# Potential Transformer Failure due to Ferroresonance

**Sergio R. Sagardía** **Atef Morched**

Ontario Hydro
Toronto - Ontario
Canada

*Abstract* — **This paper describes the phenomenon of ferroresonance and the conditions under which it may become sustained. The sequence of events is also described in which a sustained ferroresonance of a potential transformer resulted in its failure.**

**The severity of the effects due to ferroresonance are considered — and the effectiveness of the proposed countermeasures are verified — by modelling the power system components involved using the Electromagnetic Transients Program (EMTP). Switching sequences that resulted in the ferroresonance of a potential transformer are simulated. The effect of changing some of the parameters of the components is studied.**

**Simulation results show that a ferroresonance triggered during the de-energization of the potential transformer produced an abnormally high power dissipation in its HV winding which resulted in an unnoticed insulation damage. An attempt to re-energize the failed winding resulted in the explosive failure of the potential transformer.**

*Keywords :* *Ferroresonance, Potential Transformers, Modelling, Transient Analysis, EMTP.*

## I. INTRODUCTION

Ferroresonance is an oscillation of a charge trapped in a circuit that contains capacitor(s) and non-linear inductor(s). This oscillation is characterized by highly distorted voltage and current waveshapes.

The non-linear inductor normally works as a linear device, but is forced to operate outside its normal linear range under ferroresonance. The non-linearity is generally due to the saturation of iron, hence the name *ferroresonance.*

The non-linear inductor is usually a magnetic potential transformer (PT) used for metering or protection, or a transformer or autotransformer of any size or voltage. The capacitor may be associated with transmission line conductors, cables, breaker grading capacitances, etc.

The effects of ferroresonance vary in their severity from those that are harmlessly weak to those that are strong enough to damage equipment.

Ferroresonance is one of the most complex phenomena in the field of electromagnetic transients. Due to nonlinearities, time domain simulation seems to be the only reliable approach to predict the severity of a ferroresonance and to verify the effectiveness of countermeasures. The effective use of simulation requires familiarity with the simulation tools, in particular with the Electromagnetic Transients Program (EMTP). It is also essential to understand how ferroresonance starts and how it becomes sustained.

### 1. How ferroresonance starts.

Ferroresonance begins as a ferromagnetic oscillation that is triggered when a transformer is driven into saturation, in many cases as a result of de-energizing a conductor in such a manner that a section of it remains connected to a transformer.

The sustained ferroresonance of a transformer requires a continuous transfer of power from one or more energized conductors that are capacitively coupled to the de-energized conductor that remains connected to the transformer.

Consider first an ideal case in which there is no coupling to energized conductors and all losses in the de-energized circuit are neglected. The effect of losses and of coupled phases will be taken into account later. The components in the single phase case are connected as shown in Fig. 1.

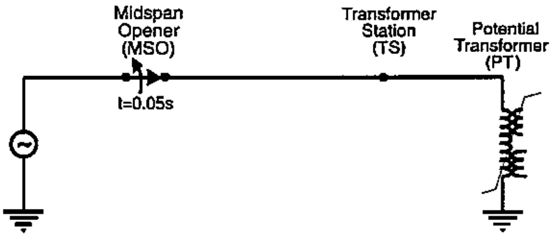

Fig. 1. The single phase ferroresonant circuit

Let us first realize that removing the midspan opener (MSO) shown in Fig. 1 —or any interrupting devise in its place— generally leaves a trapped charge on the line section that remains connected to the transformer. This trapped charge results from the fact that current interruption occurs when the current becomes zero, after the contacts open. At the instant of interruption the voltage on the conductor reaches its peak (since the line current and voltage on an unloaded line are nearly 90 degrees out of phase.) Therefore the voltage associated with the trapped charge nearly equals the peak value of the line to ground voltage.

The trapped charge has a path to ground through the transformer winding. The discharging current will increase with time and will eventually saturate the core if the conductor is long enough to trap sufficient charge.

The transformer core is usually designed to approach but not reach saturation at the end of each half cycle of the rated voltage. Since the voltage stays at nearly its peak value after interruption, the saturation of the core is quickly reached. When that happens the reactance presented by the transformer changes from its magnetizing to its leakage value, which is several orders of magnitude smaller. The low reactance of the saturated transformer provides the trapped charge with an easy path to ground. If there are no losses, the trapped charge and therefore the line to ground voltage will oscillate as shown in Fig. 2.

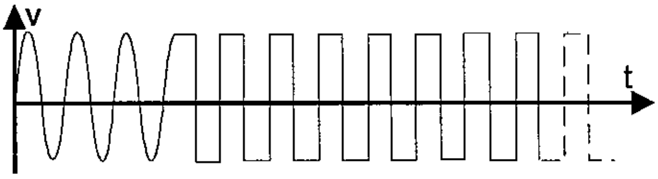

Fig. 2. Voltage waveshape neglecting losses.

It has been assumed in Fig. 2 that the MSO shown in Fig. 1 opens after 3 cycles. The oscillation of the line voltage results from the fact that the discharge current flowing through the saturated transformer reaches its maximum when the voltage across the transformer reaches zero; at this instant the energy initially stored in the circuit capacitance is now stored in the circuit inductance. The current will keep flowing and the line voltage will increase with opposite polarity, until all the energy is again stored in the line capacitance. In the absence of losses the negative line voltage will reach the same peak value it started with, and the process would be repeated indefinitely.

In practice, due to losses in the line and specially in the transformer, the peak voltage will decrease with time, as illustrated in the following figure.

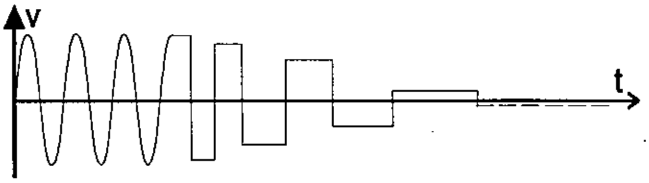

Fig. 3. Voltage waveshape considering losses

The smaller voltage applied to the transformer winding after each reversal, results in a longer period of time taken by the transformer core to reach saturation. Therefore the ferroresonant frequency gradually decreases, as shown in Fig.3. The maximum current reached by the discharge of the trapped through the winding also decrease until it becomes too small to saturate the transformer core and the ferromagnetic oscillation stops.

## 2. How ferroresonance becomes sustained.

For ferroresonance to become sustained, enough power must be continuously supplied to offset the losses associated with the ferroresonance. That power can be provided by other phases of the same circuit to which the transformer is connected or by phases of other circuits; in either case those phases must be energized and capacitively coupled to the de-energized conductor connected to the ferroresonant transformer.

As already described, the frequency of the ferromagnetic oscillations decreases with time due to losses. If the initial frequency is equal or greater than the frequency of the system, then there is a chance that the frequency of the oscillations will lock-in at the power frequency. In this way the ferromagnetic oscillation turns into a ferroresonance. If, on the other hand, the initial ferromagnetic frequency is smaller than the power frequency, then there is a chance that the ferromagnetic oscillations will lock-in at an odd subharmonic of the system frequency, for instance at 60/3=20 Hz, or at 60/5=12 Hz in the case of a 60-Hz power system.

Higher ferroresonant frequencies are generally associated with larger peak voltages. Ferroresonant voltage waveshapes with a peak higher than the system peak voltage usually have the power frequency or are chaotic. Subharmonic ferroresonant waveshapes generally have peaks lower than that of the system.

### 3. How ferroresonance is predicted.

The concepts described above are useful when it comes to deciding whether a sustained ferroresonance could possibly occur in a given configuration.

Once the possibility of ferroresonance has been established, deciding whether ferroresonance will actually occur, and if it does how severe its effects will be, requires solving a complex non-linear problem. Time domain simulation seems to be the only reliable tool to solve this problem and to assess the effectiveness of countermeasures.

The computer program most widely used to simulate power system transients in general and ferroresonance in particular is the Electromagnetic Transient Program (EMTP). All the relevant components must be modelled in detail, including transmission lines (considering line length, tower geometry, conductor size, phasing etc), cables, transformers (including hysteresis and core losses), interrupting devices (the timing of the interruptions and the sequence in which the phases are opened are also important.)

### 4. How ferroresonance depends on line length

Simulation studies show that the length of the de-energized line section that remains connected to the potential transformer is an important factor in determining the risk of ferroresonance. Moreover, the studies show that within the range of section line lengths for which there is sustained ferroresonance, the power dissipated in the transformer winding generally increases with the line length until a critical line length is reached at which the ferroresonance stops. These facts have considerable practical value.

### 5. How ferroresonance causes failure of a PT.

Time domain simulations of a typical 115-kV 400-VA PT show that under ferroresonance the HV winding may dissipate several hundred watts. The dissipation in the HV winding under normal conditions is about one quarter of a watt when the PT is fully loaded. The fact that the dissipation in the HV winding can exceed the dissipation at rated capacity by a factor that can reach several thousands suggests that damage due to overheating is the main cause of PT failure under ferroresonant conditions.

An attempt to re-energize a failed PT is likely to result in its explosive failure.

### 6. How ferroresonance can be prevented.

The best countermeasure, if at all possible, is to isolate the transformers at risk of ferroresonating before any lines connected to them are de-energized. This can be accomplished by installing appropriate disconnecting devices or by installing the transformers themselves on the station side rather than on the line side of the station disconnecting device.

In cases in which there is a single potential transformer connected from phase to ground, sustained ferroresonance can be avoided by de-energizing last the phase to which the transformer is connected, and by re-energizing that phase first.

Once ferroresonance has set in, it can be stopped by removing the conditions that make it sustained. Restoring power to the transformer, for instance, will stop the ferroresonance.

De-energizing the phases capacitively coupled to the ferroresonating phases removes the source of energy that sustains the ferroresonance, effectively stoping it.

As a way of preventing ferroresonance from becoming sustained one can simultaneously interrupt all the phases connected to PTs and the phases of all coupled circuits.

Moving the interrupting devices (usually mid span openers) closer to the PT results in reducing the power dissipation in the PTs HV winding, and possibly in preventing the onset of ferroresonance altogether.

Sustained ferroresonance can sometimes be avoided by loading the transformer with an appropriate resistive or reactive device.

A load connected across an open delta is much more effective than a load connected in the usual way and has the additional advantage of avoiding power dissipation during normal balanced operation.

The appropriate specification of the resistance of this load requires the help of computer simulation. The power rating of this resistor should be sufficient for it to withstand the power dissipation under ferroresonance and under a single phase to ground fault.

## II. THE FAILURE SCENARIO

This study was motivated by the explosive failure of a PT. Line maintenance work was to be done in a line section adjacent to a transformer station (TS). A set of 3 Y-connected PTs remained connected to the line after the line was disconnected at the TS. The circuit and the PTs were still energized from the far end of that circuit.

A crew of linemen was dispatched to remove the midspan openers (MSOs) installed a few kilometres away from the TS. A specially equipped truck was used to raise a lineman who manually removed the MSOs from each phase; each removal took several minutes.

As soon as the first MSO was removed the PT connected to the de-energized line section begun ferroresonating and probably continued to ferroresonate until it failed or until the last MSO was removed. The removal of the second MSO affected another PT in the same manner. Only the third PT was spared a sustained ferroresonance when the third MSO was removed, since at that time the other two phases were already de-energized.

The failures of the PTs remained unnoticed during the time the maintenance work was done, until an attempt to re-energize one of the failed PTs resulted in its explosive failure.

## III. EMTP MODELLING

The Magnetic Potential Transformers (PTs) modelled in this study have a capacity of 400 VA, a HV winding voltage of 115-69 kV and a dc resistance of 7480 Ω, with two LV windings of 115-69 V and a dc resistance of 0.019 ohms each. The magnetization curve has its knee point at 1.9 pu voltage. The air core impedance was assumed 1000 times smaller than the magnetizing impedance, which was computed from test data. The leakage reactance of the transformer windings was assumed to be 0.01 pu.

The line models are based on conductors 477-ACSR strung on towers that raise the conductors to a height of 38.42 ft at the towers and 30 ft at mid span with a horizontal separation of 10.67 ft between them. Nominal Pi EMTP line models were used, considering that they provide good accuracy in the frequency range associated with ferroresonance, which does not greatly depart from 60 Hz.

The transformer was modelled using the Saturable Transformer Component of the EMTP [1. The nonlinearity due to saturation of the core was represented by an EMTP Pseudononlinear Hysteretic Reactor.

The voltage sources were set to produce 115 kV rms line to line (66.4 kV rms line to ground).

## IV. EMTP SIMULATIONS

The figures on the next page show voltage waveshapes in the white phase of the ferroresonant circuits shown at the top of the corresponding columns. All time axes span 1 second, and all vertical axes are labelled in kilovolts.

The midspan opener (MSO) in the white phase opens at t=0.05 seconds; that is, after 3 60-Hz cycles which are shown in each figure as a convenient reference.

Fig. 4a shows the configuration that resulted in the most severe ferroresonance. The four waveshapes on the left column; that is, Figs. 4b, 4c, 4d and 4e, correspond to increasing lengths of 1000, 1500, 4250 and 4500 metres, respectively, of the line section between the MSO and the transformer station (TS). Note that in this case only the Red phase remains energized after the MSO on the White phase opens.

Fig 5a shows a similar configuration with the Blue and the Red phases remain energized after the MSO in the White phase opens. The waveshapes in the right column, that is, Figs. 5b, 5c, 5d and 5e correspond to line section lengths of 500, 1000, 3000 and 3500 metres, respectively.

The power dissipation in the winding corresponding to the configuration of Fig. 4a is given in Table 1, and that corresponding to Fig. 5a is given in Table 2. Note that both sets of waveshapes and the corresponding tables show that ferroresonance is not sustained for the shortest and for the longest line sections.

Some of the rows in Tables 1 and 2 show the power in watts (W) continuously dissipated in the HV winding when the ferroresonance is sustained. The rows that show energy in joules (J), however, correspond to ferromagnetic oscillations which stop in a fraction of a second and are harmless.

In order to appreciate the significance of the magnitudes of the power dissipation in the HV winding shown in Tables 1 and 2, let us recall that HV winding of a fully loaded 115-kV 400-VA PT draws about 6 mA and dissipates about ¼ of a Watt in its 7480-Ω HV winding when its secondary feeds a full load burden.

The tables show that the power dissipated in the HV winding under ferroresonance are hundreds and sometimes thousands of times higher than the power normally dissipated by that winding under full load.

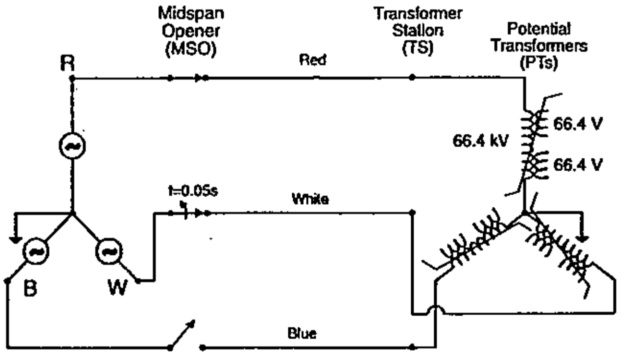

Fig. 4a. White phase opens and ferroresonates.
Red phase energized and Blue phase de-energized.

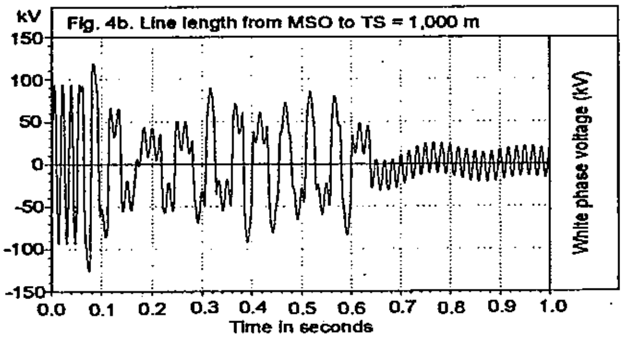
Fig. 4b. Line length from MSO to TS = 1,000 m

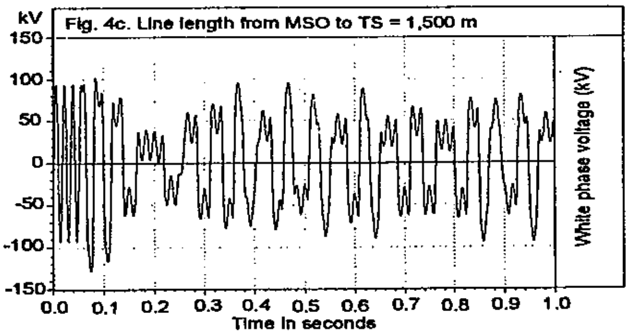
Fig. 4c. Line length from MSO to TS = 1,500 m

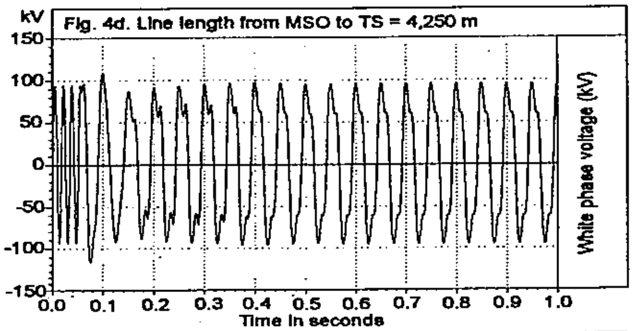
Fig. 4d. Line length from MSO to TS = 4,250 m

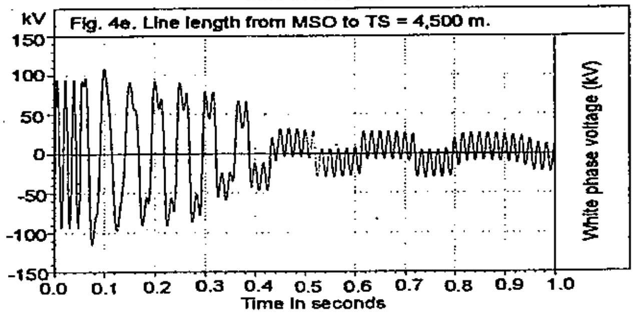
Fig. 4e. Line length from MSO to TS = 4,500 m.

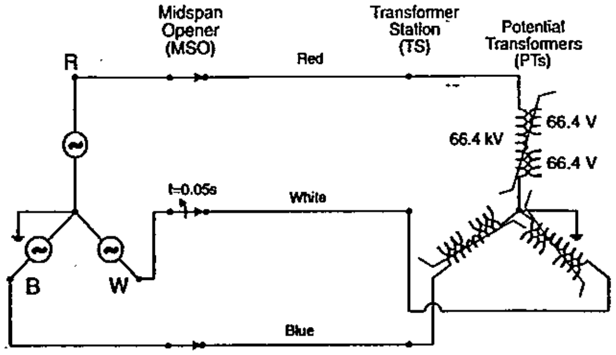

Fig. 5a. White phase opens and ferroresonates.
Red and Blue phases are energized.

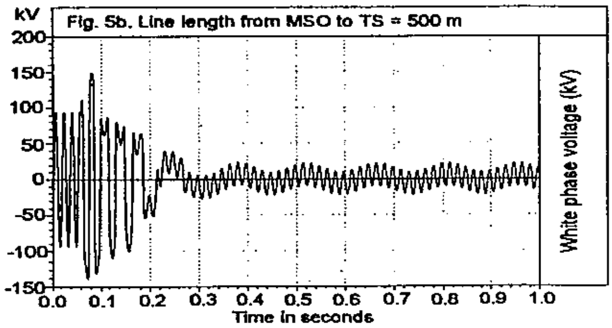
Fig. 5b. Line length from MSO to TS = 500 m

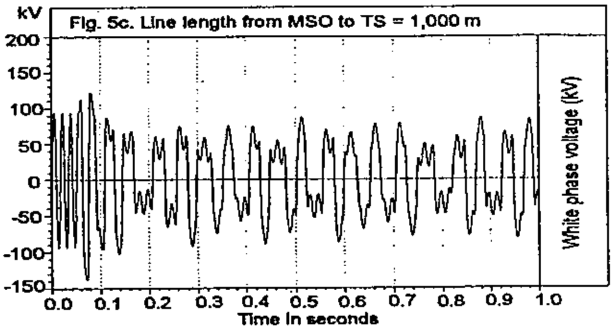
Fig. 5c. Line length from MSO to TS = 1,000 m

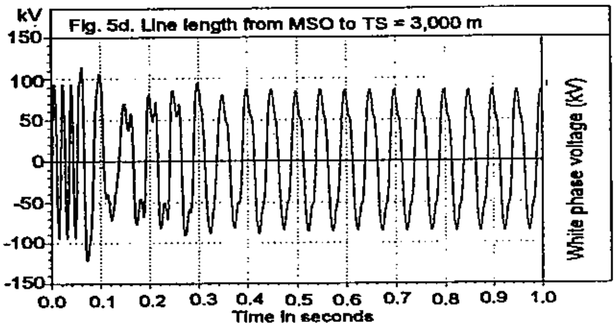
Fig. 5d. Line length from MSO to TS = 3,000 m

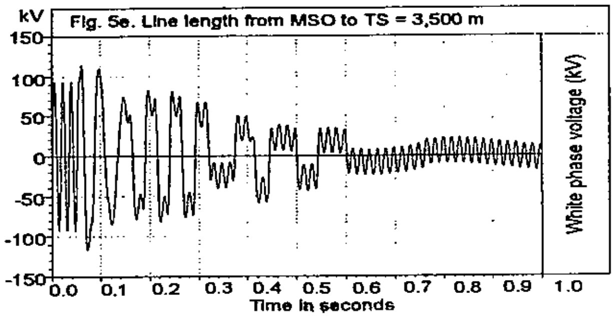
Fig. 5e. Line length from MSO to TS = 3,500 m

Table 1. Power dissipated in the HV winding of the PT connected to the White phase when only the Red Phase remains energized after the White phase opens.

| LINE SECTION LENGTH | HV WINDING DISSIPATION W OR J | HV WINDING FERRORESONATES? |
|---|---|---|
| 500 m | 10 J | NO |
| 1,000 m | 33 J | NO |
| 1,500 m | 102 W | YES |
| 2,000 m | 181 W | YES |
| 3,000 m | 390 W | YES |
| 3,500 m | 543 W | YES |
| 3,750 m | 638 W | YES |
| 4,000 m | 740 W | YES |
| 4,250 m | 874 W | YES |
| 5,000 m | 311 J | NO |
| 7,000 m | 157 J | NO |
| 10,000 m | 220 J | NO |
| 20,000 m | 437 J | NO |

Table 2. Power dissipated in the HV winding of the PT connected to the White phase when the Red and Blue Phases remain energized after the White phase opens.

| LINE SECTION LENGTH | HV WINDING DISSIPATION W OR J | HV WINDING FERRORESONATES? |
|---|---|---|
| 500 m | 13 J | NO |
| 1,000 m | 63 W | YES |
| 2,000 m | 181 W | YES |
| 3,000 m | 417 W | YES |
| 3,500 m | 189 J | NO |
| 4,250 m | 280 J | NO |
| 8,000 m | 173 J | NO |

Let us recall that in Tables 1 and 2 the power in watts (W) is continuously dissipated in the HV winding during sustained ferroresonanc. The rows that show energy in joules (J), on the other hand, correspond to energy transiently dissipated by ferromagnetic oscillations which stop in a fraction of a second and are harmless.

## IV. CONCLUSIONS

This paper presents a description of the phenomenon of ferroresonance, the conditions that make it sustained, and an analysis of the sequence of events that lead to an explosive failure of a potential transformer (PT).

The following conclusions are drawn from time domain simulation studies:

(a) There is a range of lengths of the line section that remains connected to a PT for which sustained ferroresonance is possible.

(b) Within range of line lengths described in (a), the power dissipated in the HV winding due to a sustained ferroresonance generally increases with the line length.

(c) The power dissipation in the HV winding of a ferroresonating PT can be several orders of magnitude larger than that normally dissipated under full load.

(d) Failure of the PT can result from a ferroresonance triggered during the de-energization and sustained during the time it takes to de-energize all the phases of the circuit to which the PTs are connected (and those of other companion circuits, if any). This failure may not be noticed.

(e) If the failure described in (d) goes unnoticed a re-energization of the failed PT may be attempted and result in an explosive failure.

A number of countermeasures are described to avoid the conditions that result in PT failure.

## V. REFERENCES

[1] Electric Power Research Institute / EMTP Development Coordination Group, *DCG/EPRI EMTP Rule Books Version 3.0*, July 1996.

A good conceptual introduction to ferroresonance is found in the following reference:

[2] R. Rüdenberg, *Transient Performance of Electric Power Systems*, McGraw-Hill Book Company, New York, NY, 1950.