Tutorial: Power System Overvoltages

Low Frequency Transients

Presented by
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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
- Received 1999 PES Working Group Award for Technical Report.

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**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)

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**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
- AVR
- 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.

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: Ferroresonance**

- 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.

- 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 SHELL FORM
- 5-LEG WOUND CORE
- 3-LEG STACKED CORE
- 5-LEG STACKED 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

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**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**

\[ C = 9 \ \mu F \]

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 Vx1
ONLY ODD HARMONICS

VOLTAGE X1-X0
C = 10 µF
X2, X3 ENERGIZED
X1 OPEN
" PERIOD TWO "

PHASE PLANE
DIAGRAM FOR Vx1
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
“TRANITIONAL CHAOS”
DFT FOR Vx1

NOTE:
DISTRIBUTED SPECTRUM.

VOLTAGE X1-X0
C = 17 µF
X2, X3 ENERGIZED
X1 OPEN
“PERIOD FIVE”

PHASE PLANE DIAGRAM FOR VX1
VOLTAGE X1-X0

C = 17 µF

X2, X3 ENERGIZED
X1 OPEN

“PERIOD FIVE”

DFT FOR Vx1

HARMONICS AT
“ODD ONE-FIFTH” SPACINGS.

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

PHASE PLANE DIAGRAM FOR Vx1

NOTE:
TRAJECTORY DOES NOT REPEAT.
VOLTAGE X1-X0
C = 18 \mu F

X2, X3 ENERGIZED
X1 OPEN

“TRANSITIONAL CHAOS”

DFT FOR V_{X1}

NOTE:
DISTRIBUTED SPECTRUM.

VOLTAGE X1-X0
C = 25 \mu F

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\(x_1\)
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\(x_1\)
ONE POINT PER CYCLE SAMPLED FROM PHASE PLANE TRAJECTORY.
VOLTAGE X1-X0
C = 40 \mu F
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 POINCARE 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.
BIFURCATION DIAGRAMS:
ENERGIZE X2, X3. X1 LEFT OPEN.

CAPACITANCE VARIED 0 - 30 \( \mu F \)

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

CAPACITANCE VARIED 30 - 0 \( \mu F \)

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**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 $V_{\text{peak}}$ 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?