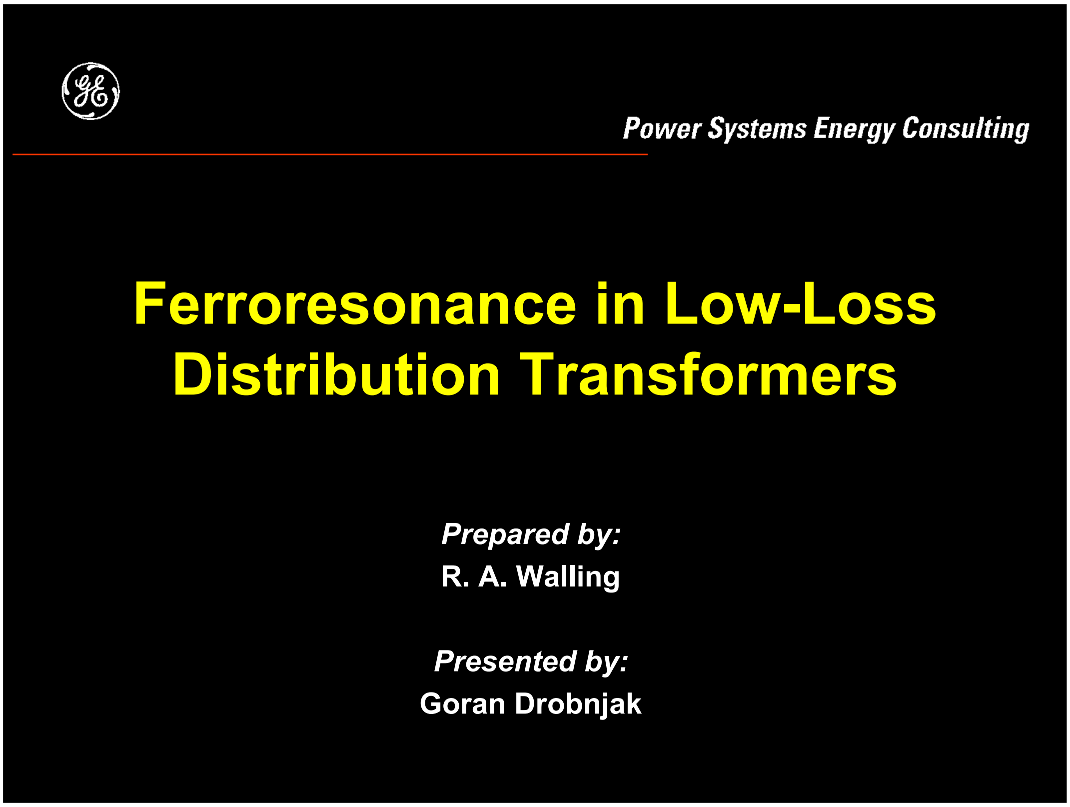


I am filling in for Mr. Walling who regrets to not be able to make this presentation

Today I will be talking about an extensive testing project which we believe has revealed new insights into the relevant factors affecting ferroresonance in today's lower-loss distribution transformers

When the industry moved to URD in the 1960's, there were a lot of problems with ferroresonance

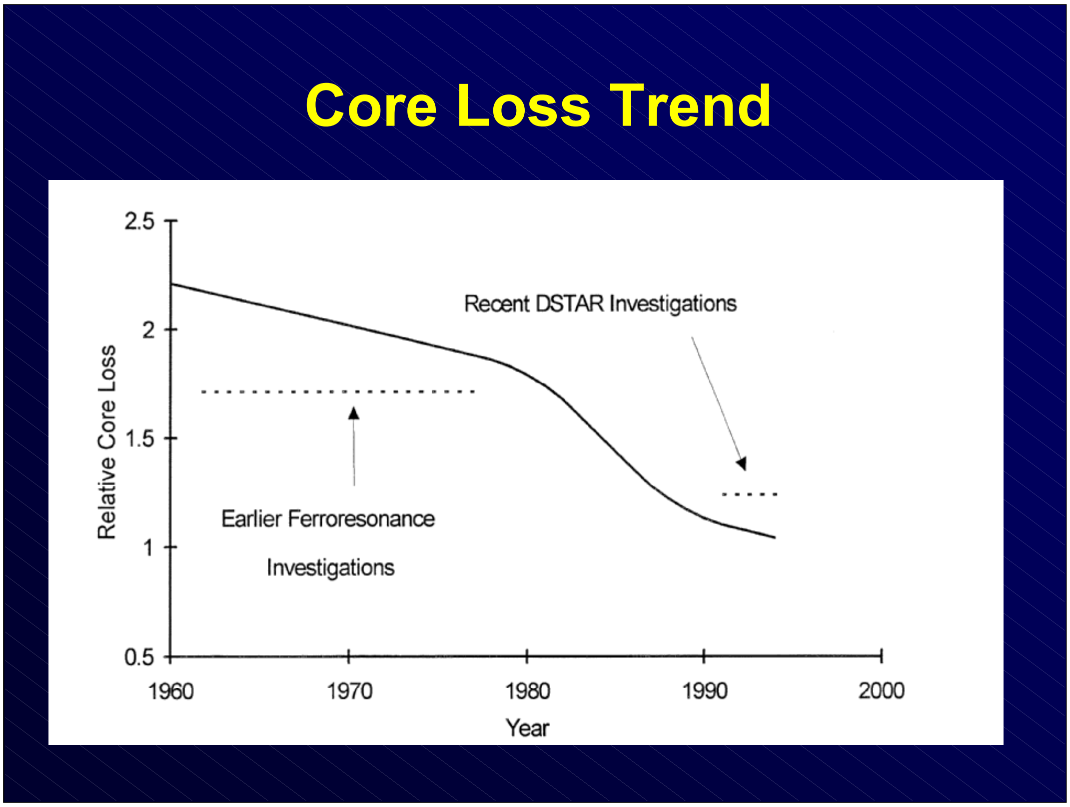
At that time, delta primary windings were the norm.

There was a shift to grounded-wye three-phase padmounted transformers. To avoid tank heating problems due to zero sequence, there was a shift to five-leg core designs

It was originally thought that grounded-wye padmounts were immune to ferroresonance, but Dave Smith published a landmark paper in 1975 showing that the magnetic coupling of the 5-leg core design results in ferroresonance for even this winding configuration.

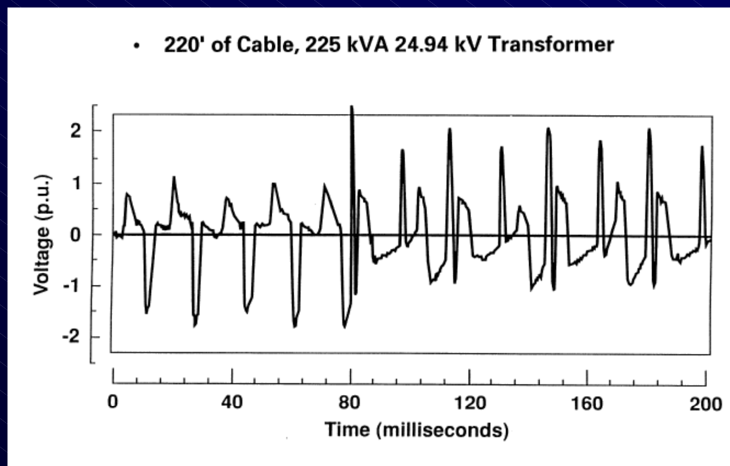
Guidelines indicating how much cable capacitance can be switched with a certain transformer were developed and used by the industry.

In the 80's, these guidelines began to fail, ferroresonance began to occur for "safe" conditions.



At this time, there was also a sharp drop in typical distribution transformer core loss levels, due to widespread adoption of loss evaluation in this period.

Previously "Safe" Condition



Here is so-called "safe" condition under the old guidelines, which indicate that no overvoltage would occur. These are pretty serious overvoltages, which persist for as long as the transformer is open-phased.

Previous Ferroresonance Avoidance Guidelines

- Developed prior to DT loss evaluation
- Based on X_c/X_m or similar criteria
  - X_c = capacitive reactance of cable on open phase
  - X_m = transformer excitation impedance
- Transformer winding capacitance ignored

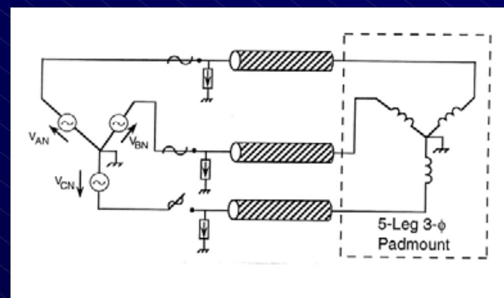
The old guidelines were developed prior to loss evaluation.

They also were based on Xc/Xm , or similar criteria, based on the excitation impedance of the transformer.

Also, transformer winding capacitance was ignored in these guidelines.

Open-Phase Circuit Configuration

- Phase-by-phase switching routine in distribution
- Switching may be at a remote point
  - Leaves cable capacitance on open phase
- Core magnetic coupling causes open-phase to be backfed via nonlinear excitation impedance



5-Leg core configuration

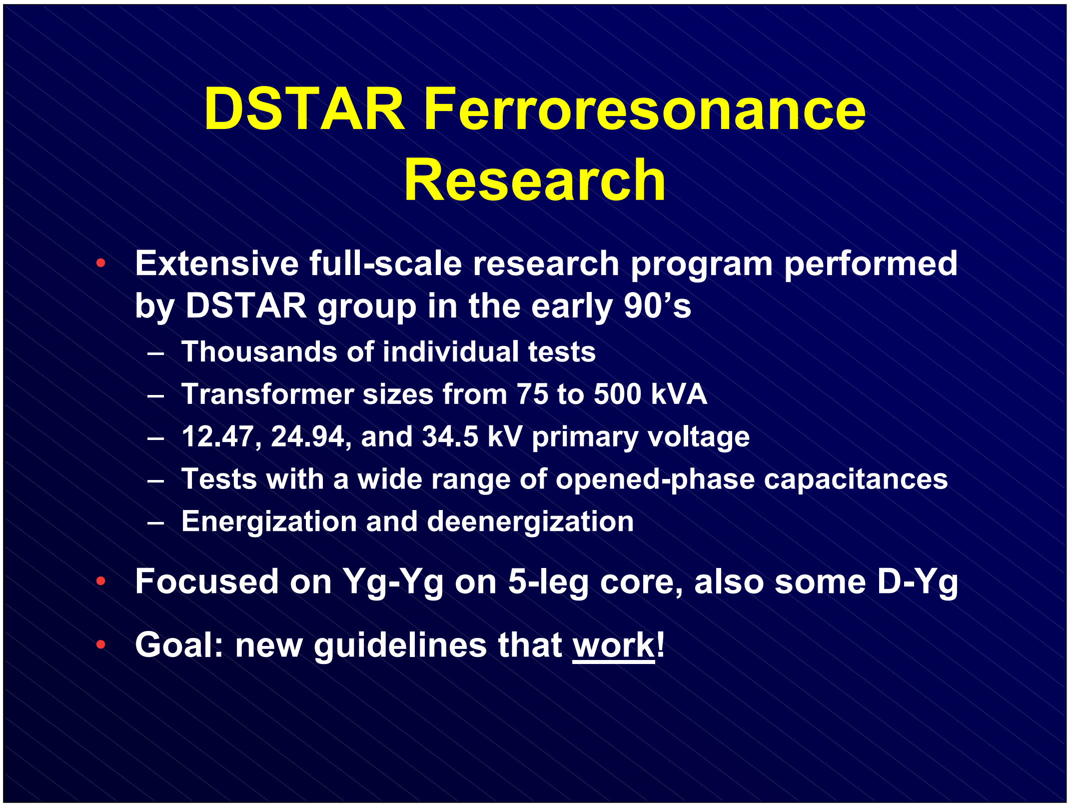
Here it the circuit configuration we are talking about.

Distribution transformers are typically switched a phase at a time, usually by pulling loadbreak elbows or opening fused cutouts.

The convenient switching point may be remote from the transformer, say at the riser pole where the underground cable feeding the transformer taps into the overhead line.

The remote switching leaves a transformer phase open, with significant phase-to-ground capacitance connected to the open phase.

At the bottom, you see a drawing of the 5-leg wound-core design, which gives the interphase couplling which effectively backfeeds the cable through the transformer’s nonlinear excitation impedance.



Because of these failures of the old guidelines, The DSTAR utility research group commissioned GE to perform extensive research involving thousands of individual tests.

These tests covered the range of common distribution voltages and 3-phase padmount transformer sizes up to 500 kVA.

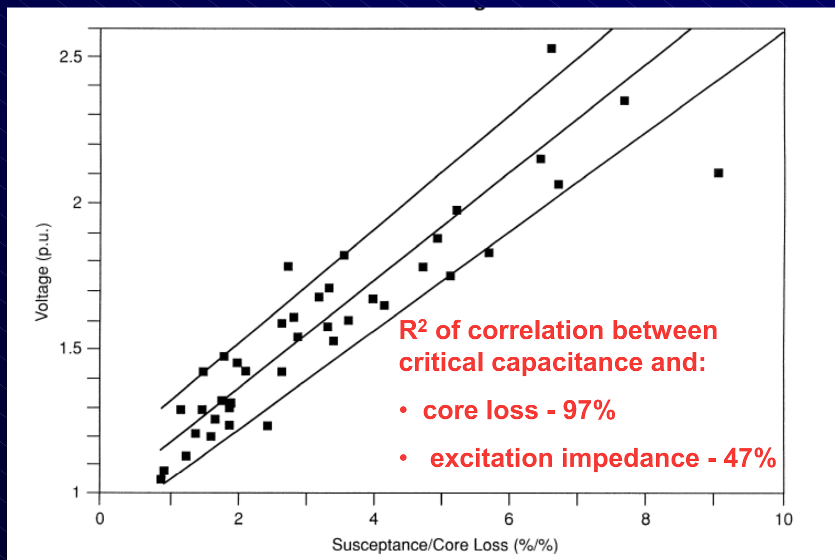
Various lengths of cable were used to test different capacitance values.

The tests included phase-by-phase closing and opening operations in a variety of phase orders

We focused on grounded-wye-wye transformer on 5-leg cores, but also included some testing on delta-wye padmounts.

Our goal was to develop new guidelines that work!

Correlation of Ferroresonant Overvoltage to Core Loss



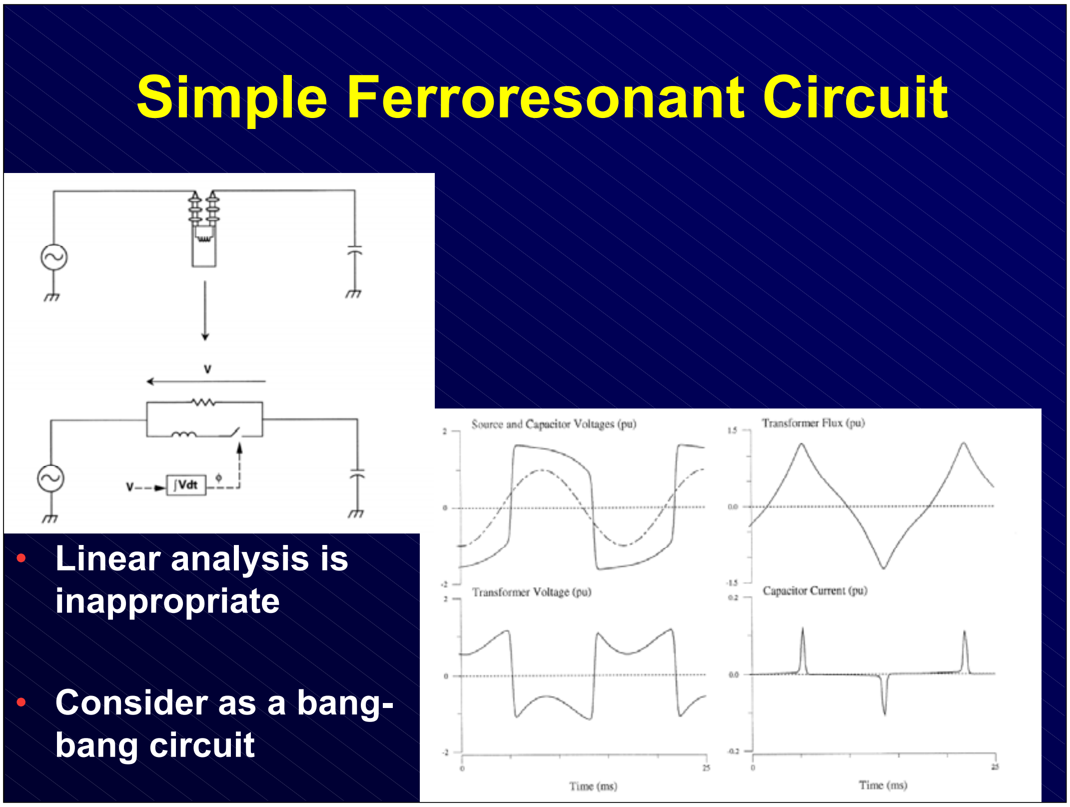
In our reduction of test results, we originally tried to correlate the critical capacitance causing ferroresonance to the transformer's excitation impedance.

Very poor correlations were found.

We discovered that the correlation of per-unit capacitive susceptance to per-unit core loss was excellent.

Furthermore, when the totality of tests is included, the worst-case overvoltage magnitude for a specific transformer and cable length pair tended also to be linear to the susceptance to core loss ratio.

This was true for both maximum peak overvoltage and sustained peak overvoltage after several seconds.



•The simplified single-phase ferroresonant circuit shown here helps to understand why core loss is so important.

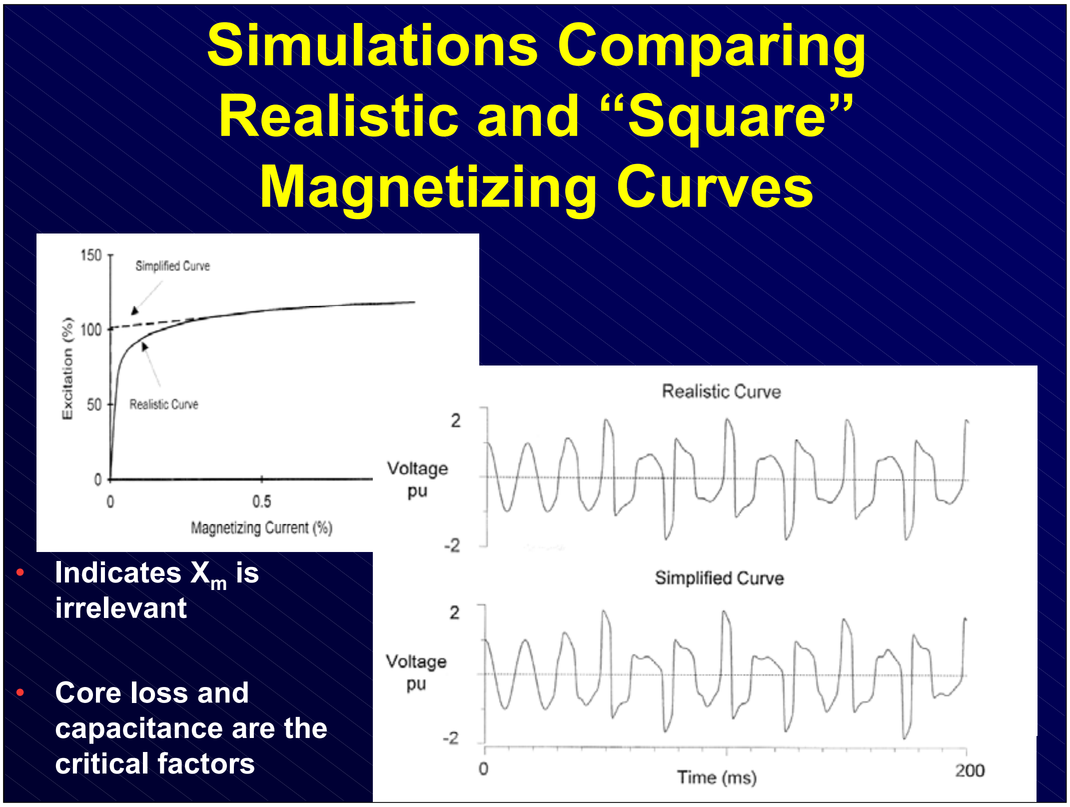
Rather than consider the transformer in a linear manner, consider it to be a flux-controlled switch. When the flux is below the saturation level, the switch is open, and the capacitance and ac source are only connected through the high core-loss resistance. If this resistance were infinite (or no core loss), the voltage on the capacitance is trapped.

•The transformer voltage is the difference between the trapped capacitive voltage and the ac source. The integral of this voltage is the flux. The flux increases linearly with time until the saturation point is reached.

•When saturation is reached, the flux-controlled switch closes, the capacitance discharges into the source via the air-core inductance. Because we have an L-C circuit, the voltage overshoots the source voltage. At about the peak overshoot, the core comes out of saturation, and the voltage is again trapped. This process repeats to create roughly square waves of overvoltage.

•The core loss allows some of the trapped charge to "leak off". If the leakage is sufficient, the amount of voltage at saturation is too small to overshoot sufficiently to continue the process, and there is no ferroresonance

•Thus we see how core loss affects the ability of the circuit to sustain ferroresonance



We did some EMTP simulations, using a duality model of the 5-leg transformer core.

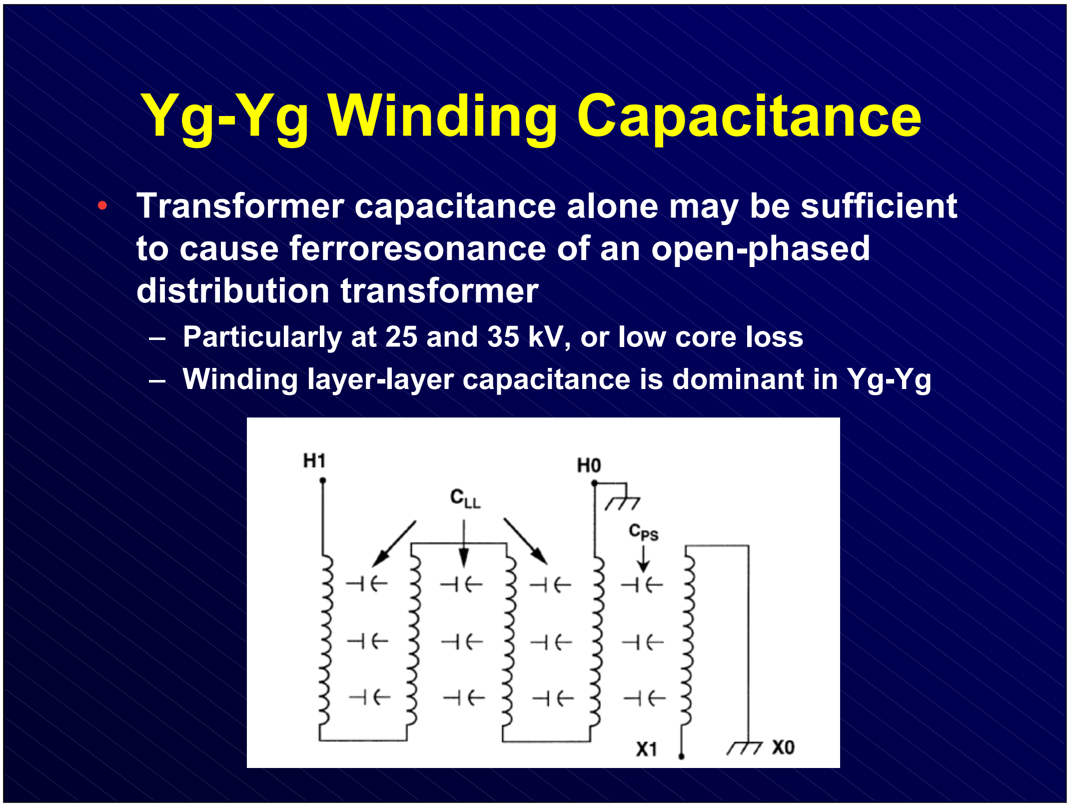
We used two different saturation curves to evaluate the effect of magnetizing impedance on ferroresonance.

One is a realistic curve.

The other represents only the air core impedance slope, and the saturation level. The unsaturated magnetizing inductance is infinite.

Note that the time-domain results are almost completely identical.

This is further evidence that the inductive component of excitation is not of practical relevance to ferroresonance.



Also, we noted that transformers sometimes go into ferroresonance with no external capacitance or cable on the open phases.

We found that there is significant winding capacitance in a distribution transformer.

In a wye-wye transformer, the net effect of the layer-to-layer capacitance is dominant. This capacitance can be several nano-farads

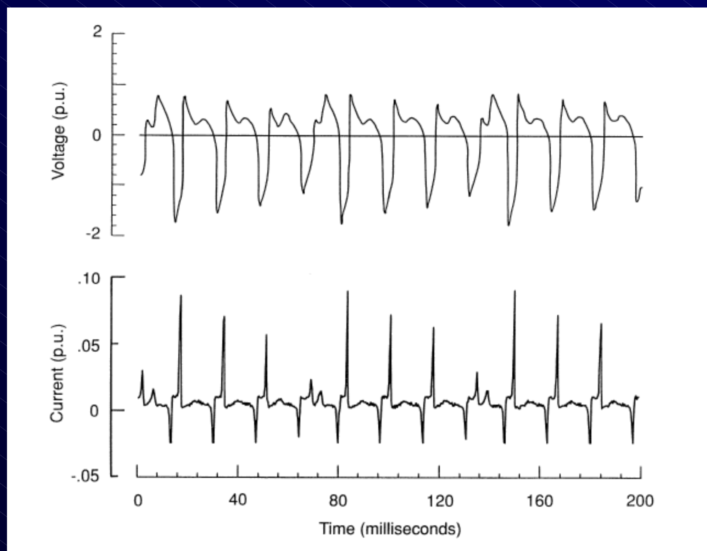
Transformer capacitance assumptions were also built into our guidelines

Summary

- Capacitance and core loss are the key determinants for ferroresonance
- Inductive component of exciting current is not of practical relevance
- Must consider transformer capacitance in addition to external (cable) capacitance
- DSTAR guidelines based on this research have been successfully used to avoid ferroresonance problems by dozens of utilities for the past decade

Read them

Transformer Exciting Currents Small, Minimal Thermal Duty on Transformer

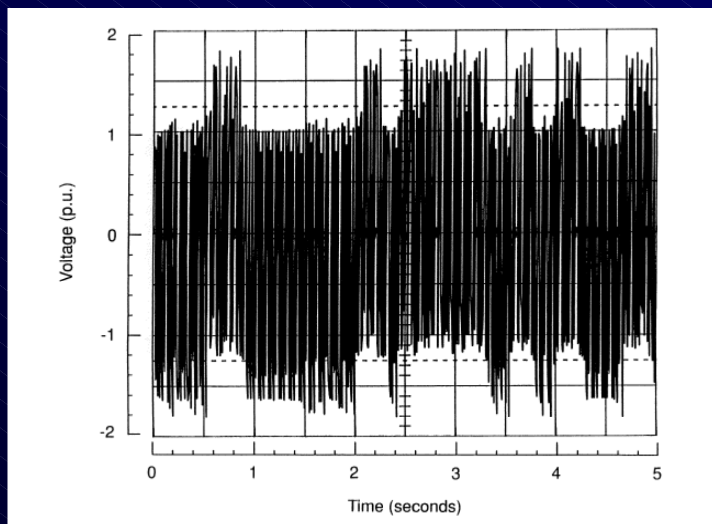


Here are some additional waveform plots of interest from our research.

Measured exciting currents during ferroresonance were quite small; the flux just gets to the rounded part of the saturation curve.

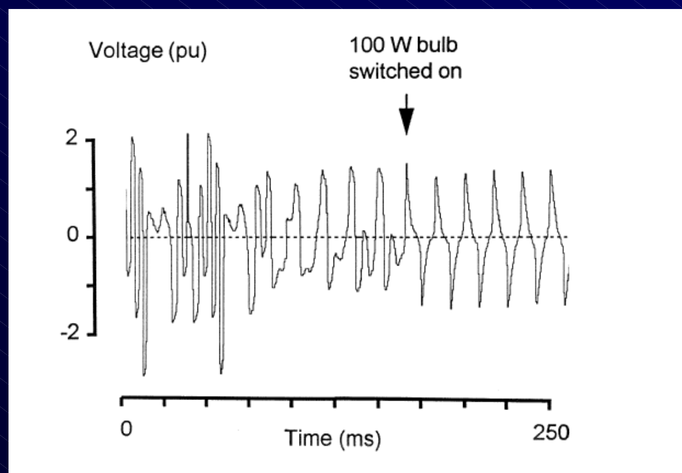
These low currents should not create a significant thermal duty on the transformer. We did not notice any significant heating on our test transformers in ferroresonance, including on some tests which continued for many tens of minutes.

Chaotic Ferroresonance



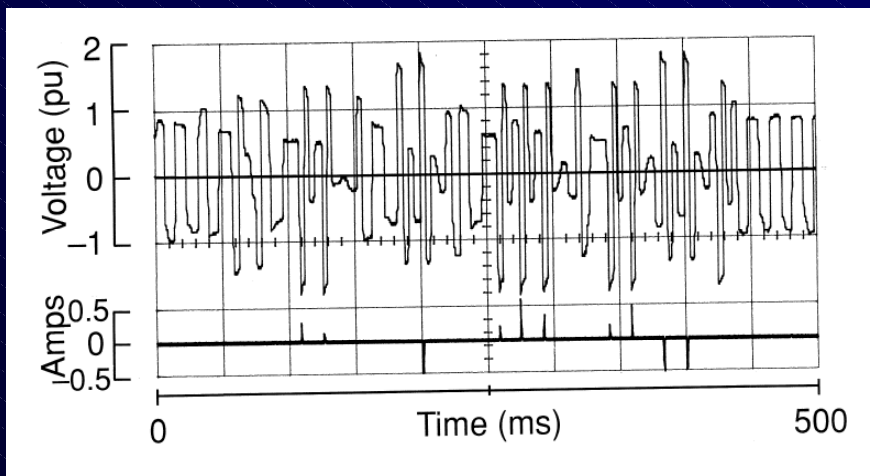
Here is Bruce's favorite topic. This shows the voltage waveform envelope for a transformer in chaotic ferroresonance.

Lightbulb Load Squelches Severe Ferroresonance on 75 kVA Amorphous Transformer



In this test, overvoltages were greater than 3 p.u., we connected a 100 W light bulb on the secondary side of the open phase, and the resulting peak voltage is only a little above rated, and the rms value is even less.

Chaotic Ferroresonance MOV Arrester Limits Voltage with Light Arrester Duty

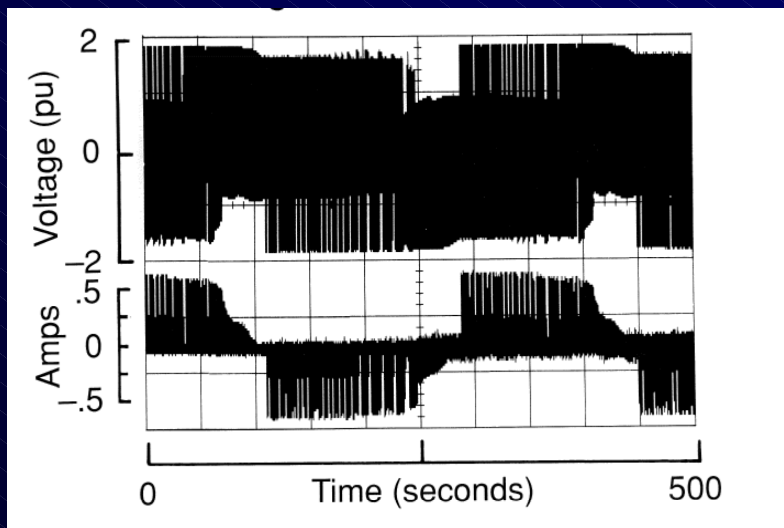


Here is a test with an MOV arrester on the open phase.

The overvoltages are clipped to less than 2 p.u., yet arrester current peaks are on the order of a few hundred milliamps. In this case, the voltage without the arrester would be on the order of 3 p.u.

Note also that the arrester conduction is sporadic, with periods of no conduction at all.

Very Slow Cyclic Interaction Between Ferroresonance and MOV Arrester Conduction



We also noted some strange cyclic interactions between ferroresonance and arrester conduction with some very long periods.

In this test, the pattern of the voltage and arrester current envelopes repeat exactly with a five-minute period.

This appears to be an interaction with the ferroresonant voltage, which is asymmetric about the zero-volt line, or even-order distorted. The arrester conducts only on one polarity. The "dc" current component slowly shifts the flux bias in the transformer, and the wave asymmetry abruptly reverses, causing the dc component to reverse. Really, the dc component in the arrester is very low frequency ac.