Modeling Ferroresonance Phenomena in an Underground Distribution System

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Abstract – **The objective of this paper is to provide an overview of ferroresonance phenomena, its modeling aspects, and practical experience in recognizing, avoiding, and solving the problem. In particular, we will present symptoms of ferroresonance and personal accounts of engineers who witnessed the situations. An actual case involving an underground cable circuit with blown fuses is presented along with solutions to avoid ferroresonance was presented.**

Keywords: Transient Analysis, Modeling, Lightning, Insulation Coordination, Surge Arresters, EMTP.

I. INTRODUCTION

Ferroresonance is a general term applied to a wide variety of resonance interactions involving capacitors and saturable iron-core inductor. During the resonance the capacitive and inductive reactances are equal with opposite values, thus the current is only limited by the system resistance resulting in unusually high voltages and/or currents. Ferroresonance in transformers are more common than any other power equipment since their cores are made of saturable ferrous materials.

Ferroresonant overvoltages on distribution systems were observed early in the history of power systems (i.e., early 1900s). Many analytical and experimental work have been carried out to understand the phenomena. One of the first analytical work was presented in [1] and [2]. A more recent paper on modeling and analysis of ferroresonant phenomena was described in [4].

In this paper, the theory of ferroresonance is briefly presented (in Section II). More theoretical description can be found in many literature. Section III describes symptoms of ferroresonance and personal accounts of engineers who witnessed the phenomena. Sections IV and V present ferroresonant modeling, and a case study of an actual ferroresonance problem with its corresponding solutions.

II. PRINCIPLES OF FERRORESONANCE

There are various ways to understand ferroresonance. A simpler method is to begin with a review of a simple RLC circuit. Figure 1 shows a voltage source with some arbitrary frequency such as 50 Hz or 60 Hz.
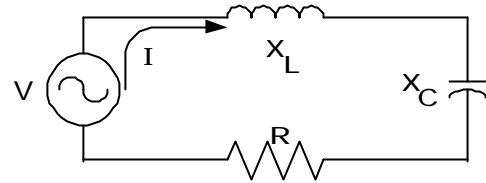

Figure 1 – Simple series RLC circuit for explaining ferroresonance.

The inductive (X_L) and capacitive (X_c) reactances are assumed in full absolute constant or linear. Furthermore we assume the resistance R is much smaller than $|X_L|$ and $|X_C|$. The magnitude of current flowing in the circuit is approximately:

$$I = \frac{V}{R + X_L - X_C} \cong \frac{V}{X_L - X_C} \qquad (1)$$

Let us vary X_C and hold R and X_L at a constant value. When $X_C = 0$, the current flowing in the circuit is $I = V/X_L$, and when X_C is very large, the current becomes negligible. In between these two extremes, $|X_C| = |X_L|$. The current becomes very large limited only by R, i.e., $I = V/R$. The large current can produce considerable overvoltage. Figure 2 illustrates the magnitude of current under various X_C values. The possibility of X_C exactly matches X_L is remote since both values have are linear or constant. However, if the value of X_L varies such as in an iron core transformer, the possibility of X_C to match X_L increases considerably.
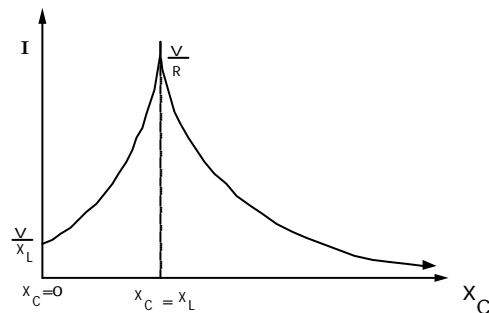

Figure 2 – Current in the simple series RLC circuit with various X_C values.

Alternatively, the solution to the above circuit can be written as follows:

$$V_L = jX_L I = V - (-jX_C)I \text{ or,} \quad (2)$$

$v = X_L I$, and

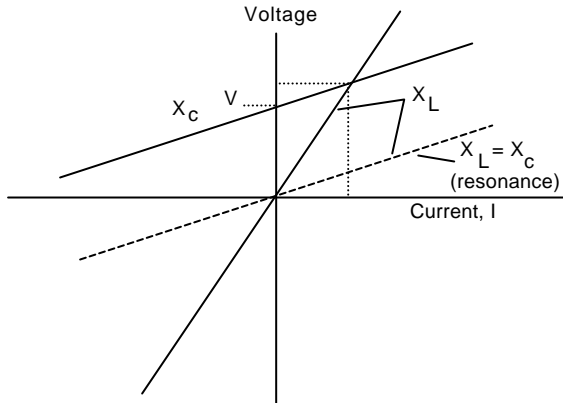$v = V - X_C I$, where v is an arbitrary voltage.

Figure 3 – Graphical solution of linear LC circuit.

The intersection between the inductive reactance X_L line and the capacitive reactance X_C line yields the current in the circuit and the voltage across the inductor, V_L. The above solution is depicted in Figure 3. At resonance, these two lines become parallel, yielding solutions of infinite voltage and current (assuming lossless element).

When X_L is no longer linear such as a saturable inductor, the X_L reactance can no longer be represented with a straight line. The graphical solution is now as shown in Figure 4.
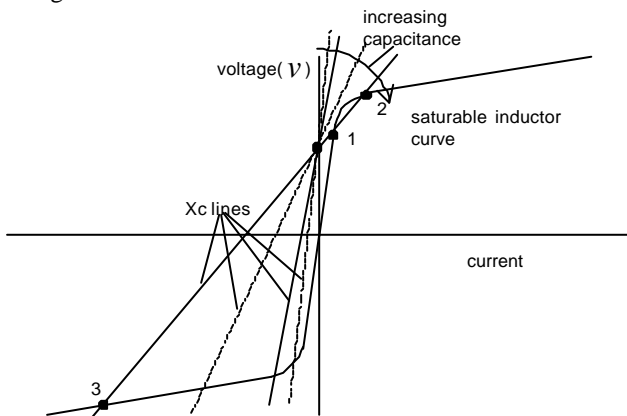

Figure 4 – Graphical solution of nonlinear LC circuit.

It is obvious that there may be as many as three intersections of the capacitive reactance line with the inductive reactance curve. Intersection 2 is an unstable operating point and the solution will not remain there in the steady sate. However, it may pass through this point during a transient. Intersections 1 and 3 are stable and will exist in the steady state. Obviously, if we get into an intersection 3 solution, there will be both high voltages and high currents. For small capacitances, the X_C line is very

steep, usually resulting in only one intersection in the third quadrant. The capacitive reactance is larger than the inductive reactance, resulting in a leading current and higher than normal voltages across the capacitor. The voltage across the capacitor is the length of the line from the system voltage intersection to the intersection with the inductor curve. As the capacitance increases, we can achieve multiple intersections as shown. The natural tendency then is to achieve a solution at intersection 1, which is an inductive solution with lagging current and little voltage across the capacitor. Note that the voltage across the capacitor will be the line-to-ground voltage on the cable in a typical power system ferroresonance case.

If we were then to get a slight increase in the voltage, the capacitor line would shift upward, eliminating the solution at intersection 1. The solution would then try to jump to the third quadrant. Of course, the resulting current might be so great that the voltage then drops again and we get the solution point jumping between 1 and 3. Indeed, phenomena like this are observed during instances of ferroresonance. The voltage and current appear to vary randomly and unpredictably.

In the usual power system case ferroresonance occurs when a transformer becomes isolated on a cable section in such a manner that the cable capacitance appears to be in series with the magnetizing characteristic of the transformer. For short lengths of cable, the capacitance is very small and there is one solution in the third quadrant at relatively low voltage levels. As the capacitance increases the solution point creeps up the saturation curve in the third quadrant until the voltage across the capacitor is well above normal. These operating points may be relatively stable, depending on the nature of the transient events that precipitated the ferroresonance.

III. SYMPTOMS OF FERRORESONANCE:
Practical Experience

There are several modes of ferroresonance with varying physical and electrical displays. Some have very high voltages and currents while others have voltages close to normal. In this section symptoms of ferroresonance are presented.

A. Audible Noise

One thing common to all types of ferroresonance is that the steel core is driven into saturation, often deeply and randomly (otherwise, it is conventional resonance and not considered ferroresonance). As the core goes into a high flux density, it will make an audible noise due to the magnetostriction of the steel and to the actual movement of the core laminations. In ferroresonance, this noise is often likened to shaking a bucket of bolts, whining, or to a chorus of a thousand hammers pounding on the transformer from within. In any case, the sound is distinctly different and louder than the normal hum of a transformer. It is difficult to describe accurately, but if one has the opportunity to be standing near a transformer that goes into ferroresonance, he or see will probably know immediately what it is. As one experienced person put it, "it will incite your fight-or-flight reflex to want to flee."

B. Overheating

Another reported symptom of the high magnetic field is due to stray flux heating in parts of the transformer where magnetic flux is not expected. Since the core is saturated repeatedly, the magnetic flux will find its way into the tank wall and other metallic parts. One possible side effect is the charring or bubbling of paint on the top of the tank. This is not necessarily an indication that the unit is damaged, but damage can occur in this situation if the ferroresonance has persisted sufficiently long to cause overheating of some of the larger internal connections. This may in turn damage insulation structures beyond repair. There is some disagreement in the industry over whether ferroresonance causes overheating. Some investigators have reported leaving transformers in ferroresonance for hours without increased heating. Of course, that may be dependent on both design and the mode of ferroresonance being observed. Apparently some modes do not drive the core into saturation very deeply.

If high overvoltages accompany the ferroresonance, there could be electrical damage to both the primary and secondary circuits. Surge arresters are common victims. They are designed to intercept brief overvoltages and clamp them to an acceptable level. While they may be able to take several overvoltage events, there is a definite limit to how much energy they can absorb. Ferroresonant modes with a lot of available energy and high voltages would be expected to fail arresters quickly. However, even modes with little energy available can cause arrester failure if the ferroresonance is allowed to persist for many minutes or hours.

C. Arrester and Surge Protector Failure

The arrester failures are related to heating of the arrester block. One common failure scenario is for line personnel to discover an open fused cutout and to simply replace the fuse. Meanwhile, the arrester on that phase has become very hot and goes into thermal runaway upon restoration of full power to that phase. Failures are often catastrophic with parts being expelled from the arrester housing. Under-oil arresters are less susceptible to this problem because they are able to dissipate the heat due to the ferroresonance current more rapidly.

With surge protectors now common in computers and other consumer appliances, office equipment, and factory machines, these are probably the most common casualties of ferroresonance on the customer side. In one case we investigated, an automobile struck a power pole causing one phase to become open-circuited. This caused ferroresonance in a three-phase transformer feeding a shopping mall through a run of several hundred feet of cable. When utility personnel arrived on the scene, they found a circular spot of charred paint on top of the mall's service transformer. In addition, many computer-connected cash registers in the mall were damaged by the sustained overvoltages, mostly, it is believed, due to the failure of MOV surge protectors in the power circuits. A number of primary arresters on the overhead line had also failed and blown their isolators.

D. Flicker

Customers are frequently subjected to a wavering voltage magnitude. Light bulbs will flicker between very bright and dim. Some electronic appliances are reportedly very susceptible to the voltages that result from some types of ferroresonance, but we have no knowledge of the alleged failure mode. Perhaps, it is simply MOV failure in the power front end. These frequently fail catastrophically, going into thermal runaway and then burning open with considerable arcing display. This may do nothing more than pop a breaker, but surge protection is lost for any subsequent surge that might damage the appliance. Some have suggested that the high voltage is particularly hard on TV and microwave oven tubes. The evidence for this is more anecdotal than scientific, but rings true.

E. Cable Switching

The transformers themselves can usually withstand the overvoltages without failing. Of course, they would not be expected to endure this stress repeatedly because the forces often shake things loose inside and abrade insulation structures. The cable is also in little danger unless its insulation stress had been reduced by aging or physical damage. Of course, operating a solid dielectric system above its normal stress level for an extended period can be expected to create some shortage of life.

It may be difficult to clear arcs when pulling cable elbows if ferroresonance is in progress. The currents may be much higher than expected and the peak voltages may be high enough to cause reignition of the arc.

Some utilities will not perform cable switching involving three-phase padmount transformers without first verifying that there is substantial load on the transformers. Some have reported carrying a "light board" in the line truck for such purposes. This is a dummy resistive load consisting of several light bulbs that can be clipped onto the secondary bushings of the transformer of the smaller 3-phase pads until switching is complete. This practice was reported for one East Coast utility specifically for switching transformers with delta primaries.

One of the common solutions to ferroresonance during cable switching is to always pull the elbows and energize the unit at the primary terminals. This will normally work because there is no external cable capacitance to cause ferroresonance. There is little internal capacitance, and the losses of the transformers are usually sufficient to prevent resonance with this small capacitance. Unfortunately, modern transformers are changing the old rules of thumb. The newer low-loss transformers, particularly, those with amorphous metal core, are prone to ferroresonance.

IV. TRANSFORMER MODELING

Ferroresonance is a mysterious subject that many analysts find difficult to deal with. Probably the main reason is that the analysis requires sophisticated nonlinear circuit analysis techniques that are not familiar to many. The results are sometimes unpredictable and certainly difficult to visualize like many engineers can visualize linear circuit phenomena. Another issue that complicates the analysis of ferroresonance is that there are several different types of 3-phase transformers such as three single-phase transformers connected as a three-phase transformer, three-legged core transformers, three-phase shell-type transformers, four-legged core, and five-legged cores. American utilities have thousands of five-legged core transformers in service. Therefore, we will describe the

modeling issues associated with the five-legged core design, but first we review the conventional T model of a two-winding transformer.

For single-phase transformers, three-phase shell form transformers, and three-phase triplexed transformers (three single-phase units stacked in one can), the conventional T model will suffice because there is no coupling between the magnetic circuits. Figure 5 shows the T model for a two winding transformer, which will suffice for standard switching surge and ferroresonance studies. For higher frequencies, it would be necessary to model the capacitances and inner winding construction, territory best left for transformer design specialists.
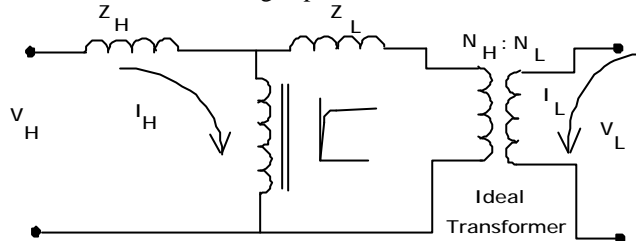

Figure 5 – Standard T Model of a two-winding transformer.

The terminals of this model can be connected to represent any two-winding transformer with magnetically independent phases. The saturable inductance data are readily available from the manufacturer's test data. Note that manufacturers supply the *rms* v-i curve. This must be converted to a *peak* flux-current curve before it can be used in EMTP or other transients programs. This conversion is a bit tricky because the current waveforms are not sinusoidal. Therefore, one cannot simply multiply the current values on the rms curve by 1.414 and arrive at the correct peak value. The usual procedure is to use a computer program that reconstructs the peak saturation curve by iterative solution. The first point can be established by multiplying by 1.414. Then a guess is made at the next point and the waveform reconstructed. The guess is adjusted until the rms of the reconstructed waveform matches that supplied by the manufacturer. The AUX program with EMTP provides such a facility.

The five-legged core transformer designed [3] is illustrated in Figure 6. The design typically consists of four individual cores tied together to create the five-legged core transformer. The inner three legs carry the phase windings with flux paths as indicated. The equivalent circuit can be derived from the flux path direction and is shown in Figure 7.
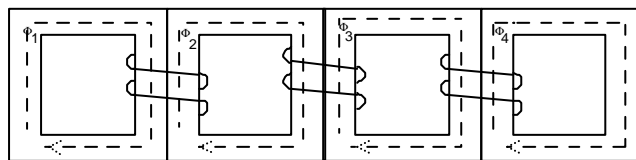

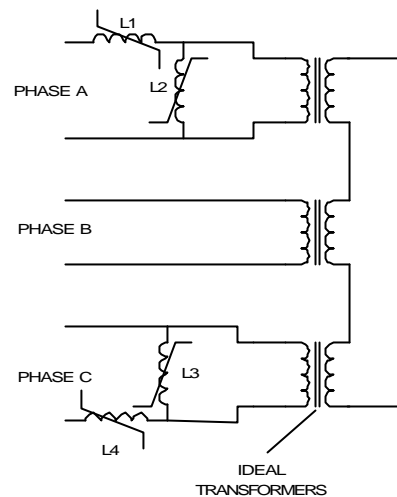Figure 6 – Five-legged transformer design and its flux paths.

Figure 7 – Equivalent circuit for a five-legged transformer

V. A CASE STUDY

In this section, an actual case study is presented. A ferroresonance condition developed on an approximately 5,000-foot underground cable feed to a medical facility. When one of the riser pole fuses blew, severe voltage fluctuations occurred at the load. As a temporary solution the utility replaced the fuses with a three-phase recloser and wanted to see under what conditions the three-phase recloser might be removed and the fuses reinstalled. Therefore, the purpose of this case study is to determine under what condition the ferroresonance at the underground distribution network can be avoided, and whether fuses might be reinstalled instead of keeping the three-phase recloser.

The ferroresonance condition apparently did not cause damages to the two 500 kVA transformers nor the customer loads at the medical facility. However, it is reported that a sudden overvoltage did occur and lights flickered between bright and dim.

A simplified one-line diagram to study the ferroresonance problem is shown in Figure 8. The simulation model was developed using the EMTP simulation package.
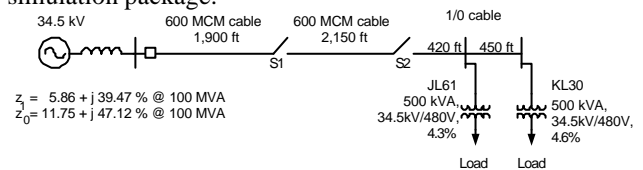

Figure 8 – A simplified one-line diagram for the underground cable feed run.

The lengths of the cable from the first pole to the first switch (S1), and from the first switch (S1) to the second switch (S2) are approximately 1,900 feet and 2,150 feet long. The cable size is 600 MCM with the following characteristics:

Insulation: 0.1406 outside diameter in feet,
Jacket   : 0.1412 outside diameter in feet,
Neutral : 0.1409 outside diameter in feet.

A line constant program was used to compute the positive and zero-sequence impedances of the cable, yielding the following results:

$z_1 = 0.0231 + j\,0.0824$ ohm/1000ft,

$z_0 = 0.1828 + j\,0.6854$ ohm/1000ft,
$C_1 = C_0 = 78.24$ nF/1000 ft.

The lengths of the underground cable from the second switch (S2) to the first transformer (JL61), and from the first transformer (JL61) to the second transformer (KL30) are 420 and 450 feet long, respectively. The type of the cable is 1/0 with the following characteristics:

  Insulation: 0.0629 outside diameter in feet,
  Jacket : 0.0688 outside diameter in feet,
  Neutral : 0.0794 outside diameter in feet.

The computed positive and zero-sequence impedances are as follows:

$z_1 = 0.0803 + j\,0.0952$ ohm/1000ft,
$z_0 = 0.4061 + j\,0.5150$ ohm/1000ft,
$C_1 = C_0 = 97.34$ nF/1000 ft.

The two 500 kVA transformers were modeled according to the five-legged core transformer design.

In order to investigate overvoltage due to ferroresonance, one phase of the cable was intentionally opened to simulate circumstances leading to ferroresonance (e.g., fuse blows, cable connector or splice opening, etc). In the simulation, phase B at the first pole was open-circuited, while switches S1 and S2 shown in Figure 8 were closed at all times. Resistive loads at the secondary winding of transformers JL61 and KL30 were increased successively from zero to 30% of the transformer capacities, i.e., from 0 to 150 kW.

Figure 9 shows voltage waveforms at the secondary winding of transformer JL61 when both JL61 and KL30 transformers are unloaded. Since the voltage at the secondary of transformer KL30 is nearly identical to that of JL61, the voltage waveforms are not shown. Industry analysts have historically assumed that when the voltage exceeds 1.25 per unit, the system is said to be "in ferroresonance". Figure 9 clearly illustrates that the system is in ferroresonance condition since phase B exhibits sustained overvoltage approaches 3.0 per unit.

Figure 10 (top) shows the voltage waveforms at the secondary winding of JL61 transformer when both JL61 and KL30 transformers are loaded with resistive load equivalent to 5% of transformer capacities. In other words, JL61 and KL30 transformers are loaded with 25 kW loads. The overvoltage at phase B is now approximately 2 per unit, much less compare to when both transformers are unloaded

In the similar fashion, loads at both transformers are added successively, i.e., 10, 15, 20, 25, and 30% of the transformer capacities. As loads increase the overvoltage drops quickly. Figure 10 shows the voltage waveforms at the secondary winding of transformer JL61 when both transformers are loaded with 5, %15%, 20%, and 30% of their respective capacities.
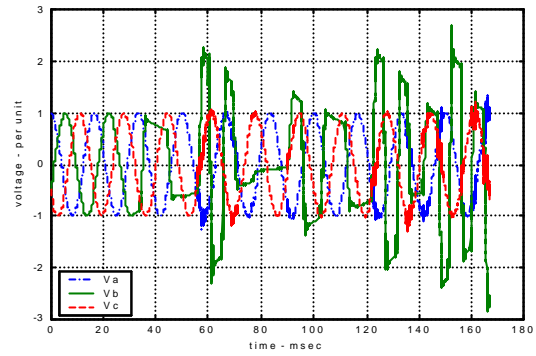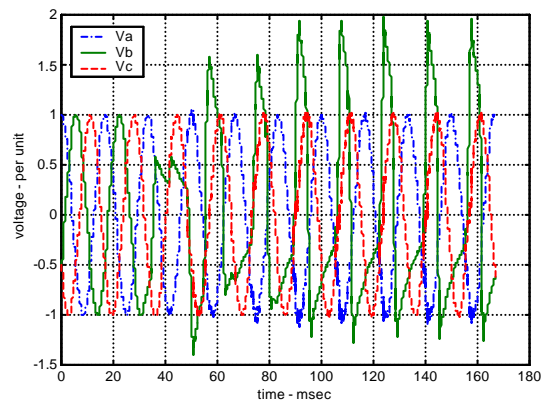

Figure 9 – Voltage waveforms at the secondary winding of transformer JL61. Both transformers are unloaded.

With 15% of load, the system remains in ferroresonance condition since it exhibits sustained overvoltage of 1.5 per unit. The ferroresonance condition is practically eliminated when both transformers are loaded with 20% of resistive load. The overvoltage magnitude is about 1.4 per unit at when phase B is open, however this overvoltage is not sustained and quickly decays to a low voltage. With 30% of load, the system is not in ferroresonance either. Twenty percent of resistive load is sufficient to avoid the ferroresonance condition.

Figure 11 shows the summary of peak overvoltage when both transformers are loaded from 0% up to 30% of their capacities. The overvoltage at phase B drops quickly as both transformers become more loaded. From the analysis presented in this section, it can be concluded that both transformers should be loaded with a minimum of 100 kW resistive load or loads equivalent to 20% of transformer capacity to avoid the ferroresonance condition. The rapid drop in ferroresonant voltage magnitude is due in large part to the introduction of the resistive load.

Based on the study, the ferroresonance condition can be avoided by having both transformers loaded with at least 20 percent of their respective capacities. In other words, each transformer must have 100 kW (resistive) at its secondary winding. When one phase is open-circuit, there will be a momentary overvoltage as high as 1.4 per unit, however it quickly decays to a low voltage. There will be no sustained ferroresonance overvoltage. If this minimum loading can be guaranteed, it is safe to replace a three-phase recloser with three fuses.
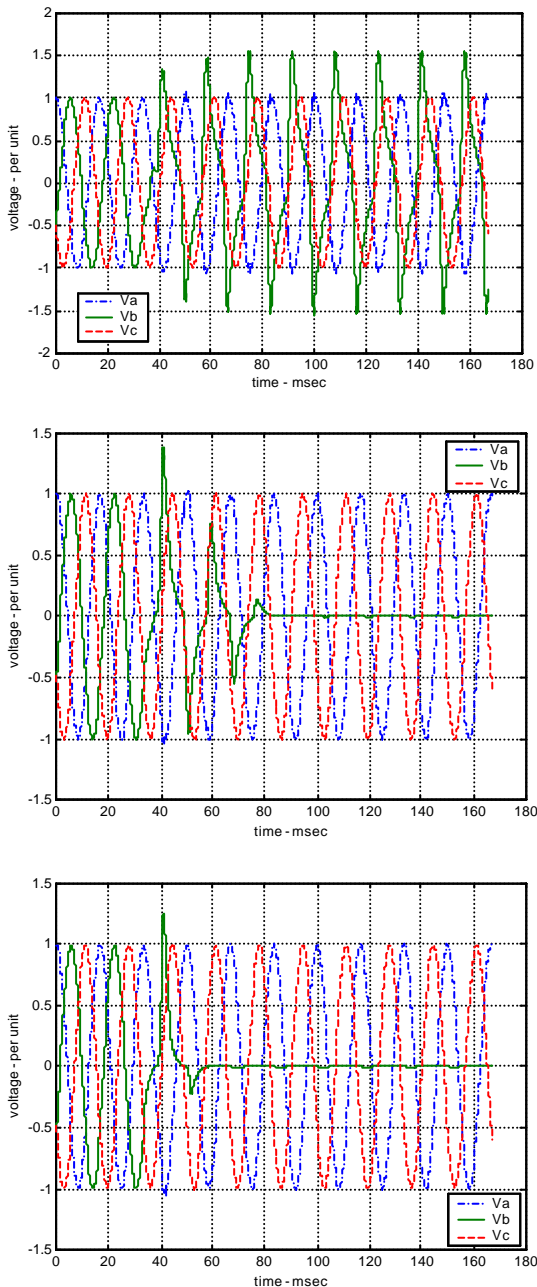
Figure 11. Change in peak transient overvoltage vs. percent resistive load on a 500 kVA transformer

VI. SUMMARY

In this paper we have presented a fundamental description of ferroresonance. In particular, various solutions leading to ferroresonance condition based on a simple graphical approach is presented. Symptoms of ferroresonance are presented along with personal accounts from field engineers.

A case study was presented to avoid ferroresonance in an underground cable circuit. The cable was nearly one mile long. The minimum load needed to avoid ferroresonance is 20%, which is much higher than the typical rule of 5% of minimum load. The higher value is attributed to the length of cable involved.

VI. REFERENCES

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Figure 10 – Voltage waveforms at the secondary winding of transformer JL61 with (a) 5%, (b) 15%, (c) 20%, (d) 30% of their respective capacities.

In the event that the loading cannot be achieved, it is advised to use the three-phase switchgear to avoid the ferroresonance condition. The minimum load of 20% to avoid ferroresonance is much higher than the usual minimum load of 5%. The higher minimum is primarily due to the length of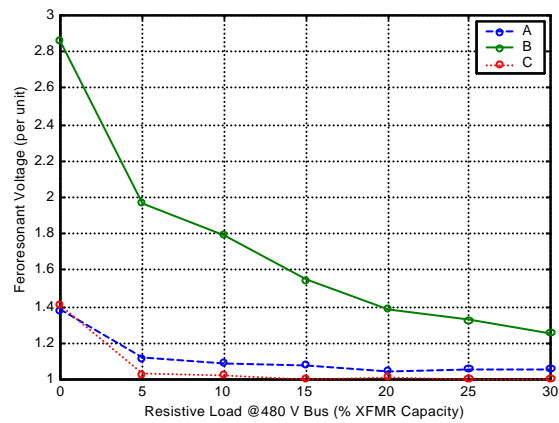 the cable involved, which is approximately 1 mile long.