IEEE Power Engineering Society General Meeting
Toronto, July 13-17, 2003

Panel Session

Practical Aspects of Ferroresonance

by

IEEE T&D General Systems Subcommittee
Practical Aspects of Ferroresonance WG
Chairman: Bruce Mork, Michigan Tech University

http://www.ee.mtu.edu/faculty/bamork/FR_WG/

Working Group Objectives

- Comprehensive Literature Survey of FR issues.
- "Accessible" explanation of FR for practicing engineers. Help understand and deal with FR.
- Document scenarios under which FR can occur, providing practical insights and mitigation measures.
- Document scenarios that are often confused with FR but are NOT FR. Identify misinformation and correct.
- IEEE Special Publication, panel, tutorial, papers, etc.

Working Group Activities

- Meet 1-2 times/ year, first met at SM 2001.
- 34 total members, 11 active contributors
- Information being gathered, literature search, compiling scenarios leading to FR,
- Deliverables:
  - Panel Session - July 2003 GM, Toronto
  - Panel Session - June 2004 GM, Denver
  - Special publication complete in Q3/Q4 2004.
  - Summary papers submitted during 2004/2005.
  - Tutorial - 2005 GM.

Acknowledgements

- T&D General Subsystems Committee:
  - This work grew out of TF on Slow Transients, IEEE Special Publication TP-133-0, Chapter 5.
  - **Albert Keri** came up with idea for this WG.
- Nucleus of Key Contributors to kick things off:
  - **David Jacobson,** Manitoba Hydro
  - **Atef Morched,** Labelec
  - **Bruce Mork**, Michigan Tech University
  - **Reigh Walling**, General Electric
- The 30 others who are contributing, reviewing, sharing insights, otherwise participating.

Today’s Panelists

- **Bruce Mork**, Panel Chair, Michigan Technological University - **Intro/Overview of Ferroresonance**
- **David Jacobson**, Manitoba Hydro, Canada - **Useful References & Examples of Ferroresonance in a High-Voltage Power System**
- **Roger Dugan**, Electrotek Concepts - **Examples of Ferroresonance in Distribution Systems**
- **B. Tanggawelu**, TNB Research, Malaysia - **Ferroresonance Studies in Malaysian Utility's Distribution Network** (could not attend)
- **Reigh Walling/Goran Drobnjak**, General Electric - **Ferroresonance in Low-Loss Distribution Transformers**
- **Juan Martinez**, Universitat Politecnica de Barcelona - **Transformer Modeling for Simulation of Low-Frequency Transients** (coauthored with Bruce Mork)

INTRODUCTION

TO

FERRORESONANCE

Ferroresonance Basics

- A “Resonance” involving a capacitance in series with a saturable inductance L_M. Maximum frequency: 2-3kHz.

- Unpredictable due to nonlinearities. Lots of harmonics.

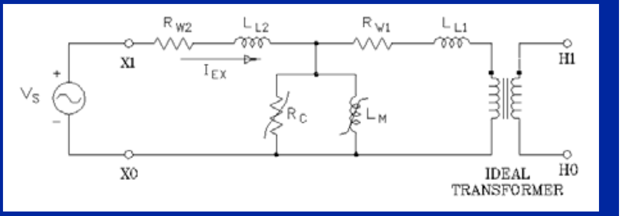
- More likely when little load or damping, and for unbalanced 3-phase excitation with coupling between phases, or between circuits of double-circuit lines.

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

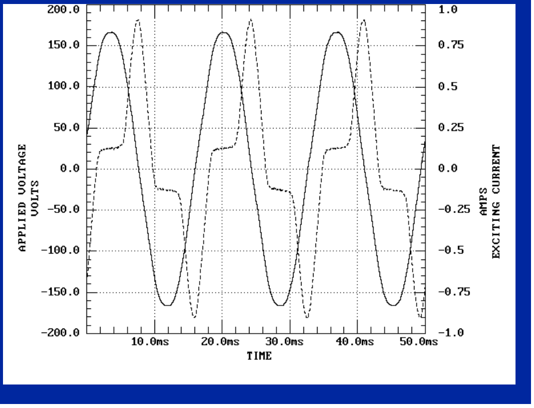
Some Available Literature:

- 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.
- Jacobson, others: continuing work, late 90s onward.

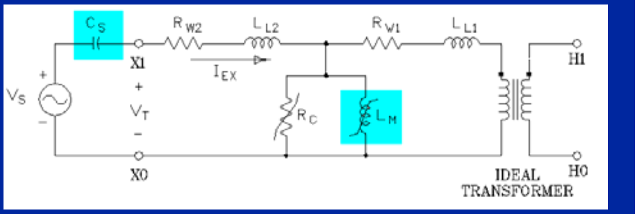
Single Phase Transformer: Normal Excitation



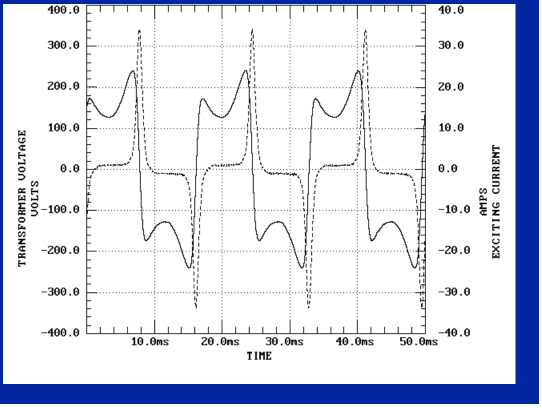
- 120 Volts RMS is applied (1.0 pu)
- Peak exciting current is less than one amp.
- Exciting current distorted due to eddy currents and hysteresis.

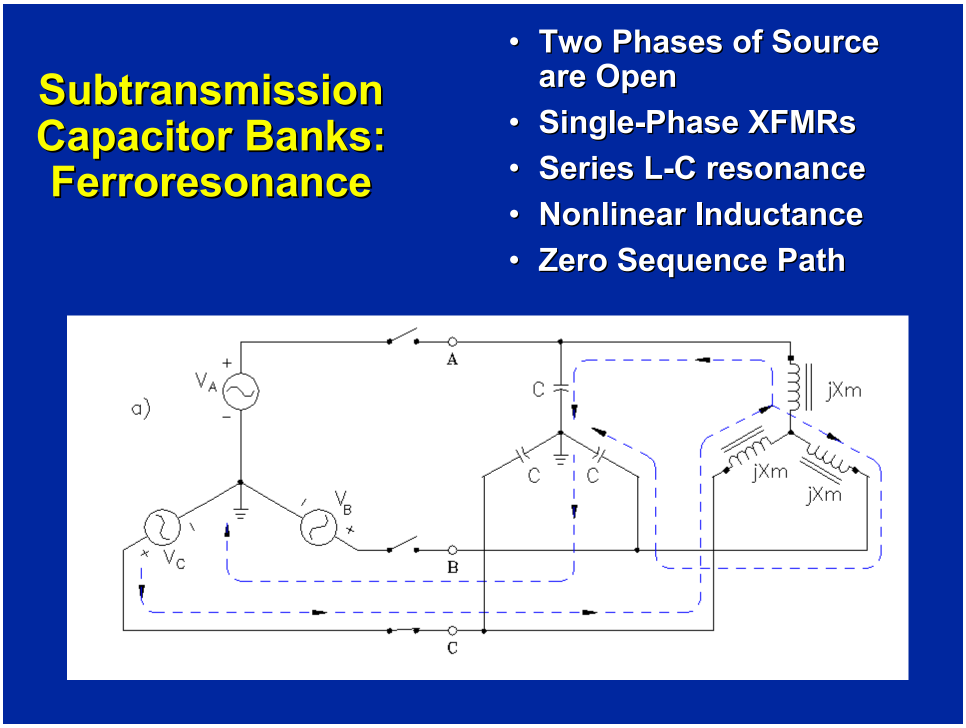


Single Phase Transformer: Ferro-resonance



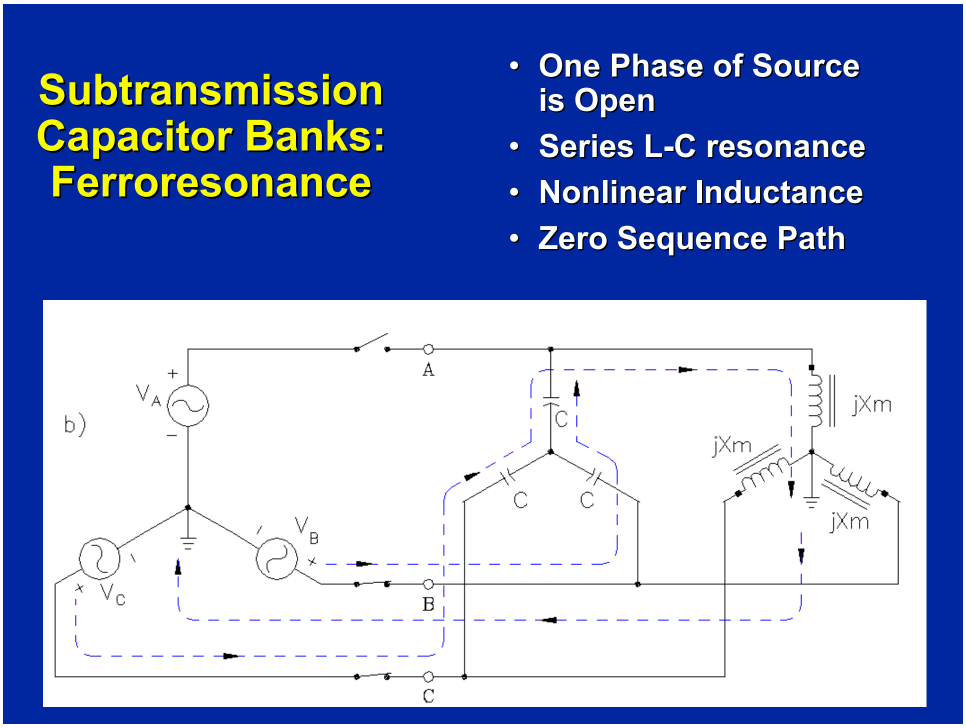
- Series Capacitance
- 120 Volts RMS is applied (1.0 pu)
- Peak exciting current is about 34 amps (1.94 pu).
- Terminal voltage of transformer is 240 volts peak (1.44 pu).





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

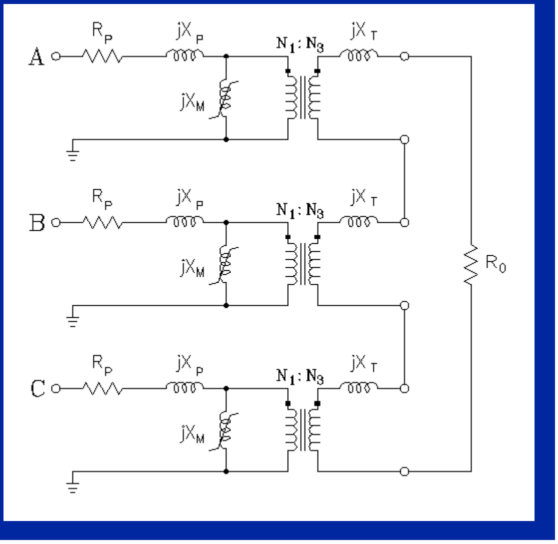
Important System Components

- 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: Model must be of correct topology, and include core saturation & losses.

EXAMPLE CASES

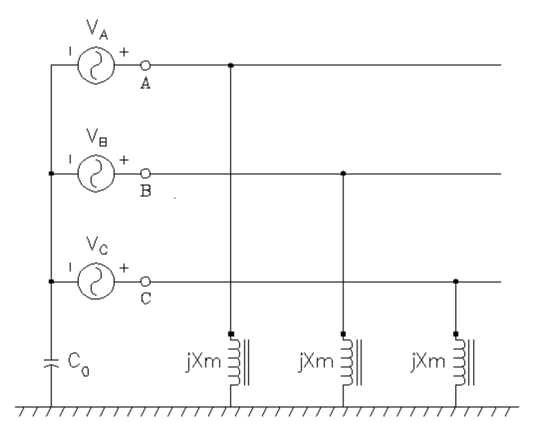
Case 1: VT FERRORESONANCE IN Temporarily Ungrounded 50-kV System

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



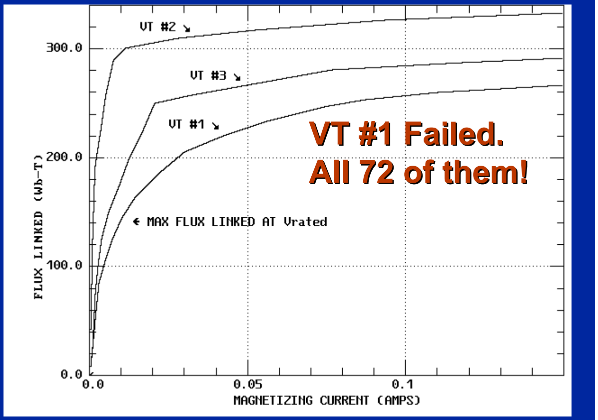
Case 1: VT FERRORESONANCE IN Temporarily Ungrounded 50-kV System

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



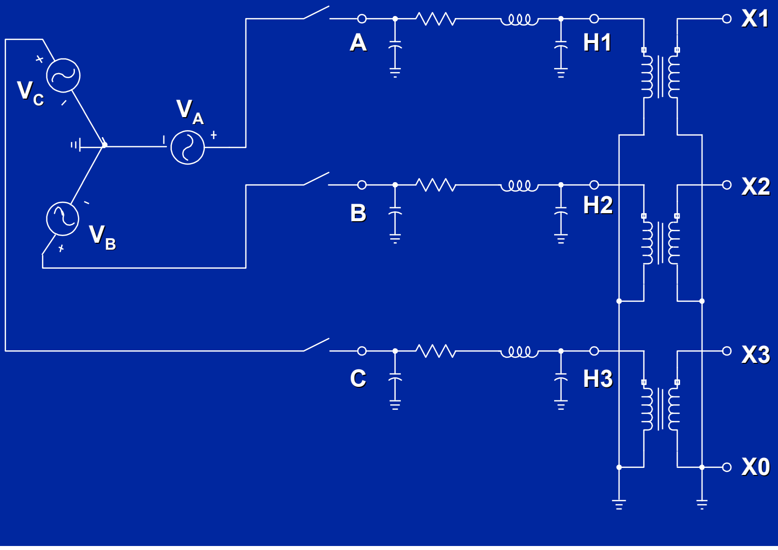
Case 1: VT FERRORESONANCE IN Temporarily Ungrounded 50-kV System

- 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!

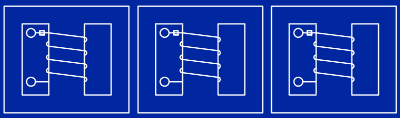
Case 2: FERRORESONANCE IN WYE-CONNECTED SYSTEMS



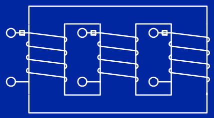
Details of Case #2

- 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.

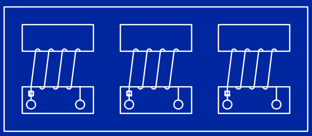
BACKFED VOLTAGE DEPENDS ON CORE CONFIGURATION



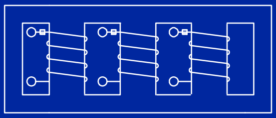
TRIPLEX WOUND OR STACKED



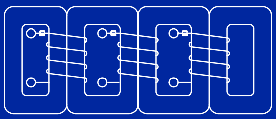
3-LEG STACKED CORE



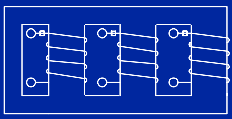
SHELL FORM



5-LEG STACKED CORE



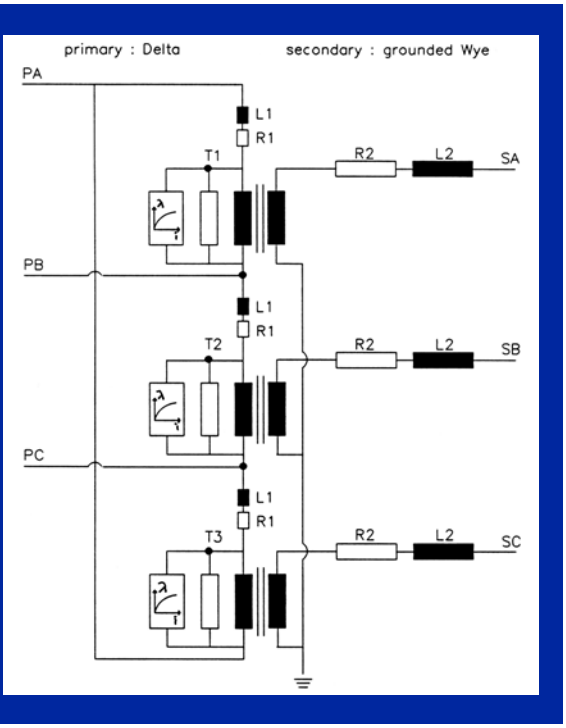
5-LEG WOUND CORE



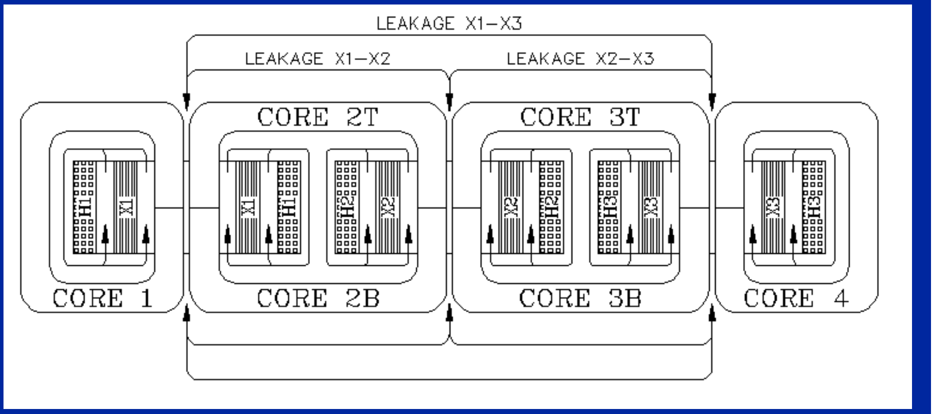
4-LEG STACKED CORE

Don't Do This!

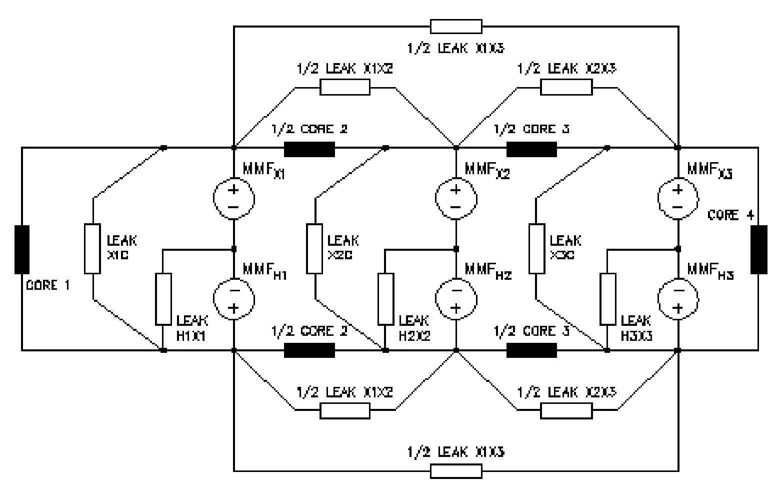
- Basic Delta-Wye Transformer Model as Presented in EMTP Rule Book.
- Composed of three single-phase transformers
- Phase-to-phase coupling is not included



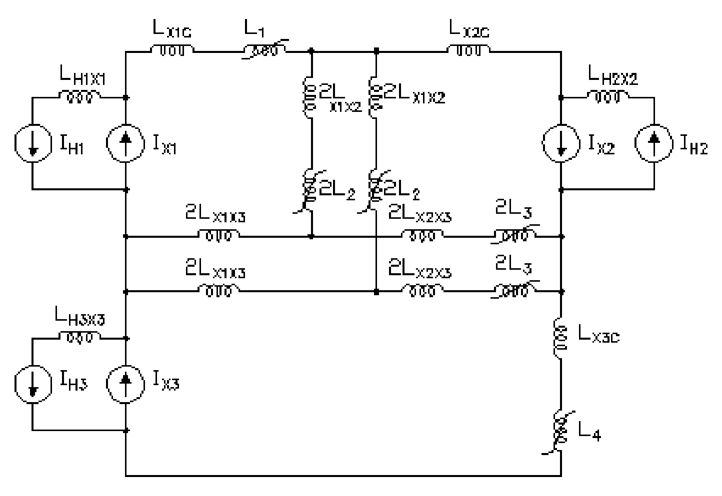
5-Legged Wound-Core Transformer Cross Section with Flux Paths/Tubes



5-Legged Wound-Core Transformer Lumped Magnetic Circuit

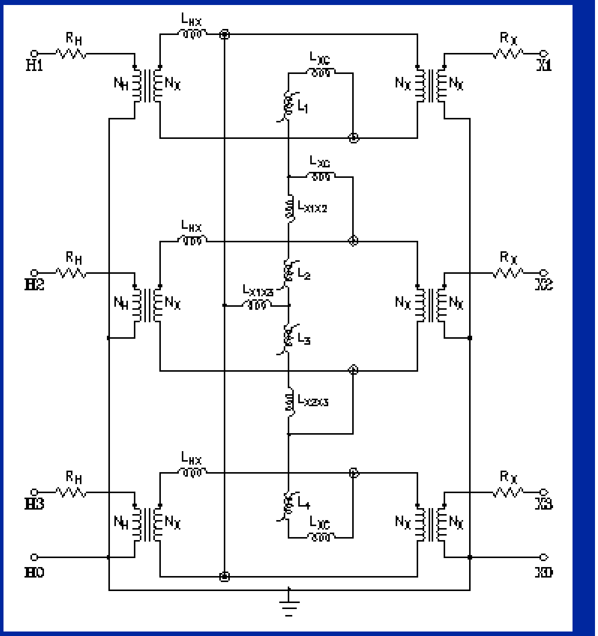


5-Legged Wound-Core Transformer Electrical Dual Equivalent Circuit



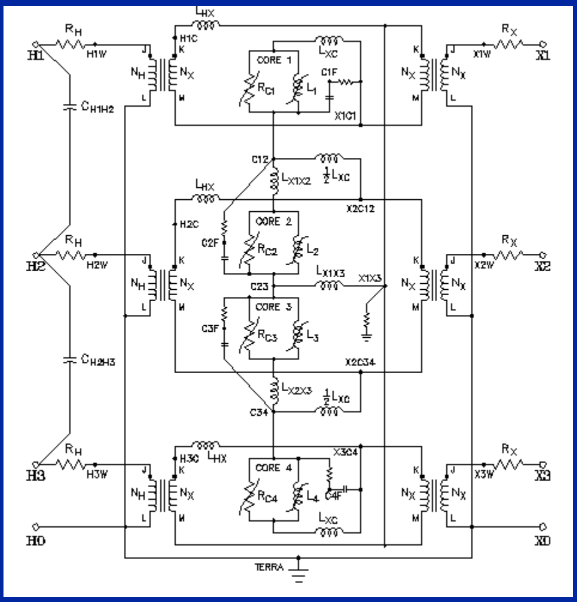
5-LEGGED WOUND-CORE MODEL

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

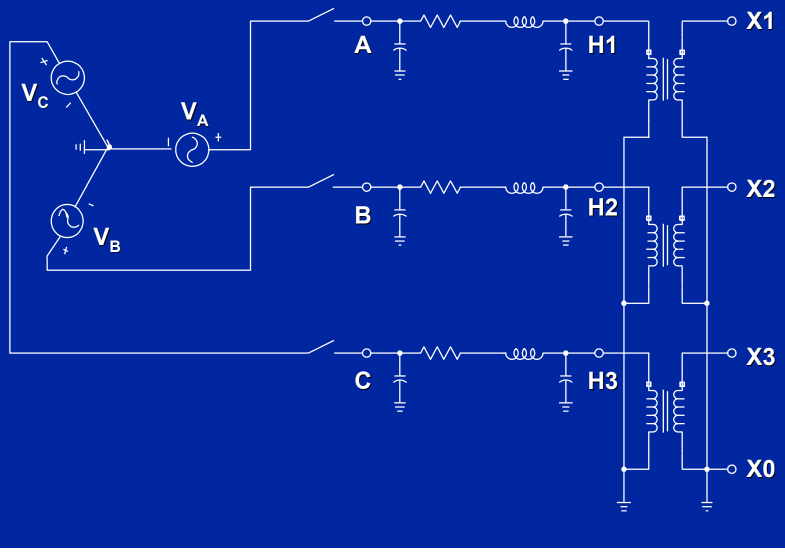


EMTP Model, 5-Legged Wound-Core

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



Case 2: FERRORESONANCE IN WYE-CONNECTED SYSTEMS



NONLINEAR DYNAMICAL SYSTEMS: BASIC CHARACTERISTICS

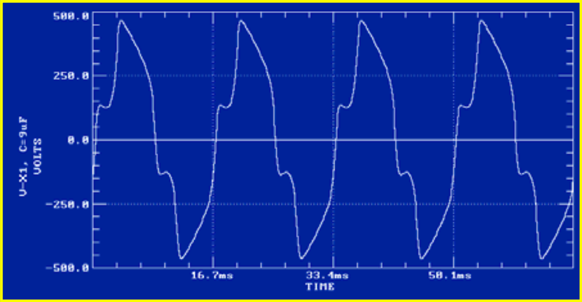
- MULTIPLE MODES OF RESPONSE POSSIBLE FOR IDENTICAL SYSTEM PARAMETERS.
- STEADY STATE RESPONSES MAY BE OF DIFFERENT PERIOD THAN FORCING FUNCTION, OR NONPERIODIC (CHAOTIC).
- STEADY STATE RESPONSE MAY BE EXTREMELY SENSITIVE TO INITIAL CONDITIONS OR PERTURBATIONS .
- BEHAVIORS CANNOT PROPERLY BE PREDICTED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

VOLTAGE X1-X0

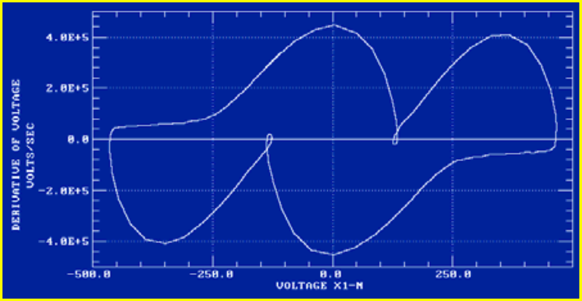
C = 9 μF

X2, X3 ENERGIZED
X1 OPEN

“ PERIOD ONE ”



PHASE PLANE DIAGRAM FOR V_{X1}



VOLTAGE X1-X0

C = 9 μF

X2, X3 ENERGIZED
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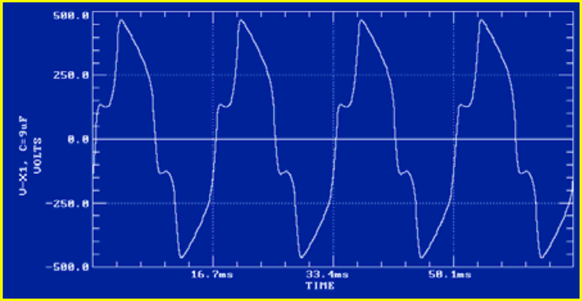
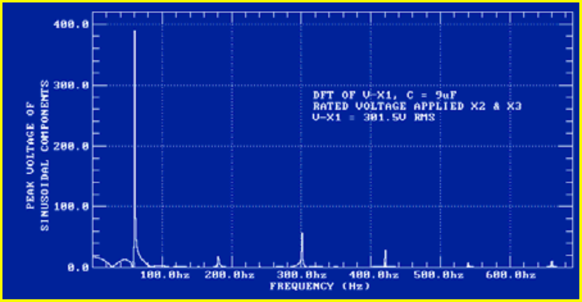
“ PERIOD ONE ”



DFT FOR V_{X1}

ONLY ODD
HARMONICS

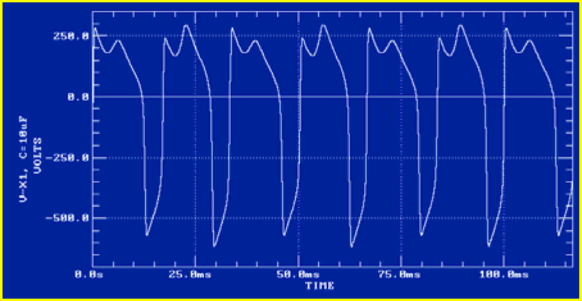


VOLTAGE X1-X0

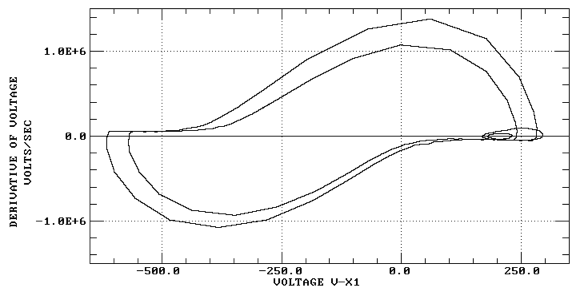
C = 10 μF

X2, X3 ENERGIZED
X1 OPEN

“ PERIOD TWO ”



PHASE PLANE DIAGRAM FOR V_{X1}

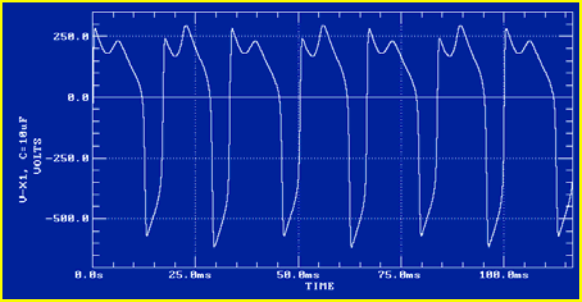


VOLTAGE X1-X0

C = 10 μF

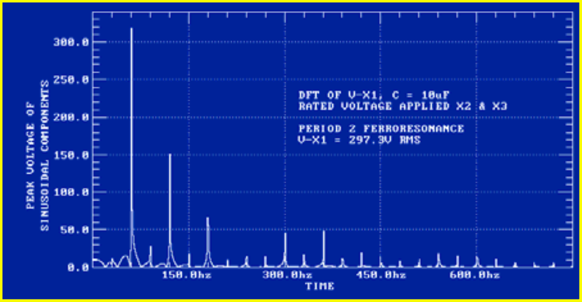
X2, X3 ENERGIZED
X1 OPEN

“ PERIOD TWO ”



DFT FOR V_{X1}

HARMONICS AT MULTIPLES OF 30 Hz.

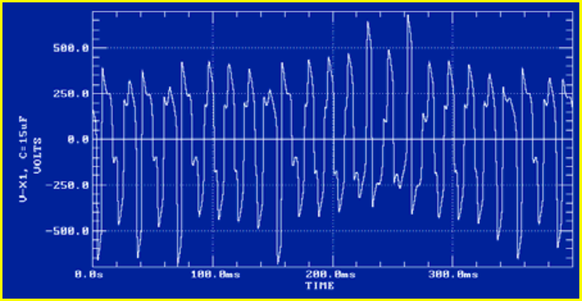


VOLTAGE X1-X0

C = 15 μF

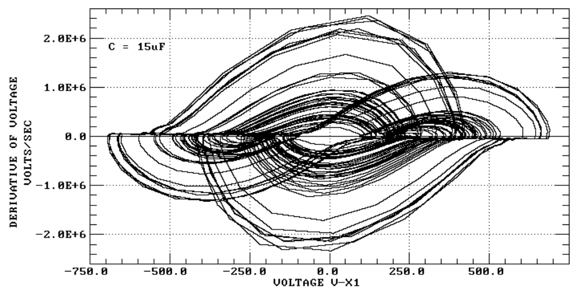
X2, X3 ENERGIZED
X1 OPEN

“ TRANSITIONAL
CHAOS ”



PHASE PLANE DIAGRAM FOR V_{X1}

TRAJECTORY
DOES NOT
REPEAT.

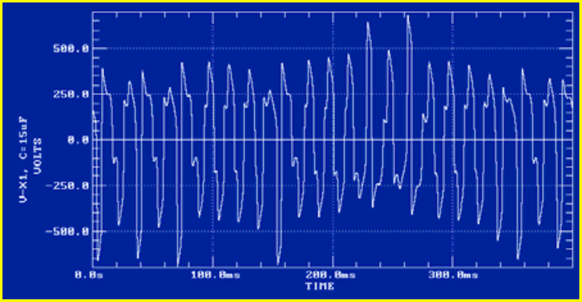


VOLTAGE X1-X0

C = 15 μF

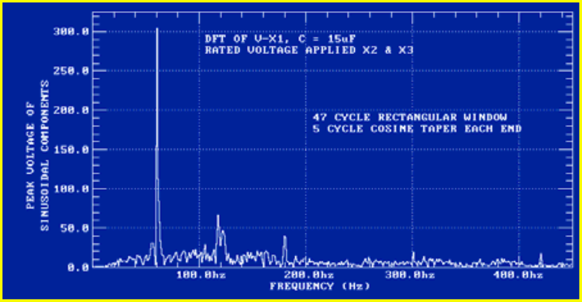
X2, X3 ENERGIZED
X1 OPEN

“ TRANSITIONAL
CHAOS ”



DFT FOR V_{X1}

NOTE:
DISTRIBUTED
SPECTRUM.

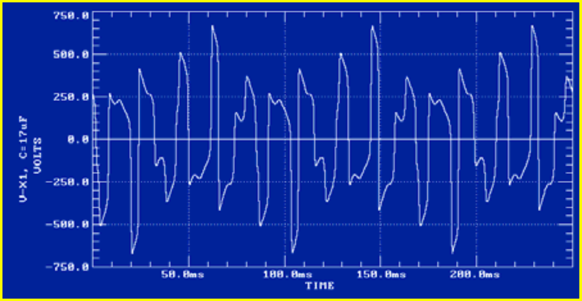


VOLTAGE X1-X0

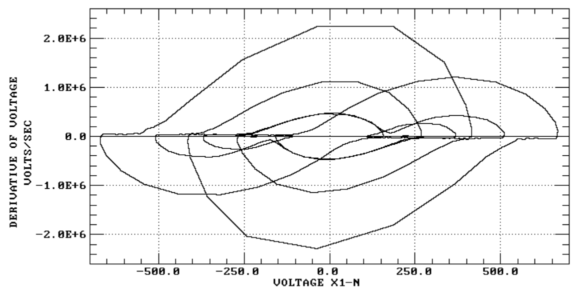
C = 17 μF

X2, X3 ENERGIZED
X1 OPEN

" PERIOD FIVE "



PHASE PLANE DIAGRAM FOR V_{X1}

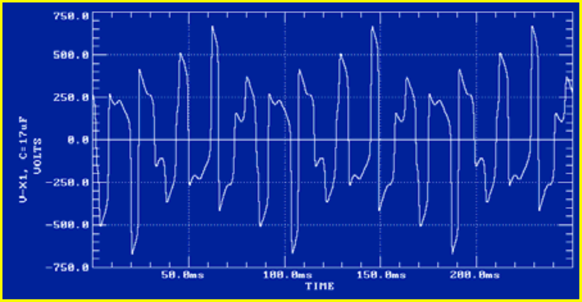


VOLTAGE X1-X0

C = 17 μF

X2, X3 ENERGIZED
X1 OPEN

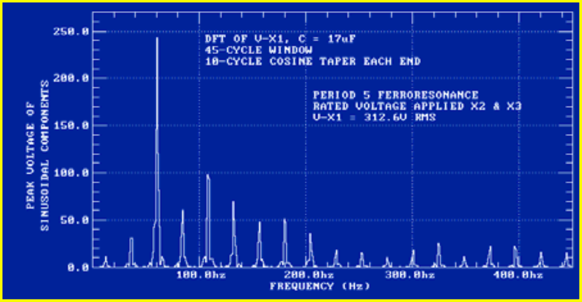
" PERIOD FIVE "



DFT FOR V_{X1}

HARMONICS AT "ODD ONE-FIFTH" SPACINGS.

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

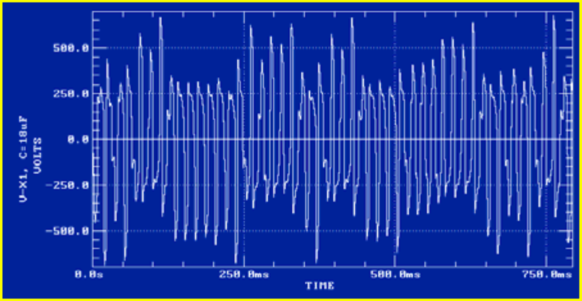


VOLTAGE X1-X0

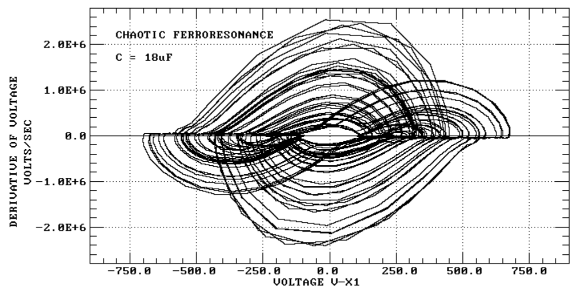
C = 18 μF

X2, X3 ENERGIZED
X1 OPEN

" TRANSITIONAL
CHAOS "



PHASE PLANE DIAGRAM FOR V_{X1}



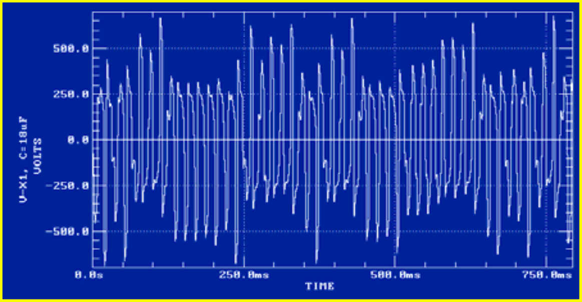
NOTE:
TRAJECTORY
DOES NOT
REPEAT.

VOLTAGE X1-X0

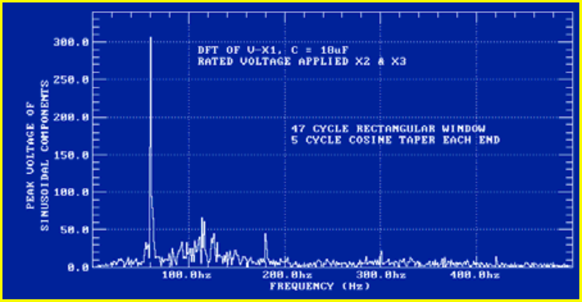
C = 18 μF

X2, X3 ENERGIZED
X1 OPEN

" TRANSITIONAL
CHAOS "



DFT FOR V_{X1}



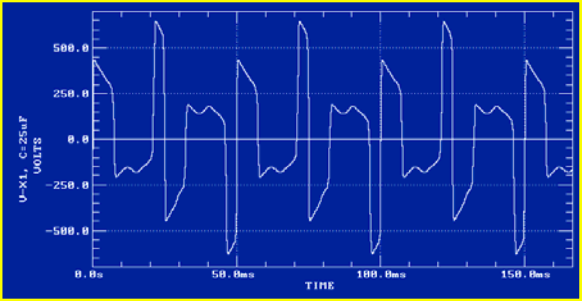
NOTE:
DISTRIBUTED
SPECTRUM.

VOLTAGE X1-X0

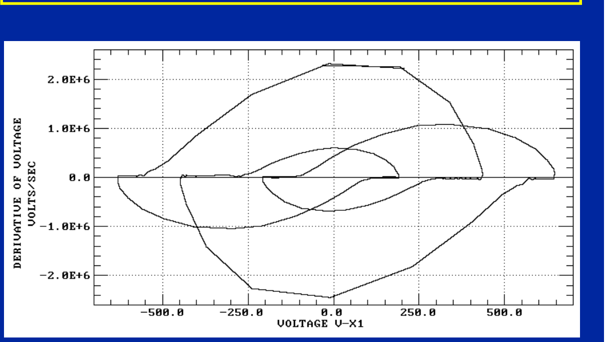
C = 25 μF

X2, X3 ENERGIZED
X1 OPEN

“ PERIOD THREE ”



PHASE PLANE DIAGRAM FOR V_{X1}

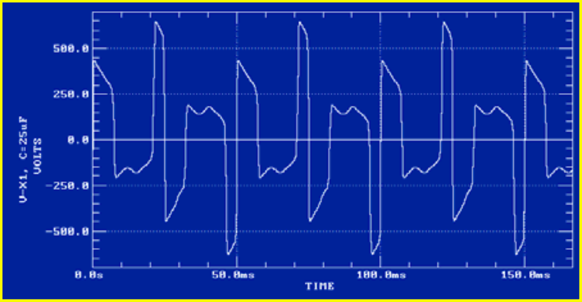


VOLTAGE X1-X0

C = 25 μF

X2, X3 ENERGIZED
X1 OPEN

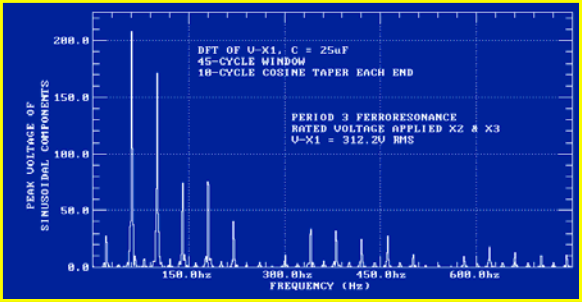
“ PERIOD THREE ”



DFT FOR V_{X1}

HARMONICS AT
“ODD ONE-THIRD”
SPACINGS.

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

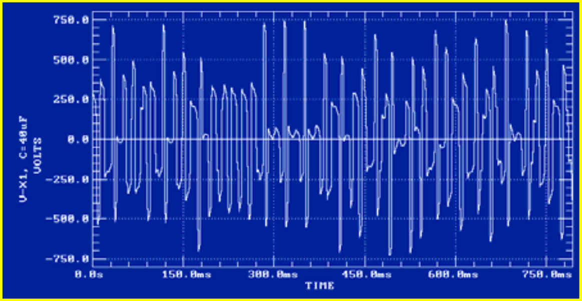


VOLTAGE X1-X0

C = 40 μF

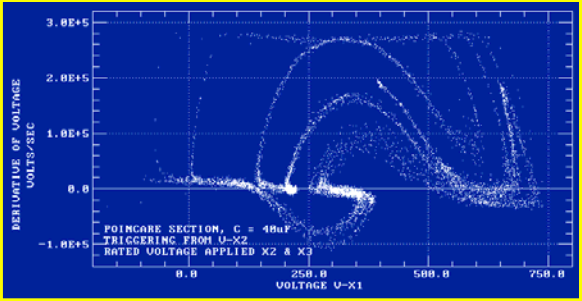
X2, X3 ENERGIZED
X1 OPEN

" CHAOS "



POINCARÉ SECTION FOR V_{X1}

ONE POINT PER CYCLE SAMPLED FROM PHASE PLANE TRAJECTORY.

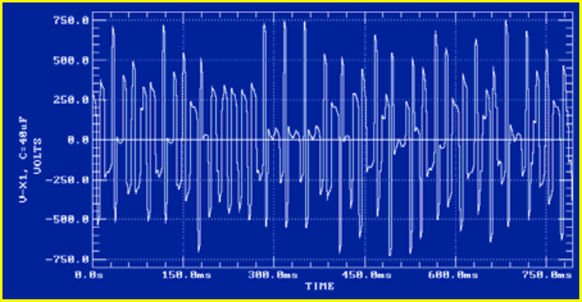


VOLTAGE X1-X0

C = 40 μF

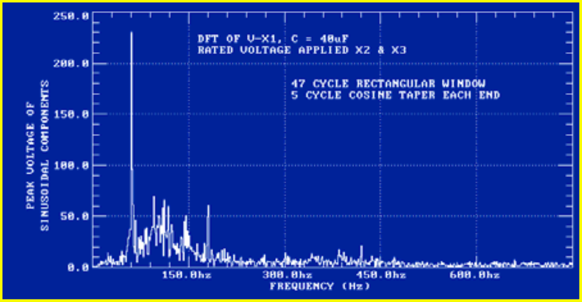
X2, X3 ENERGIZED
X1 OPEN

" CHAOS "



DFT FOR V_{X1}

NOTE:
DISTRIBUTED FREQUENCY SPECTRUM.

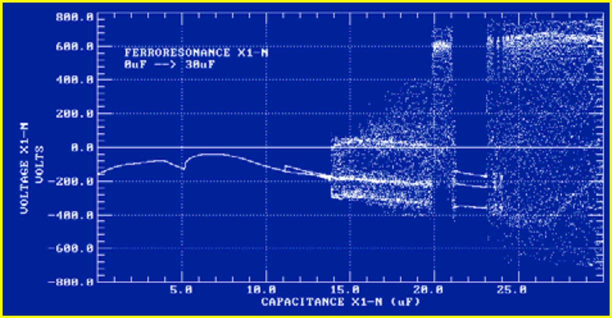


GLOBAL PREDICTION OF FERRORESONANCE

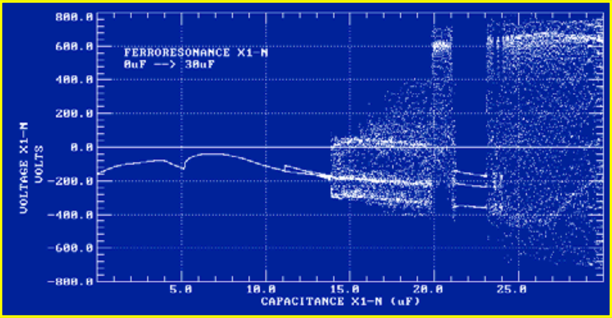
- PREDICTION APPEARS DIFFICULT DUE TO WIDE RANGE OF POSSIBLE BEHAVIORS.
- A TYPE OF **BIFURCATION DIAGRAM**, AS USED TO STUDY NONLINEAR SYSTEMS, IS INTRODUCED FOR THIS PURPOSE.
- MAGNITUDES OF VOLTAGES FROM SIMULATED POINCARÉ SECTIONS ARE PLOTTED AS THE CAPACITANCE IS SLOWLY VARIED (BOTH UP AND DOWN).
- 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



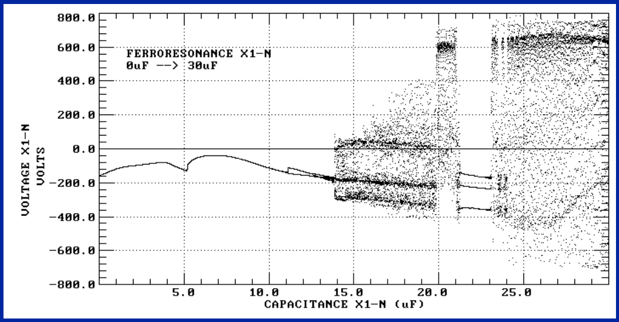
BIFURCATION DIAGRAMS: ENERGIZE X2, X3. X1 LEFT OPEN.

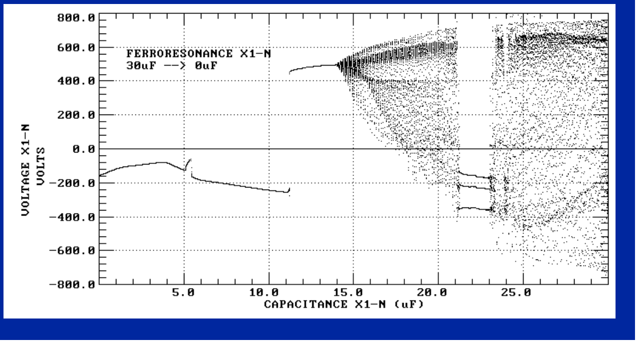


CAPACITANCE VARIED 30 - 0 μF

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?