTP studies.

  - If voltage is originally zero, bus voltage collapses to zero temporarily after switching on.
  - Creates voltage collapse on bus, as well as high inrush currents into capacitor bank.

Capacitor switching

- **Energization of capacitors**
  - High dv/dt, v, and i may create problems.
  - From Brunke and Schockelt [16]:



Transient Potentials

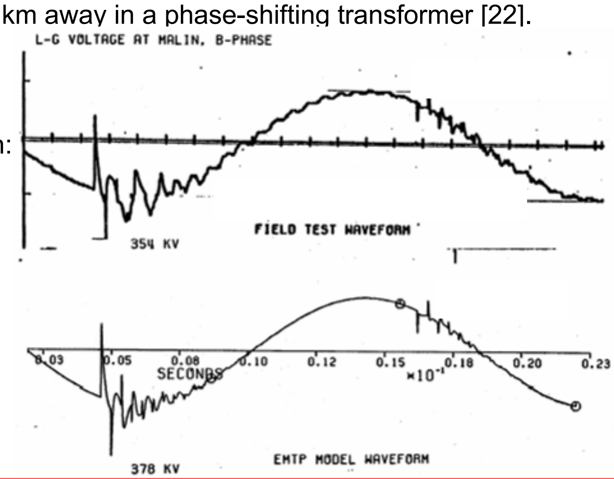
Circuit	Energized close to	Fence to Neutral Potential	Fence to Earth Potential
Single Bank	crest volt.	6.2 kV	364 V
Single Bank	zero volt.	1.2 kV	0 V
Back to Back	crest volt.	13.5 kV	912 V
Back to Back	zero volt.	0.8 kV	6 V

Capacitor switching

- **Energization of capacitors**
  - Reduction of transients with:
    - Closing (pre-insertion) resistors.
    - Synchronous (controlled) closing, close to zero voltage across contacts.
    - Current-limiting reactors in series with capacitor.

Capacitor switching

- **Effect remote from substation where capacitors are switched**
  - In case shown here, it may have caused phase-to-phase insulation failure 56 km away in a phase-shifting transformer [22].
  - Field test and simulation:



Capacitor switching

- **Back-to back switching of capacitors**
  - Back-to-back switching: one capacitor bank is energized, and another capacitor bank next to it is switched on.
  - This is worst condition, as seen in previous case.

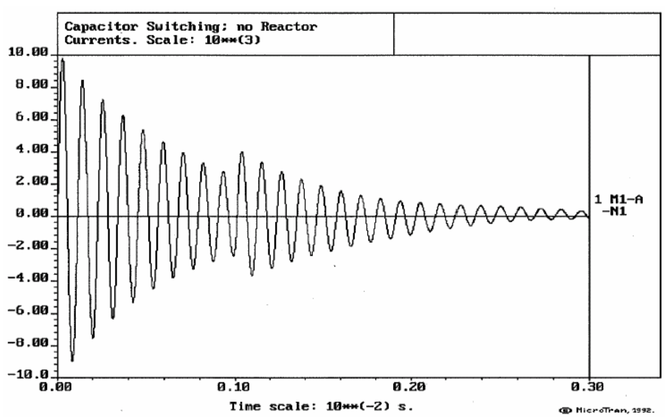
  - I analyzed a failure where an induction motor was switched on, close to another running induction motor, in a pipeline pumping station.
    - Both had capacitors connected for power factor correction.
    - When second motor was switched on with vacuum contactor, the contacts welded together, and contactor could no longer be opened.
    - After complicated modelling of induction motors, capacitors, etc., it turned out to be so simple I could have solved it with a slide rule.

Capacitor switching

- Both induction motors were 5 m apart through a cable.
- Both had a 600 kVar capacitor, rated 4.16 kV (line-to-line), 83.3 A.
- One energized capacitor discharged into the capacitor of the motor being switched on, through whatever inductance is between them.
- Creates a very high inrush current, which welded the contacts in this case.

Capacitor switching

- Simulation:



- A current-limiting reactor would solve the problem.

Capacitor switching

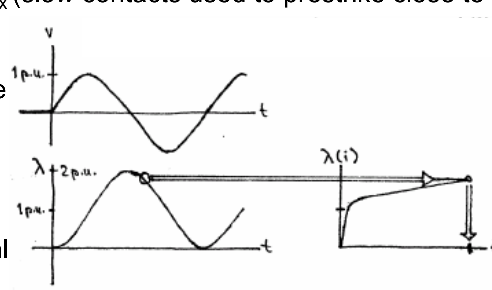
- A more likely problem in such cases is overvoltages created by re-ignitions when opening the vacuum contactor.
- This is caused by tendency of vacuum contactors or circuit breakers to chop currents (see next slide).
- Surge capacitor on load being switched helps to prevent re-ignition (not an issue in my case).

Inrush Currents

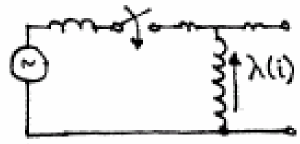
- **When an unloaded transformer is energized, high "inrush currents" may occur that are higher than rated current.**
- **Cause is the nonlinear magnetizing inductance, with its nonlinear curve for flux λ = f(i).**
  - Modern circuit breakers close with high speed. Closing at v = 0 is as probable as closing at v = V_{max} (slow contacts used to prestrike close to V_{max}).
  - Since flux is integral of voltage

$$\lambda(t) = \lambda(0) + \int_0^t v \cdot du$$

we get 2 p.u. flux if we close at v = 0, assuming the residual flux λ(0) at t = 0 is zero.



Inrush Currents



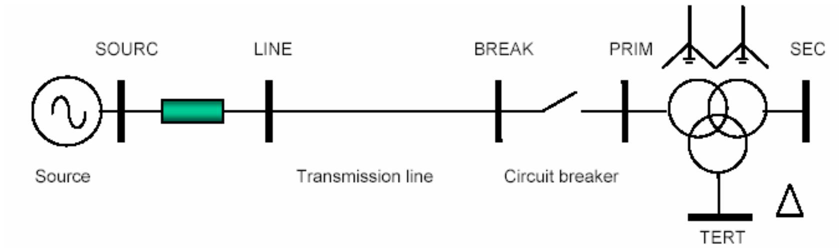
- Residual flux can make the inrush current higher or lower.
- There may also be high-frequency overvoltages in energizing three-phase banks if the closing times are more than 5 ms apart. This may have caused damages recently.

Inrush Currents

- The inrush current also depends on the tap position of the load tap changer, and by positioning it conveniently, the inrush currents can be reduced.
- If other transformers are already in operation close to the one being energized, there is “sympathetic interaction” between them that influences the inrush currents [35].
- By monitoring the flux in the transformer, and by controlling the closing of the circuit breaker contacts, it becomes possible to close at just the right moment to reduce the inrush current to very small values similar to the steady-state exciting current ([36], [37], [38]).

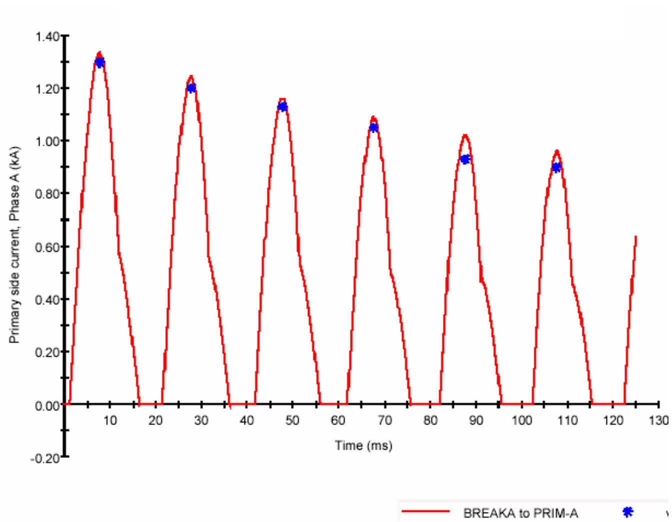
Inrush Currents

- **Example from CIGRE Working Group [34]:**



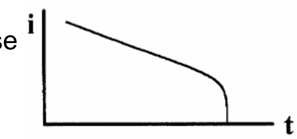
Inrush Currents

- **Example from CIGRE Working Group [34]:**

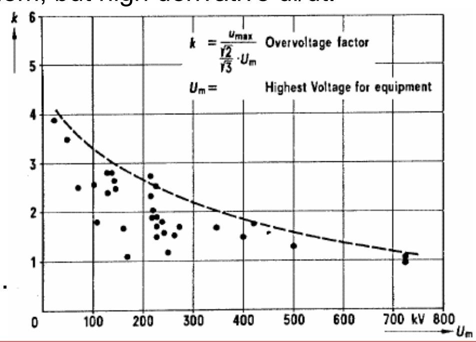


Interruption of Small Inductive Currents

- **Problem is "current chopping" in circuit breaker opening**
  - Tendency to "chop" if current is small (because of falling v(i) characteristic of arc, arc voltage becomes high when current becomes low).

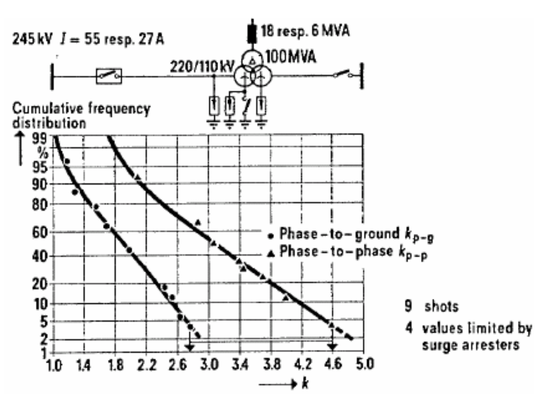


  - Small current is not the problem, but high derivative di/dt.
  - Can cause overvoltages as $L\frac{di}{dt}$.
  - Maximum overvoltage factors when interrupting magnetizing currrent of high voltage transformers [1].



Interruption of Small Inductive Currents

- Can also happen when switching off reactor-loaded transformers.



- Vacuum circuit breakers have tendency to chop even at higher currents.
- For CIGRÉ reports, see [27], [28], [29], [30].

The End

Thank you for your attention!

Any Questions?

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