Back to Table of Contents

A Review of Ferroresonance

John Horak, Basler Electric Company

There is a little confusion in literature as to what constitutes a ferroresonant circuit. In most, ferroresonance refers to electric circuit conditions where an inductance is oscillating into and out of its magnetic saturation region and where the oscillations involve an interaction with local capacitance. Some also use the term to refer to a system with transformers approaching saturation where there is voltage rise that occurs when X_L and X_C are in series and due to the effective canceling of impedance, current rises and voltages across the elements rise, even though the transformer never enters saturation. In the case of actual transformer saturation, there is a resonant mode occurring, but one that is much harder to analyze than the classical linear circuit resonance.

The concerns and damage that are most commonly associated with ferroresonance include high peak voltage relative to other equipment and relative to ground, abnormal voltage waveforms (magnitude, phase angle, and harmonic content), and high core heating resulting from a core being driven deep into saturation and from high excitation harmonics causing high eddy current losses.

The Ferroresonant Electric Circuit

Before entering into the theory of ferroresonance, it may help to be able to recognize some typical circuit configurations that have a ferroresonance risk. The listing below is not exhaustive, but gives an overview. The ferroresonant circuit involves a capacitance and a transformer core. A very lightly loaded network also is involved. Beyond this basic data, there are a multitude of possible circuits that may be involved. Basically, one is looking for series, and to a lesser extent parallel, connections of capacitance and inductance with minimal burdening resistive elements. In a series reactive circuit, the magnitude of the voltage of the capacitive and inductive elements does not algebraically add to the system voltage. As soon as an X_L is in series with an X_C there is a reduced effective impedance and an increased voltage across each element. As soon as a transformer is involved, X_L can be in two states, either $X_{M,SAT}$ or $X_{M,UNSAT}$. In the figures following, a very simplified model of the transformer is used for brevity, showing the transformer with an unloaded secondary with a core simply modeled as X_M. A more complete model will be covered later.

Single Phase Switching of Delta and Ungrounded Wye Windings

A circuit involving either an ungrounded 3 phase transformer (ungrounded wye, delta, or single phase transformer connected phase-phase) is a subject to creation of a series L-C network. The system voltage is set up to look through the magnetizing branch of the transformer into the line-ground capacitance of other phases. In each case, note that the equivalent circuit is a series connection of an inductance and capacitance.

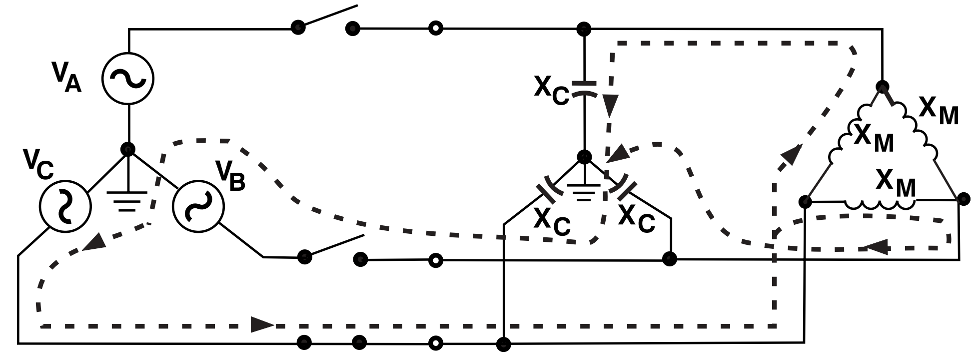


Figure 1a: Xfmr Delta Winding, One Phase Energized

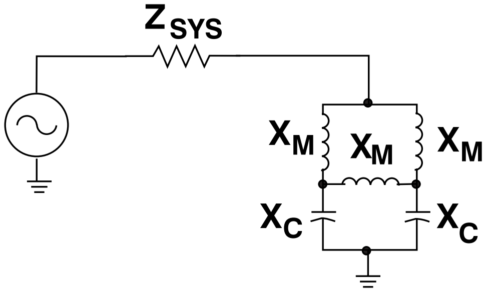


Figure 1b: Equivalent Network

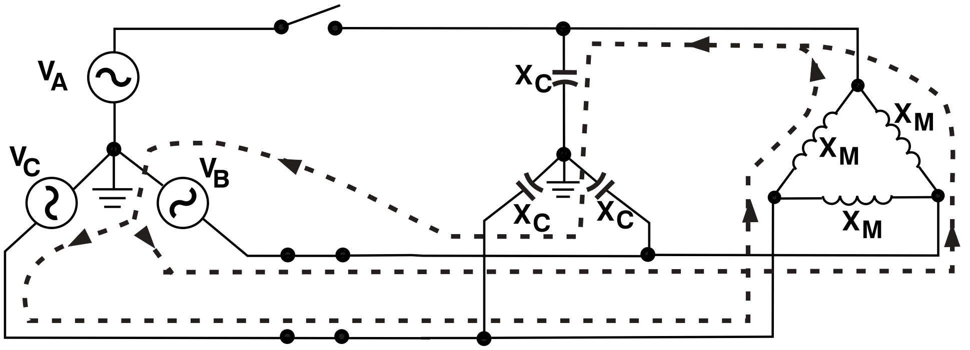


Figure 2a: Xfmr Delta Winding, Two Phases Energized

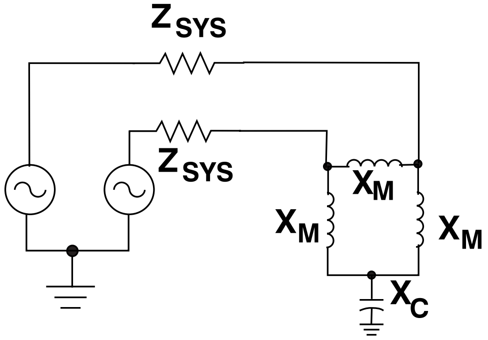


Figure 2b: Equivalent Circuit

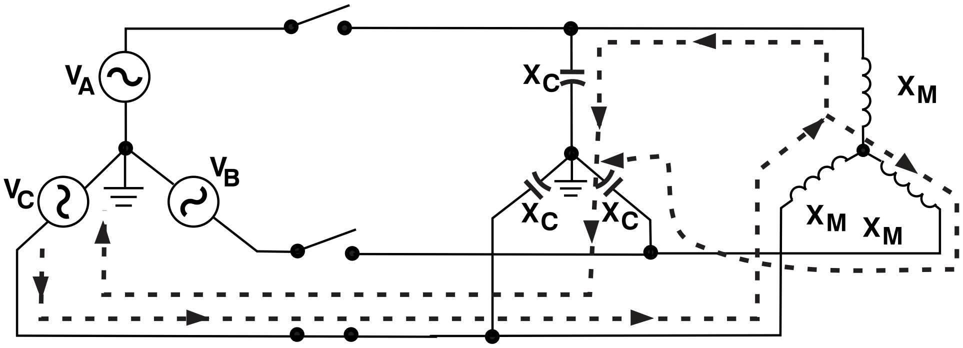


Figure 3a: Xfmr Wye-Ungrounded Winding, One Phase Energized

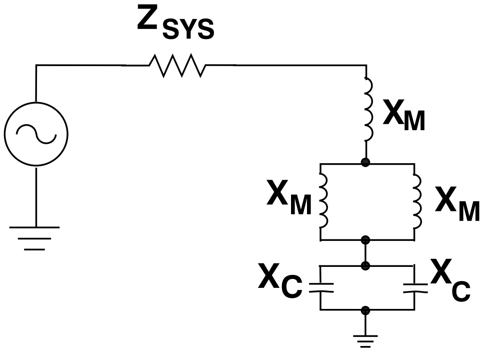


Figure 3b: Equivalent Network

In these circuits, the power system defines the voltage across the total circuit, but does not define the voltage at the midpoints in the circuit, and hence voltage of the open phase (i.e., across X_C) may be high or the voltage across the transformer may be high, which will create high voltage relative to ground and which may be a risk to surge arresters and any connected load. Peak voltage on the order of 2-4pu are commonly reported. The typical recommendation is to keep $X_C/X_{M,US}$ high so as to keep the currents low and magnitude of both voltages low. This will be discussed more later. There are numerous papers printed on the analysis of this circuit. See [1] through [18].

Single Phase Switching of Grounded Wye Transformers with Ungrounded Capacitor Banks

This configuration is very similar to the previous examples, except the system voltage looks through an ungrounded bulk power factor correction capacitor bank into the excitation branch of a grounded transformer. The X_C values here are, generally speaking, much lower in magnitude than the previous examples.

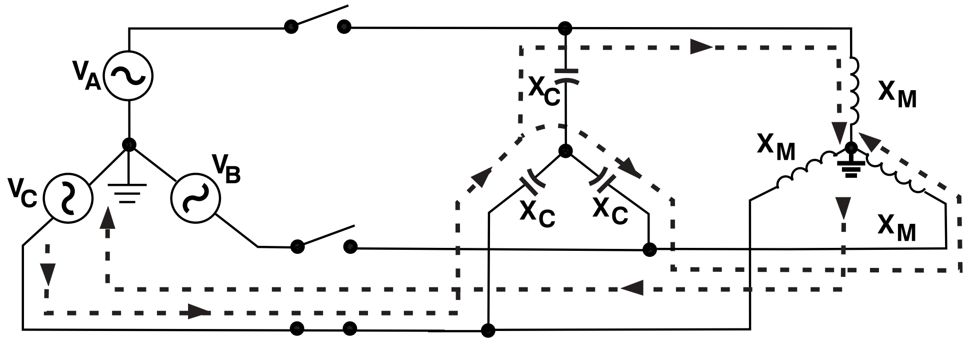


Figure 4a: Wye Grounded Winding, with Ungrounded System Capacitance, One Phase Energized

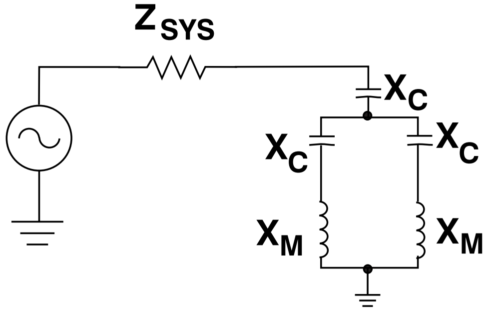


Figure 4b: Equivalent Network

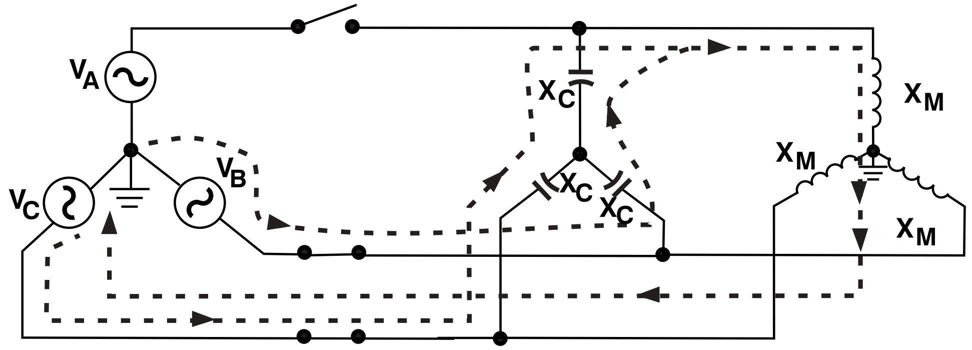


Figure 5a: Wye Grounded Winding, with Ungrounded System Capacitance, Two Phases Energized

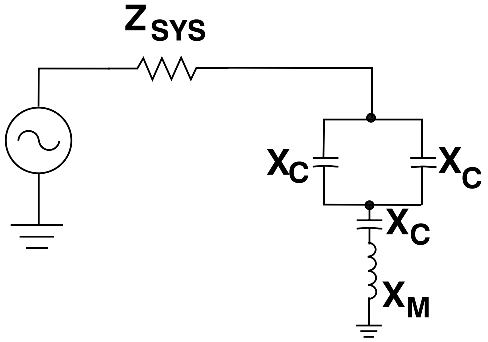


Figure 5b: Equivalent Network

This circuit is very similar to the previous topic, but the order of magnitude of the capacitance has changed. In this case, it is obvious that X_C/X_M, will not be low. Three phase switching or maintaining a load during single phase switching is important in this application for the prevention of overvoltages. This circuit is specifically analyzed in [7].

Magnetically Coupled Phases in 3 Phase Transformers

One approach to preventing ferroresonant circuits from arising is to treat the three phases as independent systems. This means all loads are connected phase to neutral, rather than phase to phase. On first pass it may appear that a three phase Wye-G/Wye-G bank accomplishes this, but that may not be the case. When the phases of a transformer share a common core, one energized phase can couple into the other disconnected phases and excite them. If there is a capacitance on those phases, a resonant condition can be set up.

Consider the 4 core/5 legged transformer design below. Assume only phase A_P is excited, that the secondary is totally disconnected, and that B_P and C_P have some level of connected capacitance but no connected load. The A_P coil sees the flux in cores 1 and 2. Initially, as long as no current flows in B_P, about half the flux needed for A_P back emf (i.e., excitation flux) flows in cores 1 and 2. The flux in core 2 however induces about 0.5 per unit voltage on B_P. This V_B causes current to be driven into the attached capacitance on B_P. The current on B_P decreases net flux in core 2, so an equal amount of increased excitation current is required on phase A. Hence, an effective 1:1 current transformer has been set up between phase A_P and B_p. When the current in A_P increases, this increases the flux in core 1. If the total current on A_P is more than normal excitation current, then core 1 is driven into saturation. Hence, more excitation current flows in A_P, which increases the flux in B_P directly proportionately, and the voltage V_B increases. Now there is a 1:1 voltage transformation between A_P and B_P. A similar transfer of current passes between phase C and phase A, and core 4 operates in saturation as well. Even core 3, depending on the relative magnitudes of X_C on phase B and C, may be operating partially into saturation. The saturation of cores occurs because the transformer is designed to transfer current from primary to secondary, on a common core leg, not from primary to primary. An inspection of the equivalent circuit shows many combinations of L-C networks that could be subject to resonance.

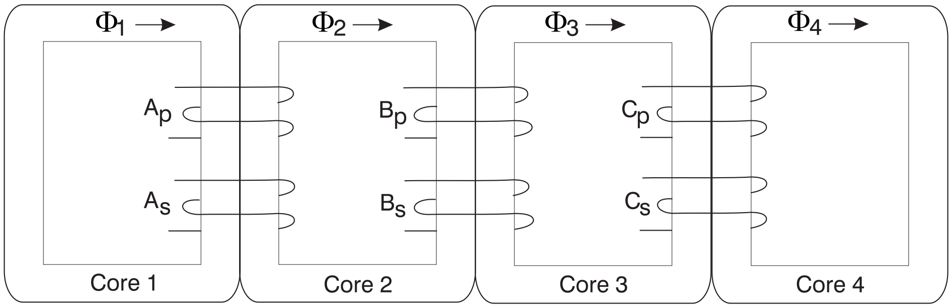


Figure 6a: 4 core 5 legged transformer design

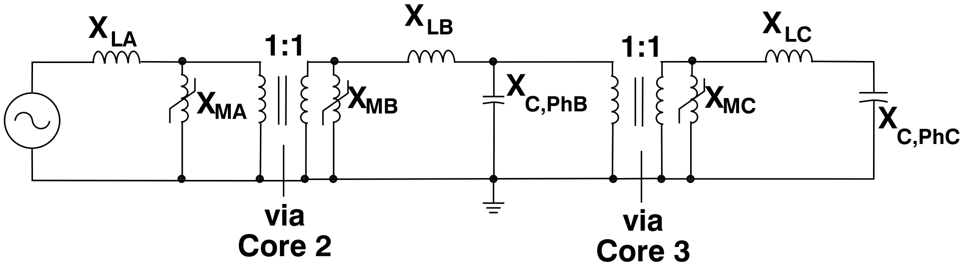


Figure 6b: Equivalent circuit: Excite Phase A and load B and C with X_C

Single core/3 legged transformer (Delta/Wye-G applications) designs and single core/4 legged transformer (Wye-G/Wye-G applications) designs have a similar ability to magnetically couple an energized phase to other phases, though a more complex flux balance analysis is involved.

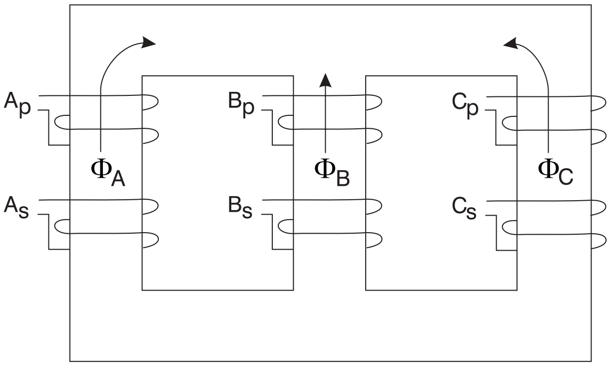


Figure 7a: 3 Legged Transformer Design, for Delta/Wye-G Applications

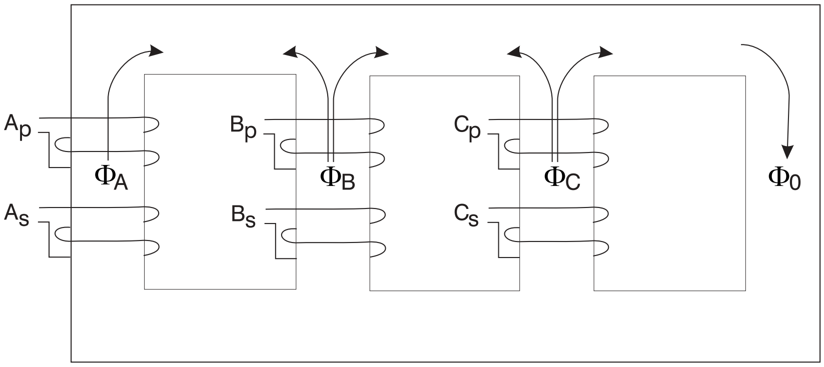


Figure 7b: 4 Legged Transformer Design, for Wye-G/Wye-G Applications

References [8] and [9] both showed that the 4 core/5 legged design transformer easily can go into ferroresonance and [8] showed in tests of actual transformers that the single core/4 legged transformer has just as much capability to enter ferroresonance as the 4 core/5 legged transformer. The peak voltages are typically relatively low, on the order of 1.2 - 1.8 pu, however.

Mutual Coupling onto De-Energized Line that has a Connected Transformer

In most power system engineers' experience, the coupling between two lines is discussed only in terms of zero sequence coupling; i.e., zero sequence current on one line can induce a zero sequence voltage on an adjacent line. There is a similar but weaker coupling between two lines that exists when only normal positive sequence voltages and currents are present. The coupling can be both capacitive and inductive. Assume lines X (phase A, B, C) and line Y (phase A', B' and C') being run on a common tower. The coupling may be simply the effect of phase A and A' being closer together than A-B' and A-C' for an extended distance, hence an open phase A is capacitively coupled more closely to A' than B' and C' and hence A is partially energized to the potential of A'. Similar single phase weak magnetic coupling can occur as well. In most cases the coupling is too minor to be considered in power system studies, but it may be sufficient to create a ferroresonant condition between line to ground capacitance and a de-energized transformer on an isolated section of a line.

Consider the circuit shown below. The only load on the supposedly de-energized line is the magnetizing impedance of the transformer, which could be a VT or a power transformer. The energized line couples, capacitively and inductively, to the de-energized line. As the transformer and lines are low loss devices, once the circuit starts to oscillate (possibly initiated by a through fault on the energized line that induces a large zero sequence voltage on the parallel line), a sustained resonance can be set up, limited mainly by the transformer and line losses.

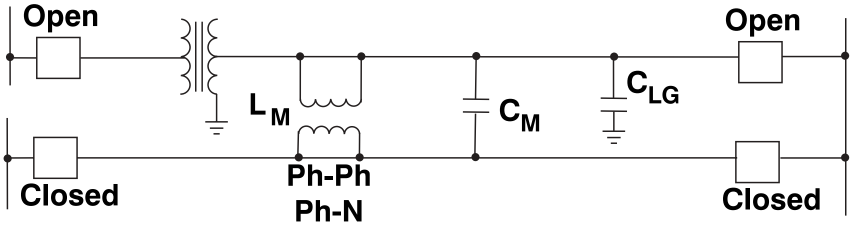


Figure 8: Mutual Coupling to De-energized line

Reference [17] is a report of an occurrence of this condition.

Breaker Contact Capacitance Feeding a Bus with a Voltage Transformer

Breakers can partially energize a dead bus via the capacitance across open contacts, especially breakers with multiple breaks surrounded by grading capacitors. Multiple break circuit breakers are becoming less common, but there are still some being produced and there is an installed base of these devices. The circuit has the elements for ferroresonance: a series L-C network created between the power system, the breaker (and bus) capacitance, and the VTs on the bus. In breakers without grading capacitors, the capacitance across open contacts is on the order of 50pf, which is on the order of 50megohms at 60Hz, so a ferroresonant condition will likely need to involve several breakers in parallel before enough current can be pulled to support ferroresonance. For multiple break breakers the capacitance is on the order of 1000pf.

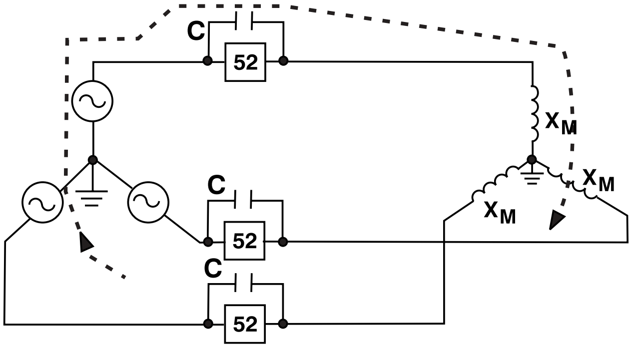


Figure 9: Breaker with Grading Capacitor Feeding a VT

Reference [18] is a report of an occurrence of this condition.

Delta Source Feeding Wye-G/Wye-G Transformers with Ongoing Ph-Gnd Fault

This case is different than the other examples. In this application, (See Figure 10) a nominal to high voltage is applied to a parallel L-C connection so that the voltages across the L and C elements is defined by the source, and now the current in the elements is free to vary from that seen at the source, rather than the voltage across the elements. One way this application arises is when a load entity, fed by a Delta/Wye-G transformer (utility on Delta winding), obtains generation and becomes a Distributed Generator (DG). Upon a ground fault in the utility system, the utility separates. The DG is unable to feed the ground fault with this transformer configuration. One relatively inexpensive protection scheme allowed by some utilities is for the DG to install a Wye G/Wye G connected VT with a 3Vo calculating relay, or a Wye G/Broken Delta connected VT with a 59N element monitoring the broken delta voltage. During a line to ground fault, one VT sees 0 volts, and the remaining two see voltage that is 1.732 per unit of nominal line to ground duty. At this elevated voltage it is easier to see the saturation of the VT and a subsequent resonance. If the VT had inadvertently been ordered based upon only line-ground voltage ratings, rather than line to line voltage ratings, the VT would virtually be assured of saturation on every ground fault, and hence the risk of ferroresonance would an order of magnitude higher. A similar saturation and subsequent resonance can be set up between any line-to-neutral connected power transformers on the line.

If the VT saturates and possibly enters ferroresonance, the secondary voltage will be distorted, the fundamental voltage output may be severely reduced and phase shifted, and hence reducing measured 3Vo. A subsequent failure of the relaying to trip may ensue.

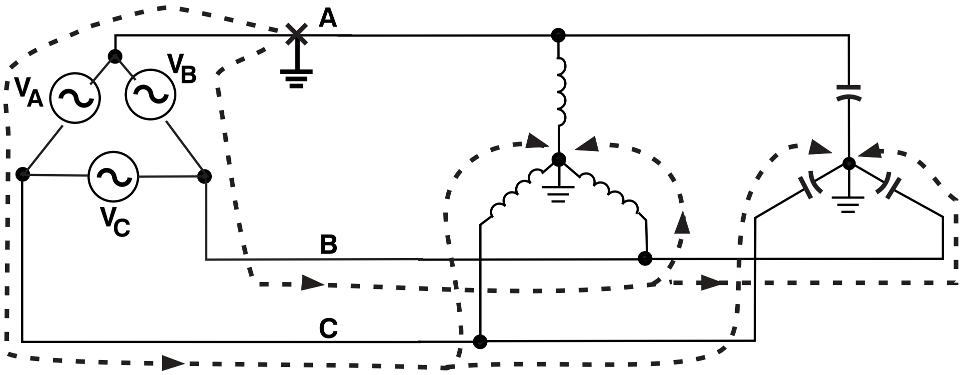


Figure 10: Delta Source Feeding a Ground Fault with Wye-G Transformers

It is common practice in this configuration to connect the VTs secondary in broken Delta and connect a resistor across the broken delta. The intent is to burden the system down; burdening a ferroresonant circuit is a good way to dampen ferroresonance. This topic will be covered further later in the paper.

Capacitive Voltage Transformers

A CVT is a capacitive voltage divider network with a transformer tapped midway into the capacitance string. Further, inductances are added in series with the transformer and capacitance to improve regulation and to compensate for phase shifting that the capacitances introduce. The circuit is an invitation for ferroresonance.

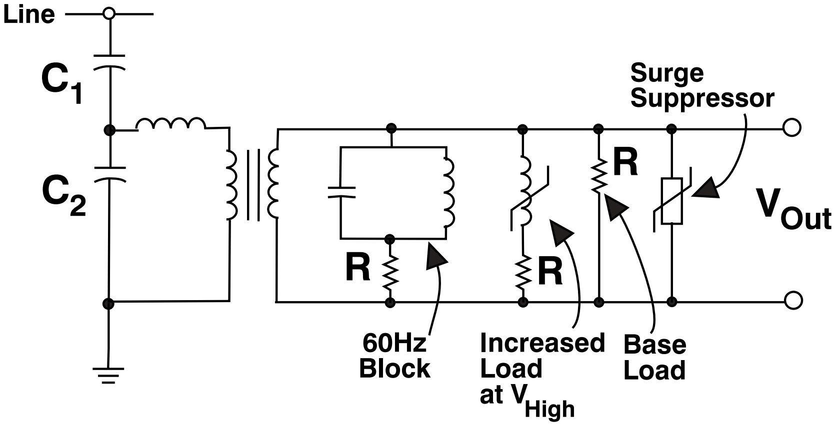


Figure 11: CVT with Possible Ferroresonant Suppression Circuits

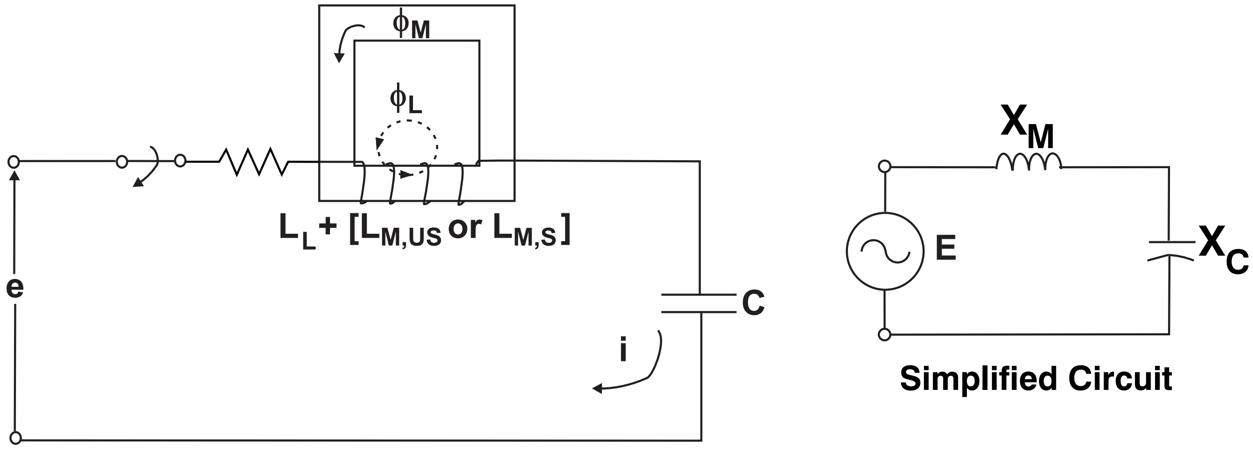
All CVT manufacturers are aware of the ferroresonance characteristics of their devices, and they install appropriate ferroresonance suppression circuits. One suppression concept is to always keep some burden on the CVT. A second approach is to install a load in series with a circuit tuned to fundamental frequency. The circuit blocks fundament frequency from the load and passes other frequencies to the load. A third approach is to add voltage sensitive loading; if voltage increases above normal, saturable reactors effectively add more load. A fourth approach is to add surge suppressors that clamp any abnormally high voltage spikes that might be associated with ferroresonance. A combination of these approaches may be used in a given CVT.

These suppression techniques built into the CVTs removes the need of the user to be concerned about ferroresonance in the CVT, but the user needs to be aware that these circuits can adversely affect the performance of the CVT, especially when rapid changes in voltage magnitude and phase angle are involved. Analysis of the transient performance of CVTs is the topic of a variety of papers and is not covered here.

Analysis of a Basic Ferroresonant Circuit

A basic series ferroresonant circuit is shown below. It includes a series connection of a voltage source, a relatively small circuit resistance, a saturable magnetic core inductor comprising the unsaturated $L_{M,US}$ (which becomes $L_{M,S}$ above saturation) and the leakage inductance L_L, and a capacitance C. The inductor in the circuit typically represents either a power transformer or a voltage transformer rated for continuous voltage 5% to maybe 15% (or higher with some VT applications) above nominal operating voltage, depending on how it is bought and applied, so the inductor is somewhat close to entering saturation.

The resistance in the simple model may be considered negligible. Also, consider that there is no transformer secondary load or primary shunt loading. If only fundamental frequency voltages and currents are involved, the circuit can be converted over to the basic impedance concepts of $X_{L,Total}$ (referred to as X_M for brevity) and X_C. The resultant highly basic circuit is shown below.



Simplified Circuit

Figure 12: Basic Circuit for Analysis

Transformer Modeling

A common measure of excitation is flux density vs. magnetic field strength (B vs. H). However, to make the data useful for power system studies, one needs to have excitation in terms of V and I. An interesting method of converting between B-H curves and the V vs. I is shown. The graph is fairly involved but self explanatory, Start at a given applied voltage. Trace upward to find the corresponding flux level. Note the voltage is the derivative of flux (v=df/dt) so if there is no offset from 0 to the flux and the input voltage is a clean sine wave, the flux is a 90^0 phase shifted reproduction of the voltage sine wave. Thereafter, trace across to find the corresponding B, then H, and then the associated current. Finally plot the current against the voltage curve to see I vs. V.

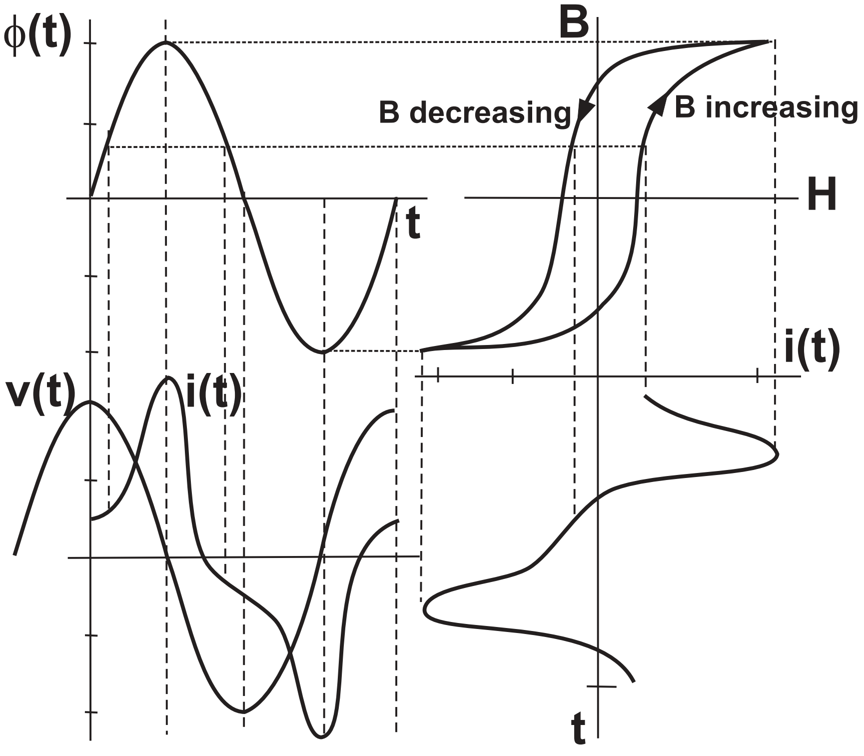


Figure 13: Steel DC / AC Excitation Curve; B vs. H

It can be seen by this example above that a notable source of error is being introduced by simply modelling the core as an equivalent X_M. The core effective impedance is fairly complex and has a high harmonic content. However, for most cases, a simple inductance can give one the conceptual tools needed. To further simplify the matter, and develop a representative transformer voltage vs. excitation current curve, an approximate AC excitation curve is shown below.

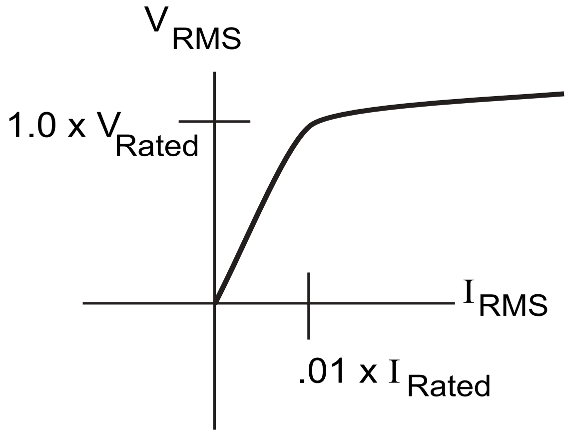


Figure 14: Transformer AC Excitation Curve, V_{RMS} vs. I_{RMS}

The RMS excitation curve loses some details of excitation current:

- Since the graph is in terms of RMS quantities, and since voltage is a derivative of flux rather than a direct measurement of flux, the harmonic quantity, phase relationship, and instantaneous magnitude of current vs. voltage is lost.
- The hysteresis effect is lost.

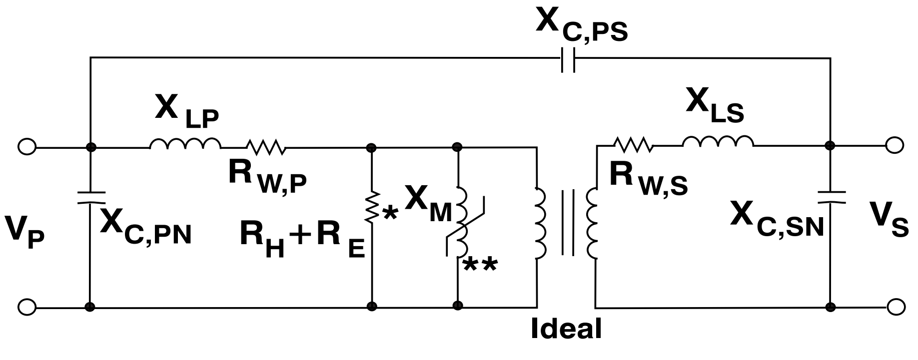
It may be a hair-splitting effort to carry transformer modeling to a high degree, but to be complete, a model will need to account for several other aspects of a transformer:

- Eddy current loading effects. It may be very difficult to separate eddy current losses from hysteresis losses.
- Capacitive current flow including winding to winding and winding to ground.
- Magnetic coupling between phases and the multiple legs of the transformer, each possibly saturating at a different current level (possibly due to current in neighboring windings).

In most published analysis of ferroresonance, transformer phase to ground and winding to winding capacitance is ignored, but as discussed in [9], there are cases where the transformer capacitance may be important in the analysis.

Typical transformer capacitance may be hard to find. The best likely source of data is likely typical transformer insulation testing. Manufacturers, when testing excitation current, typically make no attempt to separate the capacitive current flow into the excited winding from the inductive excitation current.

A model of a single phase transformer, including the capacitance, follows.



* Frequency and voltage dependent

** Complex model; highly non-linear

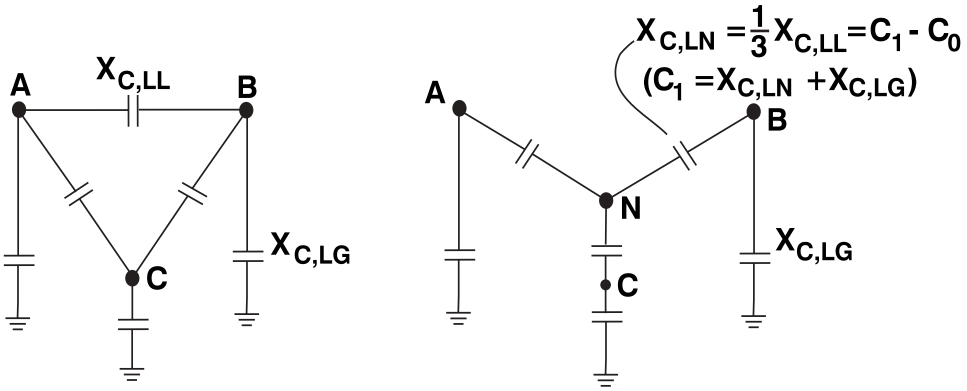
Figure 15: Transformer Model

Line Capacitance

One can refer to [22] and [23] for calculation of line sequence component capacitances. However, one should be aware of a couple aspects of sequence component capacitances.

The system positive sequence shunt capacitance is the balanced capacitive loading each phase sees. The positive sequence shunt capacitive loading includes both phase to ground capacitance and phase to phase capacitance. The phase to phase delta impedance, if completely balanced, can be represented as an equivalent wye load where $X_{C,LL} = 3X_{C,LN}$, and where the neutral of this equivalent wye will be at ground potential. Hence, to determine the phase to phase capacitance in a balanced impedance system, one needs to perform the calculation: $X_{C,LL} = 3(X_{C1} - X_{C0})$. In cables $X_{C1} = X_{C0}$ so this calculation will show $X_{C,LL} = 0$.

For real world applications, the phase to phase and phase to ground capacitances are not the same for each phase. Note sequence component impedances assume symmetrical phase impedances; e.g., $Z_{an} = Z_{bn} = Z_{cn}$. Most sequence component calculations such as those in [22] and [23] find a mean distance between the conductors and ground using an RMS-like approach, so one can only approximately recreate the individual phase and ground capacitances from X_{C1} and X_{C0}.



a) Delta Line-Line Capacitance

b) Equivalent Wye Line-Neutral Capacitance

Figure 16: Line Capacitances

Fundamental Frequency Linear Circuit Analysis

There have been numerous technical articles written over the years (see many of references) that have used a fundamental frequency linear circuit approach to analyzing the ferroresonant circuit. The material below cannot give the entire content of these resources but will serve to give the conceptual frame they work in and summarize some of their important points. The papers tend toward finding a maximum X_C that can be allowed for a given $X_{M,US}$ that will limit V_{Xfmr} and V_C to some specified maximum. As long as the transformer X_M remains in the linear $X_{M,US}$ region and system resistive elements are small, the voltage V_{Xfmr} and V_C is a simple calculation using linear circuit theory. In most of these approaches, a minimum ratio for X_C/X_M is chosen as the guideline. The typical guidelines for minimum X_C/X_M ranges greatly depending on the system and the transformer configuration.

For example gathering together the suggestions of Ralph Hopkinson in his various works:

Winding Connection (primary/secondary) vs. Minimum X_C/X_M:

Delta / Wye-g	40 for if 3x1 ph, 30 if 5 legged core
Delta/Delta	30
Wye-ug/Delta	30
Wye-g/Wye-g	0 for 3x1 ph; 0.1 for 3x1ph, overhead feeder 1 for 5 legged core

Many of the papers back up their analysis with tests of either actual transformers or small scale reproductions on transient network analyzer (TNA) systems, including Hopkinson. These reports generally work by taking actual transformers and connecting a variety of capacitances or cable lengths to the open phases. They generally do not report specific waveforms that are achieved but simply report the maximum peak voltage measured. In many of the cases they are driving the transformer into a ferroresonant condition. The limitations on X_M/X_C they provide tend to verify the linear circuit analysis, but do not depend upon it.

Before proceeding, it should be acknowledged that linear circuit analysis has its limitations. On one hand it is backed up by empirical comparison to field test data, has a basic correctness to the concept and appears to have been applied successfully by at least a few utilities. On the other hand the approach is possibly an excessive simplification of a complex non-linear region of operation. Also, there have been changes in transformer design over the last couple of decades since the original tests of the concepts were done. Modern transformers are lower loss and higher capacitance than older designs. Reference [9] mentioned above states that in their tests of 4 core/5 legged Wye-grounded/Wye-grounded the ratio of $B_C/P_{\text{Core Loss}}$ $(=X_C/R_{\text{loss}}\ @V=1\text{pu})$ appears to be a better indicating factor in preventing ferroresonance than X_C/X_M and seems to suggest X_C/R be limited to 0.5 or less.

Refer back to the AC excitation curve in Figure 14. Assume that the curve is not a chart of RMS currents and voltages, but of the fundamental frequency currents and voltages. If this is approximately true, and we can ignore the high frequency components and true non-linear nature of what is occurring, then the approximate value of X_M is simply V/I for a given point on the graph. If a transformer can be simply modeled as X_M even into saturation, and we can ignore system resistances and subtle issues such as hysteresis flux lag, hysteresis load effects, cross phase coupling in the core, cross phase coupling via external capacitances, et cetera, then the voltage drop in the simple circuit shown in Figure 12 is simply:

$$\begin{aligned} E &= \left(jX_M - jX_C\right)\cdot I \\ &= \left|V_M\right| - \left|V_C\right| \quad I \text{ lagging } E \text{ by - } j \\ &= \left|V_C\right| - \left|V_M\right| \quad I \text{ leading } E \text{ by } j \end{aligned} \qquad \text{Eq. 1}$$

If X_C remains very high relative to X_M, then I and V_M is low, and V_C is approximately equal to E. The difficulty is that if X_C is sufficiently low, and if the transformer enters saturation so that X_M goes very low, there are alternate states that the circuit can operate in where I is high, V_M is low, and V_C is high. This alternate operating mode is harmonically rich and actually falls outside the realm of linear and phasor circuit analysis, but a basic concept of ferroresonance can be derived using linear analysis of the situation. The various operating modes are seen in Figures 17-20.

In Figure 17, X_C is greater than $X_{M,US}$. In this condition, no matter what E is applied, even if the core is sent into saturation, there is one operating point for I_{EXC} where $(jX_M - jX_C)\cdot I = E$. This is the basic safe design to prevent ferroresonance. Note, however, that operation in this region does not prevent a voltage rise in the circuit that is inherent in all L-C networks. The voltage rise is limited, however, by selecting an X_C that is high (in most papers this is done by specifying a high X_C/X_M), which limits current flow, and hence limits voltage rise.

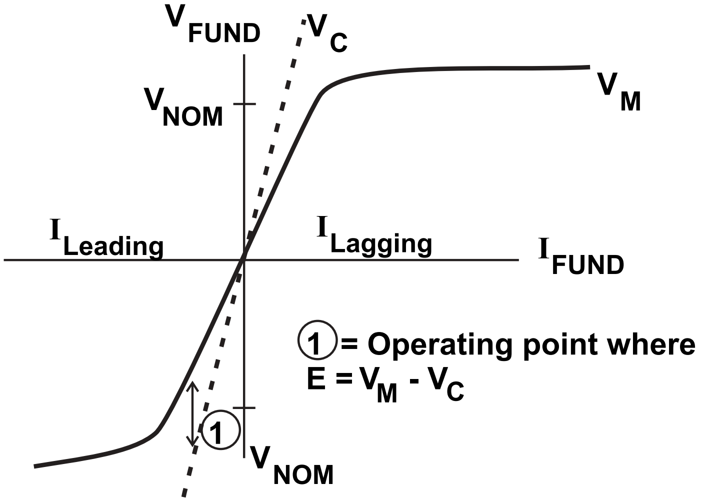


Figure 17: $X_C > X_{M,US}$

The approach of keeping $X_C > X_{M,US}$ will tend to give fairly pessimistic results. The typical $X_{M,US}$ is rather high, on the order of 50-100pu. In actual application, X_C/X_M values closer to 30-40 appear to be required to prevent ferroresonance, per references.

Figure 17 would be a 3 dimensional graph if any resistances were involved. In the graph I either leads or lags by 90°. A resistive component would require the voltages and currents to have a vector that rises out of the plane of the paper to handle leading and lagging over any degree.

In Figure 18, X_M and X_C are approximately equal. To develop sufficient current so that $(jX_M - jX_C)\cdot I = E$, the transformer has to approach saturation. The voltage across X_C relative to ground has risen above nominal voltages. A problem has started, but what is commonly referred to as a ferroresonant condition has not quite arisen.

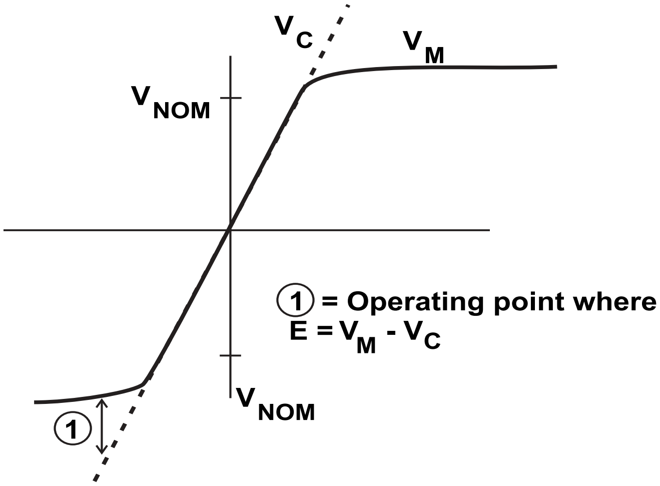


Figure 18: $X_C = X_{M,US}$

In Figure 19, the ferroresonant issue begins to be seen. Now there are three points on the curve where $(jX_M - jX_C)\cdot I = E$. Point 2 can be seen, more intuitively than mathematically, to be unstable because at point 2, if E rises, current must fall to reach the new operating point. Hence, points 1 and 3 are the possible stable operating conditions. Currents at points 1 and 3 are 180^0 out of phase with one another and much different in magnitude. The voltages relative to ground are much higher at point 3. An interesting aspect of point 3 is that once the situation has started, voltage E can be reduced greatly, and the situation maintained. As voltage reduces, this simply moves the operating point at 3 to the right, closer to the intersection of the V_C and $V_{M,S}$ curves, but there is no reason for the operation to ever transition beyond the intersection toward the origin, even as E approaches 0, in this simplified view of the circuit, due to the lack of any resistive burdening elements.

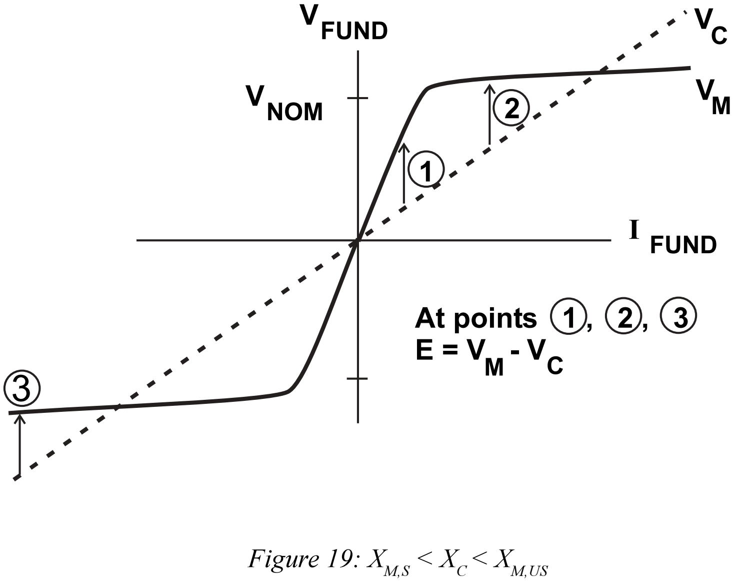


Figure 19: $X_{M,S} < X_C < X_{M,US}$

One last operating region to consider is what occurs as X_C continues to decrease, until $\theta_M > \theta_C$. This might represent the conditions where the capacitance involved is a bulk power capacitor. In this condition, it is hard to build V_C and all system voltage is developed across V_M. There is only one intersection of V_C with the V_M line, at the origin. There is one valid operating point, shown in Figure 20.

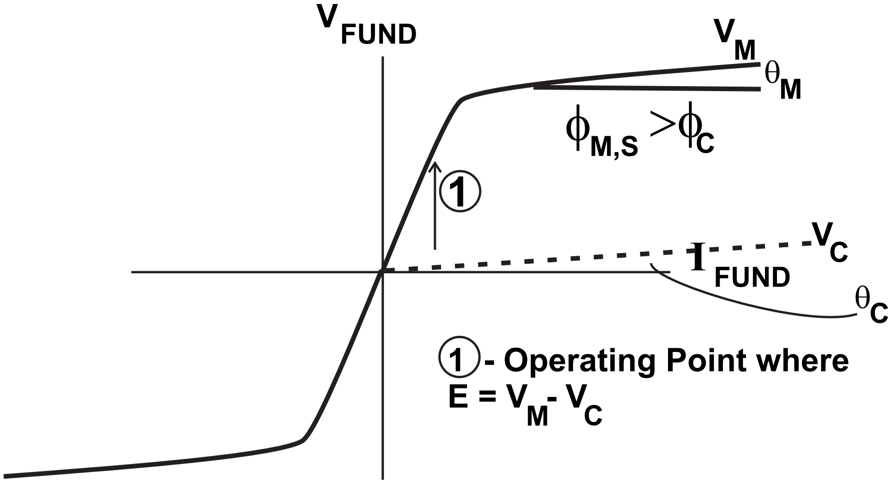


Figure 20 : $X_{M,S} > X_C$

A second reason to bring Figure 20 to the picture is it gives a hint to the impedances that are seen by the system to harmonic current flow. Ferroresonance involves a high degree of harmonic current flow. The system presents a decreasing X_C, and an increasing $X_{M,S}$ as harmonic frequency increases.

Including Resistive Elements

A more thorough model is needed to account for the dampening effect of resistive elements. For instance, consider the circuit below, which may reflect a version of the circuit in Figure 1 or 12. The line impedance contains resistance R_L. The transformer secondary load may not be negligible, so $R_{Load,SEC}$ is shown referred to the primary and in parallel with X_M. Any load remaining on the open circuited phase(s) is represented by $R_{Load,Open\ Phase}$, in parallel with the line to ground capacitance.

Resistive elements detune the circuit and change the simple voltage analysis given previously. The analysis requires complex number math and the due to the three dimensional nature introduced by quadrature voltages and currents, the easily grasped graphical nature is substantially lost.

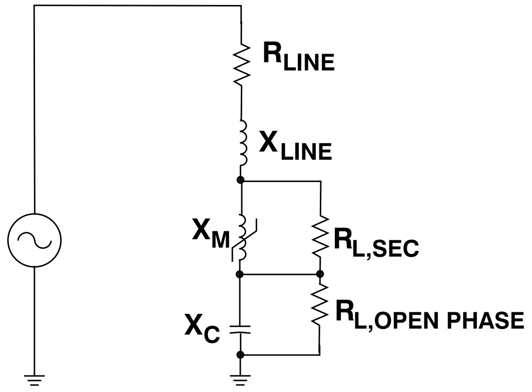


Figure 21: Circuit Model with Resistive Elements

Resistance will act to remove the voltage rise across the inductances and capacitance associated with an L-C network. Series line and transformer resistance reduces the voltage across the reactive elements, and resistive loads shunt current around the capacitor or transformer. It intuitively can be seen that if R_{Load} in parallel with X_M or X_C approaches respectively $|X_M|$ or $|X_C,|$ then the resonance capability of a circuit goes very low. This agrees with commonly reported analysis that if transformer load is only a few % of transformer MVA, ferroresonance commonly is eliminated.

This also gives some insight to why [9] promoted transformer losses as a key (though empirical) indication of how much capacitance can be added to the 5 legged wye-wye wound transformers in their studies without risk of the unit entering ferroresonance during single phasing. The core losses tend to be more than proportionate with transformer primary voltages and flux levels, tending to detune the inductive part of the circuit more linearly with increasing voltage than the unclear effect of secondary loads on a saturated transformer.

A linear circuit analysis of the above circuit is found in reference [26]. This MS Excel spreadsheet has an approximate excitation impedance model similar to that shown in Figure 14, but mapped in terms of fundamental frequency components. In the spreadsheet, given a set of impedances from the user for the elements in the figure above, the voltages and currents in the network for a range of $I_{Transformer}$ are calculated. The spreadsheet determines the fundamental voltages that will result from the design, which the user then compares to actual system voltages to see if more than one $I_{Transformer}$ will correspond to the same system voltage E, indicating a circuit that is capable of ferroresonance.

Ferroresonance Waveforms

The fundamental frequency linear circuit analysis above aids in a conceptual understanding of some aspects of ferroresonance, but is severely lacking in details of what occurs during a ferroresonant condition, and in fact, once one has an improved understanding of what occurs in ferroresonance, one should have a suspicious discomfort with projecting linear circuit analysis into the saturated region of a transformer.

A ferroresonant condition might be better seen as a circuit that is repeatedly switching between two alternate states (two values for X_M), rather than as a circuit that is an extrapolation of the unsaturated linear state with a single valued X_M. In state 1, the capacitor is charged and impressing a voltage across the transformer. The capacitor voltage adds to the voltage presented by the system. The impedance of X_M of an unsaturated transformer is high enough to be considered an open circuit to charges trapped in a series capacitance. The capacitor is effectively a DC value that eventually will saturate the transformer. The time that it takes to saturate the transformer under the application of a given voltage wave is dependent upon the area under the voltage wave form. In state 2, the transformer has reached saturation and the capacitor is discharging and then recharging to an opposite voltage state, at which time the transformer returns to state 1.

Before walking through an example ferroresonant condition, a short review of the equation relating current and voltage in pure capacitances are provided below. The equations that relate flux, current, and voltage, for a short review are:

$$\begin{aligned} v(t) &= \frac{d}{dt}\varphi(t) &&= L\frac{d}{dt}i(t) \\ \varphi(t) &= \int v(t)dt + \varphi_0 &&= Li(t) \\ i(t) &= \frac{1}{L}\int v(t)dt + i_0 && \end{aligned} \qquad \text{Eqs 2-4}$$

A negative may show up in some forms of the above equations when one wishes to indicate that induced current will oppose flux buildup (Lenz's law). A similar collection of equations for a pure capacitance, for completeness:

$$\begin{aligned} i(t) &= \frac{d}{dt}Q_C(t) &&= C\frac{d}{dt}v(t) \\ Q_C(t) &= \int i(t)dt + Q_{C,0} &&= Cv(t) \\ v(t) &= \frac{1}{C}\int i(t)dt + v_0 && \end{aligned} \qquad \text{Eqs 5-7}$$

When the transformer saturates, the trapped charges will discharge and generate high frequency currents. The discharge waveform is dependent upon the resonant frequency of the circuit during the discharge process:

$$\omega = 2\pi f \qquad X_L = \omega L \qquad X_C = \frac{1}{\omega C}$$

$$f_{\text{Resonance, (XL = Xc)}} = \frac{1}{2\pi\sqrt{LC}} = 60\sqrt{\frac{X_{C,\,60\,\text{Hz}}}{X_{L,\,60\,\text{Hz}}}} \qquad \text{Eqs 8-11}$$

When a manufacturer designs a transformer, the integration of voltage more than 1/2 of a cycle (equation 3 above), with 0 initial flux and some degree of permissible continuous overvoltage, defines the peak flux that the winding must see. Then the designer selects a steel with a defined B–H characteristic. With B nearing saturation, the core must be large enough to carry the required flux as defined by the following equations, which in turn define the excitation current requirements of the transformer:

$$\begin{aligned} \varphi &= N_{\text{Turns}} \cdot B \cdot \text{Area}_{\text{Cross section}} \\ B &= \mu H \quad (\mu \text{ at steel peak flux}) \\ H &= I_{\text{Exc}} \cdot N_{\text{Turns}} \, / \, \text{core length} \end{aligned} \qquad \text{Eqs 12-14}$$

The transformer manufacturer hence has only a few parameters to work with in transformer design.

One does not need to know the specifics of a transformer's design implied by Eqs. 12-14 in order to determine if an applied voltage will cause saturation. Note in equation 3 that flux is an integration of voltage. The transformer has to be designed to accept the normal sine wave voltage applied to it. For any voltage wave that is applied to a transformer, along with an assumption of some corresponding initial flux ϕ_0, one can determine if the wave is capable of driving a core into saturation by comparing it to the sine wave voltage rating of the transformer. This can be done visually in simple applications for an intuitive feel of the situation. Once this saturation level is reached, even transiently, there is risk that a ferroresonant condition may begin and continue indefinitely.

The details of what may occur in a ferroresonant circuit may be found by reviewing a few sample wave forms. The examples below were derived from a study of a number of resources, but much of the credit should be given to [10], [14] and [16] in their concepts.

Assume the circuit shown in Figure 12, and assume a simple flux vs. excitation current relationship shown in Figure 17. A possible trace of system voltage, capacitor voltage, flux, and current ((e(t), v_C(t), ϕ(t), and i(t)) is shown in Figure 22. Assume that at time t_0 there is no flux in the transformer, and before time t_1 that X_M is very high relative to X_C. Virtually all of the system voltage is across the transformer. Excitation current and hence transformer flux rises until at time t_1 the transformer enters saturation. At this point the excitation current becomes relatively large and hence the capacitor starts to charge rapidly. Midway between time t_1 and t_2 the capacitor voltage reaches the system voltage, so that the voltage across the transformer is now 0, but leakage inductance in the lines and transformer force current to continue and then gradually decay until time t_2, when current drops low enough for the transformer to leave excitation. Hence, the first current spike has been formed and at time t_2 the capacitor voltage is possibly, for this example, 0.75 times the peak system voltage.

When the transformer enters saturation there will be an L-C-R circuit in operation that will have a very large impact on the ferroresonant waveform. Note the half sine wave that is associated with the discharge and subsequent over-swing and recharge of the capacitance. One can intuitively see a notably different waveform will result if $f_{Resonance}$ for the saturated condition is very low, giving a slow discharge of the capacitance, compared to what the waveform will look like if $f_{Resonance}$ for the saturated condition is very high, giving a fast discharge of the capacitance. Further, if resistance is high, then the capacitively held energy will be less on each transition, dampening the resonance.

In the next half cycle, the voltage across the transformer is not just e(t), but e(t) + $v_C(t)$. Hence, excitation current and transformer flux builds at a much higher rate, but the excitation current has to be totally reversed. At time t_3 the transformer enters saturation again, but with flux in the opposite direction compared to t_1. Because the voltage across the transformer includes the capacitor voltage, a larger current spike occurs than at t_1. The charge/discharge/recharge routine continues one more time, then at t_4 an interesting point is reached where the capacitor voltage $v_C(t)$ is pulled in phase with e(t). Then the condition becomes even more interesting. If the system voltage were reduced at this point, the voltage across the transformer would actually increase (note $v_{Xfmr}(t) = e(t) - v_C(t)$). Inspecting the waveform, it can be seen this means the resonant condition could continue indefinitely even if e(t) were reduced to a magnitude well below a value that would not have driven the transformer into the initial saturation condition.

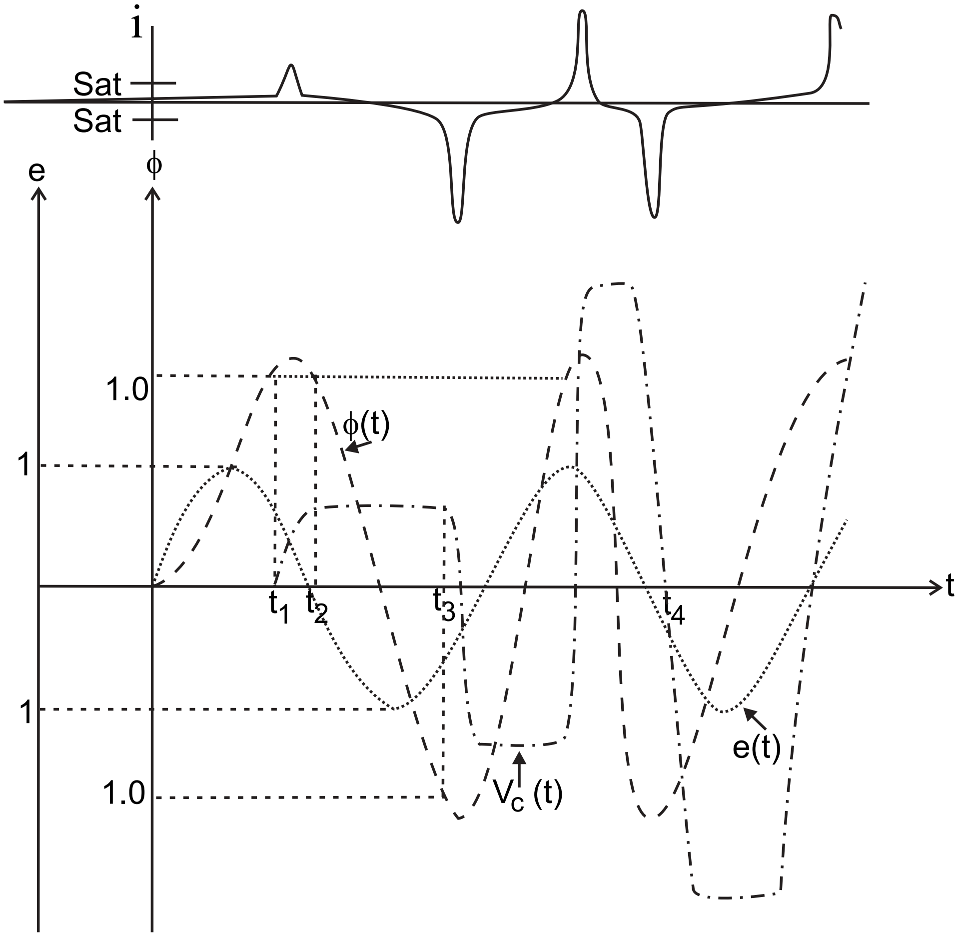


Figure 22: Example Square Wave Capacitive Voltage

The previous example does not show $v_{Xfmr}(t)$, but it can be seen by the reader by subtracting $v_C(t)$ from $e(t)$. The next example shows another case where $v_{Xfmr}(t)$ in a steady state condition and shows how a sub-harmonic voltage is developed. The integration of the voltage across the transformer determines when the core will enter saturation. It is possible for this time to exceed one system frequency cycle. (It should be noted that hysteresis also has a role in causing sub harmonic oscillations.) If this time exceeds one cycle, then the ferroresonant circuit will oscillate at the fundamental frequency and the given sub-multiple of the system frequency. The figure below shows the voltage across the transformer for two symmetrical cases of the transformer entering saturation at approximately the same point in the voltage waveform on each cycle.

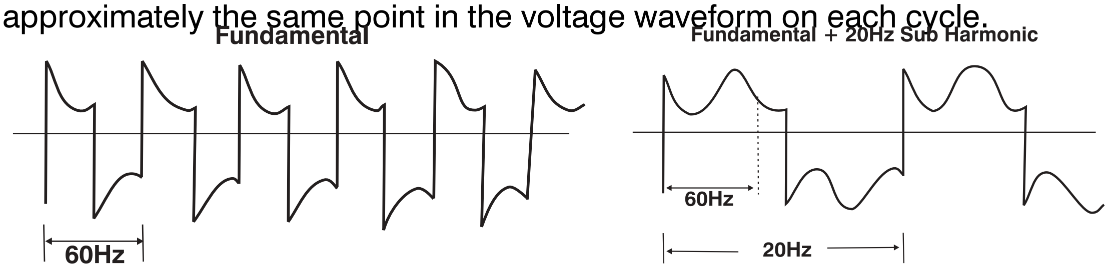


Figure 23: Example Transformer Voltages

Ferroresonance involves multiple time constants, transformers entering saturation at various points on the applied voltage wave form, different capacitive discharge time constants, and hysteresis effects that allow some current reversal without a change in core flux. These compound to create waveforms much messier than shown in these examples. There are both higher frequency components and a random nature to the events. There may be components randomly moving between the in phase and 180^0 out of phase form seen in Figure 22. Voltage peaks may be close to nominal voltage peaks, or may be 2-4 times nominal. There is commonly at least a partial chaotic look to the waveforms, such as seen in Figure 24.

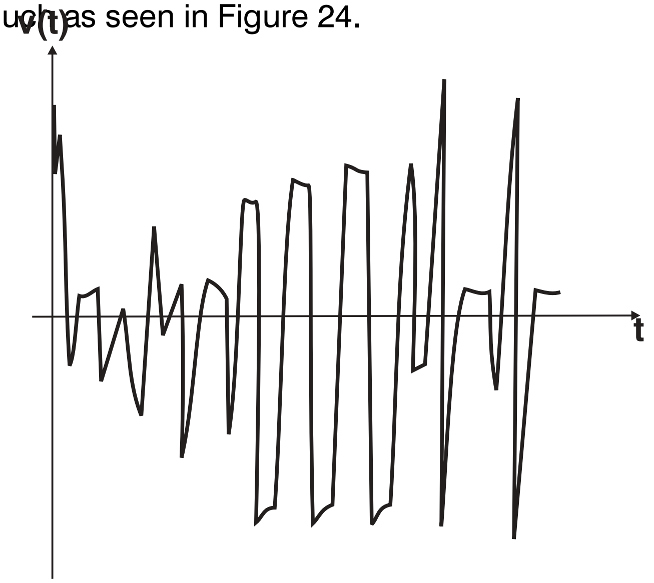


Figure 24: Chaotic Waveform

Peak Voltages and Currents

One of the large concerns of ferroresonance is the peak voltage that will be generated and the resultant damage that will occur. In delta-wye and other ungrounded primary transformers, fed by a grounded source, it is commonly mentioned in papers on the topic and by those performing tests of sample transformers, that peak voltages of 2 per unit (relative to normal sine wave peaks), with occasional spikes to even 4 or 5 per unit, are easily obtained. See results found in many of the references.

When the more common three phase 5 legged/4 core wye-g/wye-g transformer is used, ferroresonance is still possible, but the peak voltages are much less. Peak voltages are on the order of 1 to 1.5 per unit, with some short spikes to 2 per unit. The waveforms have low enough energy that high energy surge arresters (especially types that soak in the transformer oil) have the capability of absorbing the energy and detuning the ferroresonant circuit without much risk of damage. See [19], [20], and [21].

The current levels associated with ferroresonance are not typically very high, peaking on the order of 1-20% of transformer rating. Most reports of ferroresonance do not record current levels, so it may be the case that sometimes current is high but not noted.

Associated Issues

Preventing Ferroresonance

The most common recommended means to prevent ferroresonance includes recommendations to always switch transformers using three phase devices, so as to prevent a series inductive/capacitive (SLC) circuit. Directly related to this is a recommendation to energize transformers using switches directly adjacent to the transformer, so a core is never energized from one terminal with an open circuited long un-energized capacitive circuit (esp. a cable) connected on another terminal.

If a circuit must be switched single phase remote from the transformer, then limit the capacitance on the open phase, which translates to limiting the cable or overhead conductor on the circuit. Some references that give guidelines on the length of cable that would be used include [1] - [4]. A summary of the suggested X_C/X_M from one source was given earlier in this paper.

When transformers are powered via ungrounded windings (delta, ungrounded wye, open delta, Scott-T, etc.) special care should be made to implement ferroresonance prevention techniques because such windings have the greatest ability to create a series LC network.

If a circuit must be switched single phase and the circuit has the possibility of setting up an SLC circuit, have a load on the transformer secondary or in parallel with the capacitance to detune the resonant circuit. Most papers show that a load on the transformer secondary only needs to be a few percent of the transformer rating to block ferroresonance though in some references cases are shown where required load exceeded 10%. This is approximately equivalent to detuning the X_M branch so that it has an apparent impedance angle of around 45^0 or lower. Since during transformer saturation the effective value of X_M becomes lower, transformer action may not be complete, the secondary may not see the same voltage as seen on the primary, and loads may not respond to the voltage waveforms seen during ferroresonance, a load resistance closer to $|X_{M,S}|$ may be needed to detune the transformer reactance during ferroresonance. Similarly, an R_{Load} in parallel with X_C to create a net phase angle of 45^0 should be sufficient, to block ferroresonance.

The load values discussed above are not tested concepts; the references should be consulted for a more complete discussion of how much load is required to block ferroresonance.

Transformers may be bought with a low flux density design. Such transformers will of course be larger. A low flux density design will be harder to drive into saturation. Once in saturation, they still have the ability to be a non-linear circuit through which a system capacitance is charged and discharged. A larger core will have higher core loss associated with hysteresis and eddy currents, so such a design may serve to cause the transformer to be self loading if it enters into a ferroresonant condition.

Surge arresters have some minor ability to block low level ferroresonant conditions. See [19] and [20] for some in-depth analysis.

Numerical Modeling

This paper is left as a review of the ferroresonant circuit and will not broach the task of ATP/EMTP type numerical modeling of the ferroresonant condition. See [13] for more information. Numerical modeling is a case of diminishing returns: If a valuable substation is being built it is becoming a common practice to model the substation in a numerical analysis program such as ATP/EMTP, but one would not analyze many distribution circuits to this level of detail. Numerical modeling is pitfall ridden. Numerous quantities involved with ferroresonance are only vaguely known. For instance, reference [13] indicates that present transformer core modeling in modern numerical analysis programs may not be sufficiently advanced to reliably model complex core transformers.

Wye - Broken Delta Ground Fault Sensing

A classical method to sense ground faults on ungrounded systems is with a Wye-Gnd/ Broken Delta VT, and then monitor the broken delta voltage, which will be $3V_0$. VTs in this application have the elements of ferroresonance. When VTs are purchased for this application, they should be bought rated for full line to line potential across each Wye-Gnd VT due to the high voltage that will be seen by the windings during line-ground faults. The VT will by nature operate at a lower flux density under normal operating condition.

It is typical for such VTs to have a resistor in the broken delta to dampen out ferroresonant conditions. There are two approaches to selecting the resistance:

A) Determine the rated current of the VT, then size the resistor such that rated current flows in the delta during a line to ground fault.
B) Determine the 3 phase VA rating of the VT, and size the resistor so that full transformer VA is applied to the VT during a line to ground fault. This latter method will run higher current than rated through the transformer, but this may be satisfactory for short time events.

It is shown in tests in [10] that burdening down the broken delta is not a 100% reliable method of preventing ferroresonance. The broken delta approach assumes that the ferroresonance condition is creating zero sequence voltage. In [10] it is shown that sometimes such transformer banks can enter into a three phase ferroresonance that may produce negligible voltage at the broken delta resistor.

A modern microprocessor relay calculates $3V_0$ internally so the broken delta connection is not required for ground fault sensing. However, some cases may arise where a relay may see the condition, such as the broken delta in systems with low system capacitance can act to help stabilize the neutral and hence should still be considered, even when microprocessor based relaying is utilized.

Protective Relaying

Relays commonly are not located at a point in the power system to detect ferroresonant conditions on the distribution network. Further, a relay is typically designed to operate a breaker, so if there is a relay, the single phase switching that is associated with ferroresonance would likely not be occurring. However, some cases may arise where a relay may see the condition. For example, a relay could sense ferroresonance on the VT that it is using to monitor a circuit. Another issue is that protective relays are commonly fundamental frequency sensing devices. Ferroresonant circuits have a distorted waveform that may have high peaks but have low fundamental components. Hence, the typical relay may have trouble sensing the ferroresonant condition. One approach would be to have the relay trip if it repeatedly senses a random single sample high voltage spike.

Surge Arresters

Surge arresters are at high risk of being damaged by ferroresonance conditions associated with Figures 1-5. The voltage peaks and energy involved is too high to be absorbed by surge arresters reliably. However, for the 4 and 5 legged grounded wye transformer associated with Figure 6, the voltage peaks and energy involved in ferroresonant conditions are not as large. References [19] and [20] indicate that for these transformer configurations, a surge arrester with sufficient energy absorption capability can withstand the condition and in a few cases help dampen the event.

Issues with Distributed Generation

Distributed generation adds increased risk that the power system will be fed from directions not normally intended, and hence an increased risk of single phasing of the power system.

Induction generators where sufficient power factor correction capacitance has been installed can result in an unexpected ferroresonance condition. Induction generators and motors, when power factor correction approaches creating a unity power factor condition, may not automatically shut down when the utility opens its breaker. In fact, continuous high voltages may exist. This paper will not review this application; see reference [24].

Summary

The basics of a ferroresonant condition have been covered:

- The network circuits involved
- A simple analysis process
- A review of the details of the process of a ferroresonant condition
- A review of how ferroresonance is prevented
- A variety of other issues were discussed

References

Databases such as IEEE Explore (http://ieeexplore.ieee.org) or Engineering Village (http://www.engineeringvillage.org) list literally hundreds of documents on the subject "ferroresonance." These databases mainly cover papers since the mid 1980s and do not contain the contents of many good resources such as George Tech, Texas A&M, and Washington State Protective Relay Conferences, Doble Conferences, and Edison Electric Conferences, and the early GE and WH materials. Most good foundational and basic explanatory papers predate these databases. The list below is a subset of the many papers that are available with some stress on early foundational documents.

1 Ralph H. Hopkinson, "Ferroresonance During Single-Phase Switching of 3-Phase Distribution Banks," IEEE Transactions on Power Apparatus and Systems (PAS), p289-293, PAS-84, April 1965, discussion June 1965, p514-517
2 Ralph H. Hopkinson, "Ferroresonant Overvoltage Control Based on TNA Tests on Three Phase Delta-Wye Transformer Banks," IEEE Trans. on PAS, p1258-1263, PAS-86, Oct. 1967
3 Ralph H. Hopkinson, "Ferroresonant Overvoltage Control Based on TNA Tests on Three-Phase Wye-Delta Transformer Banks," IEEE Trans. on PAS, p352-361, PAS-87, Feb. 1968
(Note: Ralph Hopkinson wrote other material on Wye-g/Wye-g transformers, but as best I can tell this material remained as internal GE documents. I have not found

where they were published for wide distribution.)

4 S. Prusty, M. Panda, “Predetermination of lateral length to prevent overvoltage problems due to open conductors in three-phase systems,” IEE Proceedings, p49, Vol 132, Pt. C, No.1 Jan. 1985

5 Philippe Ferracci, “Ferroresonance,” Group Schneider Cahier Technique Series, No 90, http://www.schneider-electric.com/en/expert/e2a.htm

6 George E. Kelley, “The Ferroresonant Circuit,” AIEE Transactions on PAS, p843-848, PAS-78, Pt III, Jan 1959; discussion p1061

7 P. E. Hendrickson, I. B. Johnson, N. R. Schultz, “Abnormal Voltage Conditions Produced by Open Conductors on 3-Phase Circuits Using Shunt Capacitors,” AIEE Transactions on PAS, p1183-1193, PAS-72, Pt III, Dec. 1953

8 D. R. Smith, S. R. Swanson, J. D. Borst, “Overvoltages with Remotely Switched Cable Fed Grounded Wye-Wye Transformers,” IEEE Transactions on PAS, p1843-1853, PAS-94, Sept. 1975

9 R. A. Walling, K. D, Parker, T. M. Compton, L. E. Zimmerman, “Ferroresonant Overvoltages in Grounded Wye-Wye Padmount Transformers with Low-Loss Silicon Steel Cores,” IEEE Transactions on Power Delivery, p1647-1660, Vol. 8 No. 3, July 1993

10 Elmo D. Price, “Voltage Transformer Ferroresonance in Transmission Substations,” Texas A&M 30th Annual Conference for Protective Relay Engineers, April 25-27, 1977

11 Harold Peterson, book: “Transients in Power Systems,” Chapter 9: “Overvoltages Caused by Open Conductors,” John Wiley and Sons, 1951, then republished with slight corrections by Dover Publications for GE, 1966

12 Reinhold Rüdenberg, book: “Transient Performance of Electric Power Systems,” Chapter 48, “Saturation of Iron in Oscillatory Circuits,” McGraw Hill, 1950, then reprinted 169/1970 by MIT Press. ISBN 0 262 180367

13 M. R. Iravani, Chair, IEEE Working Group, Slow Transients Task Force of IEEE Working Group on Modeling and Analysis of System Transients Using Digital Programs, “Modelling and Analysis Guidelines for Slow Transients - Part III: The Study of Ferroresonance,” IEEE Transactions on Power Delivery, p255-265, Vol 15, No, 1, Jan. 2000; Discussion in Trans. on Pwr Del., Vol 18, No 2, April 2003.

14 Frank S. Young, Ronald L. Schmid, Petter I Fergestad, "A Laboratory Investigation of Ferroresonance in Cable Connected Transformers," IEEE Transactions on PAS, p1240-1249, PAS 87, May 1968

15 Eugene C. Lister, “Ferroresonance on Rural Distribution Systems,” IEEE Transactions on Industry Applications, p105-111, Vol IA-9, No. 1, Jan/Feb 1973.

16 R. H. Dennard, “Behaviour of the Ferroresonant Series Circuit Containing a Square-Loop Reactor” AIEE Transactions, Communications and Electronics, p903-911, Jan 1959

17 E. J. Dolan, D. A. Gillies, E. W. Kimbark, “Ferroresonance in a Transformer Switched with an EHV Line,” IEEE Transactions, p1273-1289, PAS-91, 1972

18 W. S. Vilcheck, M. V. Haddad, “Voltage Transformer Ferroresonance in Cogeneration Substation,” Pulp and Paper Industry Technical Conference, p 148-158, Annual Mtg, Jun 8-12, 1992, Available via IEEEXplore

19 Thomas A. Short, James J. Burke, Ramon T. Mancao, “Application of MOVs in the Distribution Environment,” IEEE Transactions on Power Delivery, p 293-305, Vol. 9, No. 1, Jan. 1994
20 R. A. Walling, R. K. Hartana, M. P. Sampat, T. R. Balgie, “Performance of Metal Oxide Arresters Exposed to Ferroresonance in Padmount Transformers,” IEEE Transactions on Power Delivery, p788-795, Vol. 9, No. 2, April, 1994
21 Leonard J. Bohmann, John McDaniel, E. Keith Stanek, “Lightning Arrester Failure and Ferroresonance On A Distribution System,” IEEE Transactions on Industry Applications, p1189-1195, Vol. 29, No. 6, Nov. 1993.
22 William D. Stevenson, text: “Elements of Power System Analysis,” McGraw Hill, 1982
23 Westinghouse (ABB) Central Station Engineers, “Electrical Transmission And Distribution Reference Book,” Westinghouse/ABB 1964
24 Ferroresonance and Loading Relationships For DSG Installations,” W.B. Gish, W. E. Feero, S. Greuel, IEEE Transactions on Power Deliver, p953-959, Vol PWRD-2, No 3, July 1987

The mathematically inclined should refer to the references listed in Reference 13. Also refer to this article; it has a listing of some early highly technical resources on the topic:

25 Glen Swift, “An Analytical Approach to Ferroresonance,” IEEE Transactions on Power Apparatus and Systems, p42-46, Vol PAS-88, No. 1, Jan 1969

As a last reference:

26 Excel Spreadsheet to Analyze the Circuit Shown in Figure 21. “Ferro.xls” available at www.basler.com

AUTHOR'S BIOGRAPHY

John Horak received his BSEE degree from the University of Houston in 1988 and his MSEE degree from the University of Colorado in 1995. He worked for nine years with Stone and Webster Engineering and was on assignment for six years in the System Protection Engineering offices of Public Service Company of Colorado. His work has included extensive relay coordination studies and settings, as well as detailed control design and equipment troubleshooting. He has presented technical papers at Texas A&M Relay Conference and Georgia Tech Protective Relaying Conference. John is a Senior Application Engineer for Basler Electric, based in Colorado, and is a member of IEEE, IAS and PES.

Back to Table of Contents