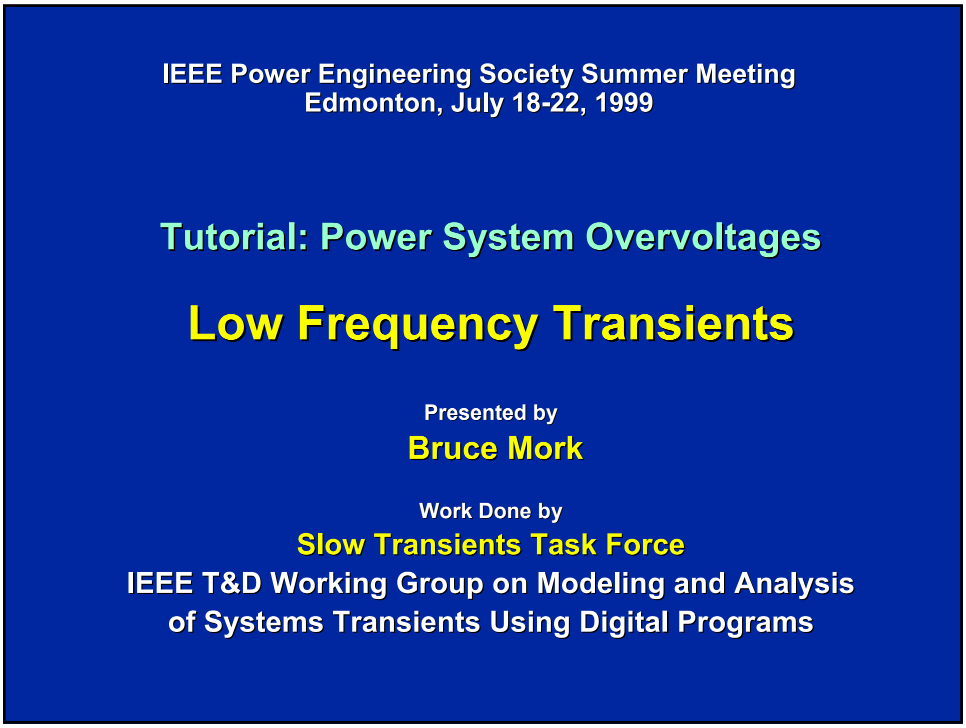


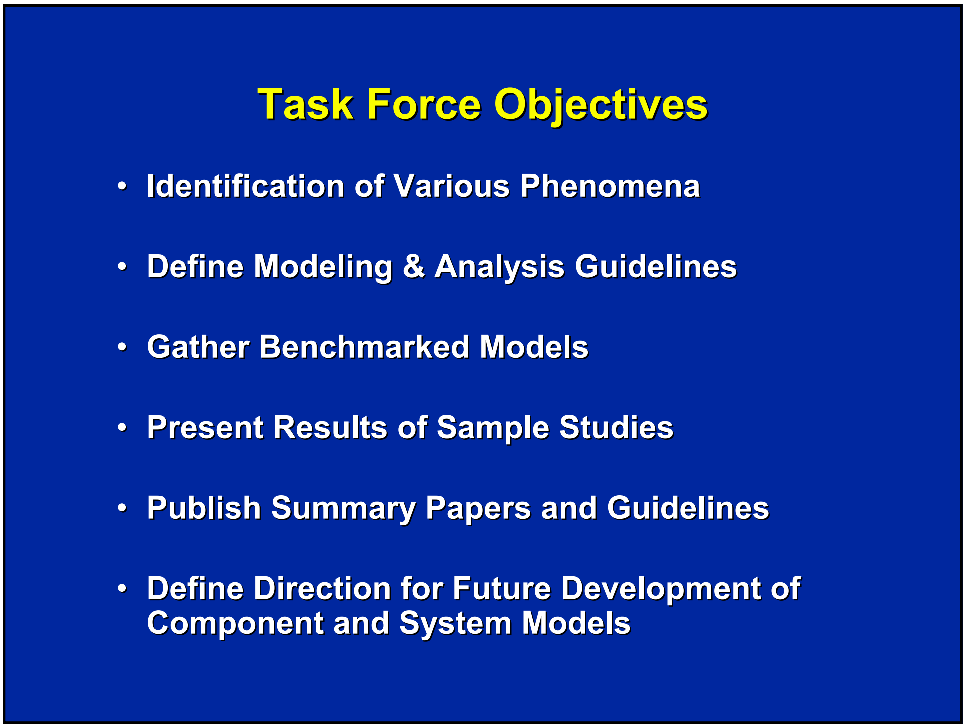
IEEE Power Engineering Society Summer Meeting
Edmonton, July 18-22, 1999

Tutorial: Power System Overvoltages

Low Frequency Transients

Presented by
Bruce Mork

Work Done by
Slow Transients Task Force
IEEE T&D Working Group on Modeling and Analysis
of Systems Transients Using Digital Programs



Task Force Objectives

- Identification of Various Phenomena
- Define Modeling & Analysis Guidelines
- Gather Benchmarked Models
- Present Results of Sample Studies
- Publish Summary Papers and Guidelines
- Define Direction for Future Development of Component and System Models

Task Force Efforts & Results

- Met twice per year, starting at WM 1993
- Three PES Summary Papers Published
- Reports were combined into a special publication:

  Modeling and Analysis of System Transients Using Digital Programs, IEEE Pub. TP-133-0

- Tutorials taught: - 1999 WM, New York City
  - 1999 SM, Edmonton
- Received 1999 PES Working Group Award for Technical Report.

Acknowledgements

- T&D Digital Programs Working Group:
  - **Albert Keri**, Chair
- Overall Slow Transients Task Force Efforts:
  - **Reza Iravani**, Chair
- Key Contributors, Ferroresonance Section:
  - **Bruce Mork**, Michigan Technological University
  - **Atef Morched**, Ontario Hydro
  - **Reigh Walling**, General Electric

Low-Frequency (Slow) Transients “Phenomena”

- Torsional Issues, Rotating Machines (5-120 Hz) p.3-2
- Transient Shaft Torques (5-50 Hz) p.3-2
- Turbine Blade Vibrations (80-250 Hz) p.3-2
- Fast Bus Transfer (up to 1000 Hz) p.3-3
- Controller Interactions (1-35 Hz) p.3-8
- Harmonic Resonances (60-600 Hz) p.3-10
- Ferroresonance (up to 1000-2000 Hz) p.3-12

- Refer to Tables 1 (p. 3 - 4) and Table 2 (omitted)

Torsional Oscillations (5-120 Hz)

Starting on p. 3-2 of Report:

- Series Capacitors (SSR)
- HVDC Converters
- Automatic Voltage Regulators (AVR)
- Power System Stabilizers (PSS)
- Static Var Compensators (SVC)

Transient Torsional Torques (5-50 Hz)

Starting on p. 3-2 of Report:

- Faults
- Switching

Turbine Blade Vibrations (90-250 Hz)

- Large Signal Disturbances
- Usually Rely on Manufacturer’s FEM Model

Fast Bus Transfer (up to 1000 Hz)

- Typically 10-15 Motors
- Understand Individual Motors
- Model must show aggregate behavior
- Benchmarking is strongly recommended
- Run a statistical study

Controller Interactions (1 - 35 Hz)

- SVCs
- HVDC Converter
- Adjustable Series Capacitors
- AVRs
- PSSs

- Interactions between multiple closed-loop controllers in a system.

Harmonic Interactions (60-600 Hz)

- Characteristic harmonics (predictable in frequency domain).
- Noncharacteristic harmonics (due to system nonlinearities).
- HVDC converters are typical example
  - Radio & TV interference
  - 2nd and 3rd Harmonic Instability

Today’s Focus: Ferroresonance

- Introduction to Ferroresonance
  - Single Phase, Three Phase, Nonlinearities

  - Modeling
    - The Study Zone
    - Transformer Models
    - Model Parameters

- Case Studies

- Recommendations

Ferroresonance Basics

- A “Resonance” involving a capacitance in series with a saturable inductance L_M.

- Unpredictable due to nonlinearities.

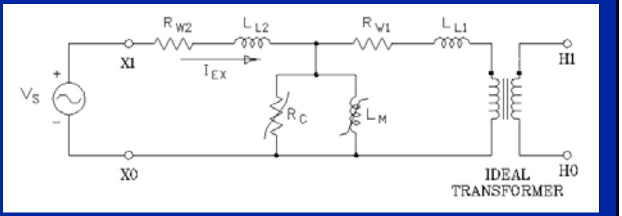
- More likely when little load or damping, and for unbalanced 3-phase excitation

- Examples of capacitances:
  - Series Compensated Lines.
  - Shunt Capacitor Banks.
  - Underground Cable.
  - Systems grounded only via stray capacitance.
  - Grading capacitors on Circuit Breakers.
  - Generator Surge Capacitors.

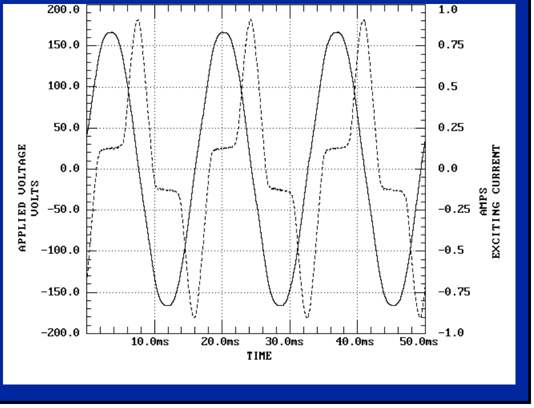
Some Available Literature:

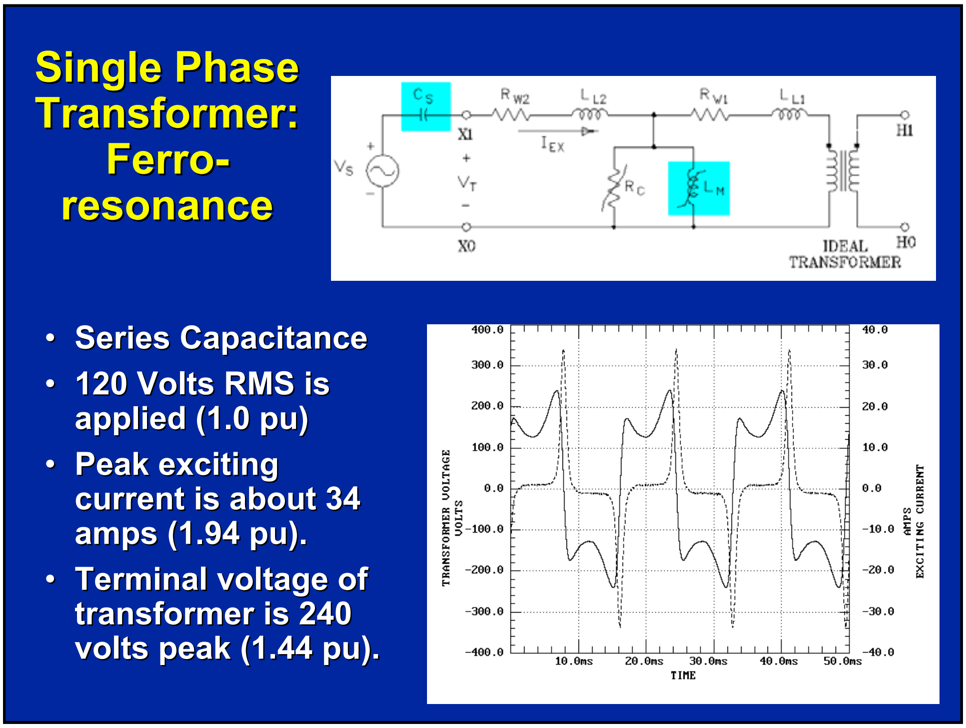
- Be careful! Some (much?) misinformation exists.
- Identified and named in 1907.
- Series Distribution Capacitors - 1930s.
- Rudenberg: Analytical Work in 1940s.
- Hopkinson, Smith: 3-phase systems, 1960-70s.
- Jiles, Frame, Swift: Core Inductances, 70s-80s
- Smith, Stuehm, Mork: Transformer Models.
- Mork, Walling: System Models, 1987-90s.
- Mork, Kieny: Nonlinear Dynamics, 1989-90s.

Single Phase Transformer: Normal Excitation



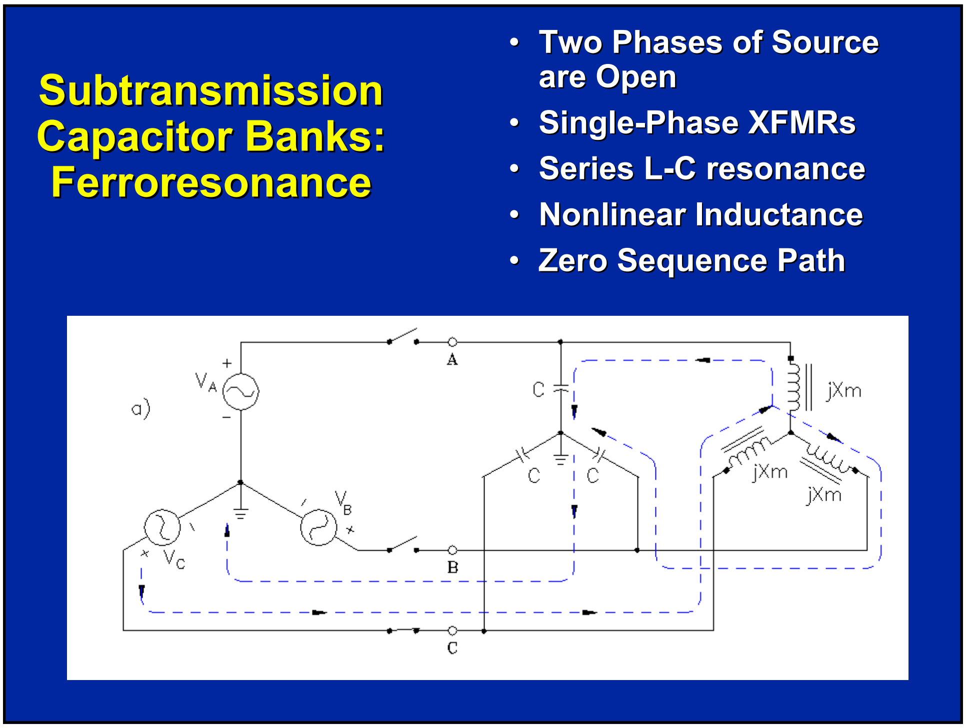
- 120 Volts RMS is applied (1.0 pu)
- Peak exciting current is less than one amp.
- Exciting current distorted due to eddy currents and hysteresis.





Single Phase Transformer: Ferro-resonance

- Series Capacitance
- 120 Volts RMS is applied (1.0 pu)
- Peak exciting current is about 34 amps (1.94 pu).
- Terminal voltage of transformer is 240 volts peak (1.44 pu).

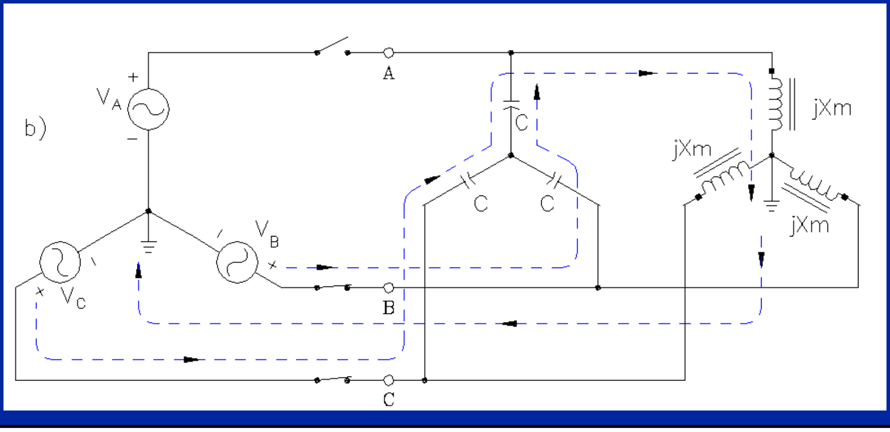


Subtransmission Capacitor Banks: Ferroresonance

- Two Phases of Source are Open
- Single-Phase XFMRs
- Series L-C resonance
- Nonlinear Inductance
- Zero Sequence Path

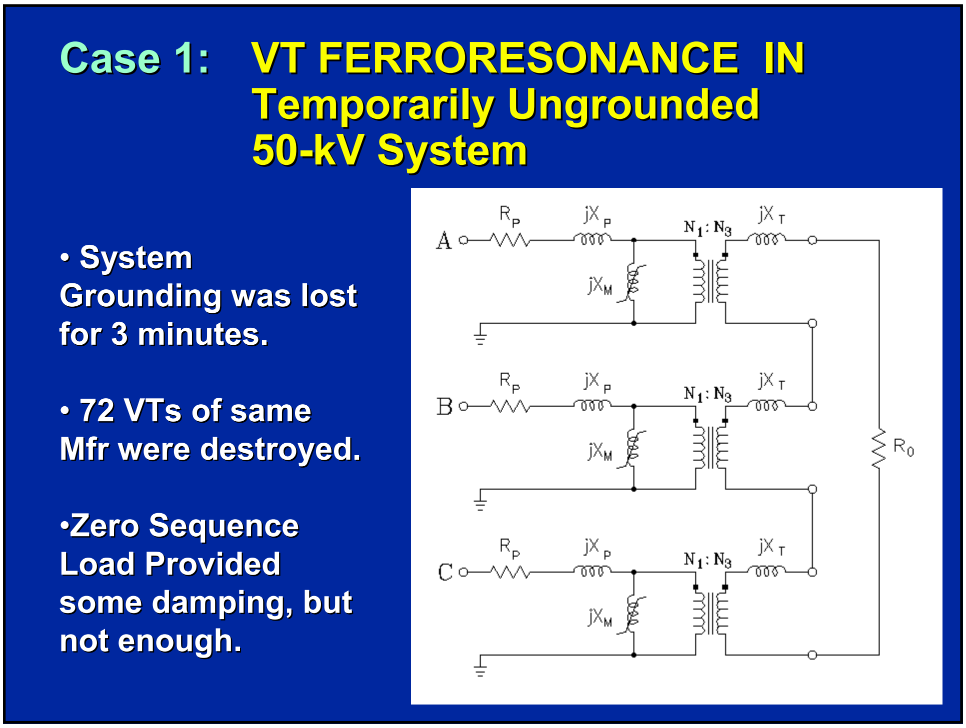
Subtransmission Capacitor Banks: Ferroresonance

- One Phase of Source is Open
- Series L-C resonance
- Nonlinear Inductance
- Zero Sequence Path



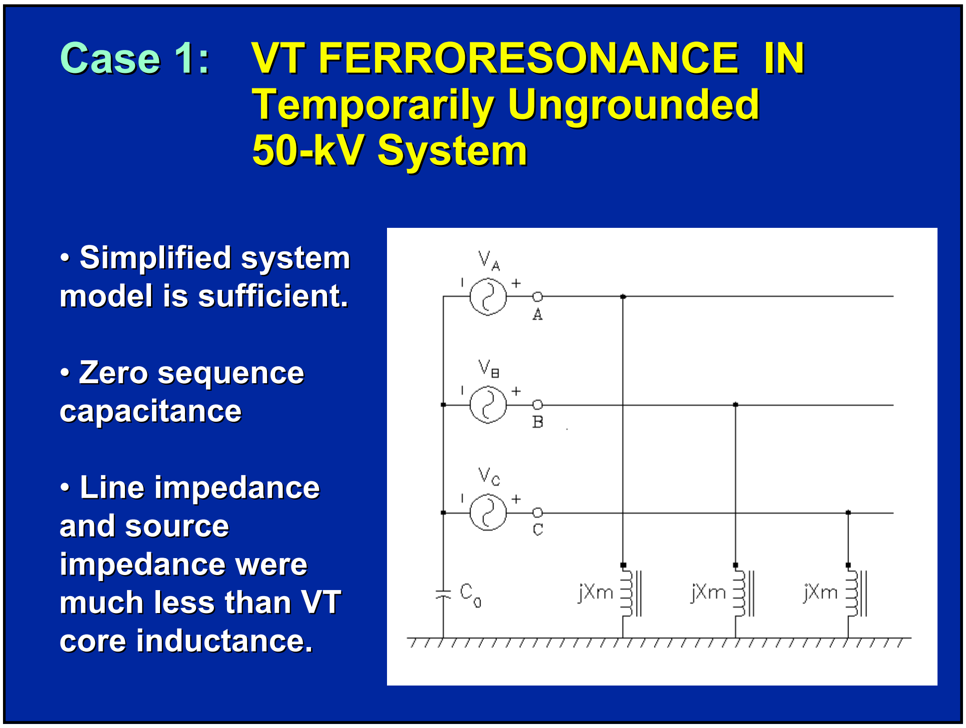
The Study Zone

- Steady-State Thevenin Equivalent
- RLC Coupled-Pi for Lines/Cables. (Cascaded for long lines).
- Shunt and Series Capacitances.
- Stray Capacitances: Interwinding and Winding-Ground.
- Transformer: Must use correct topology, and include core saturation & losses.



Case 1: VT FERRORESONANCE IN Temporarily Ungrounded 50-kV System

- System Grounding was lost for 3 minutes.
- 72 VTs of same Mfr were destroyed.
- Zero Sequence Load Provided some damping, but not enough.

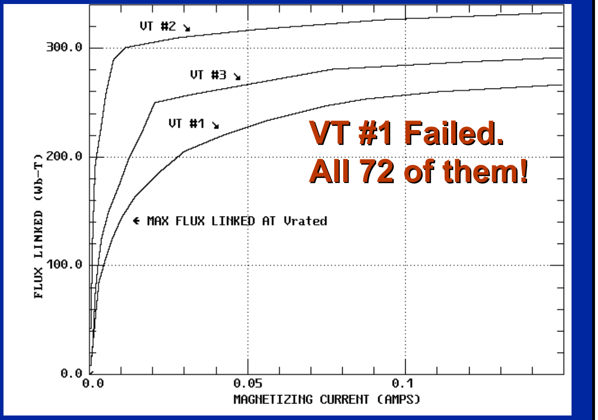


Case 1: VT FERRORESONANCE IN Temporarily Ungrounded 50-kV System

- Simplified system model is sufficient.
- Zero sequence capacitance
- Line impedance and source impedance were much less than VT core inductance.

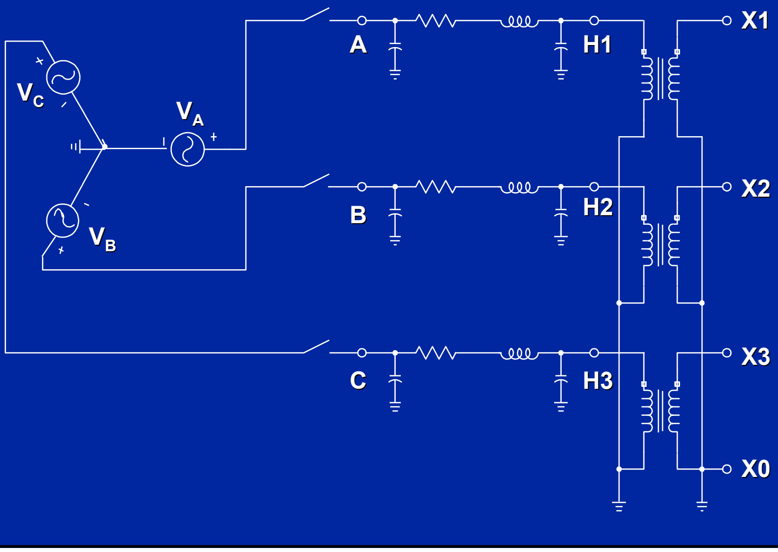
Case 1: VT FERRORESONANCE IN Temporarily Ungrounded 50-kV System

- What made one MFR’s VTs different than the others?
- Same Steady State Performance...
- Much different saturation characteristics !



VT #1 Failed.
All 72 of them!

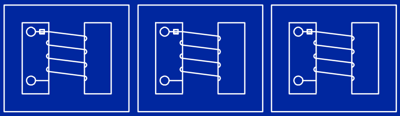
Case 2: FERRORESONANCE IN WYE-CONNECTED SYSTEMS



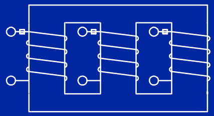
Details of Case #2

- FULL SCALE LABORATORY & FIELD TESTS.
- 5-LEG WOUND CORE, RATED 75-kVA, WINDINGS: 12,470GY/7200 - 480GY/277 (TYPICAL IN 80% OF U.S. SYSTEMS).
- RATED VOLTAGE APPLIED.
- ONE OR TWO PHASES OPEN-CIRCUITED.
- BACKFEED VOLTAGE IN UNENERGIZED PHASES
- CAPACITANCE(S) CONNECTED TO OPEN PHASE(S) TO SIMULATE CABLE.
- VOLTAGE WAVEFORMS ON OPEN PHASE(S) RECORDED AS CAPACITANCE IS VARIED.

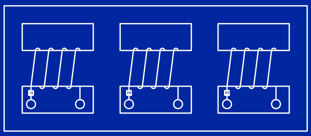
BACKFED VOLTAGE DEPENDS ON CORE CONFIGURATION



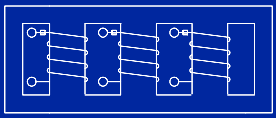
TRIPLEX WOUND OR STACKED



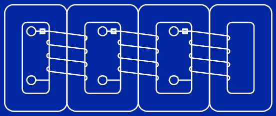
3-LEG STACKED CORE



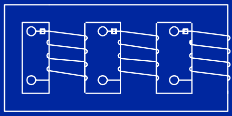
SHELL FORM



5-LEG STACKED CORE



5-LEG WOUND CORE



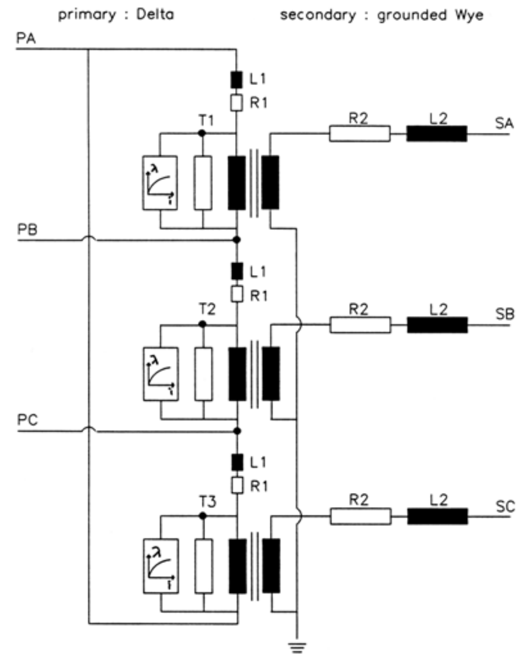
4-LEG STACKED CORE

Don’t Do This!

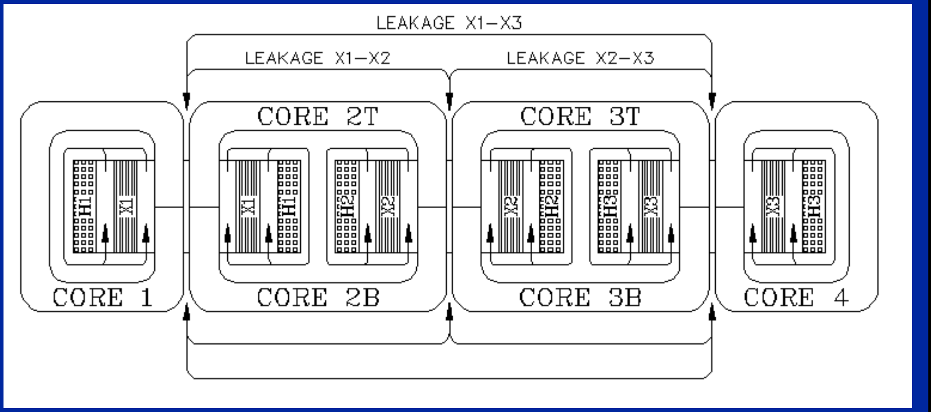
- Basic Delta-Wye Transformer Model as Presented in EMTP Rule Book.

- Composed of three single-phase transformers

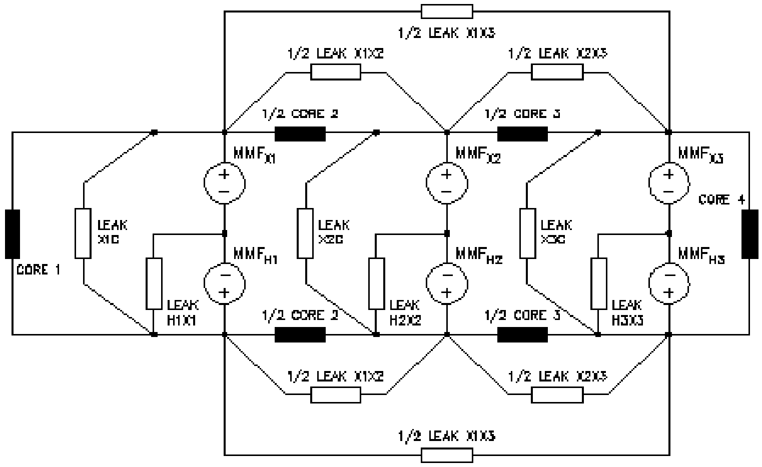
- Phase-to-phase coupling is not included



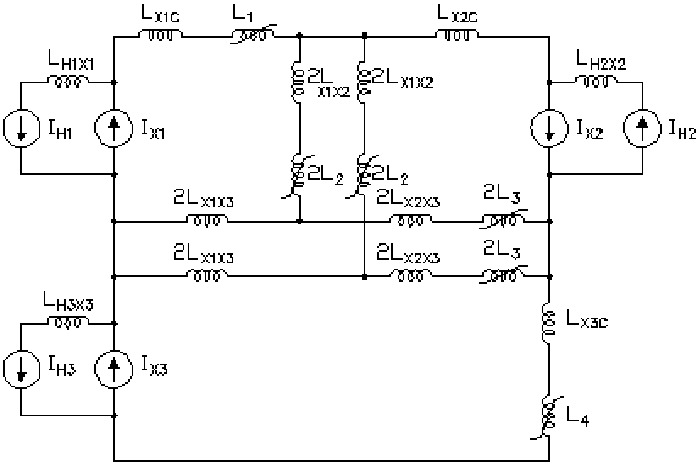
5-Legged Wound-Core Transformer Cross Section with Flux Paths/Tubes



5-Legged Wound-Core Transformer Lumped Magnetic Circuit

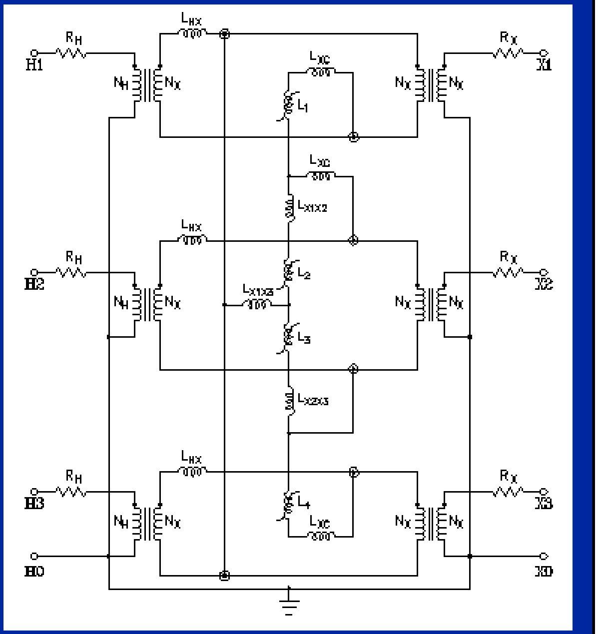


5-Legged Wound-Core Transformer Electrical Dual Equivalent Circuit



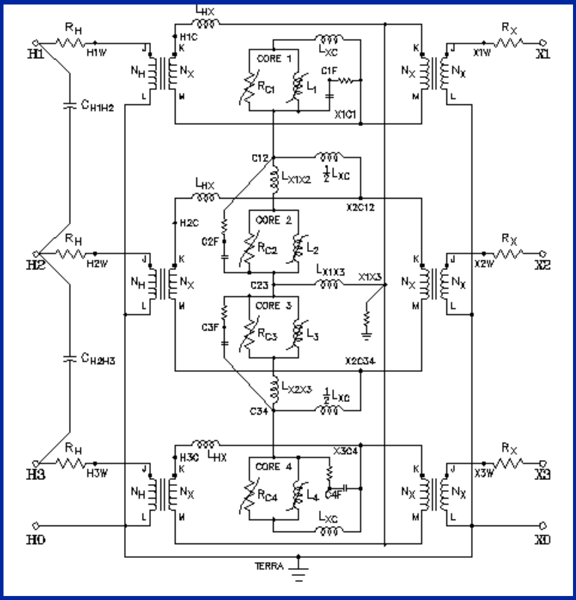
5-LEGGED WOUND-CORE MODEL

- Winding Resistances added
- Current Sources are replaced by ideal coupling transformers



EMTP Model, 5-Legged Wound-Core

- RC Integrators
- Core Losses
- Coupling Capacitors
- Winding Resistance
- Ideal Coupling Isolates Core From Winding Connections



NONLINEAR DYNAMICAL SYSTEMS: BASIC CHARACTERISTICS

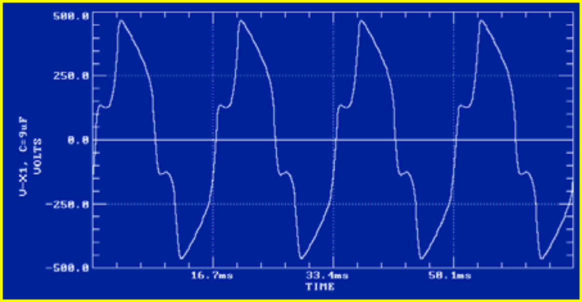
- MULTIPLE MODES OF RESPONSE POSSIBLE FOR IDENTICAL SYSTEM PARAMETERS.
- STEADY STATE RESPONSES MAY BE OF DIFFERENT PERIOD THAN FORCING FUNCTION, OR NONPERIODIC (**CHAOTIC**).
- STEADY STATE RESPONSE MAY BE EXTREMELY **SENSITIVE TO INITIAL CONDITIONS** OR PERTURBATIONS .
- BEHAVIORS CANNOT PROPERLY BE PREDICTED BY LINEARIZED OR REDUCED ORDER MODELS.
- THEORY MATURED IN LATE 70s, EARLY 80s.
- PRACTICAL APPLICATIONS FROM LATE 80s.

VOLTAGE X1-X0

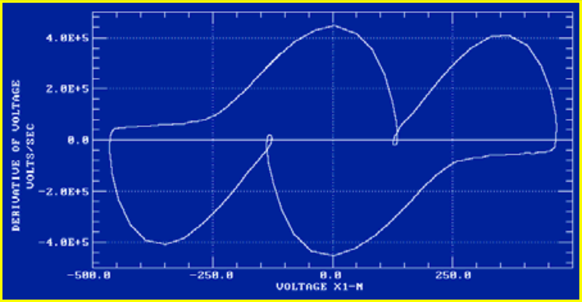
C = 9 μF

X2, X3 ENERGIZED
X1 OPEN

“ PERIOD ONE ”



PHASE PLANE DIAGRAM FOR V_{X1}

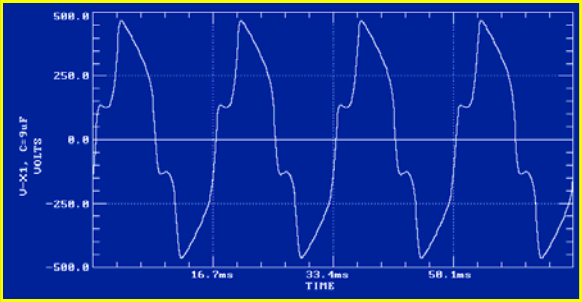


VOLTAGE X1-X0

C = 9 μF

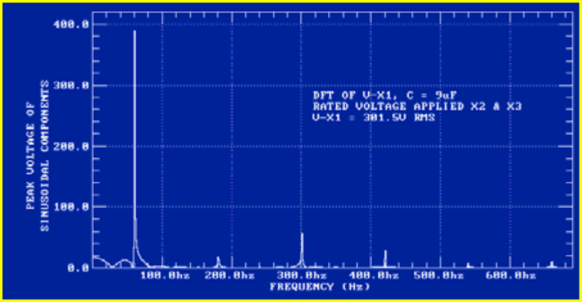
X2, X3 ENERGIZED
X1 OPEN

“ PERIOD ONE ”



DFT FOR V_{X1}

ONLY ODD
HARMONICS



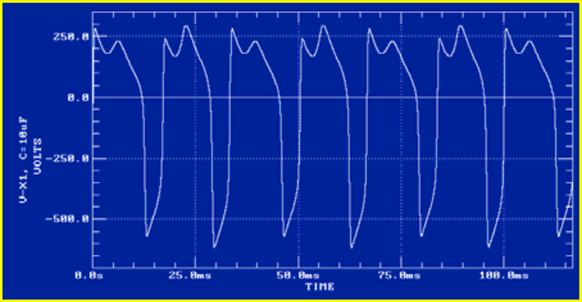
DFT OF V-X1, C = 9uF
RATED VOLTAGE APPLIED X2 & X3
V-X1 = 301.5V RMS

VOLTAGE X1-X0

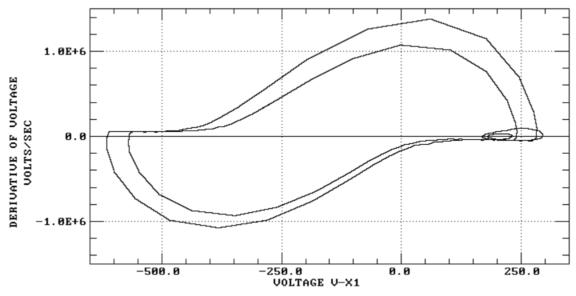
C = 10 μF

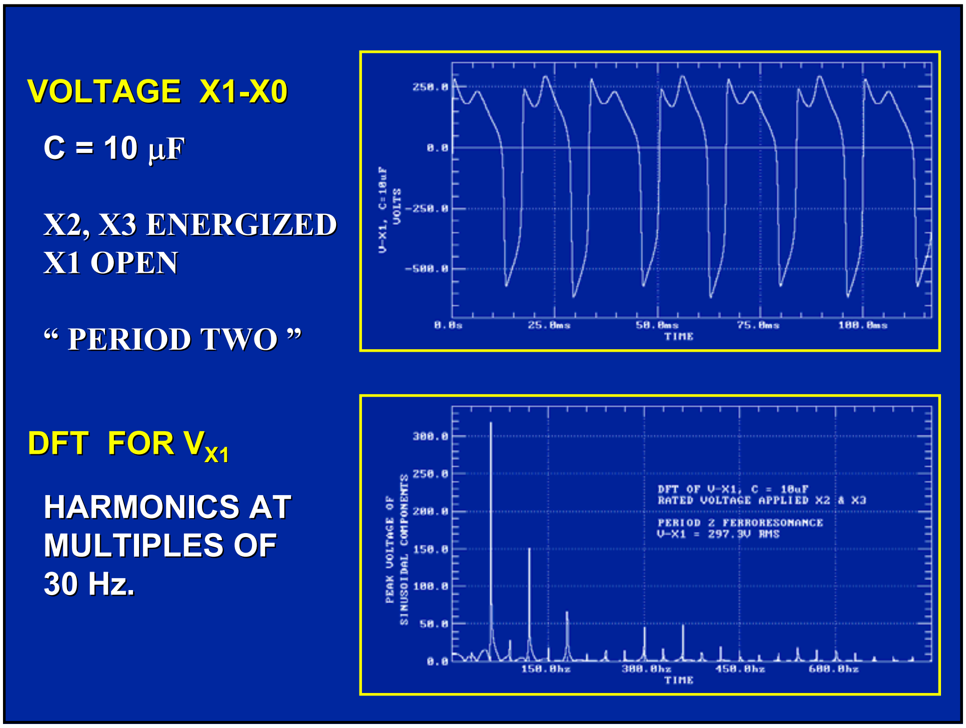
X2, X3 ENERGIZED
X1 OPEN

“ PERIOD TWO ”



PHASE PLANE DIAGRAM FOR V_{X1}





VOLTAGE X1-X0

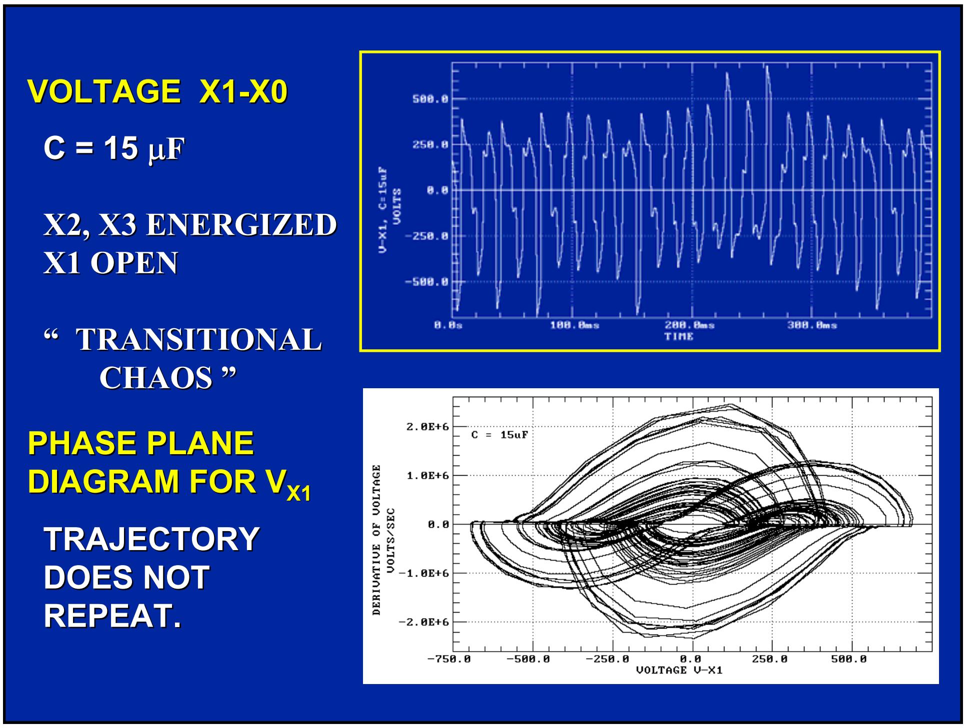
C = 10 μF

X2, X3 ENERGIZED
X1 OPEN

“ PERIOD TWO ”

DFT FOR V_{X1}

HARMONICS AT MULTIPLES OF 30 Hz.



VOLTAGE X1-X0

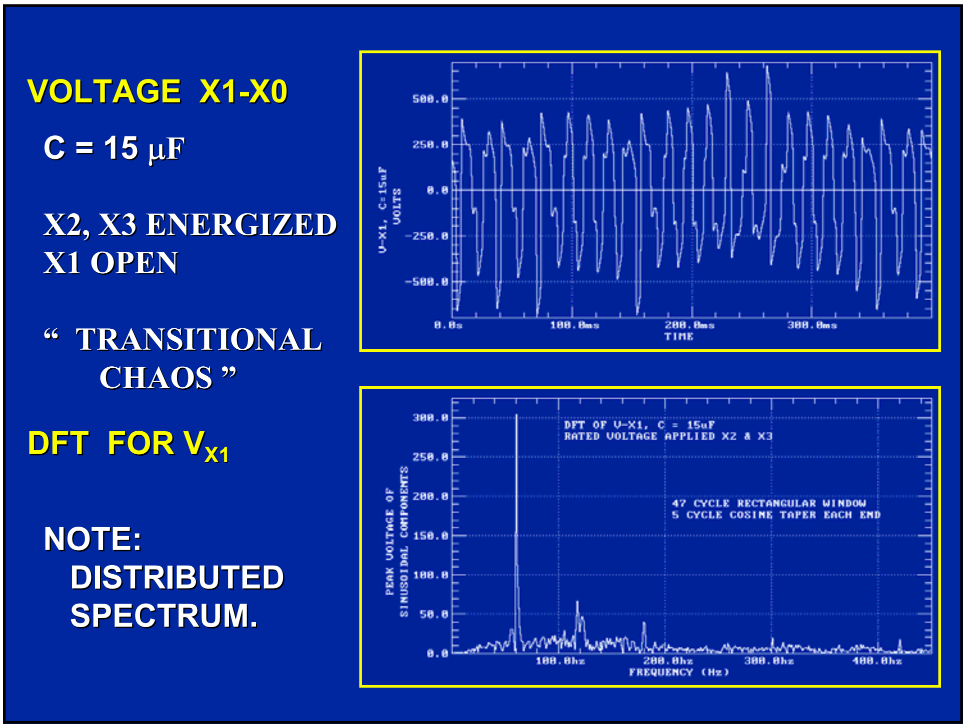
C = 15 μF

X2, X3 ENERGIZED
X1 OPEN

“ TRANSITIONAL CHAOS ”

PHASE PLANE DIAGRAM FOR V_{X1}

TRAJECTORY DOES NOT REPEAT.



VOLTAGE X1-X0

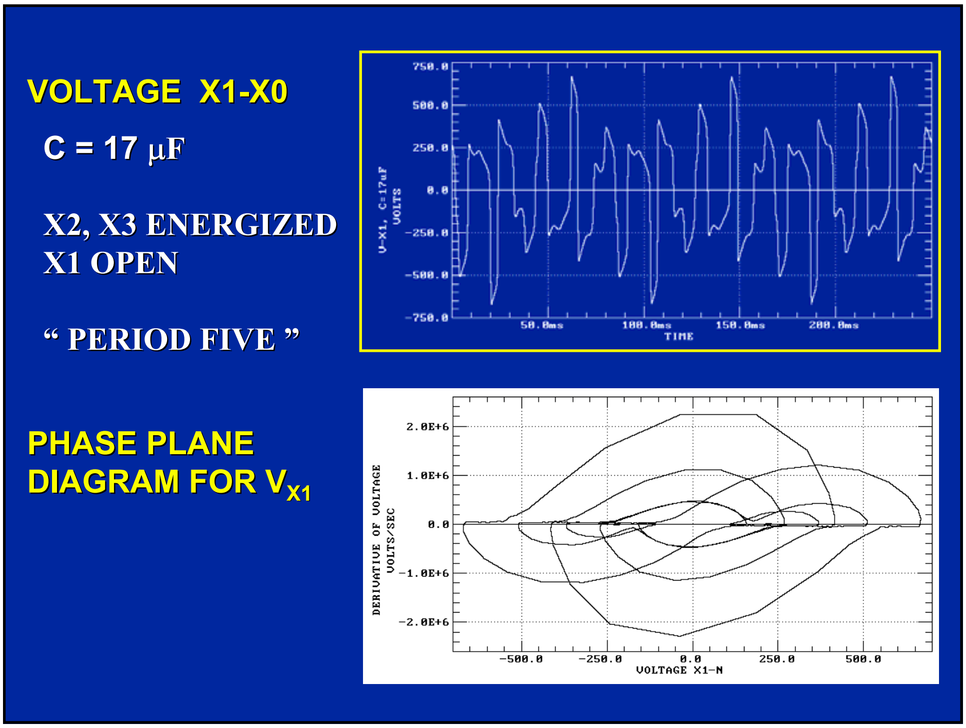
C = 15 μF

X2, X3 ENERGIZED
X1 OPEN

" TRANSITIONAL
CHAOS "

DFT FOR V_{X1}

NOTE:
DISTRIBUTED
SPECTRUM.



VOLTAGE X1-X0

C = 17 μF

X2, X3 ENERGIZED
X1 OPEN

" PERIOD FIVE "

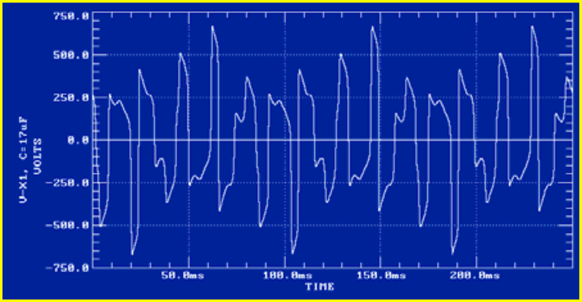
**PHASE PLANE
DIAGRAM FOR V_{X1}**

VOLTAGE X1-X0

C = 17 μF

X2, X3 ENERGIZED
X1 OPEN

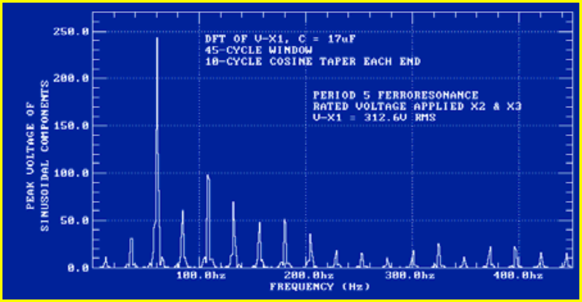
" PERIOD FIVE "



DFT FOR V_{X1}

HARMONICS AT
"ODD ONE-FIFTH"
SPACINGS.

i.e. 12, 36, 60, 84...

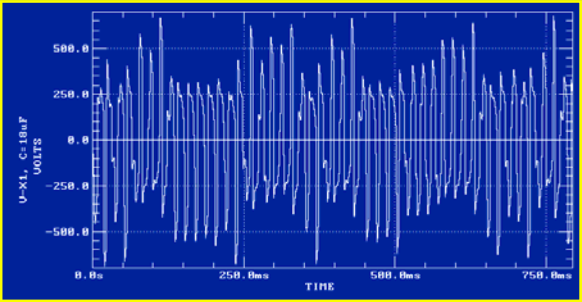


VOLTAGE X1-X0

C = 18 μF

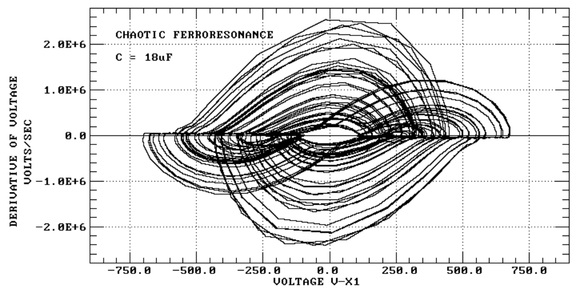
X2, X3 ENERGIZED
X1 OPEN

" TRANSITIONAL
CHAOS "



PHASE PLANE DIAGRAM FOR V_{X1}

NOTE:
TRAJECTORY
DOES NOT
REPEAT.

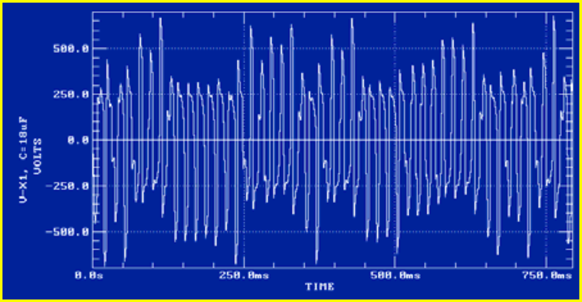


VOLTAGE X1-X0

C = 18 μF

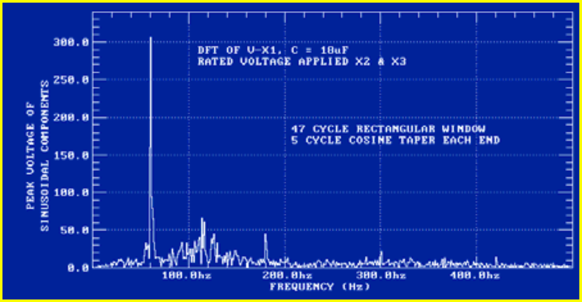
X2, X3 ENERGIZED
X1 OPEN

" TRANSITIONAL CHAOS "



DFT FOR V_{X1}

NOTE:
DISTRIBUTED SPECTRUM.

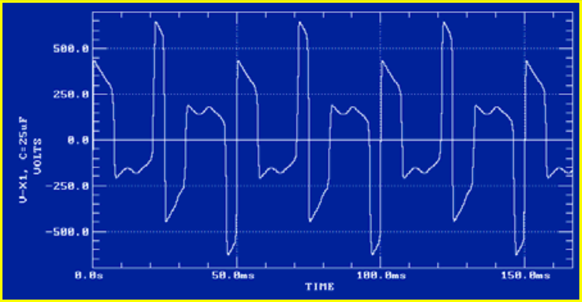


VOLTAGE X1-X0

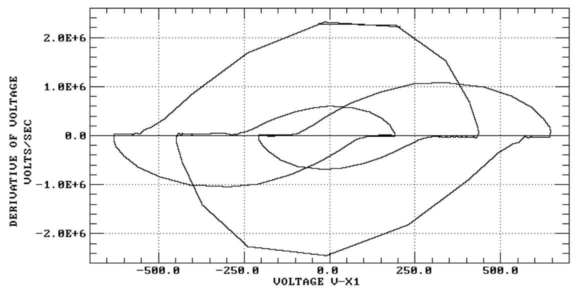
C = 25 μF

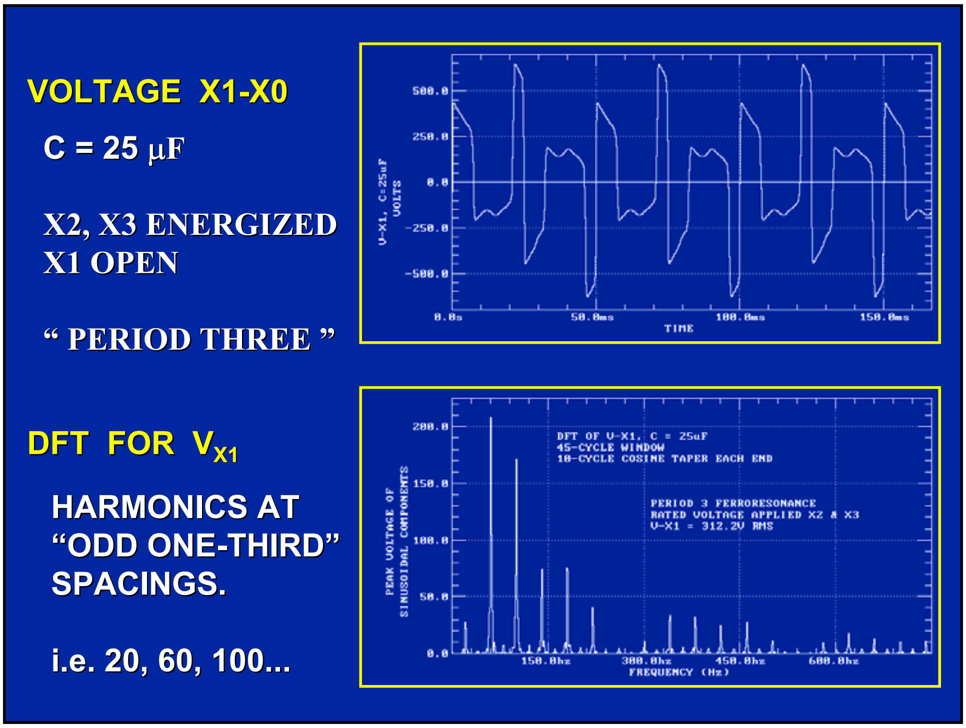
X2, X3 ENERGIZED
X1 OPEN

" PERIOD THREE "



PHASE PLANE DIAGRAM FOR V_{X1}





VOLTAGE X1-X0

C = 25 μF

X2, X3 ENERGIZED
X1 OPEN

“ PERIOD THREE ”

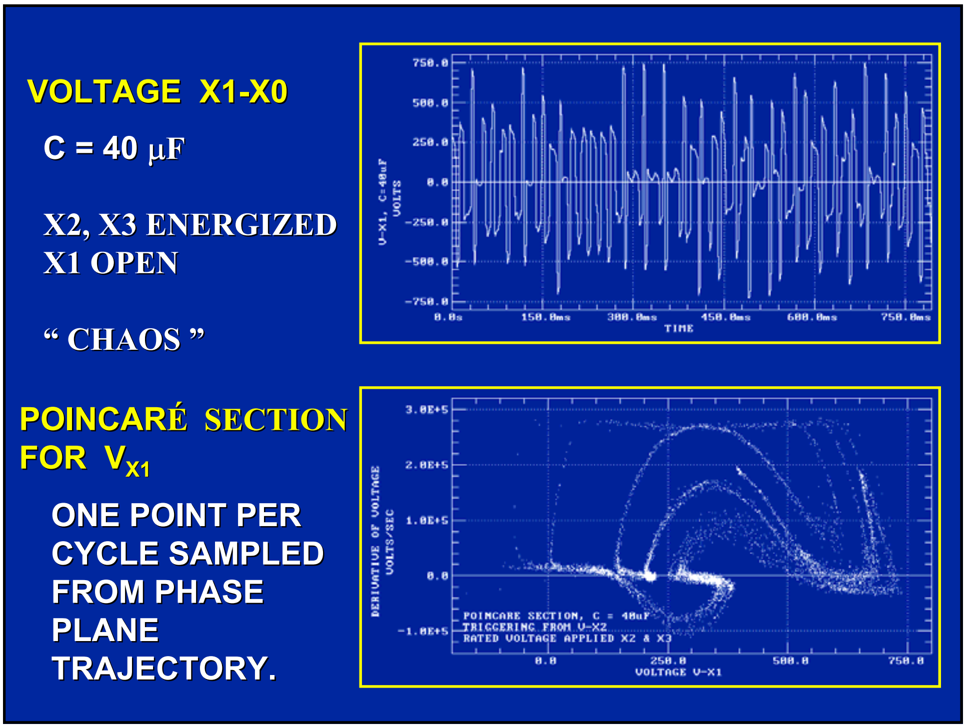
DFT FOR V_{X1}

HARMONICS AT
“ODD ONE-THIRD”
SPACINGS.

i.e. 20, 60, 100...

DFT OF V-X1, C = 25uF
45-CYCLE WINDOW
10-CYCLE COSINE TAPER EACH END

PERIOD 3 FERRORESONANCE
RATED VOLTAGE APPLIED X2 & X3
V-X1 = 312.2V RMS



VOLTAGE X1-X0

C = 40 μF

X2, X3 ENERGIZED
X1 OPEN

“ CHAOS ”

POINCARÉ SECTION FOR V_{X1}

ONE POINT PER
CYCLE SAMPLED
FROM PHASE
PLANE
TRAJECTORY.

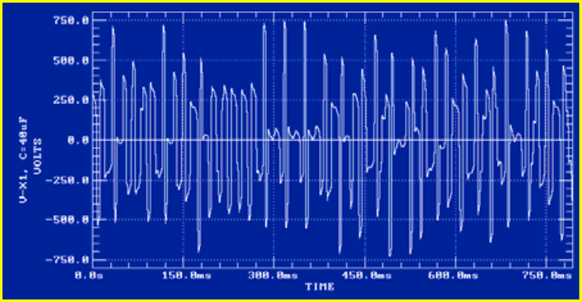
POINCARE SECTION, C = 40uF
TRIGGERING FROM V-X2
RATED VOLTAGE APPLIED X2 & X3

VOLTAGE X1-X0

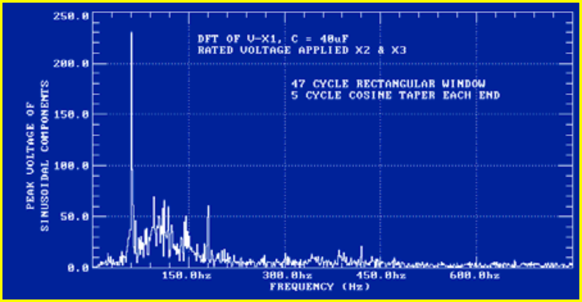
C = 40 µF

X2, X3 ENERGIZED
X1 OPEN

“ CHAOS ”



DFT FOR V_{X1}

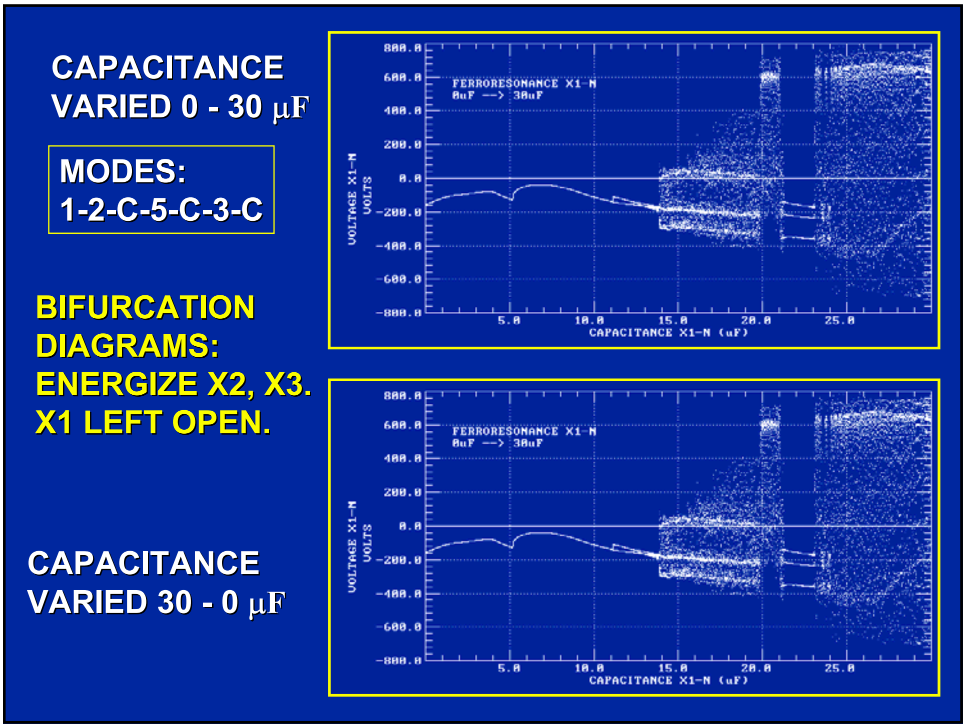


NOTE:
DISTRIBUTED
FREQUENCY
SPECTRUM.

GLOBAL PREDICTION OF FERRORESONANCE

- PREDICTION APPEARS DIFFICULT DUE TO WIDE RANGE OF POSSIBLE BEHAVIORS.

- A TYPE OF **BIFURCATION DIAGRAM**, AS USED TO STUDY NONLINEAR SYSTEMS, IS INTRODUCED FOR THIS PURPOSE.
- MAGNITUDES OF VOLTAGES FROM SIMULATED POINCARÉ SECTIONS ARE PLOTTED AS THE CAPACITANCE IS SLOWLY VARIED (BOTH UP AND DOWN).
- POINTS ARE SAMPLED ONCE EACH 60-Hz CYCLE.
- AN “ADEQUATE ” MODEL IS REQUIRED.

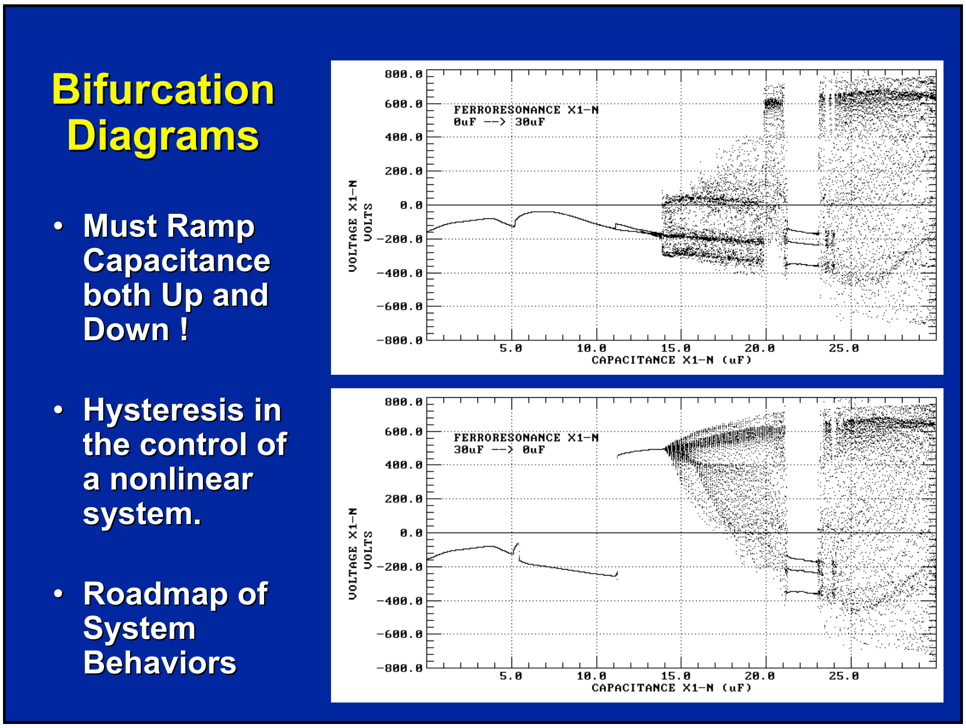


CAPACITANCE
VARIED 0 - 30 μF

MODES:
1-2-C-5-C-3-C

BIFURCATION DIAGRAMS: ENERGIZE X2, X3. X1 LEFT OPEN.

CAPACITANCE
VARIED 30 - 0 μF



Bifurcation Diagrams

- Must Ramp Capacitance both Up and Down !
- Hysteresis in the control of a nonlinear system.
- Roadmap of System Behaviors

CONCLUSIONS

- FERRORESONANT BEHAVIOR IS TYPICAL OF NONLINEAR DYNAMICAL SYSTEMS.
- RESPONSES MAY BE PERIODIC OR CHAOTIC.
- MULTIPLE MODES OF RESPONSE ARE POSSIBLE FOR THE SAME PARAMETERS.
- STEADY STATE RESPONSES CAN BE SENSITIVE TO INITIAL CONDITIONS OR PERTURBATIONS.
- SPONTANEOUS TRANSITIONS FROM ONE MODE TO ANOTHER ARE POSSIBLE.
- WHEN SIMULATING, THERE MAY NOT BE “ONE CORRECT” RESPONSE.

CONCLUSIONS (CONT’D)

- BIFURCATIONS OCCUR AS CAPACITANCE IS VARIED UPWARD OR DOWNWARD.
- PLOTTING Vpeak vs. CAPACITANCE OR OTHER VARIABLES GIVES DISCONTINUOUS OR MULTI-VALUED FUNCTIONS.
- THEREFORE, SUPPOSITION OF TRENDS BASED ON LINEARIZING A LIMITED SET OF DATA IS PARTICULARLY PRONE TO ERROR.
- BIFURCATION DIAGRAMS PROVIDE A ROAD MAP, AVOIDING NEED TO DO SEPARATE SIMULATIONS AT DISCRETE VALUES OF CAPACITANCE AND INITIAL CONDITIONS.

Recommendations

- Beware of lightly-loaded transformers operating in the presence of capacitance.
- Topologically correct transformer models are the key to simulation of ferroresonance.
- Core saturation/loss representations are still weak point of transformer models.
- Nonlinearities make ferroresonance hard to predict or confirm.
- Monitor current literature for new developments in modeling and simulation techniques.

COMMENTS?

QUESTIONS?