# Ferroresonance in Low-Loss Distribution Transformers

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*Abstract*—**Field experience indicates that ferroresonance events occur more readily with low-loss distribution transformers, compared to distribution transformers with conventional loss levels. Extensive testing of a large number of transformers has shown a very strong and direct correlation between transformer core loss and the amount of capacitance needed to sustain a ferroresonant condition. A heuristic explanation is provided to show the important role of core loss in the ferroresonant circuit.**

*Index Terms*—**ferroresonance, temporary overvoltages, distribution transformers.**

## I. INTRODUCTION

In the 1980's and 1990's, the utility industry began to recognize the role of losses in the life-cycle costs of distribution transformers. Loss evaluation factors were applied by most utilities to the transformer procurement process, adding the estimated cost of losses to the transformer price. In response, distribution transformer manufacturers developed and offered lower loss designs. The introduction of low-loss transformers, however, appeared to coincide with the increasing frequency of ferroresonant overvoltage events. Many of these events occurred under conditions which conventional ferroresonance avoidance guidelines suggested would not result in ferroresonance.

Ferroresonance is a complex nonlinear phenomenon, involving interaction between the saturation characteristics of a transformer, and a capacitance. Ferroresonance is capable of producing sustained overvoltages with peak magnitudes approaching, and sometimes exceeding, two times the rated peak voltage.

In the normal distribution context, ferroresonance occurs when one or two phases of a three-phase transformer, or a three-phase bank of transformers, are connected to a fundamental frequency source, and the remaining phases are left open with some form of capacitance left connected to the transformer terminals, such as is illustrated in Figure 1. This capacitance is most frequently provided by underground primary cables, but sometimes is provided by overhead lines or by the stray capacitance of the transformer winding itself.

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Normal distribution practice is to energize and deenergize three-phase distribution transformers a phase at a time, usually by operating fused cutouts or cable elbows (separable connectors). Often, the switching location is remote from the transformer location, resulting in a significant capacitance being connected to the unenergized terminals of the transformer. During both phase-by-phase energization and deenergization, the topological configuration needed for ferroresonance is present. Whether or not it occurs is dependent on the amount of cable capacitance connected to the open phases, and on the parameters and connection of the transformer. Ferroresonance most readily occurs for transformers with ungrounded primary windings (i.e., delta, floating wye, open delta). It can also occur for the grounded-wye-wye connection, when the transformer is on a four or five-leg three-phase core. These core configurations are universally used for three-phase padmounted wye-wye distribution transformers.
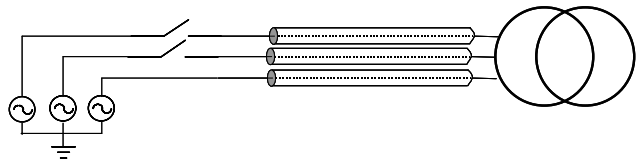


Figure 1. Illustration of a two-phase-open condition sometimes leading to ferroresonance.

## II. CONVENTIONAL GUIDELINES

Ferroresonance susceptibility has been conventionally expressed relative to the transformer excitation impedance. This impedance, as traditionally defined, is the rated transformer primary voltage divided by the rms exciting current. It is commonly denoted as $X_m$, as if it were purely reactance, even though the exciting current has significant real and imaginary components.

Conventional guidelines by Hopkinson [1, 2, 3], and others define the threshold of significant ferroresonance by the ratio of $X_m/X_c$, where $X_c$ is the reactance of the cable or line capacitance connected to the open phase or phases. Depending on the transformer winding configuration, Hopkinson provides critical $X_m/X_c$ thresholds where ferroresonance can be expected to occur.

Note that the $X_m/X_c$ threshold does not directly consider core loss. With low-loss transformers, there has been many instances of ferroresonance occurring for $X_m/X_c$ thresholds

below the critical values suggested by Hopkinson. It became evident during the 1990's that these conventional guidelines were no longer applicable for modern low-loss distribution transformers.

### III. FERRORESONANCE TESTING

Large scale testing program were initiated to investigate ferroresonance in modern low-loss distribution transformers, seeking an explanation for the increased frequency and to define the relationship to circuit parameters. These tests were performed by the author's company, and for the DSTAR (Distribution Systems Testing, Application, and Research) utility consortium. The results of the extensive testing indicate that the conventional ferroresonance avoidance guidelines were focused on parameters which are not well correlated to the ferroresonant condition, and ignored the most decisive parameter.

Thousands of individual tests were performed, using three-phase padmounted distribution transformers ranging from 75 kVA to 500 kVA, with rated primary voltages in the 15, 25, and 35 kV classes. The testing program emphasized grounded wye-wye transformers on five-leg wound cores. However, testing was also performed on padmounted transformers with five-leg stacked cores and delta primary units. The testing included transformers with both low-loss silicon-steel cores, and amorphous metal cores.

The testing involved phase-by-phase energization and deenergization of the sample transformers with varying amounts of cable capacitance connected. Phase voltages were oscillographically recorded to identify the peak phase voltage, and the peak sustained voltage present two minutes or more following the switching event. Further details on the DSTAR testing are provided in [4].

### IV. TESTING RESULTS ANALYSIS

Two different criteria were established to define the occurence of significant ferrorsonance. These are 1) a maximum overvoltage greater than 1.6 p.u., and 2) a sustained overvoltage greater than 1.25 p.u. For the various transformers tested, the critical $X_c$ for significant ferroresonance was plotted versus the $X_m$ for that transformer. The correlation was unreliable, with significant outliers from the general trend.

Analysis of the outliers indicated core loss might be a significant factor. The correlation of the critical cable capacitance to the transformer core loss was tested as an alternative. The correlation was extremely good, with an $r^2$ of 96.6% for the maximum overvoltage criterion, and 92.2% for the sustained overvoltage criterion for grounded wye-wye transformers on 5-leg cores. The maximum overvoltage correlation is shown in Figure 2. Further testing indicated that these results remain valid even for radically different transformer core materials, such as silicon steel versus amorphous metal.

For each series of tests involving a particular transformer and capacitance, the most severe maximum and sustained overvoltages were identified. These overvoltage values are plotted versus the ratio of per-unit capacitive susceptance ($B_c$) divided by the per-unit transformer core loss ($P_{nl}$), (all on the voltage and kVA base of the transformer) in Figure 3 for grounded wye-wye distribution transformers. A good correlation can be observed, indicating that the $B_c/P_{nl}$ ratio is a good predictor of the susceptibility of ferroresonance and of the overvoltage magnitude which might occur.
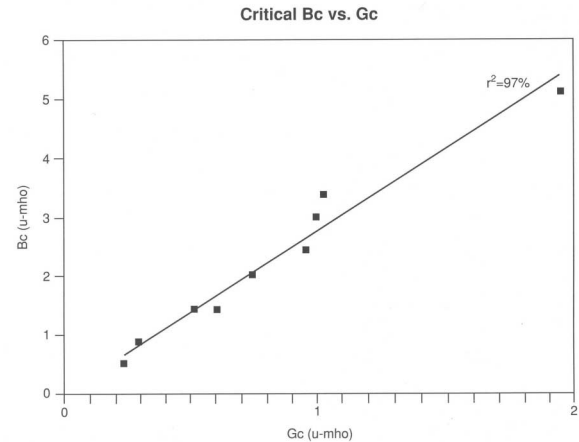


Figure 2. Correlation of the critical capacitive susceptance to reach a 1.6 p.u. peak ferroresonant overvoltage with core loss conductance, for grounded wye-wye distribution transformers constructed on 5-leg wound cores.
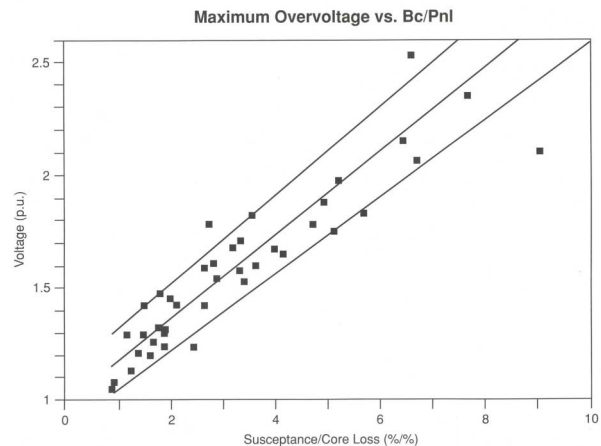


Figure 3. Correlation of peak ferroresonant overvoltage to the susceptance to core loss ratio for grounded wye-wye distribution transformers constructed on 5-leg wound cores.

### V. NEW FERRORESONANCE AVOIDANCE GUIDELINES

Using these test results, new ferroresonance guidelines were developed for each of the common primary winding configurations, based exclusively on capacitance and core loss. Unlike the conventional guidelines, the new guidlines do not include the rated transformer exciting current, or excitation impedance, as a parameter. These guidelines have been adopted and used successfully for over a decade by the

DSTAR member utilities.

Because the core loss levels of modern distribution transformers are generally substantially less than those made many years ago, prior to loss evaluation and transformer core technology improvements, the new guidelines indicate a much greater restriction on operating practices is necessary to avoid ferroresonance. Typically, the maximum cable length that can be switched with a three-phase grounded wye-wye transformer is about one-fifth of the length suggested by the conventional guidelines.

## VI. SIGNIFICANCE OF CORE LOSS

Many explanations of ferroresonance, and the significance of various circuit parameters, have been made using fundamental frequency or linear circuit analysis. Ferroresonance, by nature, is a highly nonlinear phenomenon and linear techniques are inappropriate.

Perhaps the "resonance" in the term ferroresonance leads many engineers to incorrectly think in terms of a tuned circuit. It is far better to consider the phenomenon in terms of a "bang-bang" circuit, with discrete events swinging the voltage from level to level. Rather than considering the transformer as an inductance, it can instead be considered as a flux-controlled switch, in parallel with a large resistance representing core loss. When the flux (integrated volt-seconds) across the switch reaches a critical value, it closes and remains closed until the flux drops below the critical value.

In a simple ferroresonant circuit, the transformer is in series between the fundamental frequency source and the capacitance. When the "flux-controlled switch" is open, the voltage on the capacitance is trapped, except for "leakage" through the core loss resistor. When the voltage difference between the trapped capacitor voltage and the sinsoidal source reaches the saturation value, the "switch" closes, discharging the capacitance through the small saturated inductance (air-core inductance) of the transformer. Because this is an L-C circuit, the voltage will overshoot to the opposite polarity, where it again becomes trapped when the transformer drops out of saturation and the effective "flux-controlled switch" opens. If the core loss is small, there is very little leakage of the trapped charge from half-cycle to half-cycle. This allows energy to build up in the circuit and sustain the ferroresonant behavior. If the core loss is sufficiently large, the trapped capacitor voltage decays fast enough so that the transformer flux does not reach the saturation value one-half cycle later. This breaks the ferroresonant process.

In acutality, the process is more complex than indicated by this simple analysis. The core loss has a dominant hysteresis component which is not completely reflected by representation as a linear resistance. In multi-phase circuits, there are multiple capacitances and nonlinear inductances, greatly complicating the behavior. However, this simple heuristic explanation indicates how core loss can play the overwhelmingly significant role that was empirically observed during testing.

## VII. CONCLUSIONS

Ferroresonance involving three-phase distribution transformers, when switched phase-by-phase, has been found to be strongly correlated to the ratio of per-unit capacitive susceptance to per-unit transformer core loss. Most modern distribution transformers have significantly smaller core losses than older transformer designs, thus explaining the increase in field observations of distribution ferroresonance.

## VIII. REFERENCES

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## IX. BIOGRAPHIES

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