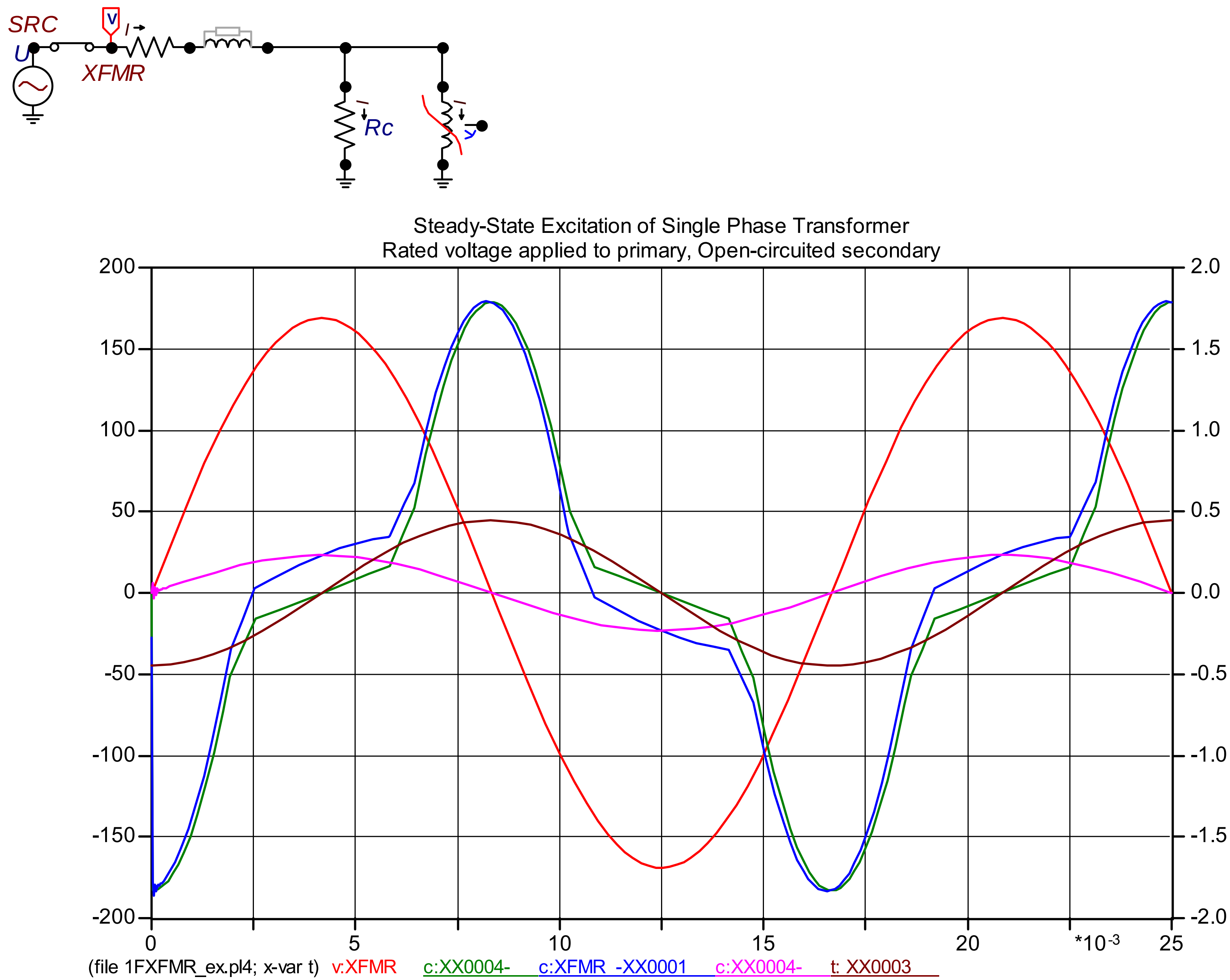
EE 5220 - Lecture 25 Mon Mar 14, 2022

Topics for Today:

- Course Info:
  - Web page: https://pages.mtu.edu/~bamork/ee5220/
  - Book, references, syllabus, more are on web page.
  - Software - Matlab. ATP/EMTP [License - www.emtp.org] ATP tutorials posted on our course web page
  - EE5220-L@mtu.edu (participation = half letter grade, 5%)

- HW#8 - Probs. 9.6, 9.12 due Tues Mar 22nd 9am.
- HW#9 - Probs. 9.2, 9.3, 9.4 due date TBA.
- Week 9 deliverable - Mon Mar 21st - a) complete reference list and b) fully-detailed table of contents according to format given in Term Project Guidelines.
- Transformer modeling - Section 11.1 of text, plus lecture notes
  - Review pre-req matls on mag circuits(as posted under Pre-Req Mat'ls)
    - Ampere's Law, Lenz' Law, magnetic circuit parameters
  - Example of single-phase transformer, Excitation
    - Waveforms for voltage, I_{EX}, I_R, I_C, λ
- Next - take stock of available ATP transformer models


SRC
U
XFMR
Rc
Steady-State Excitation of Single Phase Transformer
Rated voltage applied to primary, Open-circuited secondary
200
150
100
50
0
-50
-100
-150
-200
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
0
5
10
15
20
25
*10^-3
(file 1FXFMR_ex.pl4; x-var t) v:XFMR c:XX0004- c:XFMR -XX0001 c:XX0004- t: XX0003

Double-Circuit Lines:

Short-Circuit Studies make use of: $(Z^+ = Z^-)$

$$Z^0, \; Z^+, \; Z_{MUTUAL}$$

$$\left[\underset{6\times 6}{Z_p} \right] \Longrightarrow \begin{bmatrix} Z_{aa} & Z_{ab} & \cdots & \vdots & & Z_{az} \\ \vdots & Z_{bb} & & & & \vdots \\ & & Z_{cc} & & & \vdots \\ \cdots & \cdots & \cdots & Z_{xx} & \cdots & \cdots \\ \vdots & & & & Z_{yy} & \\ Z_{za} & \cdots & \cdots & \cdots & & Z_{zz} \end{bmatrix}$$

$$\begin{bmatrix} Z_S \\ 6\times 6 \end{bmatrix} = \begin{bmatrix} [A]^{-1} & 0 \\ 0 & [A]^{-1} \end{bmatrix} \begin{bmatrix} Z_P \\ 6\times 6 \end{bmatrix} \begin{bmatrix} [A] & 0 \\ 0 & [A] \end{bmatrix}$$

$$= \left[\begin{array}{ccc|ccc} Z_{00,1} & 0 & 0 & Z_M\,? & & Z_{0,1-2,2} \\ 0 & Z_{11,1} & 0 & & & \\ 0 & 0 & Z_{22,1} & & & \\ \hline Z_M\,? & & & Z_{00,2} & & \\ & & & & Z_{11,2} & \\ & & & & & Z_{22,2} \end{array}\right]$$

If $\underbrace{Z^+, Z^0, Z^M}$ >> $Z_{\text{OFF-DIAG}}$

Then we can approximate as de~~un~~coupled (except for Z_M).

From: EMTP Theo Book 4

untransposed case, because they would become zero for the balanced line. For the untransposed case, these off-diagonal elements are used to define unbalance factors [47, p. 93]. The full symmetrical component matrices are no longer symmetric, unless the columns for positive and negative sequence are exchanged [27]. This exchange is made in the output of the supporting routine LINE CONSTANTS with rows listed in order "zero, pos, neg, ..." and columns in order "zero, neg, pos, ...". With this trick, matrices can be printed in triangular form (elements in and below the diagonal), as is done with the matrices for individual and equivalent phase conductors.

Symmetrical components for two-phase lines are calculated with the transformation matrix of Eq. (4.63), while those of three-phase lines are calculated with

$$[v_{phase}] = [S][v_{symm}], \text{ and } [v_{symm}] = [S]^{-1}[v_{phase}], \qquad (4.68a)$$

identical for currents,

$$\text{where} \quad [v_{symm}] = \begin{bmatrix} v_{zero} \\ v_{pos} \\ v_{neg} \end{bmatrix},$$

with

$$[A] \; [S] = \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \text{ and } [S]^{-1} = \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \qquad (4.68b)$$

and $a = e^{j120°}$.

The columns in these matrices are normalized*); in that form, [S] is unitary,

$$[S]^{-1} = [S^*]^t \qquad (4.69)$$

where "*" indicates conjugate complex and "t" transposition.

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*) The electric utility industry usually uses unnormalized transformation, in which the factor for the [S]-matrix is 1 instead of $1/\sqrt{3}$, and for the $[S]^{-1}$-matrix 1/3 instead of $1/\sqrt{3}$. The symmetrical component impedances are identical in both cases, but the sequence currents and voltages differ by a factor $\sqrt{3}$.

For M>3, the supporting routine LINE CONSTANTS assumes three-phase lines in parallel. Examples:

- M = 6: Two three-phase lines in parallel
- M = 9: Three three-phase lines in parallel
- M = 8: Two three-phase lines in parallel, with equivalent phase conductors no. 7 and 8 ignored in the transformation to symmetrical components.

The matrices are then transformed to three-phase symmetrical components and not to M-phase symmetrical components of Eq. (4.62). For example for M = 6 (double-circuit three-phase line),

[S] = [A]

$$[Z'_{symm}] = \begin{bmatrix} [S]^{-1} & 0 \\ 0 & [S]^{-1} \end{bmatrix} \begin{bmatrix} Z'_{phase} \end{bmatrix} \begin{bmatrix} [S] & 0 \\ 0 & [S] \end{bmatrix} \tag{4.70}$$

with [S] defined by Eq. (4.68), Eq. (4.70) produces the three-phase symmetrical component values required in Eq. (4.67).

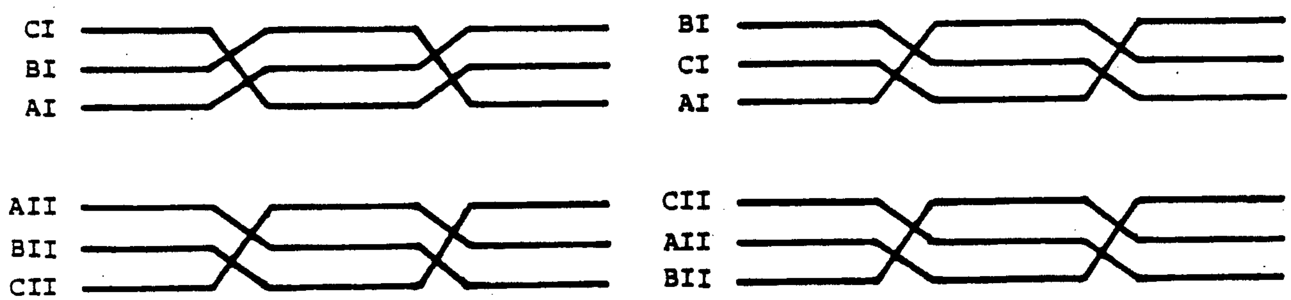
Balancing of double-circuit three-phase lines through transpositions never completely diagonalizes the respective symmetrical component matrices. The best that can be achieved is with the seldom-used transposition scheme of Fig. 4.22, which leads to

ckt 1   ZM

$$[Z'_{symm}] = \begin{bmatrix} Z'_{zero-I} & 0 & 0 & Z_{zero-coupling} & 0 & 0 \\ 0 & Z'_{pos-I} & 0 & 0 & 0 & 0 \\ 0 & 0 & Z'_{pos-I} & 0 & 0 & 0 \\ Z_{zero-coupling} & 0 & 0 & Z'_{zero-II} & 0 & 0 \\ 0 & 0 & 0 & 0 & Z'_{pos-II} & 0 \\ 0 & 0 & 0 & 0 & 0 & Z'_{pos-II} \end{bmatrix} \tag{4.71}$$

ckt 2

If both circuits are identical, then $Z'_{zero-I} = Z'_{zero-II} = Z'_{zero}$, and $Z'_{pos-I} = Z'_{pos-II} = Z'_{pos}$; in that case, the transformation matrix of Eq. (4.65) can be used for diagonalization. The more common transposition scheme of Fig. 4.23 produces positive and zero sequence coupling between the two circuits



(a) barrels rolled in opposite direction

(b) barrels rolled in same direction.

Fig. 4.23 - Double-circuit transposition scheme

as well, with the nonzero pattern of the matrix in Eq. (4.71) changing to

$$\left[\begin{array}{ccc|ccc} X & 0 & 0 & X & 0 & 0 \\ 0 & X & 0 & 0 & X & 0 \\ 0 & 0 & X & 0 & 0 & X \\ \hline X & 0 & 0 & X & 0 & 0 \\ 0 & X & 0 & 0 & X & 0 \\ 0 & 0 & X & 0 & 0 & X \end{array}\right]$$

where "X" indicates nonzero terms. Re-assigning the phases in Fig. 4.23(b) to CI, BI, AI, AII, BII, CII from top to bottom would change the matrix further to cross-couplings between positive sequence of one circuit and negative sequence of the other circuit, and vice versa,

$$\begin{bmatrix} Z'_s & Z'_m & Z'_m & Z'_p & Z'_p & Z'_p \\ Z'_m & Z'_s & Z'_m & Z'_p & Z'_p & Z'_p \\ Z'_m & Z'_m & Z'_s & Z'_p & Z'_p & Z'_p \\ Z'_p & Z'_p & Z'_p & Z'_s & Z'_m & Z'_m \\ Z'_p & Z'_p & Z'_p & Z'_m & Z'_s & Z'_m \\ Z'_p & Z'_p & Z'_p & Z'_m & Z'_m & Z'_s \end{bmatrix} \qquad (4.64)$$

The transposition scheme of Fig. 4.22 would produce such a matrix form, which implies that the two circuits are only coupled in zero sequence, but not in positive or negative sequence. Such a complicated transposition scheme is seldom, if ever, used, but the writer suspects that positive and negative sequence couplings in the more common double-circuit transposition scheme of Fig. 4.23 is often so weak that the model discussed here may be a useful approximation for the case of Fig. 4.23 as well.

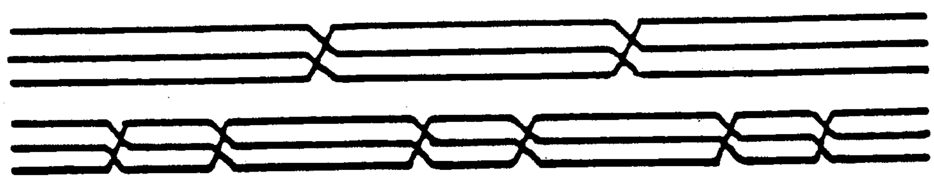


Fig. 4.22 - Double-circuit transposition scheme with zero sequence coupling only

The matrix of Eq. (4.64) is diagonalized by modifying the transformation matrix of Eq. (4.58) to

$$[T] = \frac{1}{\sqrt{6}} \begin{bmatrix} 1 & 1 & \sqrt{3} & 1 & 0 & 0 \\ 1 & 1 & -\sqrt{3} & 1 & 0 & 0 \\ 1 & 1 & 0 & -2 & 0 & 0 \\ 1 & -1 & 0 & 0 & \sqrt{3} & 1 \\ 1 & -1 & 0 & 0 & -\sqrt{3} & 1 \\ 1 & -1 & 0 & 0 & 0 & -2 \end{bmatrix} \qquad (4.65)$$

PES - Wtr. Mtg. Jan '01

Parameters for Modeling Transmission Lines and Transformers in Transient Simulations

Summary

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Michigan Technological University

Most investigations of power system transient behaviors are performed using computer simulation packages like the Electromagnetic Transients Program (EMTP). Scale modeling using Transient Network Analyzers (TNA) is still done, but decreasingly so as computer simulation models for system components are gradually improved.

Engineers and researchers who perform transient simulations typically spend only a small amount of their total project time actually running the simulations. The bulk of their time is spent

- Constructing the overall system model,
- Obtaining parameters for component models,
- Benchmarking the components models to confirm proper behaviors, and
- Benchmarking the overall system model to verify overall behavior.

Only after the component models and the overall system model have been verified can one confidently proceed to run meaningful simulations. Even then, if there are some transient event records to compare against, more model benchmarking and adjustment may be required.

Here, we present recommendations on how to obtain the parameters needed to model overhead transmission lines and transformers, the two most prevalent components of a power system. The reader is directed to references [1,2,3] for background on the overall development of transient simulation models and the simulation of transients.

Transmission Line Models

Appropriateness of line model depends on the line length and the highest frequency to be simulated. For "short" or "medium" transmission lines, a simple lumped coupled-π model, or several in series, may suffice [2 – Ch.11].

For longer lines or higher frequencies, distributed parameter behaviors must be included. Development of presently used transient transmission line models for this case are based on the "traveling wave model" presented in many textbooks [2 - Ch.9]. For multi-conductor overhead transmission lines, the basic equations are

$$-\frac{\partial v}{\partial x} = Z\,i \qquad \text{and} \qquad -\frac{\partial i}{\partial x} = Y\,v \ ,$$

where v and i are the vectors of node voltages and line currents at a distance x along the multiple conductor transmission line. Z is the matrix of coupled series impedances of the conductors for an incremental length, and Y is the matrix of coupled shunt admittances for that same length. Details of solution are given in [2] and in references [4,5,6,7,8]. Convolution methods are used to convert the frequency-domain solution to a time-domain equivalent that can be implemented in time-domain simulation programs like EMTP.

Errors in this approach are due to the fact that the solution is only valid for the frequency that the model was developed [4,5]. Improvements have been made by applying frequency-dependent weighting functions to the convolution [6,7], by developing improved frequency fitting techniques, and by developing the model directly in the phase domain and thus avoiding modal transformation [8]. In any case, it is desirable to confirm that the line model being implemented is valid within the range of frequencies to be simulated

Transmission Line Parameters

Since transient studies evolved after load flow, short circuit, and stability studies, existing databases of transmission line parameters may consist only of synchronous frequency (50- or 60-Hz) line impedances. Short-circuit line data is often just the positive, negative, zero, and series mutual impedance. Load flow line databases might contain only a per-phase positive sequence π-representation. In all cases, line data is stored only as impedances.

In order to develop line models for transient simulations, however, the ***physical*** line parameters must be available. For example,

- (x,y) coordinate, each conductor and shield wire,
- Bundle spacings,

- Phase designation of each conductor,
- Phase rotation at transposition structures,
- Physical dimensions of each conductor, and
- Earth resistivity of the ground return path.

All transient simulation packages have a so-called "line constants" utility or interface. Users of the software enter the line's physical parameters into the line constants utility, select the type of line model desired, and the model is created. *Since all models are developed from physical transmission line parameters, it is highly recommended that a database of physical line parameters be created.*

Example Cases

Two example cases will be presented: one single-circuit line and one double-circuit line. A detailed discussion will be made. Points covered will be

- Proper input of physical parameters,
- Examination of line constants output,
- Benchmarking impedances Z_0, Z_1, Z_2, and Z_M,
- Benchmarking for frequency response, and
- Application considerations.

Transformer Models

Unlike transmission lines, the physical construction details of transformers are not typically known. Many variations on core and coil construction are possible. Key physical attributes whose behavior, depending on frequency, may need to be correctly represented by the model are:

- Core configuration (core-form, shell-form, etc),
- Coil configuration,
- Capacitive effects of coils,
- Self- and mutual inductances along each coil,
- Leakage flux,
- Skin effect and proximity effect in coils,
- Magnetic core saturation, and
- Hysteresis and eddy current losses in core.

Transformer models generally available in EMTP-like programs are suitable for low frequency behaviors, such as short circuits at synchronous frequency. By adding a saturable core representation, excitation and inrush might be simulated. By adding capacitive coupling between coils, ferroresonance and higher frequency situations like switching can be simulated. Fast-front transients like lightning require a very detailed model that is usually not standardly available.

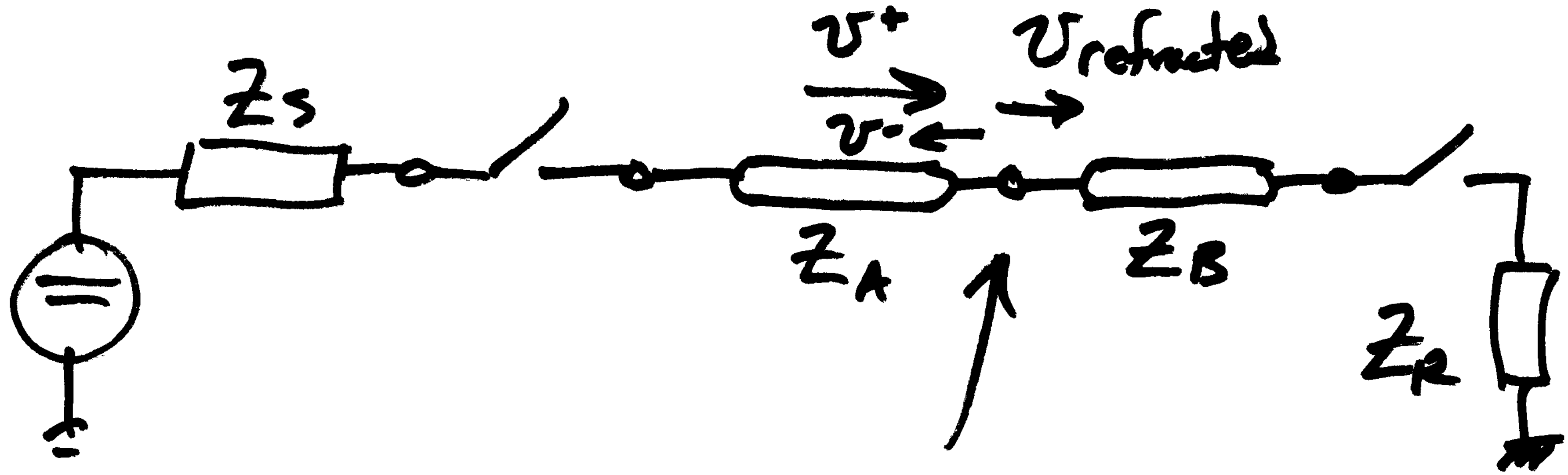
Example Cases

Two of the most frequently used models in EMTP are the multi-winding saturable transformer which can be used to implement duality-derived models [9], and the so-called BCTRAN model [10]. Parameters for both models are electrical, not physical. Example cases using both models will be presented and examined in detail.

BCTRAN is attractive to use since it has a preprocessor which converts nameplate and factory test data directly into a model. The model created represents the short-circuit impedances of all coils including mutual inductive coupling. A linearized core representation may be included in the model, or a saturable core equivalent may be attached externally at the terminals of the model.

References

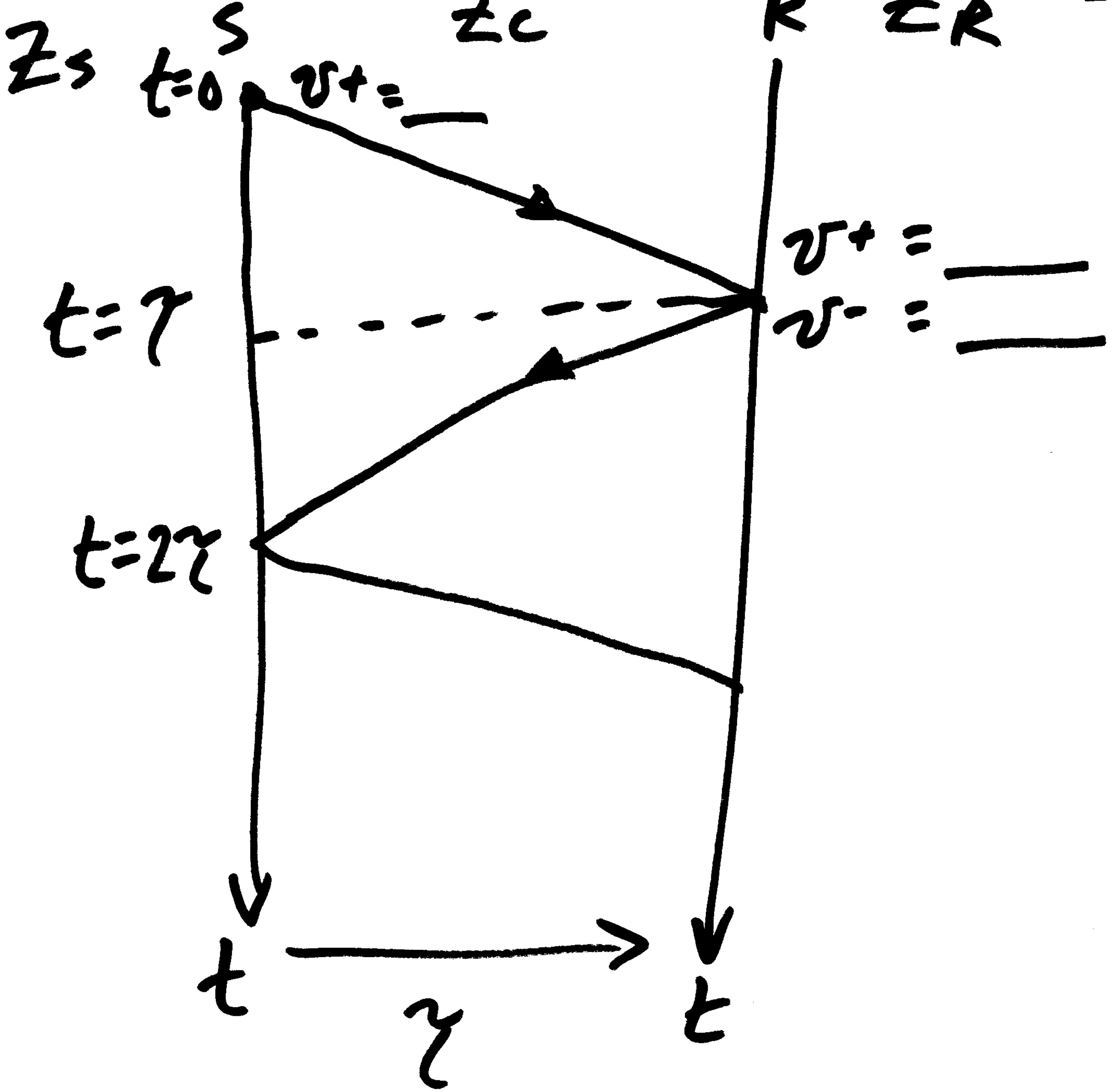
[1] Modeling and Analysis of Power System Transients Using Digital Programs, IEEE Special Publication TP-133-0, IEEE Catalog No. 99TP133-0, 1999.
[2] H.W. Dommel, *EMTP Theory Book*, Microtran Power System Analysis Corporation, Vancouver, BC, May 1992.
[3] A. Greenwood, *Electrical Transients in Power Systems*, 2nd Edition, John Wiley & Sons, Inc., ©1991.
[4] J.K. Snelson, "Propagation of Travelling Waves on Transmission Lines – Frequency Dependent Parameters," IEEE Trans. PAS, Vol. 91, pp. 85-91, 1973.
[5] W.S. Meyer and H.W. Dommel, "Numerical Modeling of Frequency-Dependent Transmission Line Parameters in an Electromagnetic Transients Program," IEEE Trans. PAS, Vol. PAS-93, pp. 1401-1409, 1974.
[6] A. Semlyen and A. Dabuleanu, "Fast and Accurate Switching Transient Calculations on Transmission Lines with Ground Return Using Recursive Convolutions," IEEE Trans. PAS, Vol. PAS-94, pp. 561-571, 1975.
[7] J.R. Marti, "Accurate Modeling of Frequency-Dependent Transmission Lines in Electromagnetic Transient Simulations," Power Industry Computer Applications, pp. 326-334, 1981.
[8] T. Noda, N. Nagaoka, A. Ametani, "Phase Domain Modeling of Frequency-Dependent Transmission Lines by Means of an ARMA Model," IEEE Trans. Power Delivery, Vol. 11, No. 1, January 1996.
[9] G.R. Slemon, "Equivalent Circuits for Transformers and Machines Including Non-Linear Effects," Proc. IEE, Vol. 100, part IV, pp. 129-143, 1953.
[10] V. Brandwajn, H.W. Dommel, I.I. Dommel, "Matrix Representation of Three-Phase N-Winding Transformers for Steady-State and Transient Studies," IEEE Trans. PAS, Vol. PAS-101, No. 6, pp. 1369-1378, June 1982.

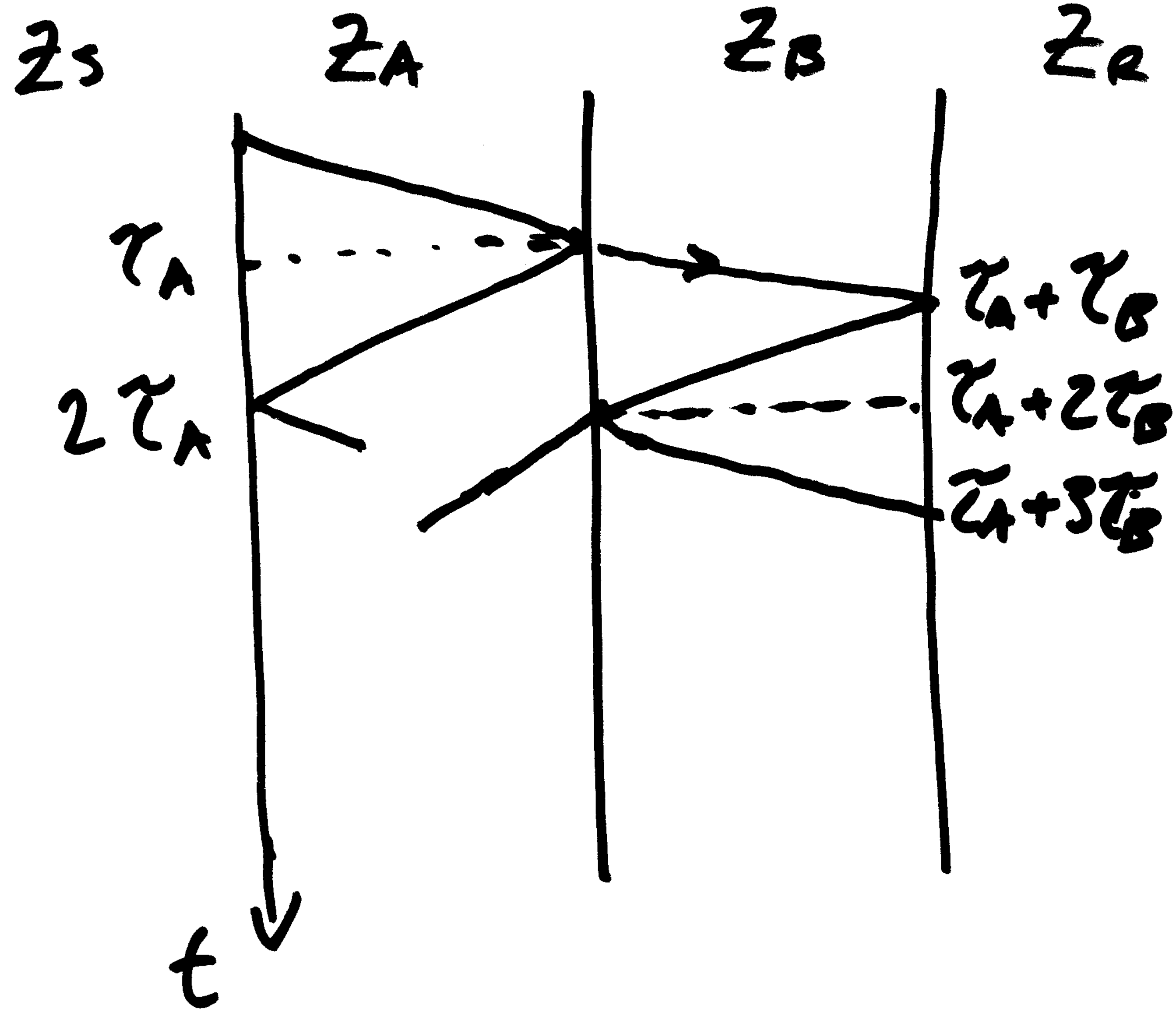


p.250

$$\begin{cases} a = \rho_R = \dfrac{Z_B - Z_A}{Z_B + Z_A} & \text{reflection coefficient} \\ b = \dfrac{2 Z_B}{Z_B + Z_A} & \text{refraction coefficient} \end{cases}$$

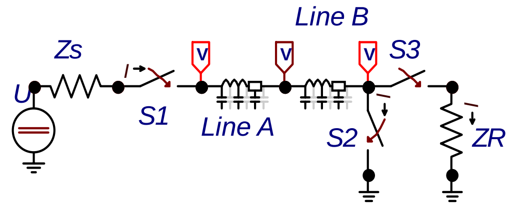
Fig. 9.16 - Lattice Diagram - Bounce Diags - Bewelay Diags.

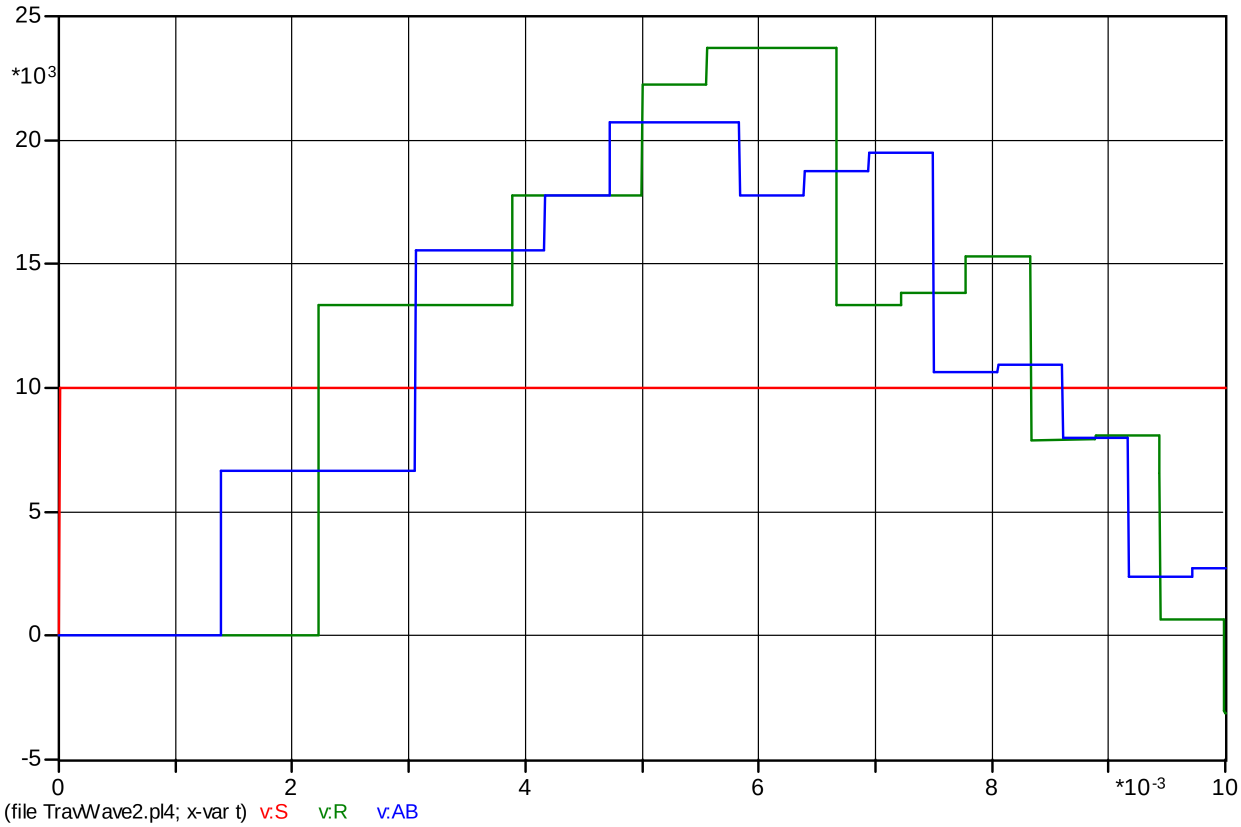



Z_S
Z_A
Z_B
Z_R
τ_A
$2\tau_A$
$\tau_A + \tau_B$
$\tau_A + 2\tau_B$
$\tau_A + 3\tau_B$
t

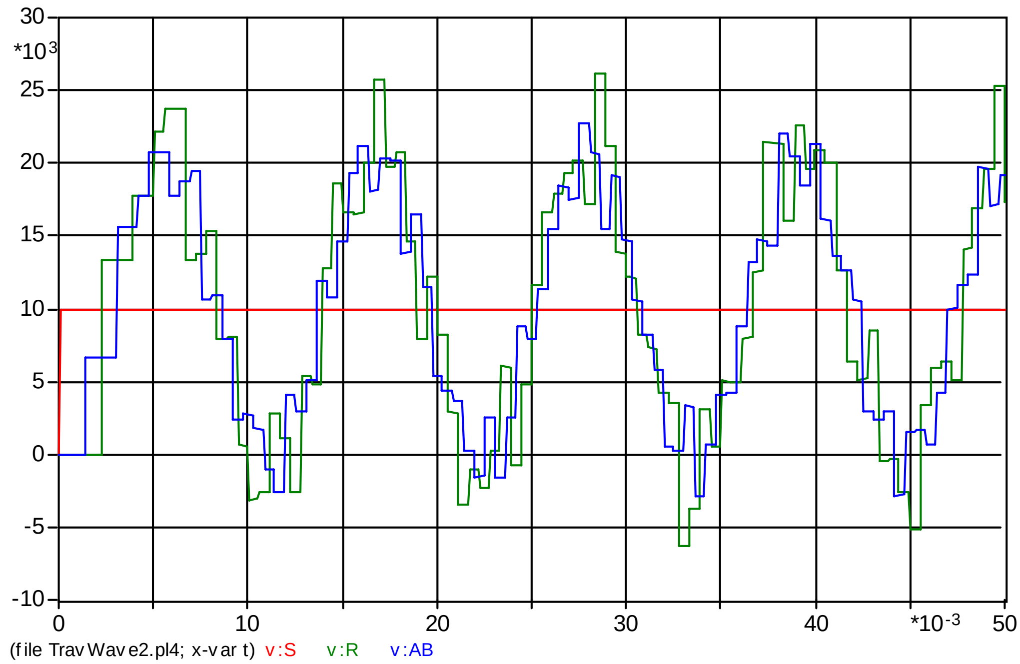
TravWave2.acp

Both lines lossless.
Line A: L’ = 0.6; C’ = 7.3; 250 mi
Line B: L’ = 0.3; C’= 14.6; 150 mi

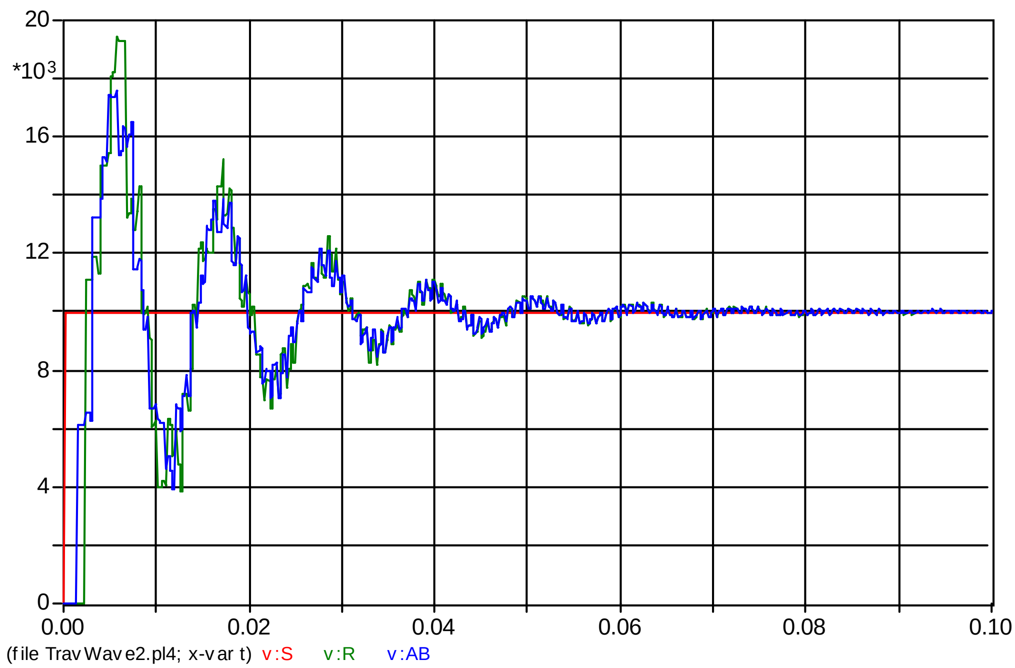




Lossless, as above, simulation out to .05 s. Receiving end never reaches steady-state 10 kV.



Losses added, R/l = 0.2 for both lines, simulation out to 0.1 s. Receiving end settles to 10 kV.

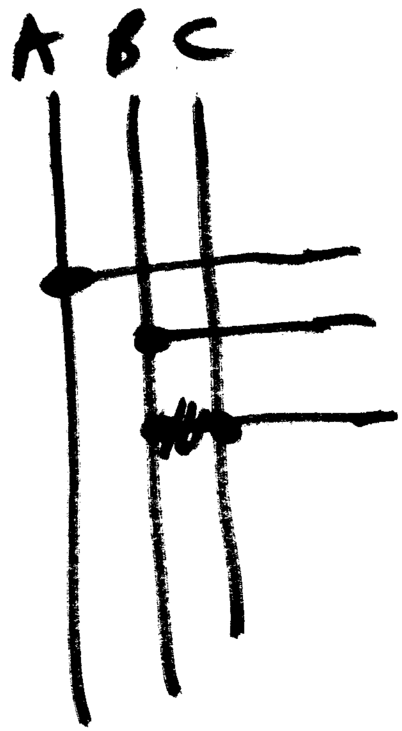


6-pulse
- 5th & 7th

12-pulse
- 11th & 13th

Objective:

Determine if harmonics may cause a problem on AC system



$\Leftarrow Z_{IN}(f)$?

ex: 6-pulse
5th & 7th harmonics

- Creates and runs an ATP frequency scan simulation to determine the open-circuit frequency response.

What is a "Frequency Scan?"

$$\bar{Z}(\omega) = \frac{\tilde{V}(\omega)}{\tilde{I}(\omega)}$$

FREQ SCAN

$f_{min} \rightarrow f_{max}$

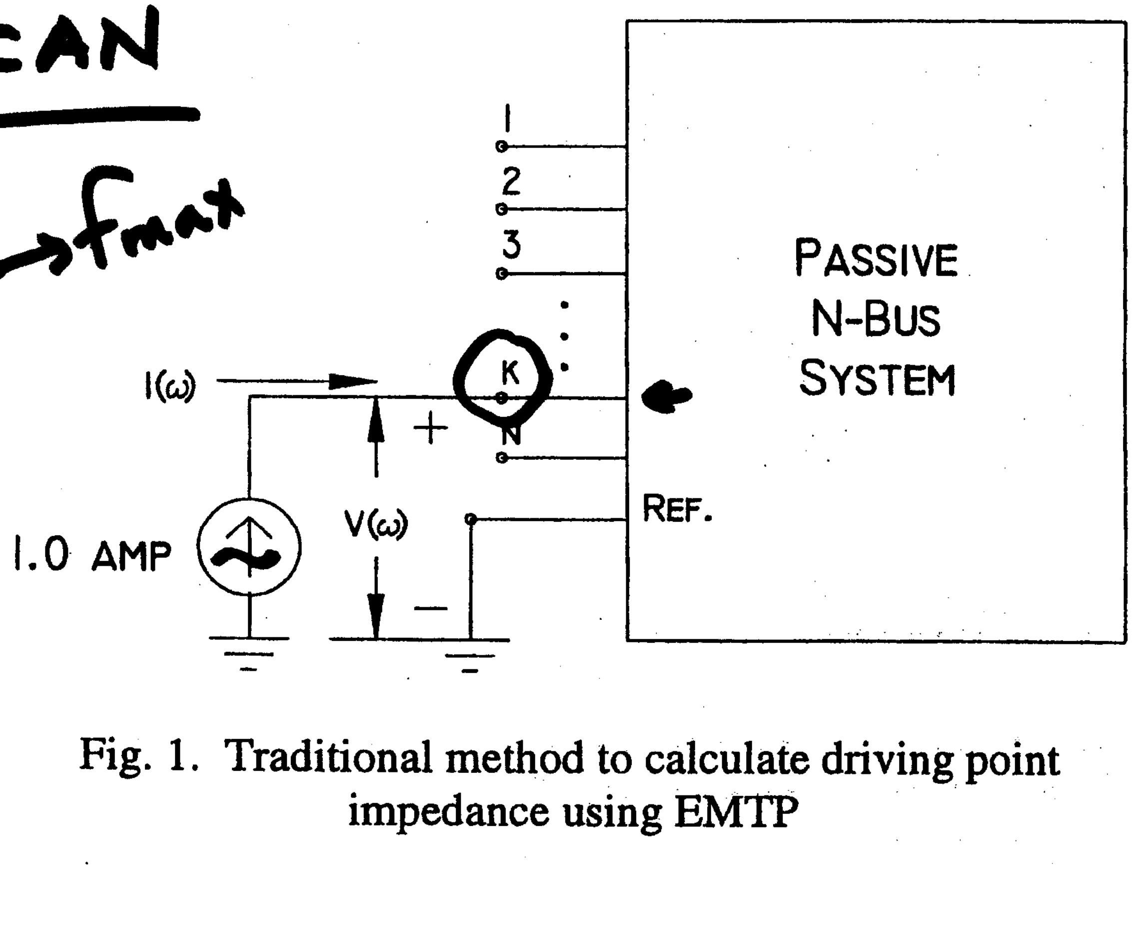
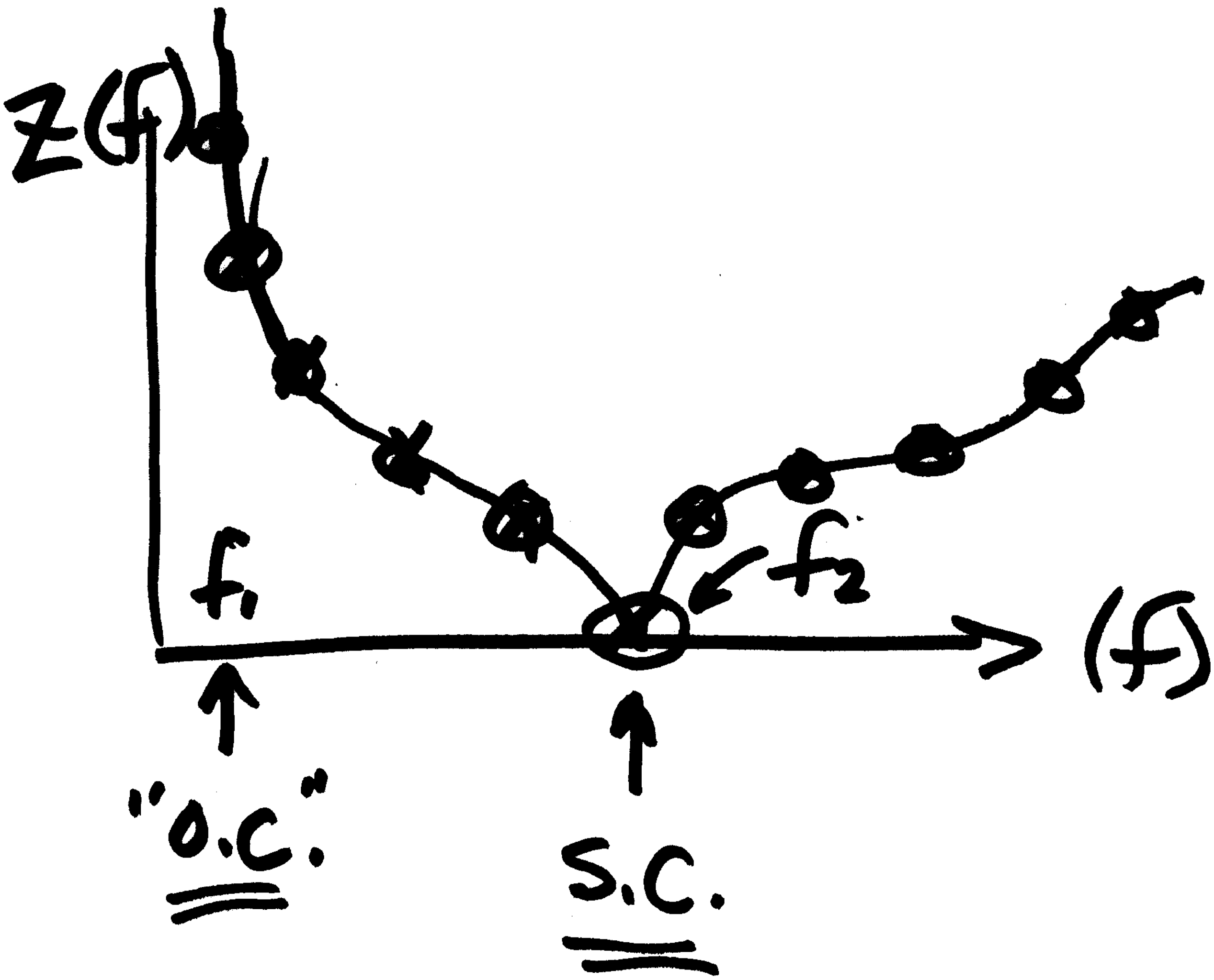


Fig. 1. Traditional method to calculate driving point impedance using EMTP

Procedure -

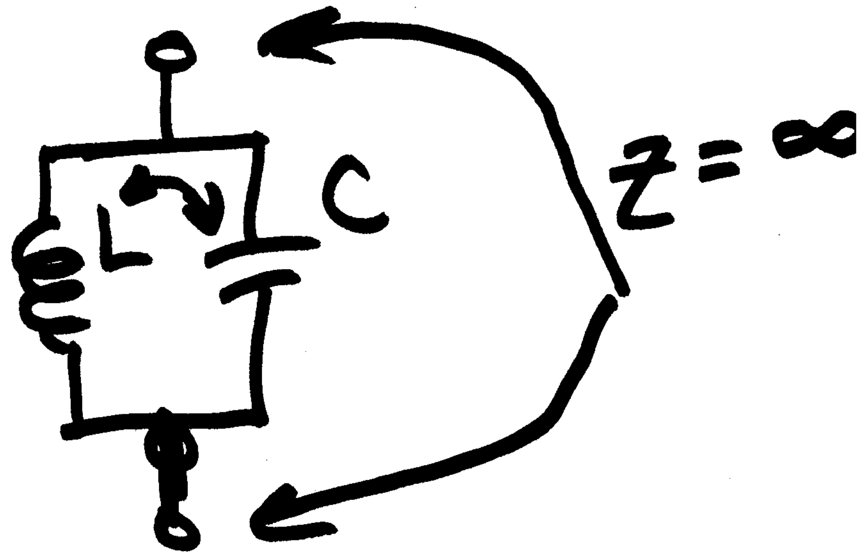
- Inject 1 amp peak
- Repeat at discrete values of f.

$$\bar{Z}_K(f) = \frac{\tilde{V}(f)_K}{\bar{I}(f)_K} = V(f)_K$$



at f_1 – o.c.

"parallel resonant"



$$f_1 = \frac{1}{2\pi\sqrt{LC}}$$

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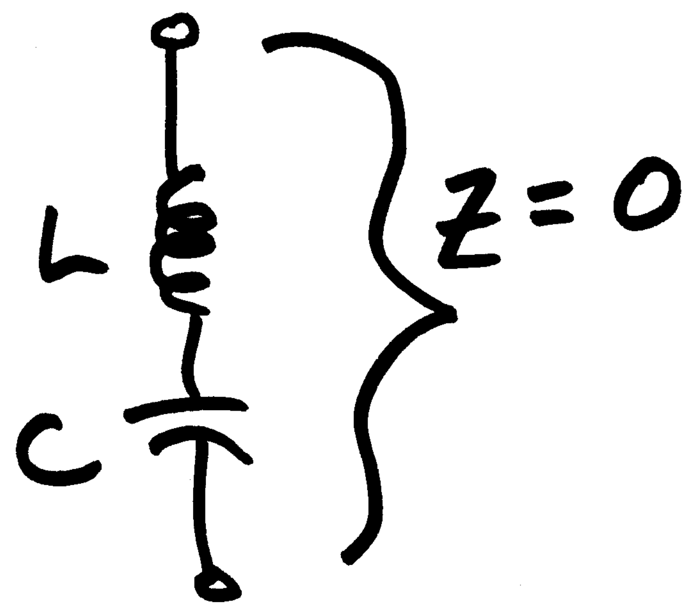
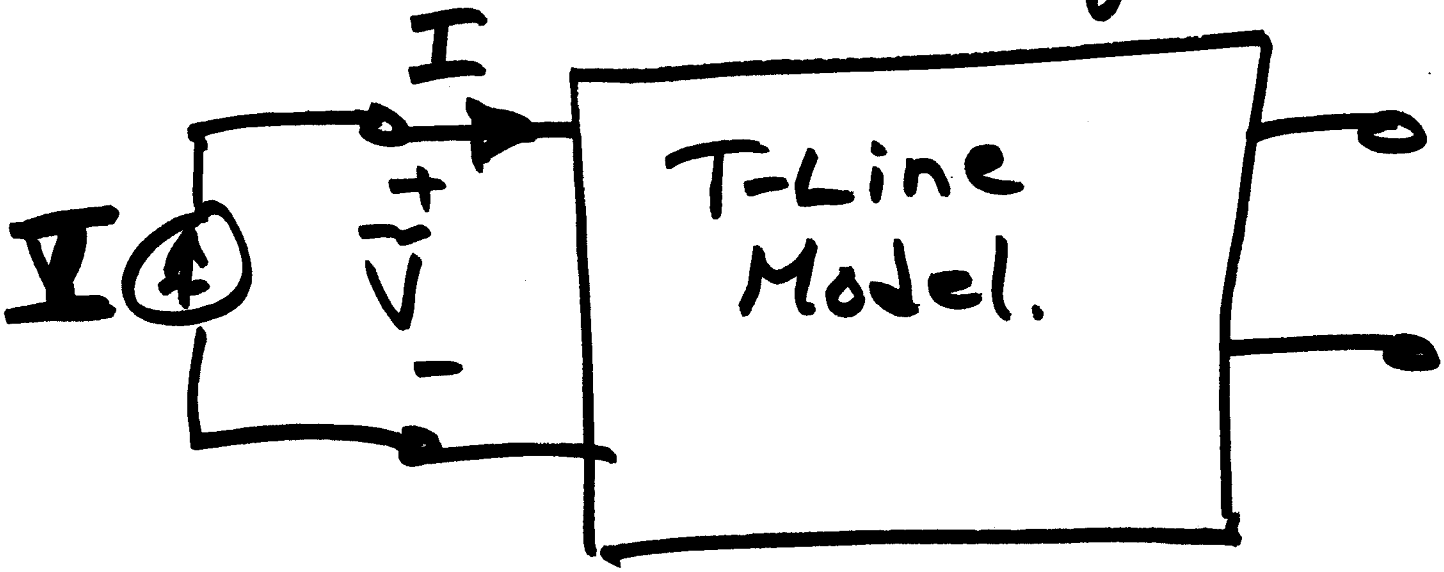
at f_2 – s.c

"series resonant"



$$f_2 = \frac{1}{2\pi\sqrt{LC}}$$

For T-Line Verification, we can also use freq. scan.



Check complete range of frequency.

- POS SEQ, Ph. 1, 2, 3 ... N
- ~~NEG~~ ZERO SEQ, Ph. 1, 2, 3 ... N

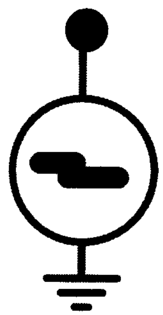
In-Class Demo

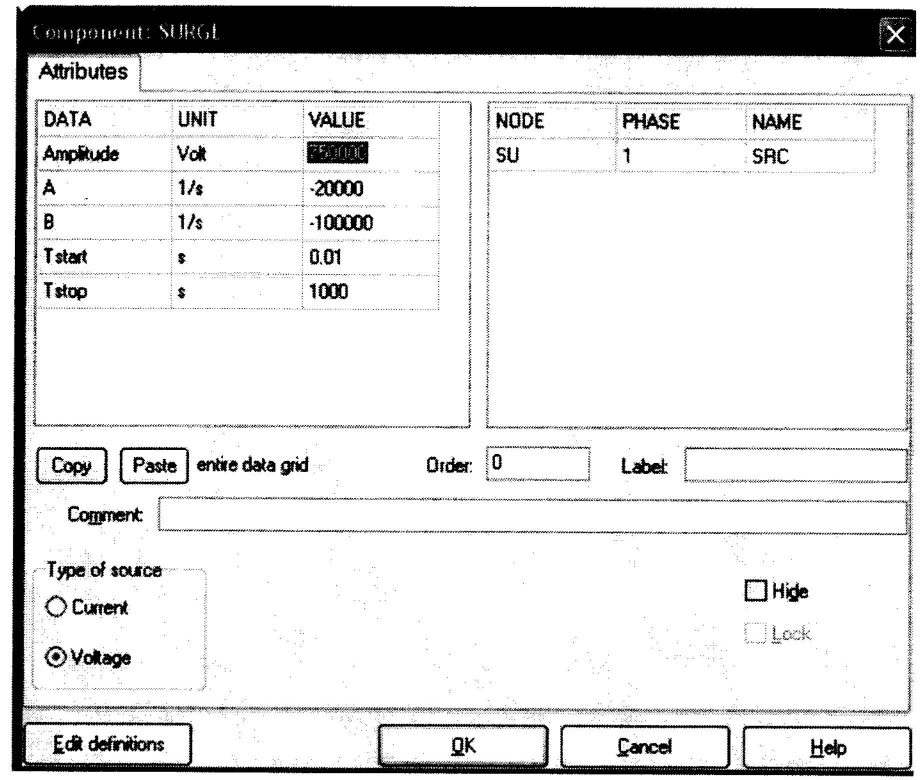
- Bergeron – Const. Z_c
- Marti – $Z_c(f)$
- Lumped Coupled Pi –

Prob 9.2 – "double-exponential" (10)

$$v(t) = 750\left(e^{-2\times10^{4}t} - e^{-10^{5}t}\right)\ \text{kV}.$$

Type 15
"Surge"

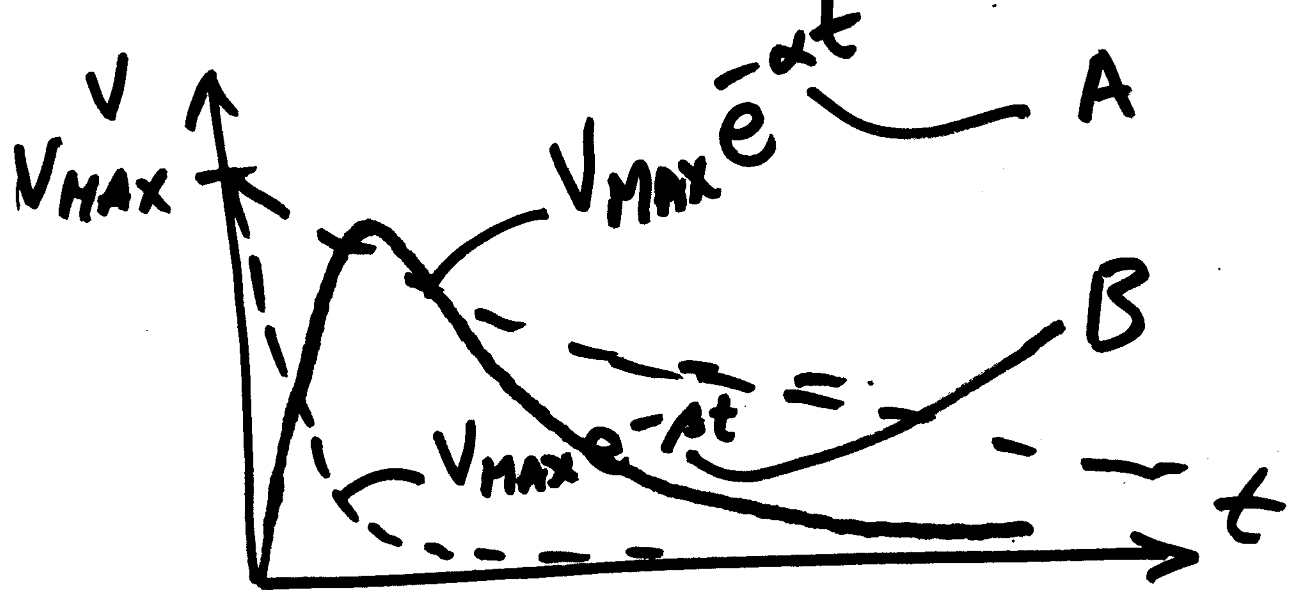




Name : SURGE - Surge function. Two exponentials. TYPE 15.
Card : SOURCE
Data : U/I= 0: Voltage source.
-1: Current source.
Amp= Constant in [A] or [V].
Does not exactly correspond to the peak value of surge.
A= Negative number specifying falling slope.
B= Negative number specifying rising slope.
Tsta= Starting time in [sec.]. Source value zero for T<Tsta.
Tsto= Ending time in [sec]. Source value zero for T>Tsto.
Node : SU= Positive node of exponential surge function.
Negative node is grounded.
SU=Amp*(exp(A*t)-exp(B*t))
RuleBook: VII.C.5

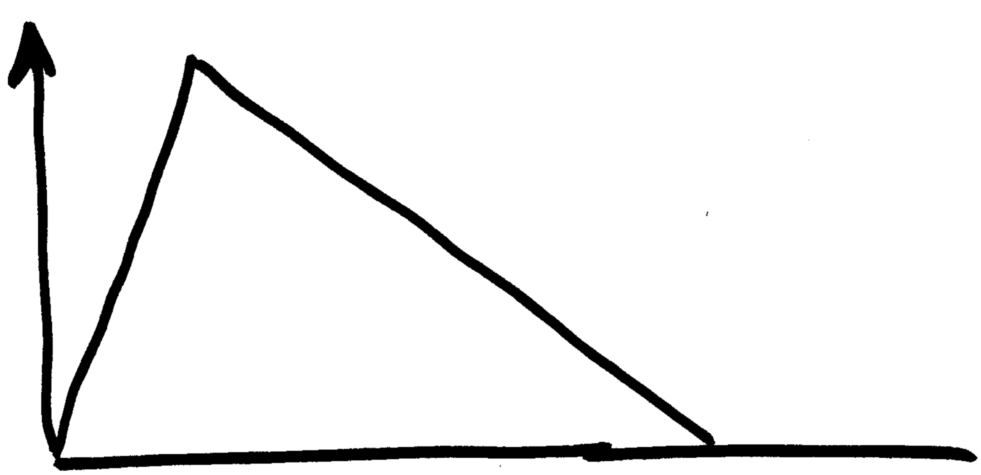
Waveshapes:

- "Double Exponential"

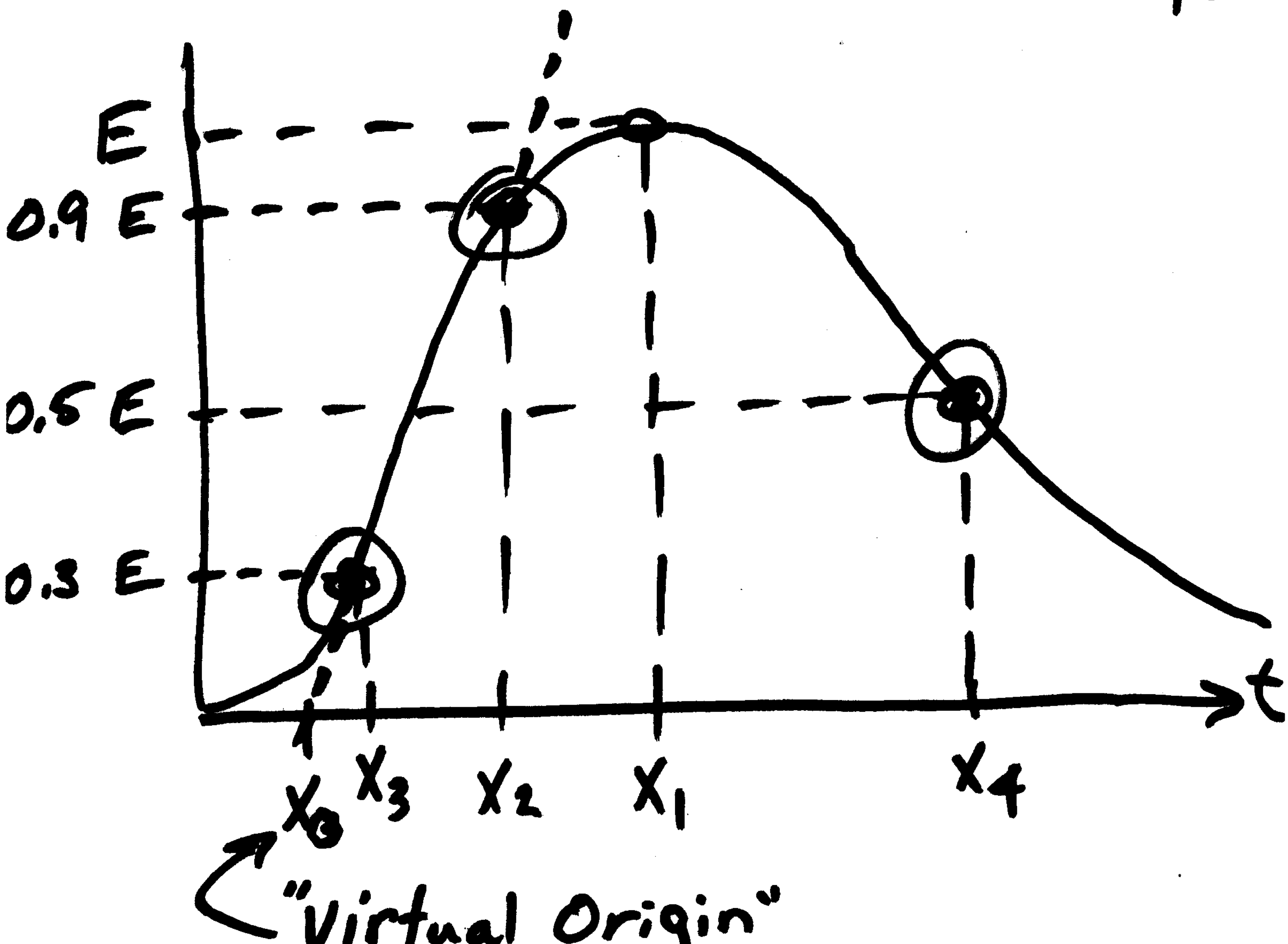


Difference: $v(t) = V_{MAX}(e^{-\alpha t} - e^{-\beta t})$

CRUDE APPROX:



Actual Lightning or Switching Surges:



Standard Reference:

"$t_f \times t_t$"

$$t_f = 1.6(X_2 - X_3)$$

$$t_t = (X_4 - X_0)$$

:57.12.90 →

<u>Stds</u>: 1.2×50 μs (Lightning Surges)
5×200 μs (impulse)