A Tutorial on Ferroresonance

Elmo Price, ABB Inc.

Introduction

Ferroresonance occurs in power system circuits containing capacitance and a non-linear transformer magnetizing inductance and is usually initiated with a transient disturbance such as opening a switch. It usually results in overvoltages and/or high current spikes that may subject system apparatus to dielectric and thermal stresses resulting in apparatus failure as well as subjecting operating personnel to hazardous conditions. Also, protective relays that measure these quantities are subject to incorrect operations causing unwanted outages. Today, ferroresonance is a widely studied phenomenon in the power system, but due to its complexity it is not well understood by those that do not study it in depth; hence the term "fuzzy-resonance." This paper will present a simple tutorial using phasors and a graphical approach to explaining the ferroresonant operating states, circuit configurations and mitigation. It will provide the basic concepts necessary to understanding more advanced investigations into unique occurrences.

Transformer Characteristics

Transformer core steel magnetizing characteristics used in transformer design are usually expressed as magnetic flux density vs. magnetic field strength (B vs. H). These parameters, however, are not readily available for measurement with the manufactured transformer. Therefore, the magnetizing curve is usually expressed as the applied voltage vs. magnetizing current at the transformer's designed operating (fundamental) frequency. This is useful when analyzing operation at the designed fundamental frequency, but falls short when evaluating the transformer at other frequencies to which it may be exposed.

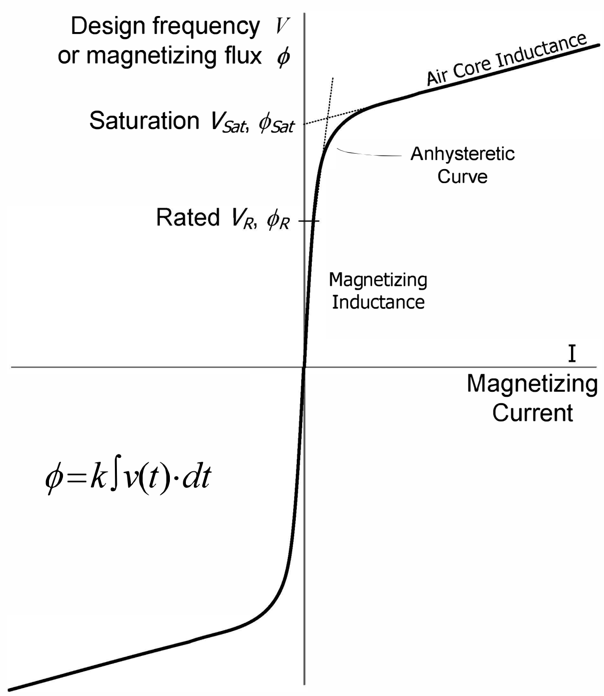

Figure 1. Transformer characteristics

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Figure 1 shows the transformer characteristic expressed as magnetizing flux or fundamental frequency voltage vs. magnetizing current. The fundamental voltage will produce the corresponding flux per equation 1. Otherwise, the curve ϕ vs. I is not tied to a specific frequency and understanding the relationship defined in equation 1 between applied voltages of any frequency and magnetizing flux will provide a better understanding to ferroresonant voltage waveforms to be discussed later. In this equation k is a constant for the core and coil design, $v(t)$ is the applied voltage and ϕ_0 is the remnant flux.

$$\emptyset = k\int_{t1}^{t2} v(t)\,dt + \emptyset_0 \qquad (1)$$

The non-linear anhysteric characteristic does not show the transformer's hysteresis and its effect on magnetizing current and remnant flux, but is more suitable for the discussion and analysis done here. There are two basic parts to the characteristic, the magnetizing inductance and the air-core inductance. The magnetizing inductance is the inductance where the flux is below ϕ_{Sat}, the saturation flux, and the transformer's core is not saturated. The air core inductance is the inductance where the flux is above ϕ_{Sat} and the core is considered saturated. This is the inductance of the winding being energized when not mounted to the transformer's core. The saturation flux, ϕ_{Sat}, (or saturating voltage, V_{Sat}) is usually 140% or more of the transformer's rated operating flux, ϕ_R (or rated voltage, V_R)

The transformer core design and winding connections also impacts the operating characteristics, particularly in regard to ferroresonance. A few of the more common core designs are shown in Figure 2.

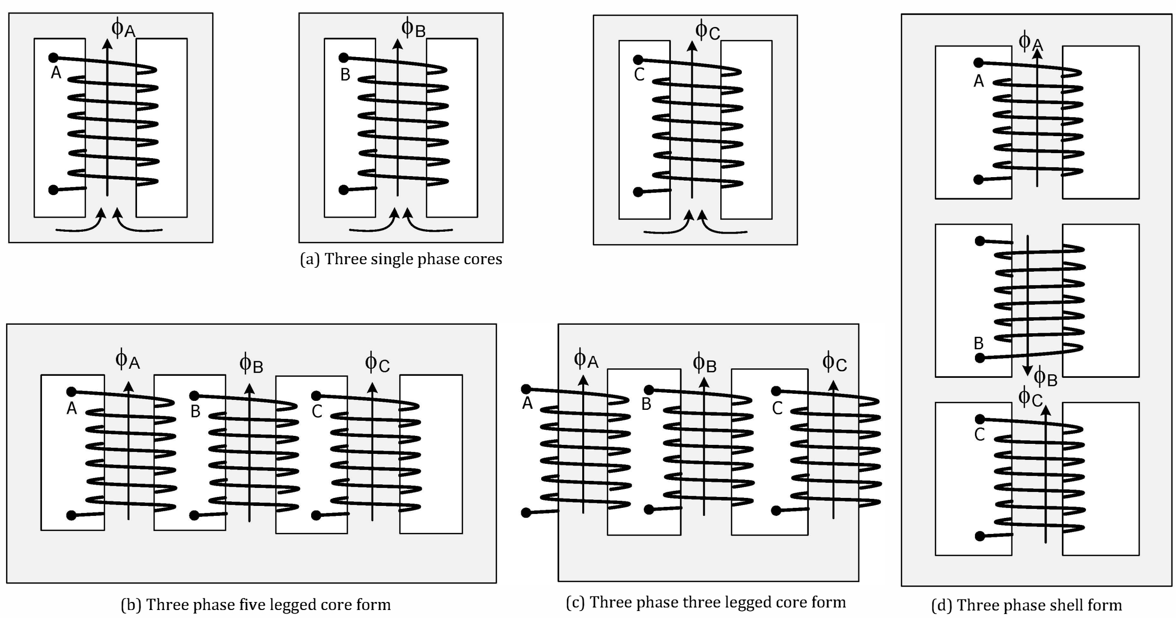


Figure 2. Common transformer core designs

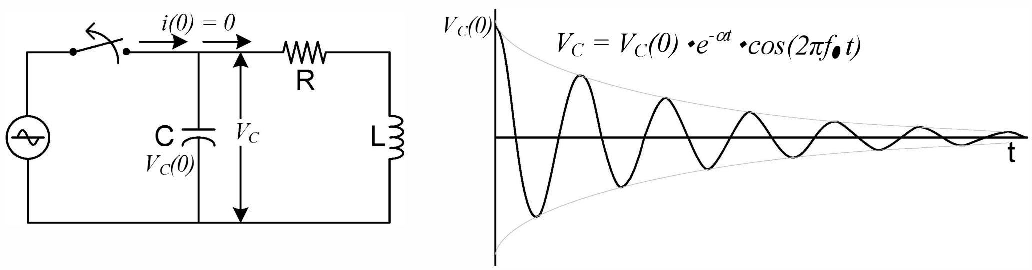
In the three-phase bank of single phase units of Figure 2(a) the phases are magnetically decoupled while in the other three phase core designs the phases are magnetically coupled and each phase is influenced by the other two. In a three-phase unit any flux unbalance in the three phase legs will produce zero sequence flux and any interconnecting part of the core (outer legs, top and bottom yokes, etc.) may become saturated. This is particularly true under ferroresonant conditions. The phases may also be magnetically coupled through delta winding connections. These inter-phase influences make the analysis of ferroresonant configurations quite complex and stresses the importance of accurate modeling for the detailed study of these configurations. Modeling is outside the scope of this paper, but more information may be found in reference 3.

The Ferroresonant Circuit

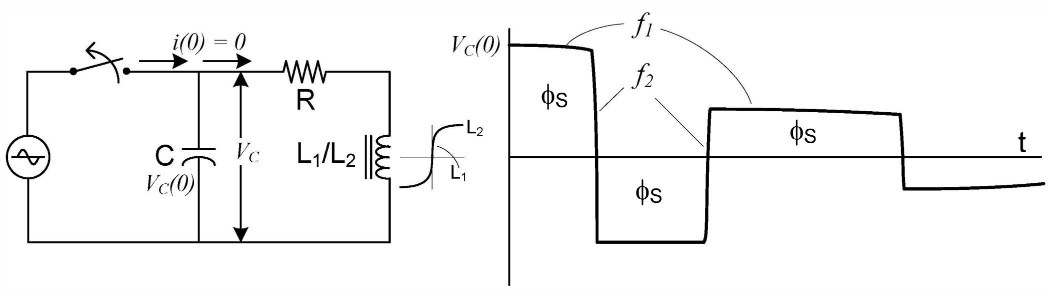
Before addressing the ferroresonant circuit we will look at a simple RLC circuit of Figure 3(a) where the inductance is linear (non-saturating). Therefore the voltage and current are linearly related in a manner which is frequency dependent. If the switch is opened at time zero and there is a charge on the capacitor, $V_C(0)$, then there will be an oscillating voltage V_C at the natural frequency f_0 (equation 3) due to the exchange of energy between L and C. If R = 0 then the oscillation would continue indefinitely without decay of amplitude. In this circuit R is very small and the circuit is under damped, therefore the oscillations will continue, but be dampened and V_C will eventually go to zero with time.

$$\alpha = \frac{R}{2L} \tag{2}$$

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \tag{3}$$



(a) RLC circuit and transient response



(b) RLC circuit with saturating inductance and transient response

Figure 3. RLC circuits with linear and non-linear inductance

Now consider Figure 3(b), which is the same circuit, but with non-linear inductance having the characteristics of Figure 1. In this case there are two major natural frequencies to consider, f_1 for the magnetizing inductance in the non-saturated region and f_2 for the air core inductance.

$$f_1 = \frac{1}{2\pi\sqrt{L_1 C}} \tag{4}$$

$$f_2 = \frac{1}{2\pi\sqrt{L_2 C}} \tag{5}$$

When the switch is opened at time zero the voltage V_C begins to oscillate at the non-saturated frequency f_1. This frequency is very small and depending on the value of C it is usually less than a few Hz. Therefore, an oscillation at this frequency (almost dc) does not occur before saturation flux of the Figure 1 characteristic occurs at ϕ_S assuming a design frequency of 50 or 60 Hz. This is graphically seen in Figure 3(b) transient response. When integrating equation 1 where $v(t) = \cos(2\pi f_1 t)$ the flux ϕ (area under the voltage curve oscillating at f_1) increases until ϕ_S is reached and there is an oscillation at f_2 during saturation, which is at a much higher frequency that is perhaps 50 or more times f_1. With this oscillation the inductor comes out of saturation with a $-V_C$ on the capacitor and the process is repeated. The magnitude of V_C will be reduced by power losses contributed by R during the f_2 oscillation. If there is no resistance (R = 0) and saturation was truly symmetrical in the positive and negative direction the waveform of figure 3(b) would be a uniform oscillating rectangular wave that would continue indefinitely. The frequency of the oscillation would be primarily determined by the magnetizing characteristics and to a much lesser extent f_1 and f_2.

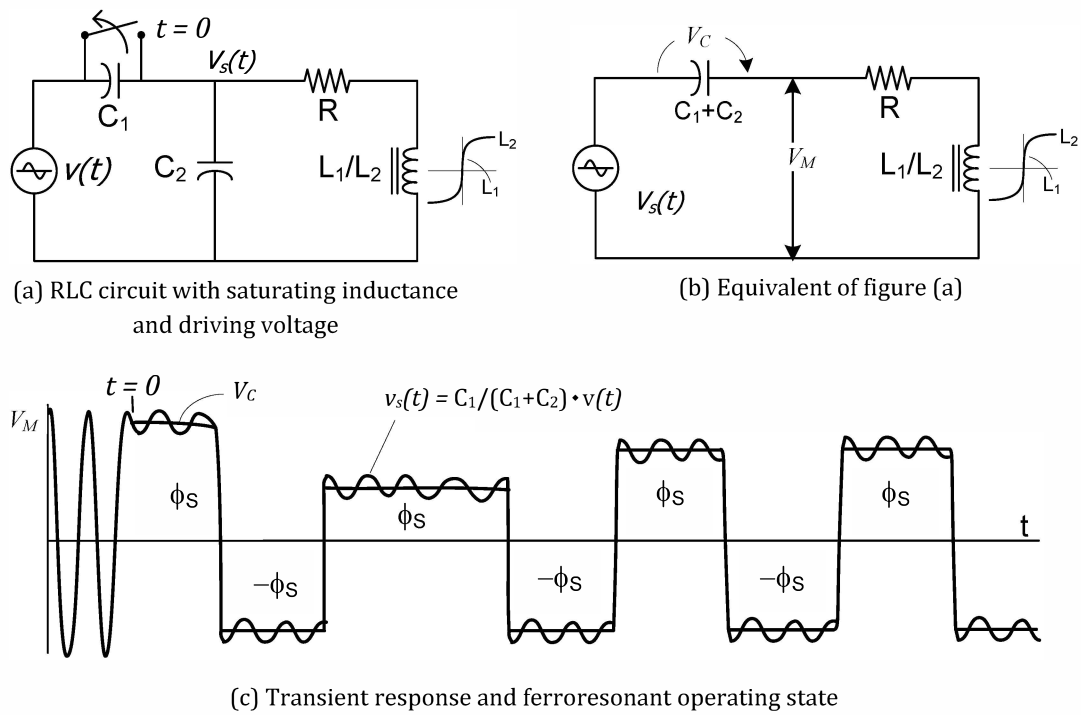


Figure 4. RLC circuits with non-linear inductance and driving source

The capacitor C_1 is added to the circuit in Figure 4(a) to illustrate the effect of a driving voltage that can sustain the oscillations. The equivalent circuit is shown in Figure 4(b) with the equivalent voltage $v_s(t)$. The voltage V_M, which is across R and L_1/L_2, is $V_C + v_s(t)$. If the equivalent voltage, $v_s(t)$, is sufficient to provide the losses due to R, and depending on the initial capacitor voltage and remnant flux at the inception of the transient (in this case opening the switch) it is possible to set up a sustained condition – an operating state in the saturated region of the transformer characteristics - known as ferroresonance.

Ferroresonant Modes

Transformer operation in the ferroresonant state is, as stated, dependent on a number of factors such as the system voltage magnitude, the initial voltage on the capacitor, the initial state of the magnetic characteristics of the transformer, the total loss in the ferroresonant circuit and the point on wave of initial switching. It is normally initiated after some type of switching event such as transformer energization, single-phase switching, fault clearing, blown fuses. breakers opening, or loss of system grounding. Given the right conditions it can lock into any of the following ferroresonant modes. The one common characteristic among these ferroresonant modes is that they all contain the fundamental frequency driving voltage component, which sustains it.

Fundamental Mode

The most frequent ferroresonant mode and simplest to analyze is the fundamental frequency mode as shown in figure 5. The ferroresonant voltage waveform (V_M) oscillates at the same frequency as the driving voltage (V_S), which is also one of its components. The wave form's positive and negative half cycles are generally symmetrical, but on a few occasions have been observed non-symmetrical. The ferroresonant voltage is also of opposite polarity as the driving (or normal state) voltage phase shifted only by the voltage drop across the circuit's resistance R. The peak ferroresonant voltage can be much larger than the system voltage causing both voltage and thermal stress issues. Sustained operation of surge protection (arresters) can lead to failure. Ferroresonance also produces large current spikes that can be thermally damaging if the condition is sustained.

Sub-harmonic Mode

The sub-harmonic mode includes those periodic oscillations that are greater than the fundamental (V_S) period, T, and uniformly repeated as illustrated in Figure 6. The positive and negative half cycles can be symmetrical or non-symmetrical. Sub-harmonic ferroresonant voltages with a period of 3T (20 Hz.) are the most common sub-harmonic occurrences, but those with a period of 2T (30 Hz.) have been frequently observed.

Quasi-periodic Mode

Some ferroresonance wave forms are as shown in figure 7 and have repeated patterns that appear periodic, but have different peak magnitudes with each repetition and periods that are not quite equal. They are referred to as quasi-periodic because of their similarity to a periodic waveform.

Chaotic Mode

Hunting occurs in the period after the initial transient disturbance and before a ferroresonance mode, which is discussed above, locks into a stable operating condition. This hunting for the stable operating point appears chaotic and can take from less than a cycle to hundreds of cycles to lock into the stable operation with repeated patterns. The hunting is characterized by non-periodic waveforms and different voltage magnitudes bouncing around in chaos. On some occasions this can go on indefinitely. The continuous hunting is usually the result of high magnetic coupling between phases and initial conditions and is referred to as the chaotic mode as illustrated in Figure 8. Usually a slight change in initial conditions of the ferroresonant circuit will allow locking into one of the stable modes of repeated patterns.

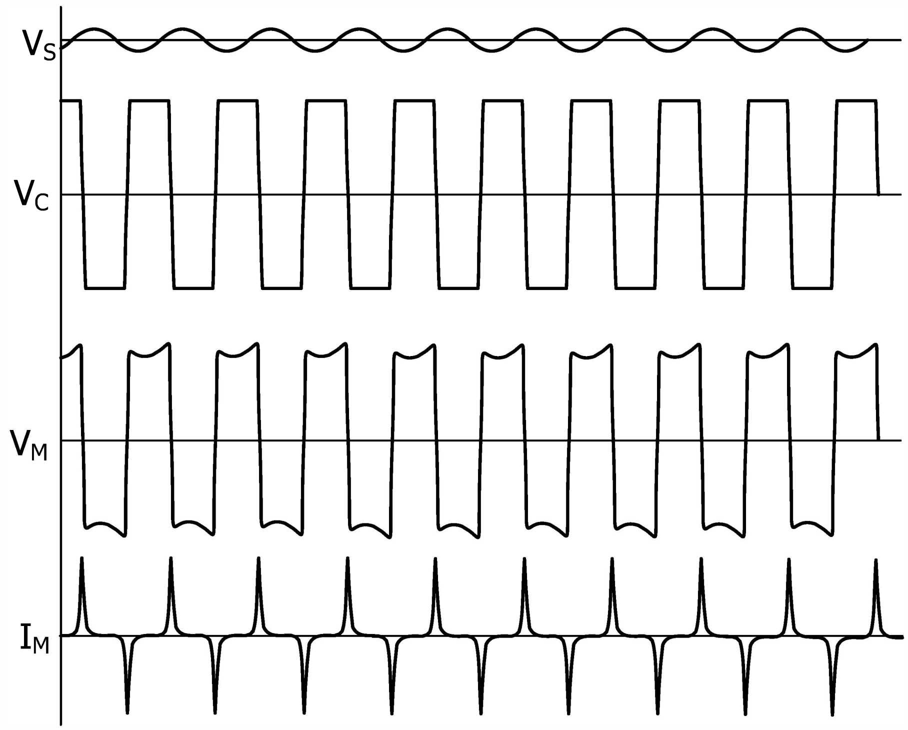


Figure 5. Fundamental mode ferroresonance

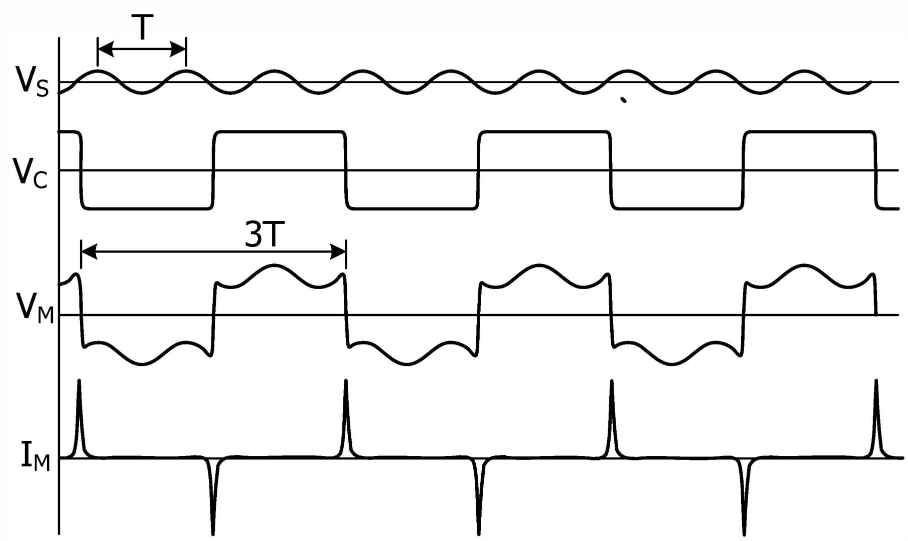


Figure 6. Sub-harmonic mode ferroresonance – 20 Hz

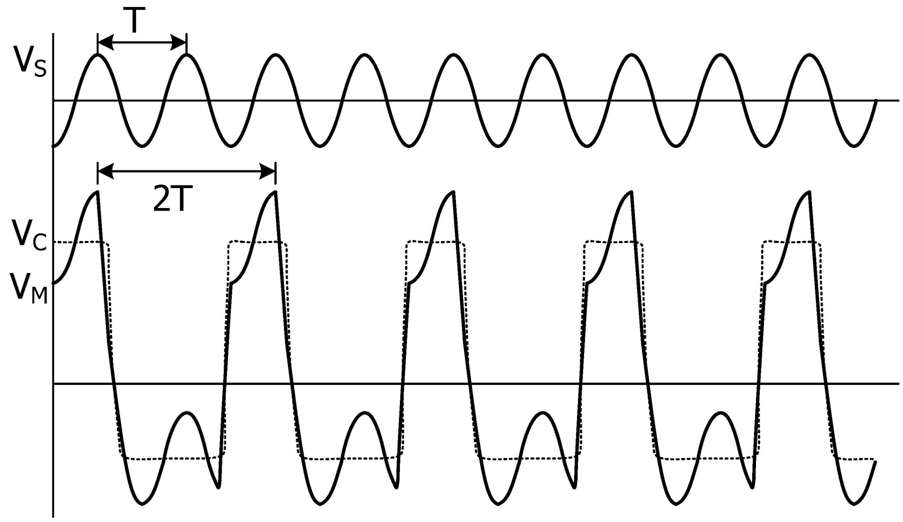


Figure 7. Sub-harmonic mode ferroresonance – 30 Hz

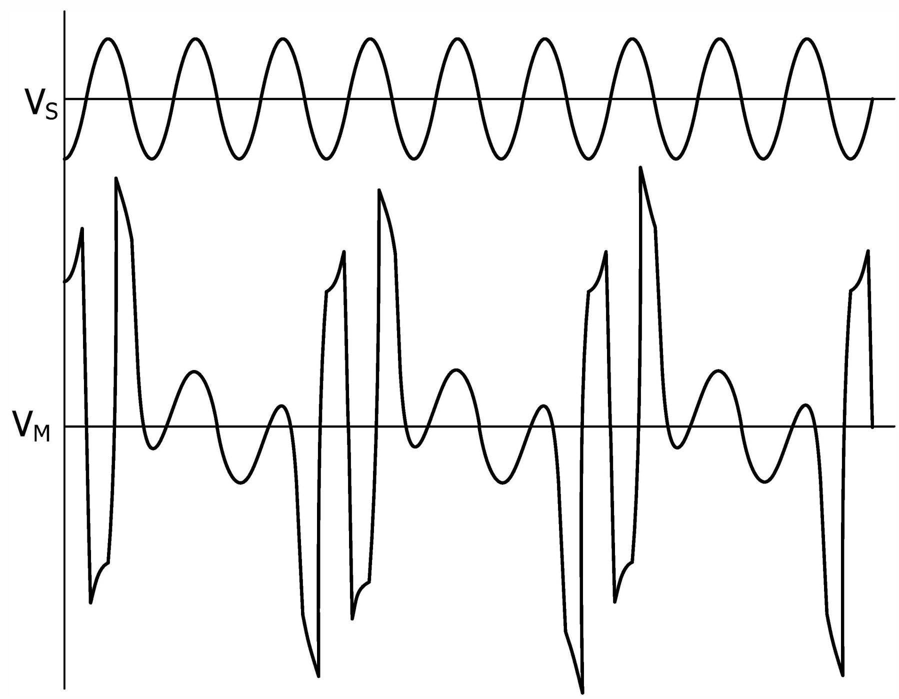


Figure 8. Quasi-periodic mode ferroresonance

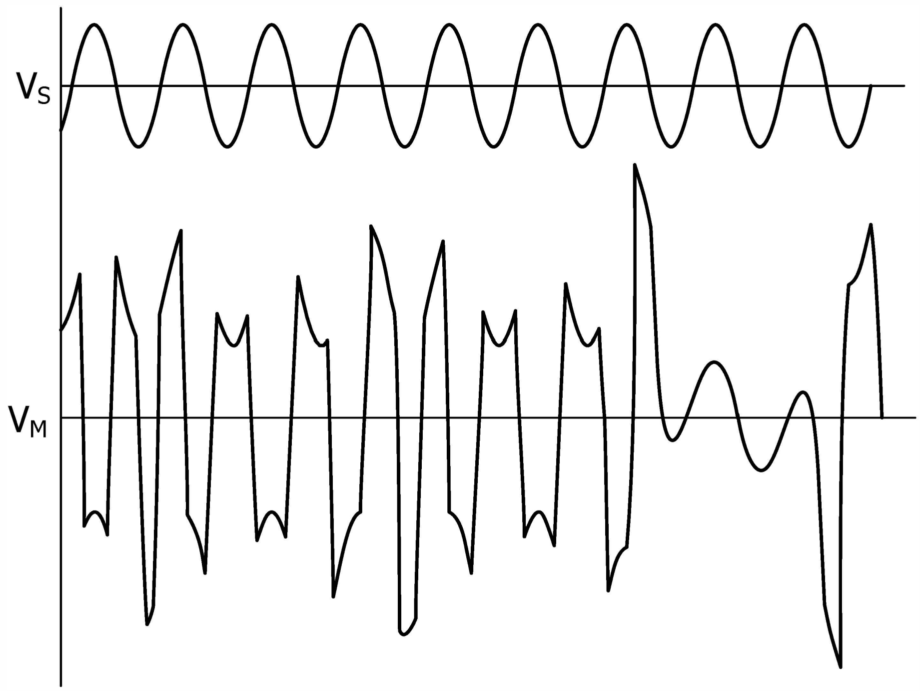


Figure 9. Chaotic mode ferroresonance

Figure 10 is a copy of a vintage magnetic strip chart recording (circa 1976) from vt ferroresonance testing in a 345 kV substation. During the testing several modes of ferroresonance were observed, but at that time categorizing the ferroresonance modes was not the objective. Several of the modes, however, are observed on this copy – fundamental, sub-harmonic and chaotic (hunting) to be sure. Unfortunately an estimated 2 to 4 seconds of recording were removed [from a long roll of recording paper] between events at t2 and t3. This test was to determine if the calculated damping resistance of 1.9 ohms would eliminate ferroresonance of a specific vt. Refer to a later section and equation 25 for discussion of the calculation method and also reference 2.

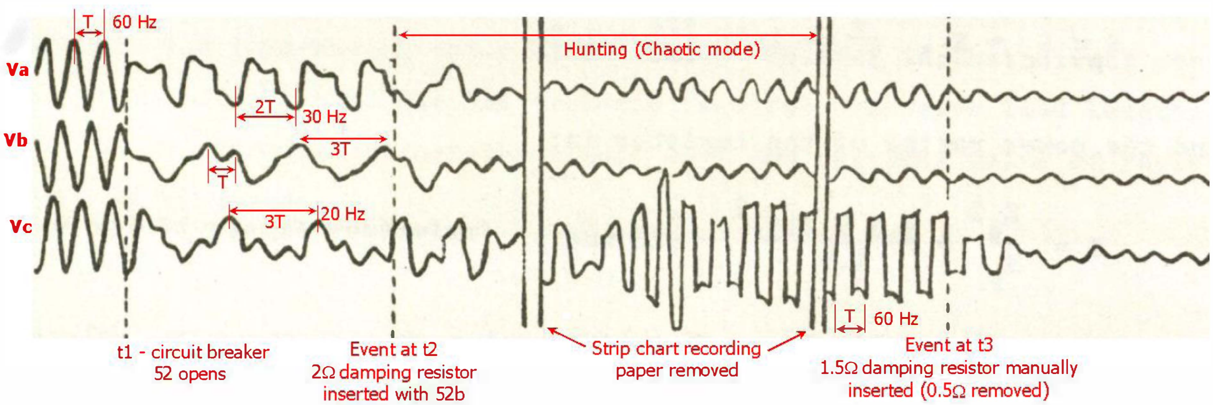


Figure 10. Vt ferroresonance in a 345 kV substation

A Study of the Ferroresonant Circuit Using Phasor Analysis

Transformer normal and ferroresonant operating states at the fundamental frequency can be graphically shown and analyzed using phasor analysis. Phasor analysis is the simplest means of analysis and has proven very effective in analyzing circuits that can be reduced to a single phase circuit that represents the ferroresonant system somewhat accurately. Due to the variability of the non-linear circuit characteristics and the harmonics that are produced other more complex forms of analysis are often preferred. [1]

Consider the circuit of figure 11(a), the basic ferroresonance circuit in its simplest form. A simple set of simultaneous equations for the solution of V_M as a function of I_M can be developed where at fundamental frequency X_C is the capacitive reactance, which is shown negative, and X_M is the non-linear transformer magnetic characteristic. Plotting equations 6 and 7 in figure 11(b) shows three intersections where V_M and I_M are satisfied for both equations.

$$V_M = X_M I_M \tag{6}$$

$$V_M = V_S + X_C I_M \tag{7}$$

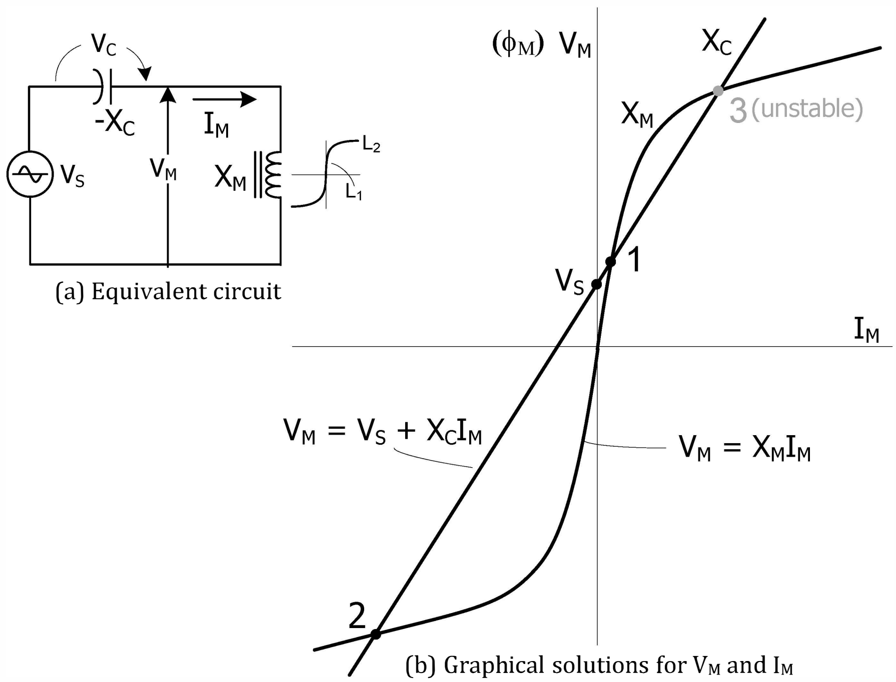


Figure 11. Graphical solution for transformer operating states at fundamental frequency applied in a circuit with series capacitance

Point 1 is the normal operating state where the transformer is operating in the non-saturated region of X_M. Point 2 is the ferroresonant state where the transformer is operating in the saturated region of X_M. Operation at point 3 cannot occur. Basically, at points 1 or 2 for small changes in current the voltage change acts in opposition to the current change and forces the operation back to the operating point. At point 3 a small change in current changes the voltage, which creates an additional current that is in the direction of the change; therefore, the current avalanches away from the operating point. This is discussed in greater detail in Appendix A. ϕ_M is noted on the V_M axis to remind the reader that the magnetizing current is the result of flux being produced by the applied fundamental frequency voltage. When other sub-harmonic voltage waveforms result during point 2 operations the value of flux, ϕ_M, being produced is still about the same. Therefore, study at fundamental frequency is appropriate.

Figure 12 shows the graphical solutions when considering the effect of resistance. Equation 6 is still used, but the second equation, equation 11, is developed using Kirchhoff's Law and summing the voltage drops around the series circuit as shown in equation 8. The equation is complex as it has real and imaginary parts. From there it's a matter substitution, rearranging terms and summing the squares to get to equation 11.

$$V_S - RI_M - (-jX_C)I_M - jX_M I_M = 0 \tag{8}$$

$$V_M = X_M I_M$$

$$V_S = RI_M + j(V_M - X_C I_M) \tag{9}$$

$$V_S{}^2 = (RI_M)^2 + (V_M - X_C I_M)^2 \tag{10}$$

$$V_M = X_C I_M \pm \sqrt{V_S^2 - (RI_M)^2} \tag{11}$$

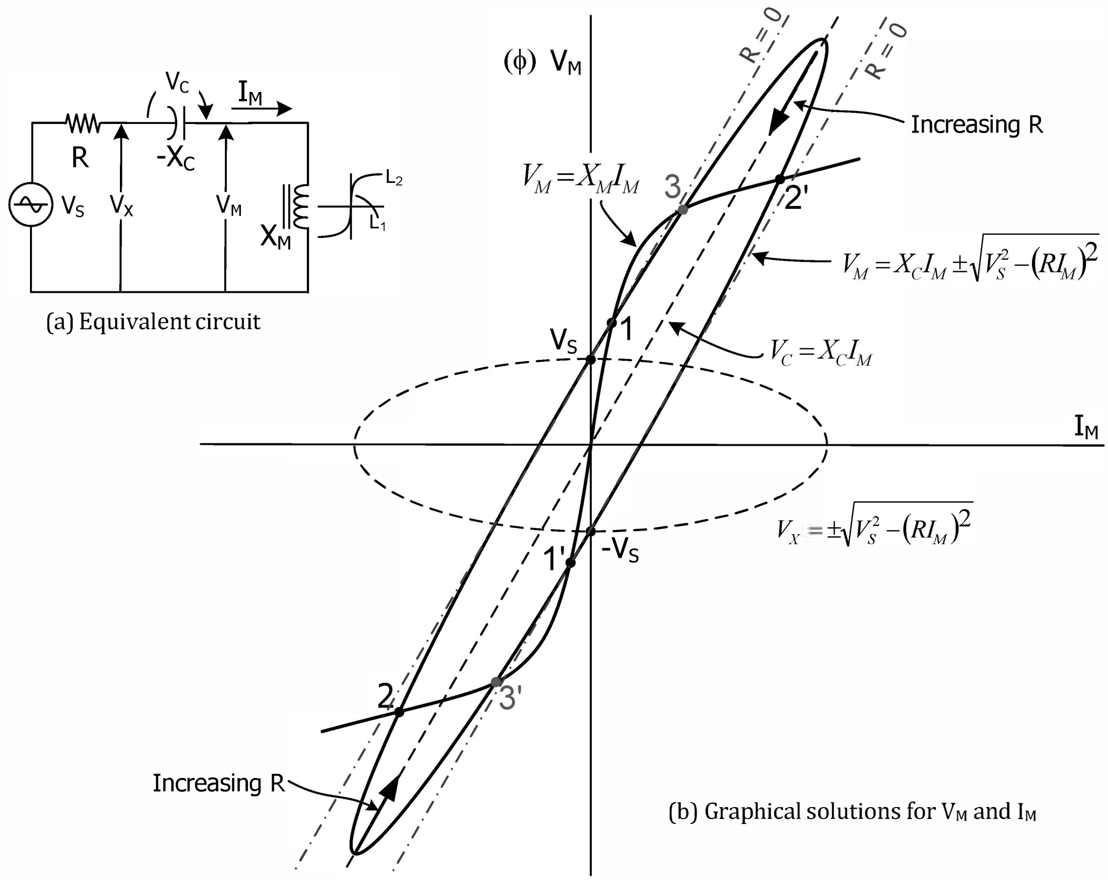


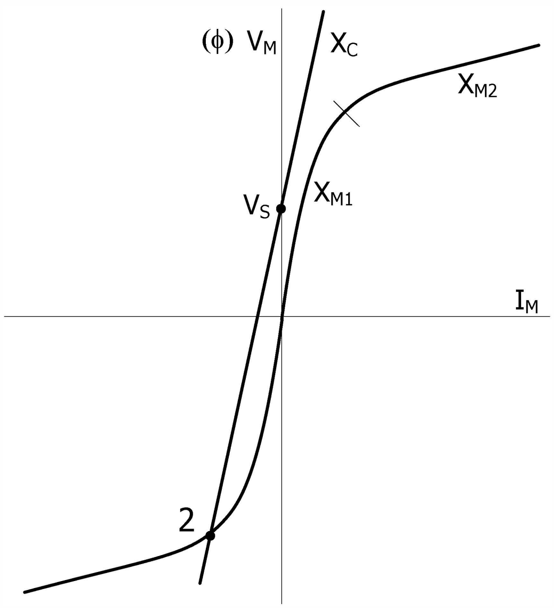
Figure 12. Graphical solution for transformer operating states at fundamental frequency applied in a circuit with series capacitance and resistance

Equation 11 is an ellipse that is symmetrical about the slope X_C. Plotting equations 6 and 11 in figure 12(b) shows six intersections where V_M and I_M are satisfied for both equations. Points 1, 2, and 3 are solutions for positive values of V_S and points 1′, 2′ and 3′ are solutions for negative values of V_S ($-V_S$). Similarly, points 1/1′ are the normal operating state, points 2/2′ are the ferroresonant state and the operation at points 3/3′ cannot occur. The ellipse contracts with increasing R. This shows the possibility of eliminating ferroresonant point 2 operations with sufficient loading. The ellipse expands with decreasing R. If R is equal to zero then equation 11 would be reduced to equation 12 (essentially the same as equation 7). This results in the two straight lines on the figure 6(b) identified as the R = 0.

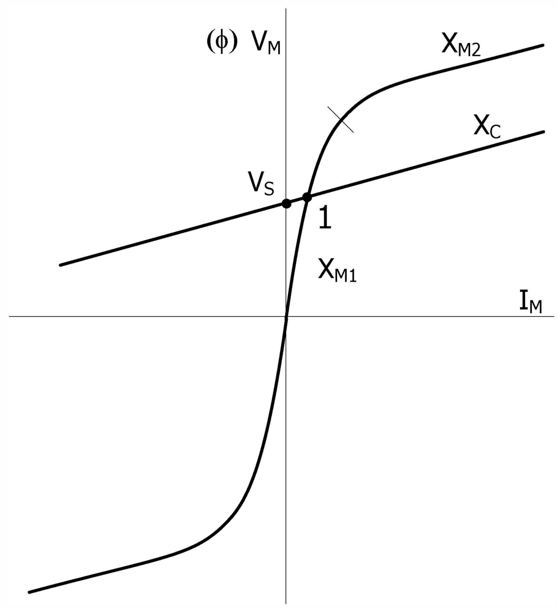
$$V_M = X_C I_M \pm V_S \tag{12}$$

Single point operations

Figure 13 shows some possible single point operating state solutions depending on the value of X_C relative to X_M. In figure 13(a) where the magnitude of X_C is equal to or greater than the non-saturated magnetizing reactance, X_{M1}, there is only a point 2 solution and the transformer will operate in an over excited state also referred to as ferroresonance. In figure 13(b) where the magnitude of X_C is equal to or less than the saturated magnetizing (air core) reactance, X_{M2}, there is only a point 1 solution and there will be no occurrence of ferroresonance.



(a) Ferroresonant (over excited) state - $|X_C| \geq X_{M1}$



(b) Normal state – $|X_C| \leq X_{M2}$

Figure 13. Single point operating state solutions

Changing operating states under transient conditions

The transformer's normal operation is in the non-saturated region of the magnetizing characteristics and ferroresonance is initiated after some type of transient event such as transformer energization, single-phase switching, fault clearing, a blown fuse, breakers opening, or loss of system grounding. Regardless of the event a transient change in voltage levels, impedance parameters and/or circuit configuration forces the jump in operating state from normal to ferroresonant. This is illustrated in figure 14 with a very simplified illustration of a rather complex and dynamic process. The ferroresonant state, when it occurs, is a legitimate operating state and will remain there without the impetus to stop it.

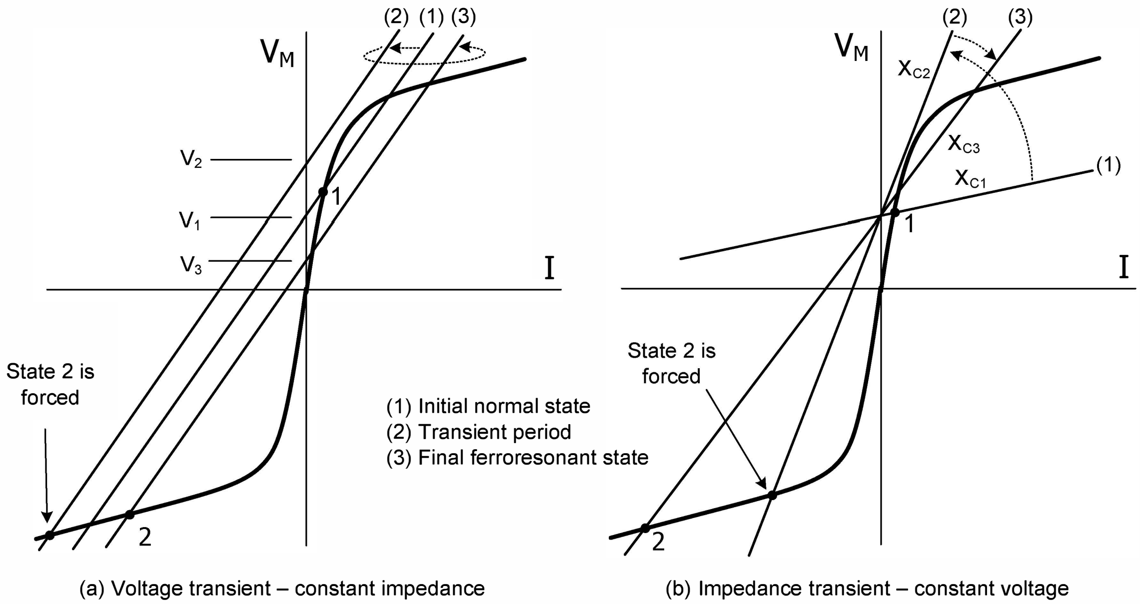


Figure 14. Forcing the ferroresonant operating state

Damping the Ferroresonant Circuit

Figure 12(b) indicates that increasing circuit resistance (load) would eliminate operation in the ferroresonant state. Load, however, must be added in parallel to the transformer magnetizing reactance as it is impractical to add series load without affecting the system operation. Figure 15(a) shows the ferroresonant circuit with parallel resistance. There are several ways to approach the development of a circuit equation for V_M as a function of I_M. The equation will be complex and require a quadratic equation solution. Figure 15(b) shows the phasor diagram for the circuit of figure 15(a) from which an equation for V_M as a function of I_M can be derived.

$$V_S^2 = (V_C \cos\alpha)^2 + (V_M - V_C \sin\alpha)^2 \tag{13}$$

Where $\cos\alpha = \frac{I_R}{I_C}$ and $\sin\alpha = \frac{I_M}{I_C}$

$$V_S^2 = \left(\frac{V_C I_R}{I_C}\right)^2 + \left(V_M - \frac{V_C I_M}{I_C}\right)^2 \tag{14}$$

$$V_S^2 = X_C^2 I_R^2 + V_M^2 - 2V_M X_C I_M + X_C^2 I_M^2 \tag{15}$$

Where $I_R = \frac{V_M}{R}$

$$V_S^2 = \frac{X_C^2 V_M^2}{R^2} + V_M^2 - 2V_M X_C I_M + X_C^2 I_M^2 \tag{16}$$

$$V_M^2\left[\left(\frac{X_C}{R}\right)^2 + 1\right] - 2X_C I_M V_M + X_C^2 I_M^2 - V_S^2 = 0 \tag{17}$$

Equation 17 is also an ellipse and is symmetrical about the slope *m* with V_M axis intercepts $\pm V_Q$. Plotting equations 6 and 17 in figure 15(c) shows the normal and ferroresonant operating state intersections. If R is increased to infinity (opened) then equation 17 would be reduced to equation 12. On the other hand the ellipse shrinks and its slope decreases with decreasing R. This shows the possibility of eliminating ferroresonant point 2 operations with sufficient parallel loading by reducing R.

Points 2′ and 3 can be analytically derived using the straight line approximation of the nonlinear magnetizing reactance curve's saturated region (air core reactance) as shown in figure 16.

$$V_M = X_{M2} I_M + V_{Sat} \tag{18}$$

Rearranging equation 18 in terms of I_M and then substituting into equation 17 and understanding that the slope X_C is greater than the slope X_{M2} for the points 2′and 3 intersections to occur we can develop equation 19.

$$V_M^2 \left[\left(\frac{X_C}{R}\right)^2 + \left(\frac{X_C - X_{M2}}{X_{M2}}\right)^2 \right] + V_M \left[-2V_{Sat} \frac{X_C}{X_{M2}} \left(\frac{X_C - X_{M2}}{X_{M2}}\right) \right] + \left(\frac{X_C V_{Sat}}{X_{M2}}\right)^2 - V_S^2 = 0 \tag{19}$$

The solutions for V_M of equation 19 can be derived using the quadratic formula.

$$V_m = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \tag{20}$$

Where

$$a = \left(\frac{X_C}{R}\right)^2 + \left(\frac{X_C - X_{M2}}{X_{M2}}\right)^2 \tag{21}$$

$$b = -2V_{Sat} \frac{X_C}{X_{M2}} \left(\frac{X_C - X_{M2}}{X_{M2}}\right) \tag{22}$$

$$c = \left(\frac{X_C V_{Sat}}{X_{M2}}\right)^2 - V_S^2. \tag{23}$$

The maximum value of resistance, R_{Max}, can be determined by graphically shrinking the ellipse until there is only a single solution with equation 18 representing the saturated region. The single solution is also the unstable point 3 solution for which operation will not occur forcing the point 1 solution for normal operation. Analytically, a single point solution will only occur when the term under the radical in equation 20 is equal to zero.

$$b^2 - 4ac = 0 \tag{24}$$

If the term is negative then the solution is complex and indicates no intersections. Therefore, any value of R less than R_{Max} will have no intersections in the saturated region. An equation for R_{Max} can be derive by substituting equations 21, 22 and 23 into equation 24 and solving for R. After a lot of careful and tedious term manipulation and reduction equation 25 is derived.

$$R_{Max} = \frac{X_C X_{M2}}{X_C - X_{M2}} \sqrt{\left(\frac{X_C V_{Sat}}{X_{M2} V_S}\right)^2 - 1} \tag{25}$$

In cases where X_C is much greater than X_{M2} equation 25 can be greatly simplified to equation 26.

$$R_{Max} = \frac{X_C V_{Sat}}{V_S} \tag{26}$$

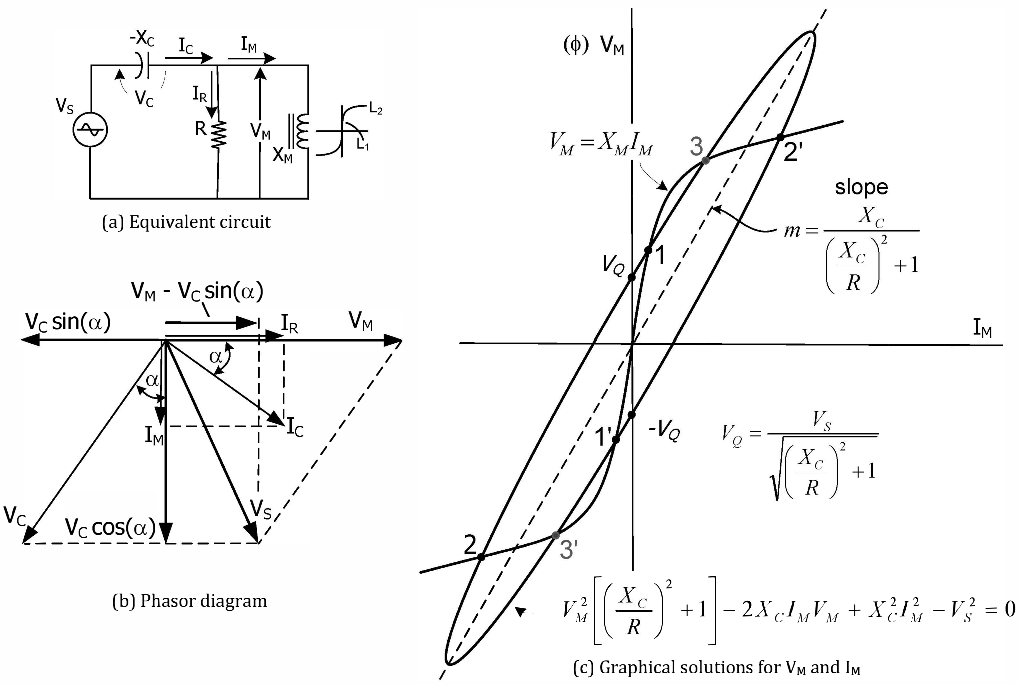


Figure 15. Graphical solution for transformer operating states at fundamental frequency applied in a circuit with series capacitance and parallel resistance

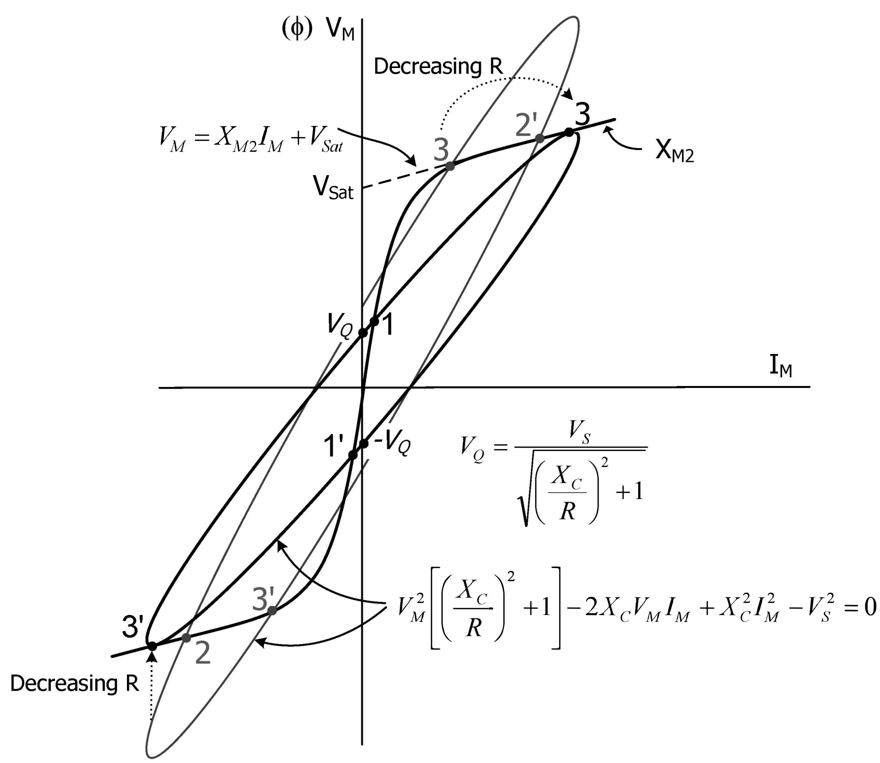


Figure 16. Graphic solution for eliminating ferroresonance

Other analysis methods

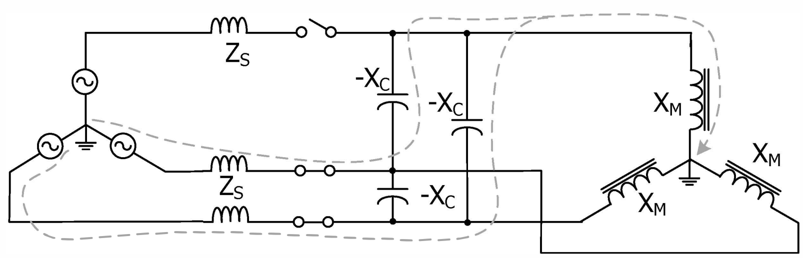
Phasor analysis as done above is the simplest method of ferroresonance analysis to use for developing a basic understanding of the phenomena. It has been used effectively where simple and accurate ferroresonant circuits could be defined. Due to the variability of the non-linear circuit characteristics and the harmonics that are produced other more complex forms of analysis are often preferred. Also, more complex configurations will require more accurate modeling and the use of time domain EMTP analysis. Other methods of analysis are discussed in detail in reference 1.

System Ferroresonant Configurations

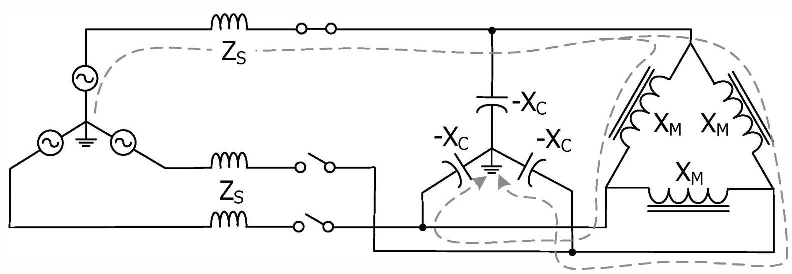
The basic ferroresonant circuit involves a transformer's non-linear magnetizing reactance, very low core and load losses (burden), a system voltage source and a series capacitance, which is usually coupled with a shunt capacitance, between the source and non-linear reactance. Figures 4(a) and 4(b) represent the basic circuits. There are many possibilities. Following is a brief discussion of some rather common cases.

Unbalanced Switching

This condition occurs more frequently on distribution systems where open phases result from blown fuses and/or single phase switching of transformers. It may also happen in three phase switching applications where unintended unbalanced switch operation occurs, e.g. a stuck pole on a breaker opening operation. This condition is illustrated in figures 17(a) and 17(b) where the ferroresonance circuit can be easily visualized. The source voltage is supplied by the remaining connected phase(s). The series capacitance is associated with the conductor characteristics … cable, transmission line, bus, etc., and may be either phase-to-phase, phase-to-ground, or both.



(a) Coupling through phase-to-phase capacitance with grounded transformer

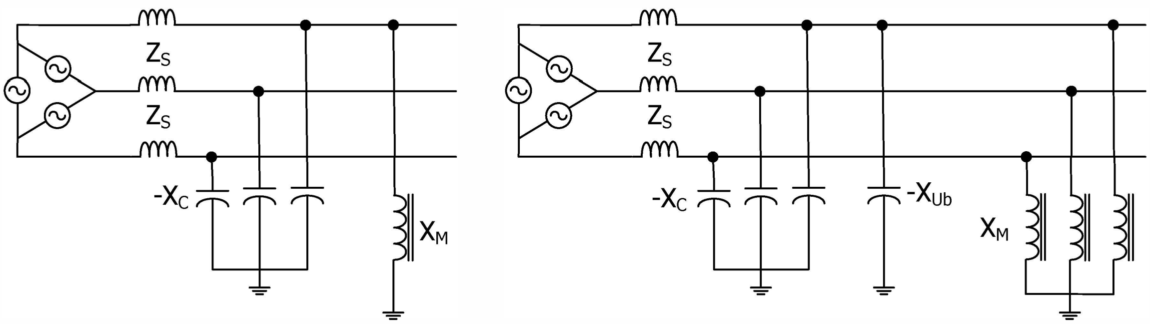


(b) Coupling through phase-to-ground capacitance with ungrounded transformer

Figure 17. Unbalanced switching conditions

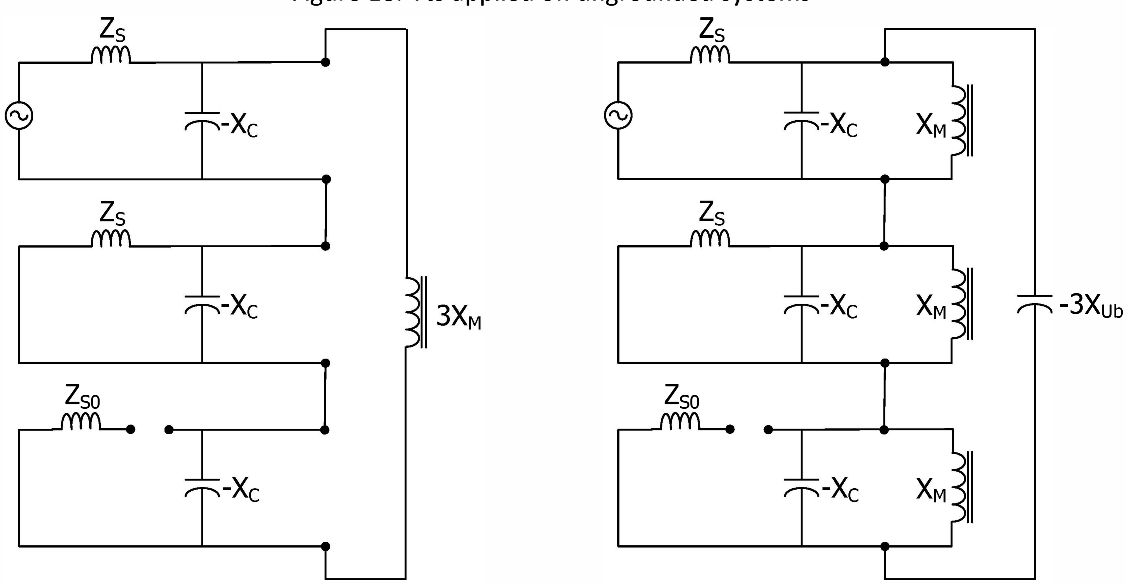
Voltage Transformer Applications on Ungrounded Systems

Although not always readily apparent, phase-to-ground connected voltage transformers (vts) applied to ungrounded system configurations are prone to ferroresonance. Such configurations should be avoided and if temporary as a result of system operation appropriate precautions taken. Two applications as shown in figure 18 are discussed here, a single phase-to-ground vt and a bank of three phase-to-ground vts with unbalanced phase-to-ground line capacitance. Sequence networks are used to derive the ferroresonant circuit.



(a) Single phase-to-ground vt (b) Three phase-to-ground vt with unbalanced capacitance

Figure 18. Vts applied on ungrounded systems



(a) Single phase vt sequence networks (c) Three phase vt sequence networks

(b) Equivalent circuit of (a) with $Z_S = 0$ (d) Equivalent circuit of (c) with $Z_S = 0$

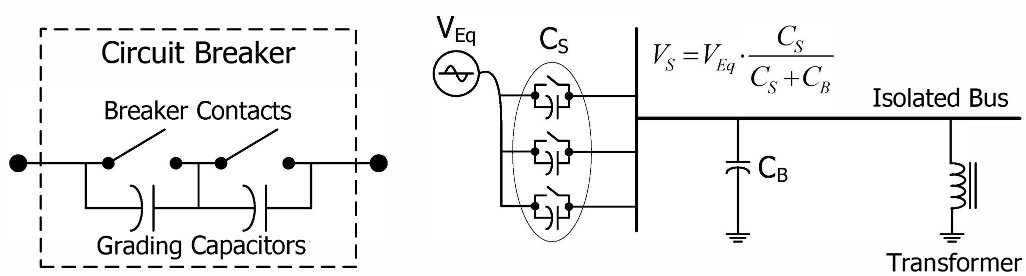
Figure 19. Sequence network interconnects and equivalent ferroresonant circuits for figure 18 systems

A single phase vt applied on an ungrounded system as shown in figure 18(a) is subject to ferroresonance due to the phase-to-ground capacitance and the unbalanced effect of the single phase transformer. The positive, negative and zero sequence circuits are connected with $3X_M$ as shown in figure 19(a). Since the source impedance magnitude, Z_S, is very small compared to X_C and X_M it can be neglected [and assumed a short]. The resulting equivalent ferroresonant circuit is shown in figure 19(b).

A three phase bank of voltage transformers applied on an ungrounded system as shown in figure 18(b) is subject to ferroresonance due to the unbalance of the phase-to-ground capacitance that usually exists. To simplify the circuit for analysis the phase-to-ground unbalance is shown as $-X_{Ub}$ lumped on one phase while the balanced capacitive reactance is shown as $-X_C$. The positive, negative and zero sequence circuits are connected with $-3X_{Ub}$ as shown in figure 19(c). Since the source impedance magnitude, Z_S, is very small compared to X_C and X_M it can be neglected. The resulting equivalent ferroresonant circuit is shown in figure 19(d).

Vt ferroresonance with circuit breaker grading capacitors

High voltage circuit breakers generally require multiple breaker contacts in series to divide the fault interrupting transient voltage stress across each breaker contact evenly. Voltage grading capacitors are connected across each contact as shown in figure 20(a) to assure an even voltage distribution during the interruption process. The net capacitance across the breaker depends on the number of breaking contacts and the value of the grading capacitor. A typical value might be 1300 ρf resulting in 650 ρf across the breaker with two series breaker contacts. The grading capacitors also serve to improve the breaker's current interruption capability (rating) and may be sized appropriately. TRV (transient recovery voltage) capacitors may be applied phase-to-ground and/or across the breaker contact. Therefore, it is possible that single contact breakers, which do not need grading capacitors, may have a TRV capacitor across the contact.



(a) Circuit breaker grading capacitors (b) Ferroresonant bus configuration

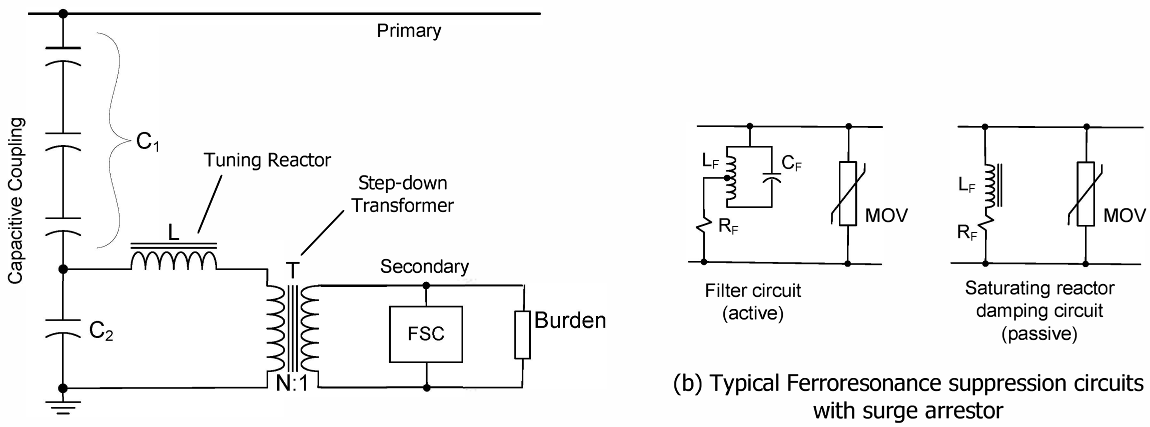
V_{Eq} – equivalent system source voltage, C_S – total series open breaker capacitance,
C_B – bus capacitance, V_S – coupled bus voltage in normal operating state

Figure 20. Ferroresonant bus configuration with circuit breaker grading capacitors

A number of breakers may be connected to the bus during the bus isolation, e.g. breaker failure lockout, and the net series capacitance, C_S, can couple a large voltage, V_S, to the bus with the bus capacitance, C_B. Depending on the aforementioned conditions this configuration may result in transformer ferroresonance. Generally, induction voltage transformers, vts, are most likely affected; however, power transformers have been affected where a large number of breakers are connected to the isolated bus.

Ccvt ferroresonance

Coupling capacitor voltage transformers are by the nature of their design very prone to ferroresonance and ccvt manufacturers provide various designs of ferroresonance suppression circuits (FSCs) applied on a secondary winding. The ccvt equivalent circuit and typical FSCs are shown in figure 21.



(a) CVT equivalent circuit

(b) Typical Ferroresonance suppression circuits with surge arrestor

Figure 21. Ccvt equivalent circuit with FSCs

The filter FSC is a fundamental frequency (50 or 60 Hz) blocking filter that allows damping of harmonics and sub-harmonic modes of ferroresonance. This leaves primarily the fundamental frequency voltage operating in the normal state. Selection of the blocking filter with a narrow bandwidth at fundamental frequency is desirable. The saturating reactor circuit uses a saturating reactor to switch in damping resistance when secondary voltages (and flux density) become excessive. It responds to all harmonic and sub-harmonic voltages. The addition of MOVs provides additional secondary surge protection and reduces the ferroresonant elimination time. While the FSCs are effective at eliminating ferroresonance they do temporarily affect ccvt voltage accuracy during system faults and protective relay operation. This must be evaluated.

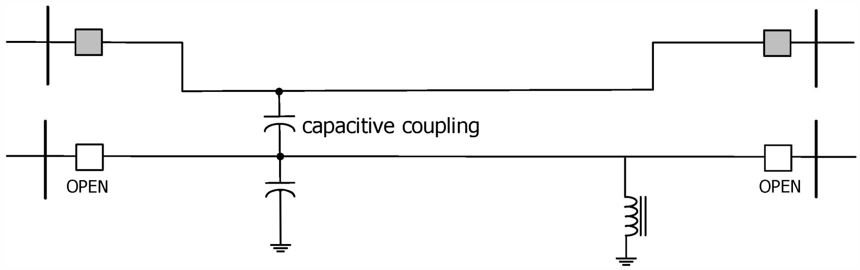
Auxiliary Transformers

Auxiliary transformers connected to the secondary of a vt or ccvt may be subject to ferroresonance. The auxiliary vt is a non-linear burden that will affect the output of the vt or ccvt. This is particularly true in the case of ccvts where capacitance is a major part of the ccvt transformer's primary circuit. The auxiliary vt's saturation characteristics should be selected such that saturation does not occur before the vt or ccvt to which it is applied. Sometimes a higher voltage rating may be preferred - e.g. 230:230 V auxiliary vt instead of 115:115. V.

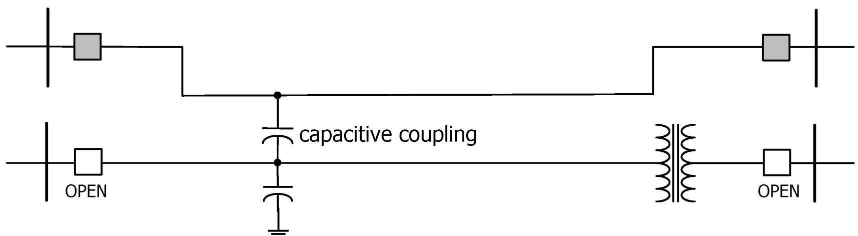
Transformer connected to an isolated line

A transformer that is connected to an isolated line (de-energized and not grounded) that is physically parallel and adjacent to an energized line for part of its length is subject to ferroresonance if sufficient capacitive coupling exists between the two circuits. Refer to figure

22. The capacitive (electrostatic) coupling would depend primarily on the geometry between the two circuits and the length of the lines.



(a) Vt or tapped transformer



(b) Transformer terminated line

Figure 22. Isolated transmission line ferroresonant configurations

Mitigation of ferroresonance

The mitigation of transformer ferroresonance usually involves one or more of the following:

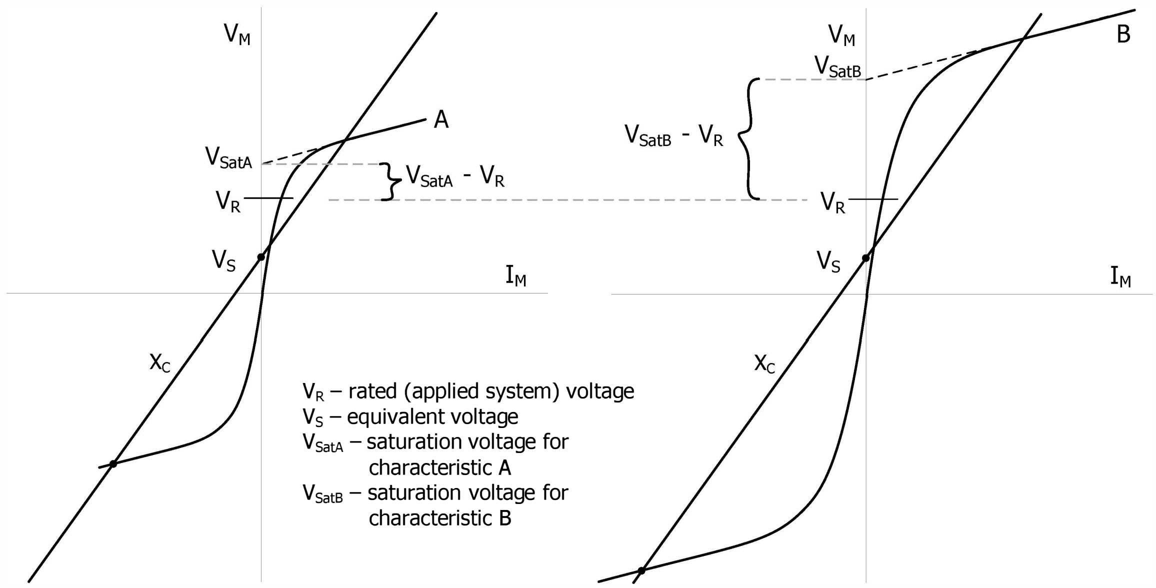
- Correcting a voltage unbalance condition
- Changing the transformer magnetic design
- Inserting damping resistance
- Detuning the circuit

Correcting voltage unbalance

Voltage unbalance can be corrected by changing operating procedures or by applying protective relays to sense and remove the unbalanced condition that drives ferroresonance. For example, single phase switching of three phase distribution transformers may be changed to three phase operation; or a voltage relay that is used to sense excessive zero sequence voltage and trip a circuit breaker. Opportunities to correct voltage unbalance should be investigated. There are, however, many applications where steady state unbalanced voltages cannot be avoided and alternative solutions are required.

Changing the transformer magnetic design

Improvements in transformer core steel design have allowed transformers to be designed at higher rated flux levels while producing acceptable excitation current and core losses. This allows rated voltage, V_R, operation closer to the saturation level V_{Sat} such that the ratio V_{Sat}/V_R is relatively small. Refer back to figure 1. This is perhaps the reason for the apparent increase in the occurrence of and the subsequent study of ferroresonance.



(a) Magnetizing characteristic A (b) Magnetizing characteristic B

Figure 23. Ferroresonance operation comparison

Figure 23 shows two different magnetizing characteristics. For characteristic A the V_{SatA}/V_R ratio is 1.38 and for characteristic B the V_{SatB}/V_R ratio is 2.17. Comparing the two characteristics it is readily observed that when using characteristic B a much higher voltage transient is required to force a jump to the ferroresonant operating state (refer to simple analysis of figure 14(a)). Also referring back to equation 25 it is observed that characteristic B has less damping (R_{Max} is larger) to eliminate ferroresonance.

Modification of the transformer's magnetizing characteristic may not always be an economically practical solution, particularly three phase power transformers. It should be looked at in critical cases. In the case of vts and distribution transformers selecting a voltage rating greater than the applied voltage and maintaining the correct turns ratio may be practical. Also, investigating the differences in magnetizing characteristics between vendors might be worthwhile. Reference 4 provides a discussion that compares three vt characteristics from different vendors with simulation studies.

Inserting damping resistance

A common way to eliminate ferroresonance is to insert damping resistance across the secondary wye connected phase-to-ground windings or in the corner of a broken delta winding as shown in figure 24. This applies to both power and instrument transformers. The damping resistor is often part of ferroresonance suppression devices (FSD) involving a damping resistor with other devices controlling it.

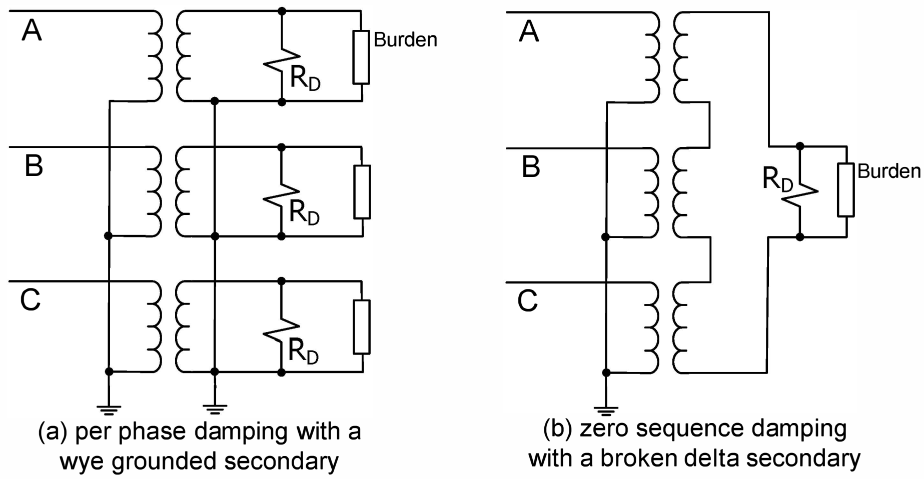


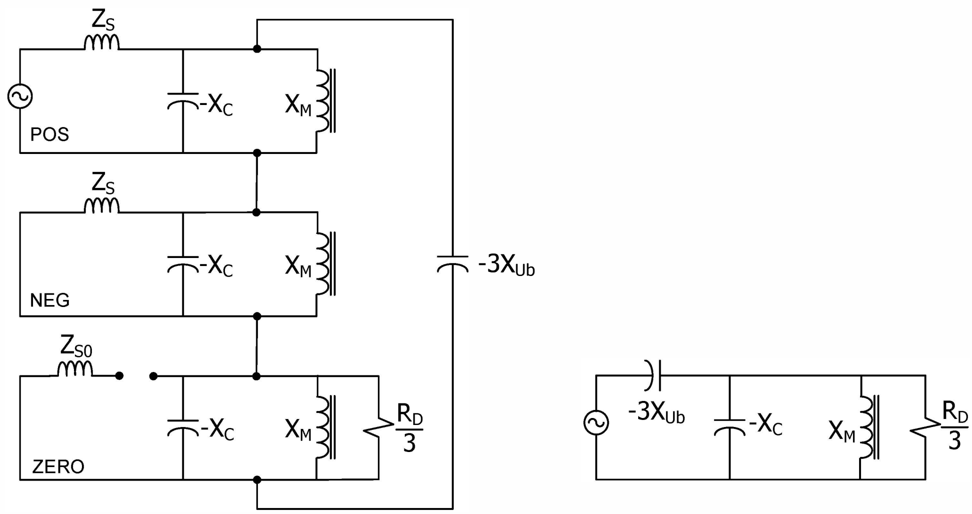
Figure 24. Ferroresonance mitigation with damping resistance

Zero Sequence Damping

Figures 17 and 18 illustrate typical unbalance conditions. Ferroresonance for these conditions is usually the result of excessive zero sequence flux that occurs in the core with the voltage unbalance. This is particularly true in the case of three phase cores. In single phase cores a large component of the phase-to-ground voltage is zero sequence. Therefore, eliminating the zero sequence voltage may be sufficient to eliminate the ferroresonant condition. The implementation of operating procedures to prevent unbalance voltages or restore balanced voltages may be sufficient, but in cases where a voltage unbalance cannot be avoided zero sequence damping as shown in Figure 24(b) is appropriate.

Unbalances also occur on systems due to the phase-to-ground capacitive unbalance as illustrated for the ungrounded system of figure 18(b). The equivalent circuit is derived from figures 19(c) and 19(d) and is predominately zero sequence as the positive and negative sequence XC and XM are shorted by the soutce impedance. Again, damping as shown in Figure 24(b) would be appropriate. Figures 19(c) and 19(d) are shown without a secondary winding connection. Modifying these figures with the secondary broken delta winding and resistor is as shown in figure 25.

Figure 26 shows the resulting phase and zero sequence ($3V_0$) coupled voltages after clearing a three phase bus and inserting grading capacitance similar to the single phase representation of figure 20(b). In this case vt ferroresonance did not occur, but in other bus clearing trips it did. The coupled phase voltage is approximately 25% of the pre-trip (system) voltage and the zero sequence voltage ($3V_0$) is about 8%. $3V_0$ is an indication of the bus capacitance unbalance. In this case where $3V_0$ is relatively small zero sequence damping per figure 18(b) will probably not be sufficient and phase damping per figure 24(a) will be required. Ferroresonance has often been mitigated in such applications with zero sequence damping, but in many cases phase damping was required. About the only generalization that can be made is that the greater the unbalance (the higher $3V_0$) the more likely zero sequence damping will be successful.



(a) Sequence network connection (b) Equivalent circuit

Figure 25. Sequence network interconnects and equivalent ferroresonant circuit for ungrounded system of figure 18(b) with damping resistor, R_D, of figure 24(b)

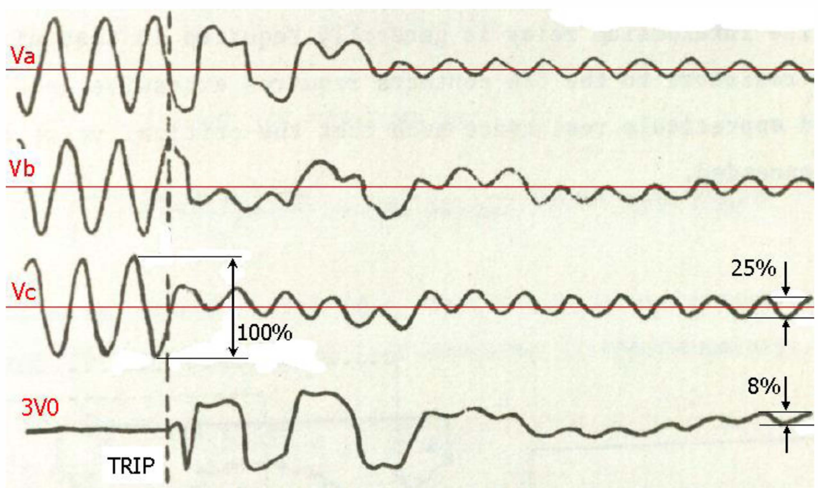


Figure 26. Coupled bus vt voltage with all breakers open

For zero sequence damping, sizing the damping resistor ohmic value, R_D, with the phasor or other method of analysis is done and then it is evaluated for meeting thermal requirements. The thermal requirements depend on the maximum normal state (non-ferroresonant) $3V_0$ that will appear across R_D during the unbalanced condition and the time that it is there. This can be the maximum time it takes protective relays to clear the unbalanced condition to an indefinite time where manual correction is required. In the latter case a damping resistor that can sustain a continuous current of $3V_0/R_D$ may be permanently connected. If not then an alternate means of ferroresonance damping is required. These are explored in a later discussion.

The effect of R_D being permanently connected must also be investigated on other devices measuring and using the broken delta $3V_0$ quantity – e.g. vt polarizing voltage for directional relays, generator resistance grounding and ground fault protection, etc. During balanced conditions $3V_0$ will be zero so there will be no effect on phase measurements.

Phase damping

Phase damping is the application of damping resistance placed across the secondary winding as shown in figure 24(a). This connection cannot generally be a permanent connection for either vts or power transformers. The damping resistor must usually be switched in and out in some manner to address the ferroresonance or some other means of ferroresonance suppression.

Ferroresonance Suppression Circuits

Figure 27 shows a number of devices that are used in ferroresonant suppression circuits. Each device is not necessarily a complete solution, but may complement other approaches. The availability of properly rated devices and their impact on the operation and performance of connected apparatus and system must be investigated.

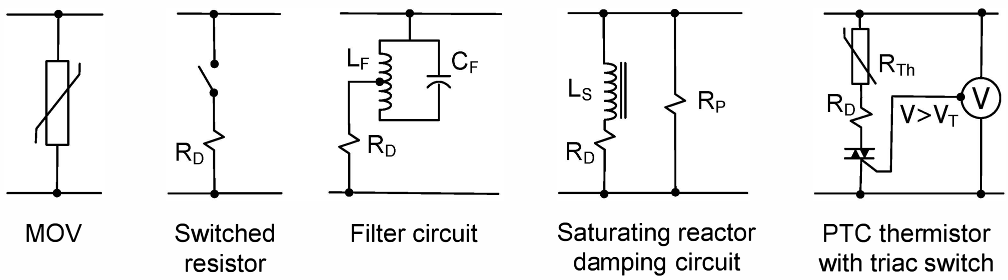


Figure 27. Ferroresonance damping devices

MOV – metal oxide varistor

The MOV provides some level of damping when it is conducting. It is able to limit, or assist in limiting; the fundamental frequency ferroresonant modes where voltages are above the MOV rating, but cannot prevent the transition to or the elimination of sub-harmonic modes where maximum sub-harmonic voltage levels are below the required MOV rating. Therefore, they are not suitable to apply alone to dampen ferroresonance. They may, however, be added in parallel to the filter circuit or saturating reactor circuit to enhance performance. Also, MOVs cannot continuously absorb energy so their application should be evaluated.

Mechanically switched resistor

A mechanically switched resistor is effective at inserting the damping resistance and eliminating ferroresonance. The problem is that opening the switch may produce a transient that puts the transformer back into the ferroresonant state. Therefore, the mechanical switch must remain closed until the ferroresonant circuit is corrected (eliminated). For example, consider the case of vt ferroresonance due to circuit breaker grading capacitors shown in figure 20. If all the breakers connected to the bus are opened then a capacitance is inserted in series with the vt and the ferroresonant circuit is created. The resistor is switched in with a series arrangement of the breakers' 52b auxiliary contacts. If one breaker is closed and system voltage is applied to the bus then the ferroresonant circuit is eliminated. This configuration is okay as long as the vt and resistor are appropriately rated. (This may potentially be a good solution with IEC 61850.)

Filter circuit

Solutions that have been applied to ccvts are appropriate for conventional vt or other transformer applications, but may require different component ratings. The filter circuit is a fundamental frequency blocking filter that allows damping of harmonic and sub-harmonic modes of ferroresonance. This leaves primarily the coupled fundamental frequency voltage operating in the normal state. Selection of the blocking filter with a narrow bandwidth at fundamental frequency provides better suppression. The addition of a MOV provides additional secondary surge protection and reduces the ferroresonant damping time. The filter circuit affects the transient response voltage accuracy during system faults and thus protective relay operational security. This must be evaluated.

Saturating reactor

A saturating reactor is used to switch in damping resistance when the secondary voltage (flux density) becomes excessive. It responds to all harmonic and sub-harmonic voltages as well as the fundamental. This solution has been broadly applied to ccvts and is also appropriate for conventional vt or other transformer applications, but may require different component ratings. The operation is relatively simple. Refer to figure 28. The saturating reactor is selected to have a saturation voltage, V_{SatR}, above, but very close, to the vt rated secondary voltage, V_R. During normal operation at rated voltage the non-saturated magnetizing reactance of the saturating reactor is so large compared to the damping resistor, R_D, that almost the entire vt secondary voltage is across the reactor. The reactor has little to no effect on the vt burden. When the ferroresonant circuit of figure 28(a) is formed inserting the series capacitance and vt ferroresonance is attempted the reactor saturates before the vt and inserts the damping resistance, R_D, into the circuit.

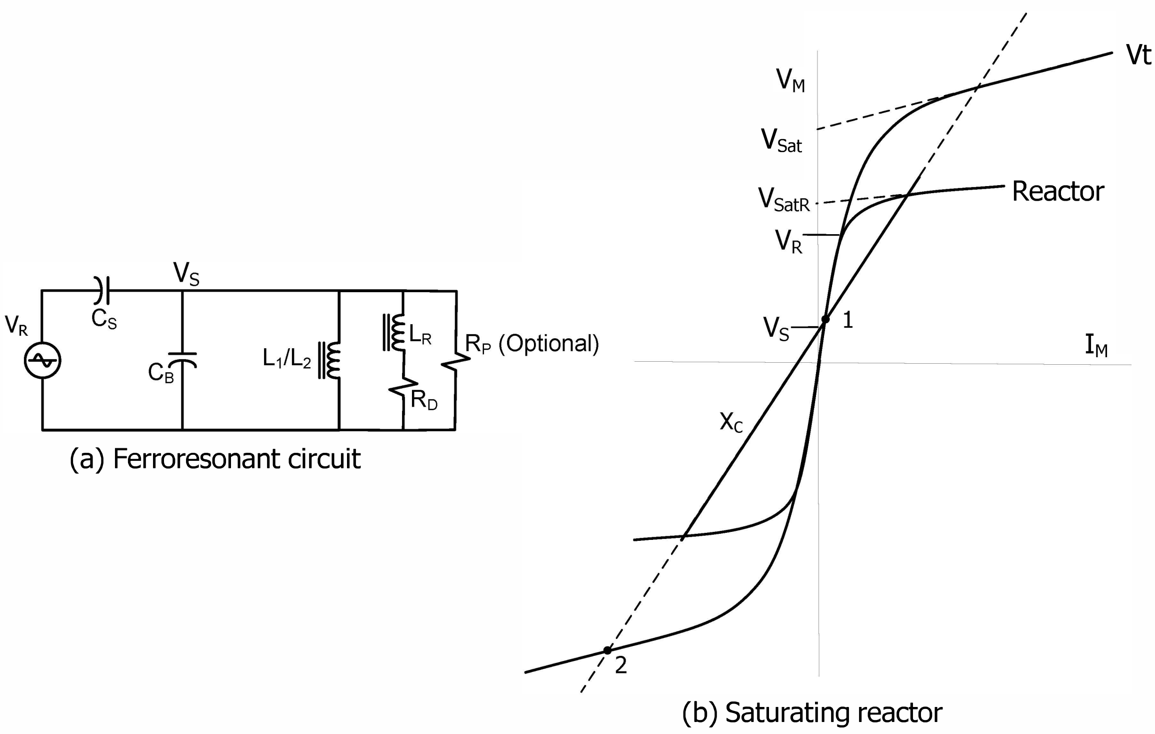


Figure 28. Saturating reactor application

The reactor being saturated is in ferroresonance, however the damping resistor, if calculated correctly, will force normal operation in a matter of cycles. Be sure to include the reactor's internal resistance when calculating R_D. It is often not negligible. In some cases the resistance in the reactor is not sufficiently low such that a parallel resistor may be useful to provide more damping. The parallel resistance must be included in the vt's maximum burden or other limitations dictated for its application.

PTC Thermistor

Refer to figures 24(b), 25 and 27. This approach is generally limited to applications where damping resistance is applied in the corner of a broken delta secondary vt winding to eliminate ferroresonance. This is particularly applicable to ungrounded systems where ferroresonance occurs and the damping resistor cannot meet the thermal requirements imposed by the normal sustained zero sequence voltage ($3V_0$) after the ferroresonance is eliminated. R_{Th} is the thermistor resistance and R_D is additional damping resistance. V represent a voltage threshold circuit such that if V_T is exceeded the triac is switched on closing the damping circuit. V_T is set to allow expected $3V_0$ unbalance when operating in the non-ferroresonant state. R_{Th}, the PTC (positive temperature coefficient) thermistor, initially has a very small resistance that will begin to increase after one to two seconds depending on the current through it. Depending on the thermistor characteristics R_{TH} can increase to several hundred ohms or more.

Consider an ungrounded system where an operating condition allows the capacitive unbalance to create ferroresonance. The zero sequence ferroresonant voltage appears across the broken delta winding and closes the damping circuit eliminating ferroresonance forcing a normal state operation in a matter of cycles. Then V decreases below V_T and the triac is turned off. When an event occurs, say a ground fault on an ungrounded system a very large $3V_0$ that is above the V_T setting will exist in the non ferroresonant state until the ground fault is removed. The large $3V_0$ would create a large damping current that would thermally damage the vt or R_D and other parallel connected loads. For these cases the triac will close the damping circuit and eliminate the ferroresonance and after a second or more R_{Th} will begin to increase substantially reducing the current "soft" way (gradual without transients) and the potential of thermal damage and preventing the reoccurrence of ferroresonance. The thermistor remains closed until the ground fault is removed.

This approach involves the application of electronics and its application is currently limited to medium voltage. At higher voltage installations there is still a reluctance to use electronics that could possibly provide better mitigation solutions. It is expected that more of these solutions will become available and will be combined with substation automation functions and IEC61850.

Detuning the Ferroresonant circuit

It is possible to have applications where the resistance in the circuit may be too large for effective damping or the slope of the circuit capacitive reactance X_C forces a single point ferroresonant solution. Consider the circuit of figure 24(a). The equivalent capacitive reactance, X_C (C_S \\ C_B and C_{Sec}) is represented in figure 24(c) by the lines with slopes A, B and C for different values of C_B and/or C_{Sec}. Curve A represents the single point solution where ferroresonance cannot be damped. The circuit must be altered or detuned to avoid these conditions. Slope A represents the XC value that results in a single point ferroresonant operating state is at point 2, the intersection of slope A with the saturated region of the transformer's magnetizing characteristic. Increasing the phase-to-ground capacitance, C_B, or adding a secondary capacitance, C_{Sec}, across the secondary winding will decrease the value (slope of line) of X_C. As capacitive reactance is decreased toward X_{M2} to a point where the ferroresonant operating point would be in severe saturation (slope B), the occurrence of ferroresonance is reduced or may even not be obtainable. Note from equation 25 that as X_C approaches the value of X_{M2} that R_{Max} increases indicating that less damping is required. This is shown in figure 29(b). If X_C continues to decrease to a value less than X_{M2} then no damping is required as there is only the normal operating point. As with any potential solution the availability of properly rated detuning capacitors and their impact on the operation and performance of connected apparatus and system.

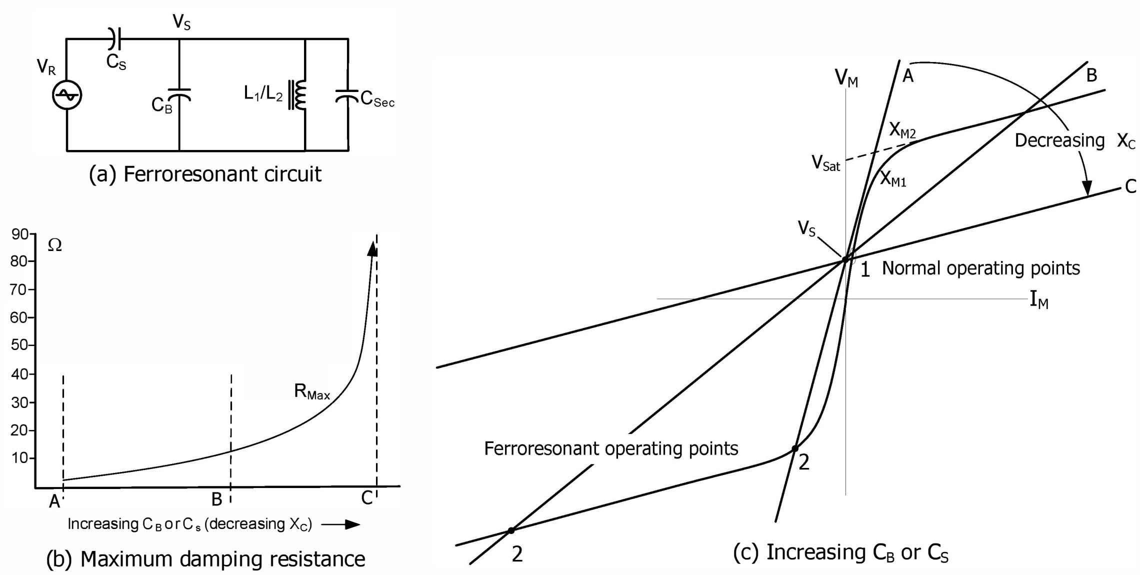


Figure 29. Detuning the ferroresonant circuit

Conclusions

Ferroresonance is a widely studied phenomenon but it is still not well understood because of its complex behavior. It is "fuzzy-resonance." A simple graphical approach using fundamental frequency phasors has been presented to elevate the readers understanding. Its occurrence and how it appears is extremely sensitive to the transformer characteristics, system parameters, transient voltages and initial conditions. More efficient transformer core material has lead to its increased occurrence and it has considerable effects on system apparatus and protection. Power system engineers should strive to recognize potential ferroresonant configurations and design solutions to prevent its occurrence.

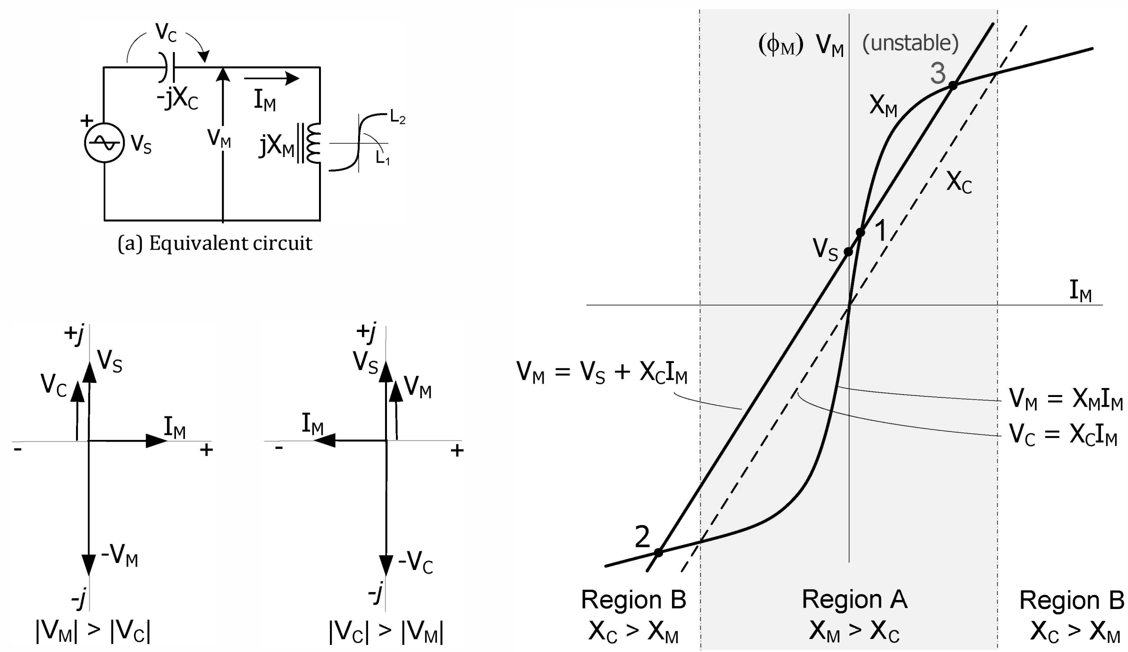
Appendix A. Stable operating point analysis

Referring to the circuit of figure 1(a) two equations for VM can be derived as

$$V_M = V_S + X_C I_M \quad (1)$$

$$V_M = X_M I_M \quad (2)$$

Where V_S is the source voltage, X_C is the capacitive (negative) reactance and X_M is the non-linear magnetizing reactance. Please note that the minus sign is shown on $-jX_C$ to illustrate that it is an impedance vector in the opposite direction of X_M and that the voltage V_C always opposes (in opposite direction) V_M. The V_M vs. I_M characteristics of both equations are plotted on figure 1(c) to derive possible solutions for V_M and I_M at their intersections. As can be observed there are three possible solutions at points 1, 2, and 3. However, further analysis is required to determine each point's stability as an operating solution.



(a) Equivalent circuit

(b)Phasor diagram for loop voltage summation of (a)

(c) Graphical solutions for V_M and I_M

Figure 1. Graphical solution for series LC circuit with non-linear inductance

In Region A of figure 1(c) the value (slope) of X_M is greater than that of X_C (shown as the dashed line). This will cause the current I_M to be lagging the source voltage V_S. The phasor diagram for this region is shown in figure 1(b). This shows that for the loop voltage summation

$$V_S + V_C - V_M = 0 \quad (3)$$

in the circuit of figure 1(a), V_M acts in opposition to source voltage V_S and V_C acts in the direction of V_S. In Region B the magnitude of X_C is greater than that of X_M. This will cause the current I_M to be leading the source voltage V_S. I_M is now negative of the previous lagging value. This shows that for equation 3 to be satisfied that V_M acts in the direction of the source voltage V_S and that V_C acts in opposition to V_S.

At point 1, which is in Region A, a small increase in current causes V_M to increase more rapidly than V_C (X_M has larger slope). The net difference (V_M-V_C) is inductive and acts in the opposition to V_S. The circuit impedance is increasing thus forcing a reduction in current back to the intersection. For a small decrease in current, V_M decreases more rapidly than V_C and the net difference (V_M-V_C) is less inductive and still acts in opposition to V_S, but less. The circuit impedance decreases forcing an increase in current back to the intersection. Without a significant change (a transient) in current or voltage operation cannot be moved from point 1; therefore, it is a stable operating point.

At point 2, which is in Region B, a small increase in current causes V_C to increase more rapidly than V_M (X_C has larger slope). The net difference (V_M-V_C) is capacitive and acts in the opposition to V_S. The circuit impedance (capacitive reactance) is increasing thus forcing a reduction in current back to the intersection. For a small decrease in current, V_C decreases more rapidly than V_M and the net difference (V_M-V_C) is less capacitive and still acts in opposition to V_S, but less. The circuit impedance (capacitive reactance) decreases forcing an increase in current back to the intersection. Without a significant current or voltage change (damping) operation cannot be moved from point 2; therefore, it is a stable operating point.

At point 3, which is in Region A, a small increase in current causes V_C to increases more rapidly than V_M (X_C has larger slope). The net difference (V_M-V_C) is capacitive and acts in the direction of V_S. The circuit impedance decreases thus resulting in an increase of current and an increase in the voltages away from the intersection. As the voltages increase the current continues to increasing and so on. For a small decrease in current, V_C decreases more rapidly than V_M and the net difference (V_M-V_C) is more inductive and acts in opposition to V_S. The circuit impedance increases forcing a decrease in current away from the intersection. Since any small change in current will avalanche away from point 3 it is an unstable operating point and cannot exist.

References

1. Rezaei-Zare, A. and Iravani, R. (2013). "Ferroresonance in Power and Instrument Transformers. In: Su, C. Q. Electromagnetic Transients in Transformer and Rotating Machine Windings. Hershey, PA: IGI Global. Chapter 5.
2. Price, E. "Voltage transformer ferroresonance in transmission substations." 25th Annual Conference for Protective Relay Engineers. Texas A & M University, March 1977.
3. R. Rudenberg. *"Transient Performance of Electric Power Systems."* McGraw Hill Company. New York, 1950.
4. Piasecki, W., Stosur, M., Florkowski, M., Fulczyk, M., Lewandowski, B., "Mitigating ferroresonance in HV inductive transformers." International Conference on Power Systems Transients. Kyoto, Japan. June 3 – 6, 2009.
5. Mork, B. "Understanding and Dealing with Ferroresonance." Minnesota Power Systems Conference, November 7-9, 2006.
6. Horak, J. "A review of ferroresonance." 30th Annual Western Protective Relay Conference. Spokane, Washington. October 21-23, 2003.
7. Hayes, S. and Vaziri, M. "A case study of ferroresonance in a CCVT secondary circuit and its impact on protective relaying." 33rd Annual Western Protective Relay Conference. Spokane, Washington. October 17-19, 2006.
8. Durbak, D. "Ferroresonance damping devices solves Amtrak's problem." Power technology. October 2004.
9. Jacobson, D. and Menzies, R. "Investigation of Station Service Transformer Ferroresonance in Manitoba Hydro's 230 kV Dorsey Converter Station." International Conference on Power System Transients. Rio de Janeiro. June 24 – 28, 2001.
10. Martinez, E., Antonova, G, and Olguin, M. "Ferroresonance phenomenon in CFE, its origin and effects." 39rd Annual Western Protective Relay Conference. Spokane, Washington. October 16-18, 2012.
11. Piasecki, W. et al. "Ironing out resonance - Ferroresonance prevention in medium voltage transformers." ABB Review. April 2005.
12. ABB Inc. "Type FSR-983 outdoor current transformer." ABB Instrument transformers and sensors.

Biography

Elmo Price received his BSEE degree in 1970 from Lamar University in Beaumont, Texas and his MSEE degree in Power Systems Engineering in 1978 from the University of Pittsburgh. He began his career with Westinghouse in 1970, which was consolidated into ABB in 1988. He has worked in many engineering and management assignments with the primary focus on protective relays. He is currently a Senior Consultant supporting product engineering and application. Elmo is a registered professional engineer and a Life Senior member of the IEEE and the IEEE Power System Relay Committee and serves on Line Protection Subcommittee. He has several patents and has written numerous papers primarily focusing on power system protection applications.