भारतीय मानक
Indian Standard

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IEC/TR 61869-102 : 2014

उपस्कर ट्रांसफार्मर

भाग 102 इंडक्टिव वोल्टता ट्रांसफार्मर वाले सबस्टेशनों में फेरोरसोनेंस दोलन

Instrument Transformers

Part 102 Ferroresonance Oscillations in Substations With Inductive Voltage Transformers

ICS 17.220.20

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NATIONAL FOREWORD

This Indian Standard (Part 102) which is identical with IEC/TR 61869-102 : 2014 'Instrument transformers — Part 102: Ferroresonance oscillations in substations with inductive voltage transformers' issued by the International Electrotechnical Commission (IEC) was adopted by the Bureau of Indian Standards on the recommendation of the Instrument Transformers Sectional Committee and approval of the Electrotechnical Division Council.

This standard provides technical information for understanding the undesirable phenomenon of ferroresonance oscillations in medium voltage and high voltage networks in connection with inductive voltage transformers. Ferroresonance can cause considerable damage to voltage transformers and other equipment. Ferroresonance oscillations may also occur with other non-linear inductive components.

The text of IEC Technical Report has been approved as suitable for publication as an Indian Standard without deviations. Certain conventions are, however, not identical to those used in Indian Standards. Attention is particularly drawn to the following:

a) Wherever the words 'International Standard' appear referring to this standard, they should be read as 'Indian Standard'.
b) Comma (,) has been used as a decimal marker while in Indian Standards, the current practice is to use a point (.) as the decimal marker.

In this adopted standard, reference appears to certain International Standards for which Indian Standards also exist. The corresponding Indian Standards, which are to be substituted in their respective places, are listed below along with their degree of equivalence for the editions indicated:

International Standard	*Corresponding Indian Standard*	*Degree of Equivalence*
IEC 61869-3 Instrument transformers — Part 3: Specific requirements for inductive voltage transformers	IS 16227 (Part 3) : 2015 Instrument transformers : Part 3 Additional requirements for inductive voltage transformers	Identical with IEC 61869-3 : 2011
IEC 61869-5 Instrument transformers — Part 5: Specific requirements for capacitive voltage transformers	IEC 16227 (Part 5) : 2015 Instrument transformers : Part 5 Additional requirements for capacitors voltage transformers	Identical with IEC 61869-5 : 2011

For the purpose of deciding whether a particular requirement of this standard is complied with, the final value, observed or calculated, expressing the result of a test or analysis, shall be rounded off in accordance with IS 2 : 1960 'Rules for rounding off numerical values (*revised*)'. The number of significant places retained in the rounded off value should be the same as that of the specified value in this standard.

Indian Standard

INSTRUMENT TRANSFORMERS

PART 102 FERRORESONANCE OSCILLATIONS IN SUBSTATIONS WITH INDUCTIVE VOLTAGE TRANSFORMERS

1 Scope

This part of IEC 61869 provides technical information for understanding the undesirable phenomenon of ferroresonance oscillations in medium voltage and high voltage networks in connection with inductive voltage transformers. Ferroresonance can cause considerable damage to voltage transformers and other equipment. Ferroresonance oscillations may also occur with other non-linear inductive components.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 61869-3, *Instrument Transformers – Part 3: Specific requirements for inductive voltage transformers*

IEC 61869-5, *Instrument Transformers – Part 5: Specific requirements for capacitive voltage transformers*

3 Introduction to ferroresonance oscillations

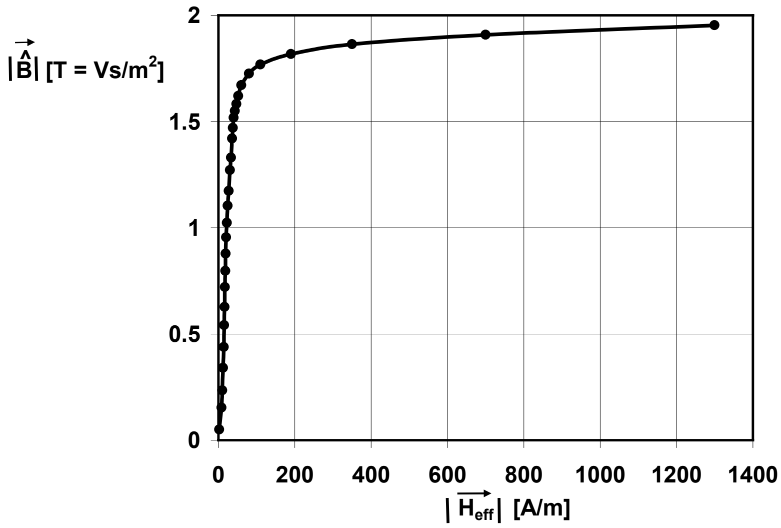
3.1 Definition of ferroresonance

Ferroresonance refers to non-linear oscillations that can occur in switching facilities where inductive components with a ferromagnetic core, together with capacitances and an AC voltage source comprise a system capable of oscillation. Numerous reports and publications on occurrences of ferroresonance have already been documented in the first half of the last century. A classic example of these occurrences comes from R. Rüdenberg [4]. His research was only done for fundamental frequencies; others carried out research on harmonics and subharmonics. A modern, didactically prepared introduction to ferroresonance problems can be found in K. Heuck and K.-D. Dettmann [5]. Much-cited basic examinations of the wide variety of ferroresonance oscillations were described by Bergmann [6, 7]. A review article on the problem was presented at the Cigré Conference in 1974 [1].

All ferromagnetic materials only allow themselves to be magnetised to a certain saturation flux density $\vec{B}_S$. If inductive voltage transformers are magnetised over their saturation flux density, the relationship between the magnetic field strength $\vec{H}_{eff}$ and the magnetic flux density $\hat{\vec{B}}$ are given by a strong non-linear characteristic (Figure 1). This means that the main inductance of an inductive voltage transformer in excess of the saturation flux density will collapse to a small fraction. This occurrence of core saturation plays an important role in the phenomena of ferroresonance.

Ferroresonance oscillations will only occur in configurations in high and medium voltage substations or in sections of networks. Single phase oscillations will occur in systems in which the high voltage winding of the inductive voltage transformer is connected in series with a capacitance to the AC voltage source (Figure 2). Three phase oscillations occur in systems in which the low voltage side of the power transformer is isolated from earth.

The above gives a basic picture about ferroresonance. In practice, ferroresonance can occur in many complicated network situations.



Key

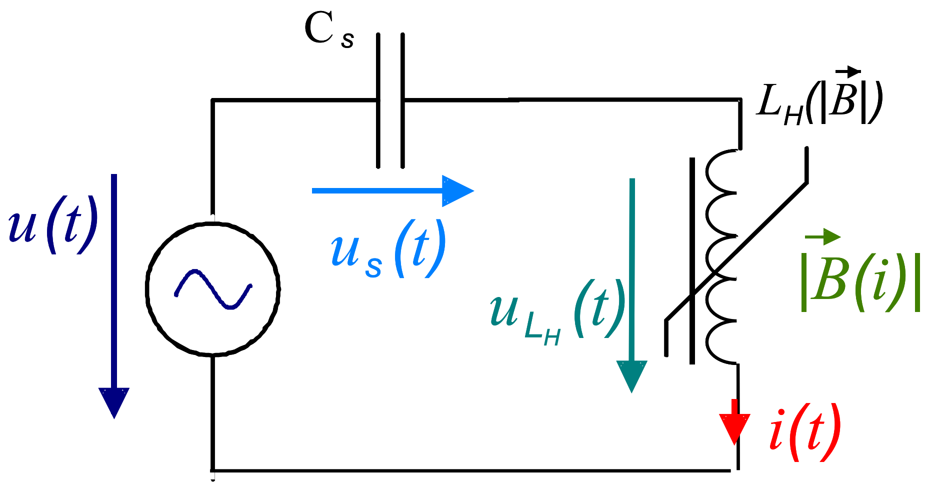
$|\hat{B}|$ Peak value of flux density in the iron core

$|\vec{H}_{eff}|$ Effective value of magnetic field strength in the iron core

The curve is valid for cold-rolled Si-iron (standard material).

Reproduced from [8], with the permission of ewz/CH.

Figure 1 – Example of a typical magnetisation characteristic of a ferromagnetic core



Key

$u(t)$ AC voltage source
$u_S(t)$ Voltage at series capacitance
$u_{LH}(t)$ Voltage at the main inductance of the voltage transformer (VT)
$i(t)$ Circuit current
C_S Series capacitance
$|\vec{B}|(i(t))$ Flux density as function of the current i(t)
$L_H(|\vec{B}|)$ Non-linear main inductance of voltage transformer

Reproduced from [8], with the permission of ewz/CH

Figure 2 – Schematic diagram of the simplest ferroresonance circuit

In practice, parts of networks endangered by ferroresonance are usually comprised by other high voltage equipment, which also play a role in determining the conditions for the occurrence of ferroresonance oscillations.

Due to the small inductance of the saturated voltage transformer at maximum saturation of the core, the very large excitation current leads to a quick reverse of the polarity of the charge of the series capacitances.

Oscillations resulting from excitation of a resonance circuit in substation sections can also occur without saturation of voltage transformers. Such linear oscillations usually occur at operating frequency and have a sinusoidal wave form.

From the theory of non-linear oscillations and modern stability theory [9] for non-linear systems follows that the occurrence of steady state oscillations requires a system comprised of an equivalent capacitor, a non-linear inductance, and an AC voltage source for covering system losses. The non-linear element for such a system is the main inductance of the inductive voltage transformer. When the voltage increases non-linear oscillations are generated on account of the saturation characteristics of the magnetic flux density according to the time depending function $\vec{B}(t) = f(\vec{H}(t))$. This is a non-linear, time-invariant relationship (hysteresis curve of the magnetic material used), indicated by the limitation characteristic [10].

The difficulty in determining whether any steady state non-linear oscillations are occurring is due to the fact that only estimated values are available for the earth capacity C_e and for the configuration of the capacitors and especially for the losses occurring in the substation on account of the leakage current from the high-voltage insulators (porcelain or composite) in air insulated substations.

The economic aspects of ferroresonance have also been discussed, and it shall be summarized that already in the planning stage of substations using inductive voltage transformers, there should be an investigation about the possibility of non-linear oscillations. This requires cooperation between switchgear manufacturers and instrument transformer manufacturers, as well as system operators [9]. This process describes the most economical solution. Ferroresonance investigations have also proven their worth in model substations. It is more costly to eliminate ferroresonance at existing substations if cases of non-linear oscillations (ferroresonance) arise as a result of component replacement such as grading capacitors of circuit breakers, coupling capacitors or inductive voltage transformers.

3.2 Excitation of steady state and non-steady state ferroresonance oscillations

A ferroresonance oscillation can be gradually ramped up by a small disturbance ("soft excitation"). Upon soft excitation the oscillations will begin at low initial amplitude.

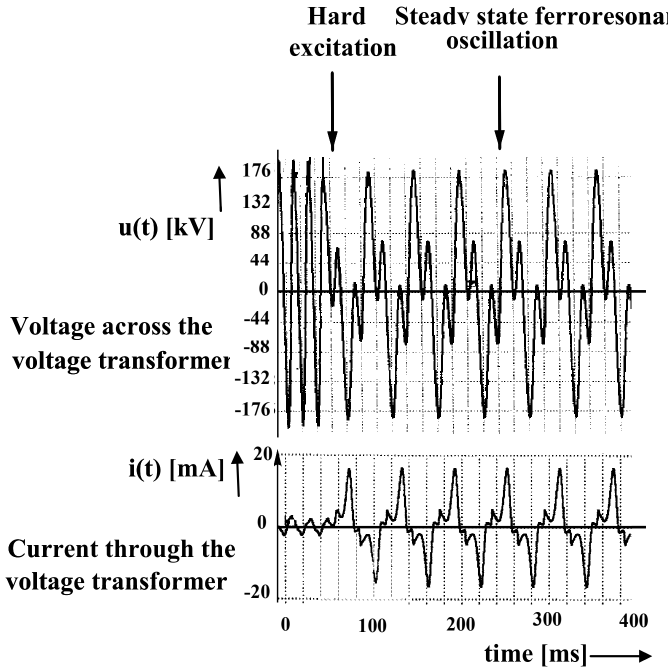
However, ferroresonance is in most cases caused or "triggered" as a result of a switching transient through which the core becomes saturated ("hard excitation").

Table 1 (reproduced from [8]) gives an overview of the two kinds of excitation and the possible developments of ferroresonance oscillations.

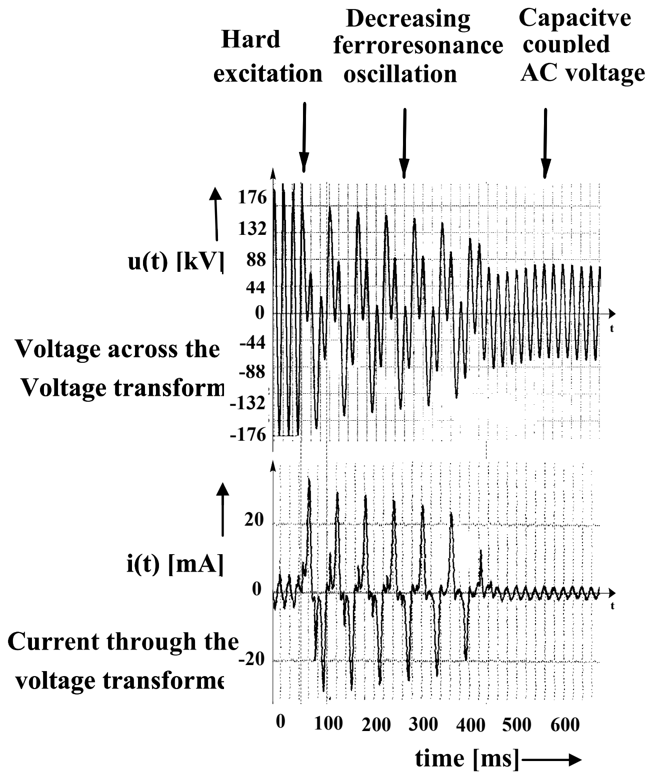
Table 1 – Types of excitation and possible developments of ferroresonance oscillations

Soft excitation Slow increasing oscillation when ferroresonance conditions are met	1a: Steady state ferroresonsnce oscillations 1b: Non-steady state increasing ferroresonance oscillations
Hard excitation e.g. through sudden saturation of a transformer core on account of a switching operation or through an intermittent earth fault, etc.	2a: Steady state ferroresonance oscillations 2b: Non-steady state increasing ferroresonance oscillations 2c: Non-steady stae decreasing ferroresonance oscillations

Ferroresonance oscillations can become steady state or non-steady state (as shown in Figure 3) with increasing or decreasing amplitude. Increasing ferroresonance oscillations can lead to thermal dielectric destruction of the inductive voltage transformer or to a flashover in the substation.



a) Single-phase steady state ferroresonance oscillations, type 2a according to Table 1



b) Single-phase decreasing ferroresonance oscillations, type 2c according to Table 1

Reproduced from [8], with the permission of Amprion (formerly RWE).

Figure 3 – Examples of measured single-phase ferroresonance oscillation with $16^2/_3$ Hz oscillation

Decreasing ferroresonance oscillations will not cause damages to voltage transformers. Steady state oscillations will increase the current in the primary transformer windings and ultimately damage transformers through overheating. The damage caused by increasing non-steady state oscillations is obvious.

Current and voltage waveforms of the primary winding are shown in Figure 3a) for steady state ferroresonance resulting from a hard excitation caused by a switching operation, and in Figure 3b) for non-steady state, decreasing ferroresonance.

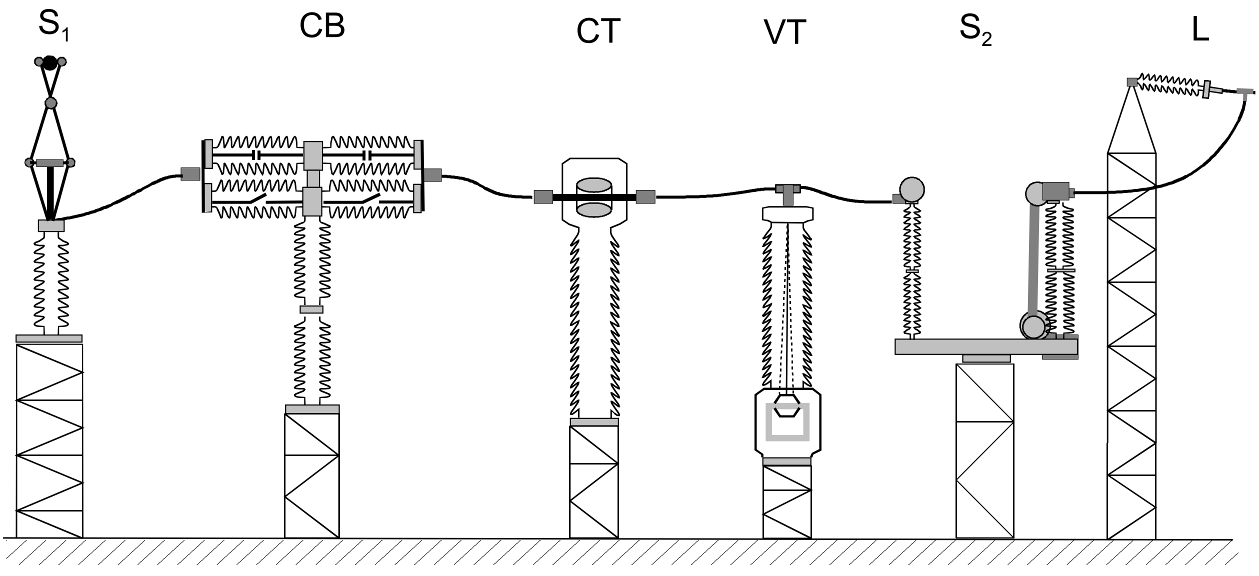
The occurrence of decreasing ferroresonance oscillations as shown in Figure 3b) is defined by statistic events: for example by the instance of switching.

4 Single phase and three phase oscillations

4.1 Single phase ferroresonance oscillations

Individual phases of a de-energised, non-earthed equipment section containing one or more inductive voltage transformers will be excited to oscillations independent of one another by the network voltage over a coupling capacity C_C. Single-phase ferroresonances can occur in all systems independently of the star point earthing.

An example of a switching configuration in which a single-phase ferroresonance can occur is shown in Figure 4. It illustrates one phase of a disconnected outgoing feeder bay at an air insulated substation. The coupling to the voltage network in this case happens over the grading capacitors of the open circuit breaker.

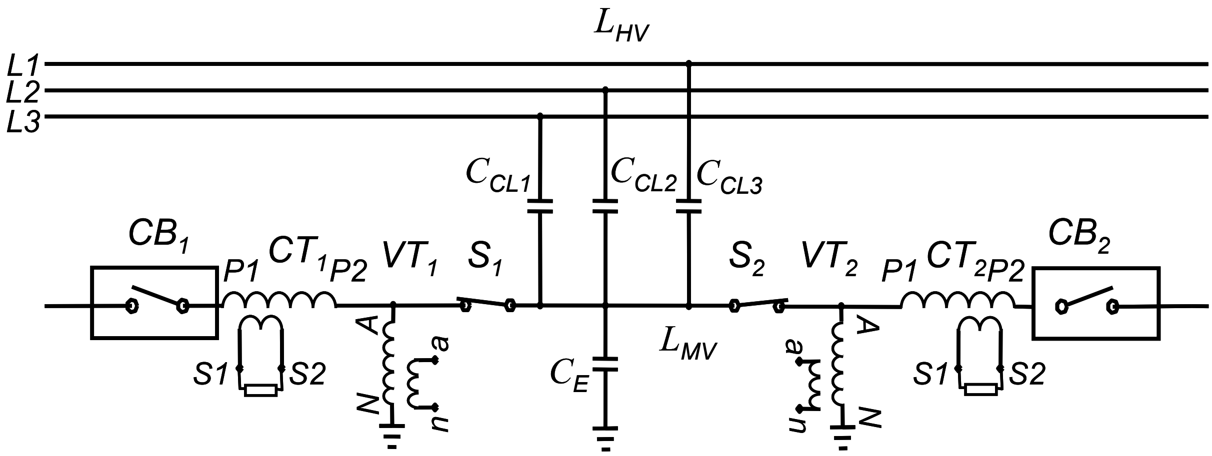


Key
S_1 Substation disconnector, closed
CB Circuit breaker, open
CT Current transformer
VT Voltage transformer
S_2 Outgoing line disconnector opened
L Outgoing power lines, earthed

Reproduced from [8], with the permission of ewz/CH.

Figure 4 – Schematic diagram of a de-energised outgoing feeder bay with voltage transformers as an example in which single-phase ferroresonance oscillations can occur

An alternative configuration that tends toward ferroresonance oscillations is that of a de-energised overhead power line system L_{MV} if it is on the same supporting tower as an activated system of a higher voltage level L_{HV}. This situation is shown in Figure 5. The phases of the de-energised system remain unearthed and they are connected to voltage transformers on one or both ends. In some circumstances this can lead to an excitation causing ferroresonance oscillations via the coupling capacity C_C between the conductor wires of the energised and de-energised overhead power lines. In this case the individual phases will oscillate independently from one another.



Key

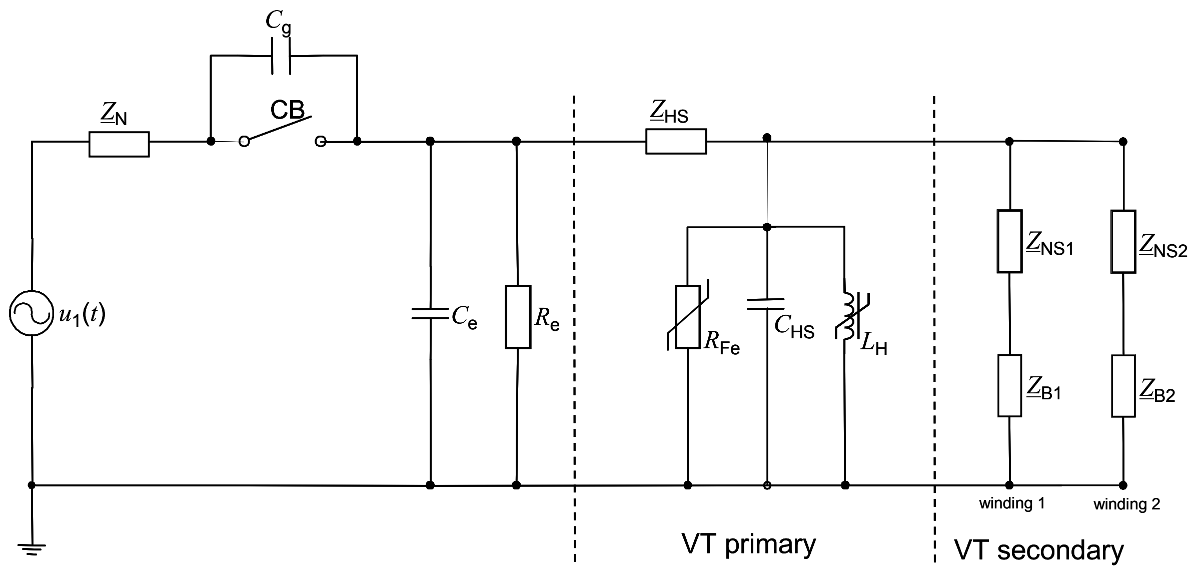
L_{MV}	Affected phase of the overhead power lines
L_{HV}	Overhead power line system of a higher voltage level
C_{CL1}, C_{CL2}, C_{CL3}	Coupling capacitances between the phase under observation and the phases of the parallel system of a higher voltage level
C_e	Earth capacity
CT_1, CT_2	Current transformers
VT_1, VT_2	Voltage transformers
CB_1, CB_2	Circuit breaker, open
S_1, S_2	Disconnector switch, closed

Reproduced from [8], with the permission of ewz/CH.

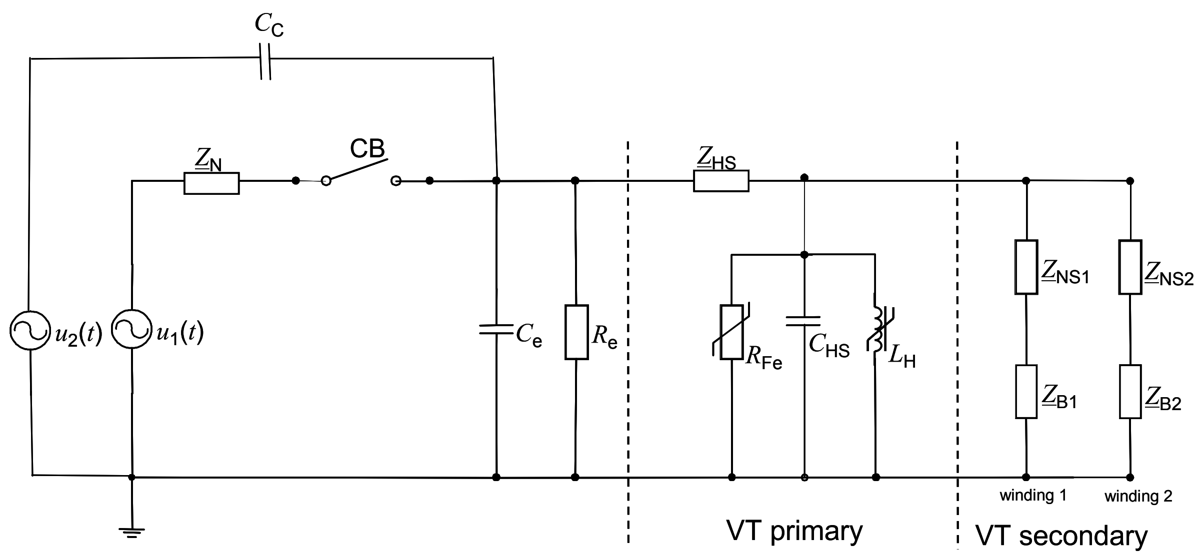
Figure 5 – Diagram of a network situation that tends toward single-phase ferroresonance oscillations, in which they can be excited and maintained over the capacitive coupling of parallel overhead power line systems

4.2 The simplified circuit for the single phase ferroresonance oscillations

The previously treated considerations and schematics will not be sufficient for a theoretical analysis of ferroresonance oscillations. In order to predict the occurrence of ferroresonance oscillations a more detailed definition and description of the electrical components and their characteristics is necessary. Figure 6 illustrates the general schematic circuits for the analysis of single-phase ferroresonance oscillation. Figures 6a) and 6b) show two different ways of excitations. A detailed treatment of the analysis and simulation methods with examples is found in Clause 9.



a) Excitation of ferroresonance oscillation through a grading capacitor



b) Ferroresonance oscillation caused by a parallel system

Key

C_e	Total earth capacitance
C_{HS}	Capacitance of the HV-winding of voltage transformer
C_C	Coupling capacitance to a parallel system of a higher voltage level
C_g	Capacitance of the grading capacitor of circuit breaker CB
R_e	External resistance phase-earth e.g. through currents in dirty surfaces, corona currents, and currents of metal oxide arrestors
R_{Fe}	Non-linear resistance representing the iron losses of the inductive VT
L_H	Non-linear main inductance of the HV-winding of the inductive VT
$u_1(t)$	Phase to earth voltage before the circuit breaker in the system
$u_2(t)$	Voltage of a neighbouring system of a higher voltage level with which there is a capacitive coupling
VT	Voltage transformer
$\underline{Z}_{B1}$	Impedance of the burden of secondary winding 1 (load impedance and inductance)
$\underline{Z}_{B2}$	Impedance of the burden of secondary winding 2 (load impedance and inductance)
$\underline{Z}_{HS}$	Impedance of the HV winding (resistance and stray inductance)
$\underline{Z}_N$	Network impedance
$\underline{Z}_{NS1}$	Impedance secondary winding 1 (resistance and stray inductance)
$\underline{Z}_{NS2}$	Impedance secondary winding 2 (resistance and stray inductance)

Reproduced from [8], with the permission of ewz/CH.

Figure 6 – Electrical circuits for theoretical analysis of a single-phase ferroresonance oscillation

4.3 Capacitive voltage transformers

Conventional capacitive voltage transformers have an inductive intermediate transformer and a compensation coil. Together with the primary and secondary capacitor they contain all the components required to form a ferroresonance circuit. Therefore capacitive voltage transformers can generate ferroresonance oscillations without additional series capacity. Their design shall be arranged to exclude the possibility of a steady state ferroresonance oscillation under all possible operational conditions (IEC 61869-5).

The most commonly used methods for damping the ferroresonance oscillations in capacitive voltage transformers are LC-resonant circuits with low losses at 50/60 Hz, rated for $16^2/_3$/20 Hz, 10/12 Hz and $7^1/_7/8^4/_7$ Hz.

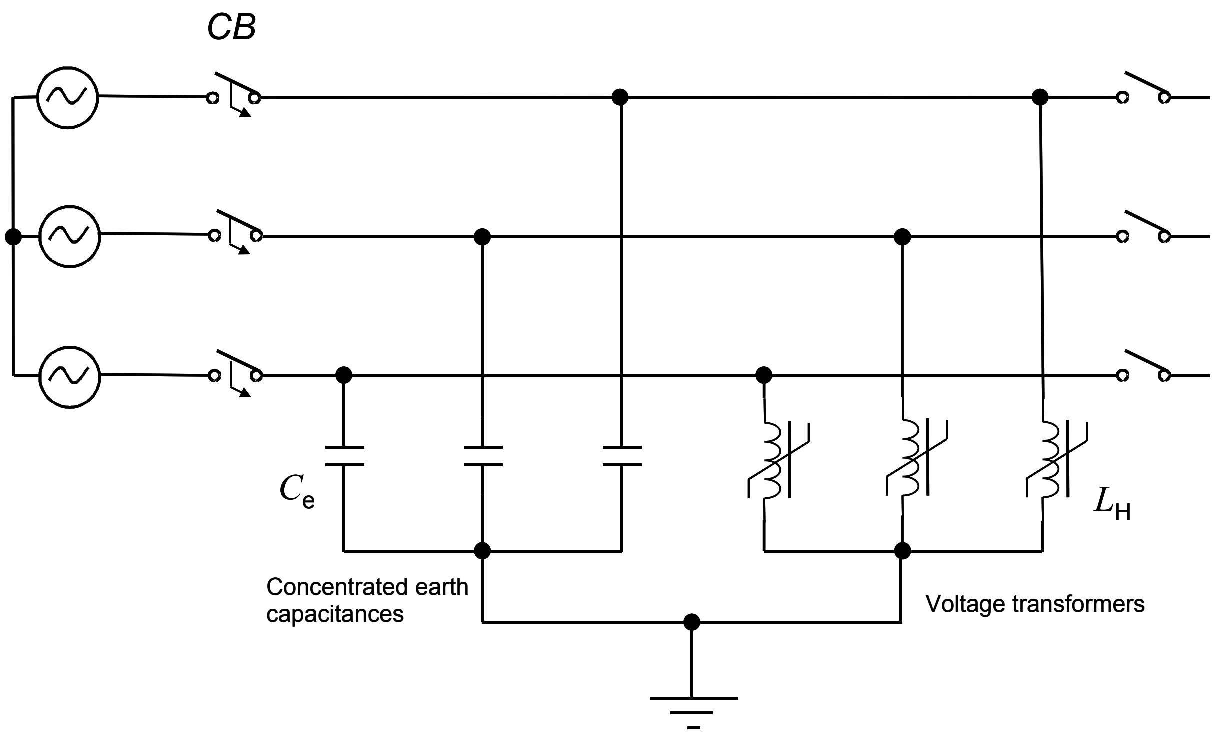
4.4 Three-phase ferroresonance oscillations

4.4.1 General

Three phase ferroresonance oscillations will occur in substations or network sections with single-phase voltage transformers where the star point of the secondary side of the power transformer is not solidly earthed. All three phases are involved in the ferroresonance oscillation.

4.4.2 Configuration

Figure 7 illustrates a configuration vulnerable to ferroresonance as it occurs in networks with a non-solidly earthed star point, if the voltage transformers are connected line to earth.



Reproduced from [8], with the permission of ewz/CH.

Figure 7 – Insulated network as an example of a schematic diagram of a situation in which a three-phase ferroresonance oscillation can occur

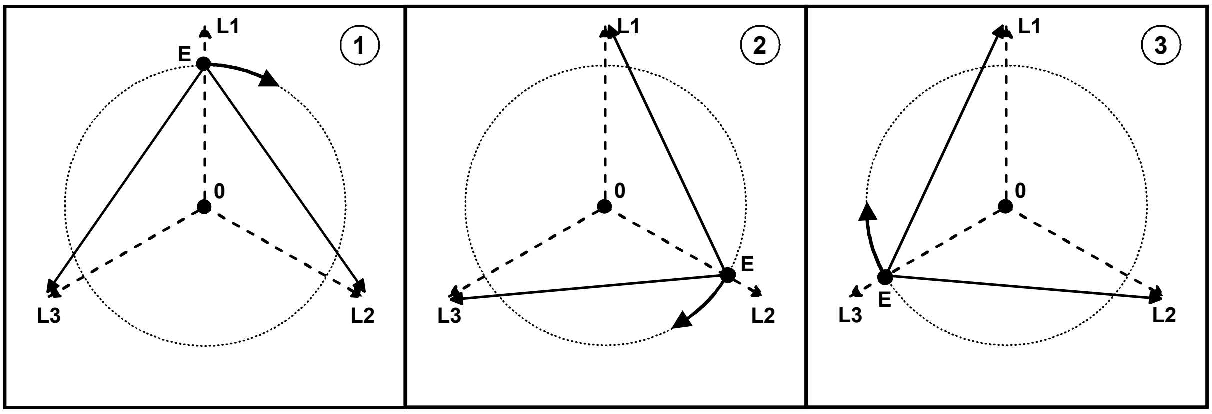
If voltage transformers are connected to the low voltage side of a power transformer, which is energised on the high voltage side, saturation of one voltage transformer can lead to over voltages on the other phases, if the star point of the secondary side of the power transformer is not solidly earthed. The star point will thus shift and ultimately produce oscillations, driving all three voltage transformers to alternately become saturated.

This movement of the star point can also occur as the result of an extinguishing earth fault.

4.4.3 Ferroresonance generation

As a consequence of the saturation of one voltage transformer, the earth capacitances of the other two voltage transformers are in series to this transformer, seen from the network voltage source and thus form a system that is temporarily capable of oscillating. The aforementioned earth capacitances of the other phases can more or less quickly change their polarity over the saturated inductance, leading in turn to the saturation of one of the transformers of the other phases.

The movement of the star point from phase to phase can be compared to a reeling motion (see phasor diagram in Figure 8).



Reproduced from [8], with the permission of ewz/CH.

Figure 8 – Phasor diagram to explain the oscillation of the earth potential

The ferroresonance progression is significantly more complex in this case, since the fluctuating oscillation energy is continually shifting between the three phases. An example for three phase ferroresonance is given in 5.3.

4.4.4 Resulting waveform of ferroresonance oscillation

Contrary to the single-phase ferroresonance case, where one harmonic or sub-harmonic can be easily distinguished in the resulting voltage oscillograms, the three phase ferroresonance oscillation, which can be clearly seen in an open delta winding, is mostly composed of one basic oscillation near the system frequency and additionally of one further sub-harmonic, which can be observed as oscillations ranging from less than 1 Hz up to 7 Hz, which can be described as beats.

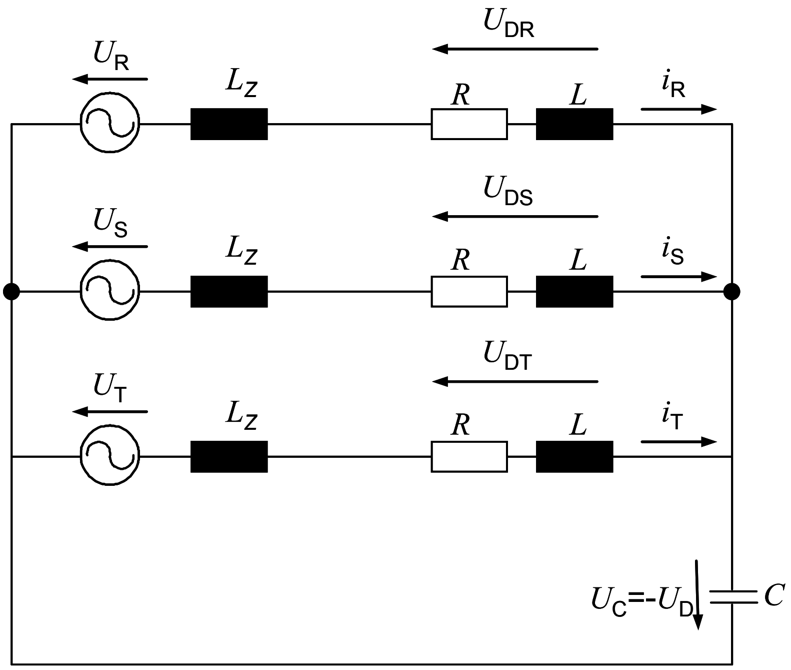
These beats will occur, if the earth capacitance of the star point is so large, that the saturation of one single voltage transformer is not enough to create the required current to completely reverse the polarity of the earth capacitance.

Some basic research into this effect has been done by Bergmann [6] in his 1966 dissertation. The result of these investigations was the information, which different modes are in principle possible for three-phase ferroresonance, even if later tests in the field showed that not all modes will occur in praxis.

Instead of the complete circuit as shown in Figure 7, Bergmann used a laboratory test set, which was composed of (see Figure 9):

– a three phase power source,
– three identical choke coils with resistance R and inductivity L (instead of voltage transformers)
– a single discreet capacitance C modeling the earth capacitance of the star point.

According to Lapierre's paper [11], who used this simplified circuit and checked it mathematically, it is correct to do this.



Key

U_R, U_S, U_T	Phase to earth voltages of the three phase power source
L_Z	Source impedance
R	Resistance of the choke coil
L	Inductivity of the choke coil
C	Earth capacitance of the star point
U_{DR}, U_{DS}, U	Voltages across the choke coils
i_R, i_S, i_T	Currents through the choke coils
U_C	Voltage across the earth capacitance of the star point
U_D	Sum of the voltages across the choke coils: $U_D = U_{DR}+U_{DS}+U_{DT}$

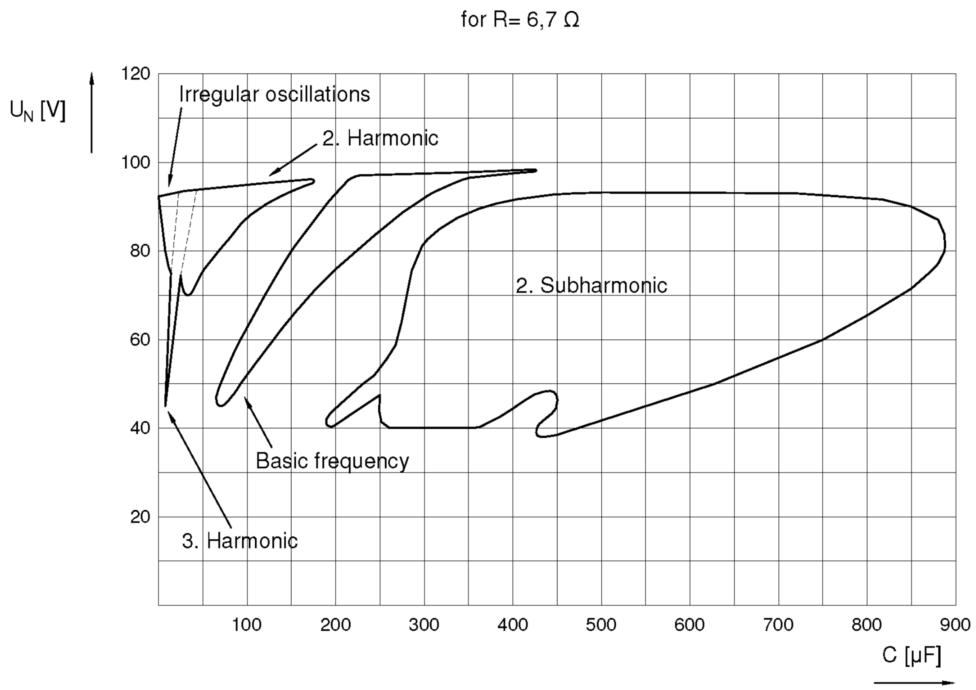
Reproduced from [6].

Figure 9 – Laboratory test set used by Bergmann

Depending on the size of the capacitance and the applied voltage, different resulting frequencies for the ferroresonance oscillation were measured, with the second sub-harmonic being found with the largest area of existence (see Figure 10).

But also oscillations with rated frequency or higher harmonics up to the third harmonic were measured.

For small capacitances C even chaotic ferroresonance oscillations can occur.

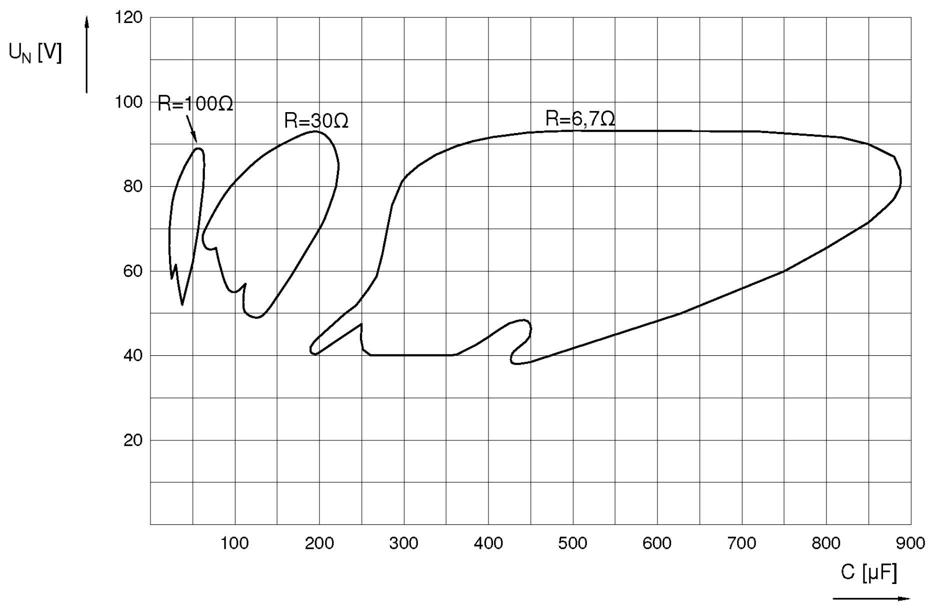


Reproduced from [6].

Figure 10 – Domains in the capacitance *C* and line voltage *U* where different harmonic and sub-harmonic ferroresonance oscillations are obtained for a given resistance *R* of 6,7 Ω in Bergmann's test set

Some mathematical considerations made by Bergmann also show that sub-harmonics higher than the second sub-harmonic are at least theoretically possible, even if these frequencies did not show up during his experiments.

Concerning the second sub-harmonic, the experiments have shown, that if the resistance *R* is increased, ferroresonance will occur only for significantly lower values of the star point capacitance *C* (see Figure 11).



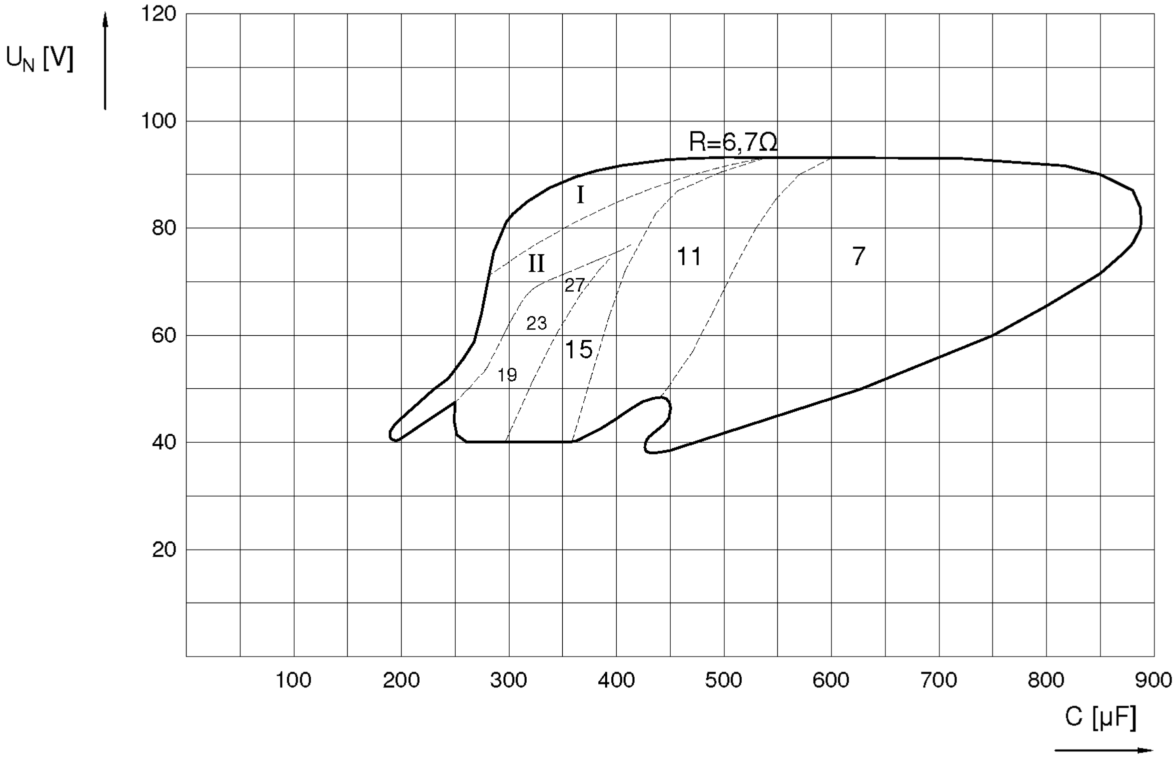
Reproduced from [6].

Figure 11 – Domains in the capacitance *C* and line voltage *U* where second sub-harmonic ferroresonance oscillations are obtained for a variation of the resistance *R* in Bergmann's test set

Looking more closely at the exact voltage and current signals in each phase for the second sub-harmonic, significantly different resonance modes can be observed.

Superimposed on the basic second sub-harmonic, a beat of 7 up to 27 times of the rated frequency was observed, with in most cases the choke coils in all three phases saturating periodically (see Figure 12, areas marked with arabic numbers).

However, for small capacitances there were modes, where only two or even only one phase saturated during the process (see Figure 12, marked by roman numbers).



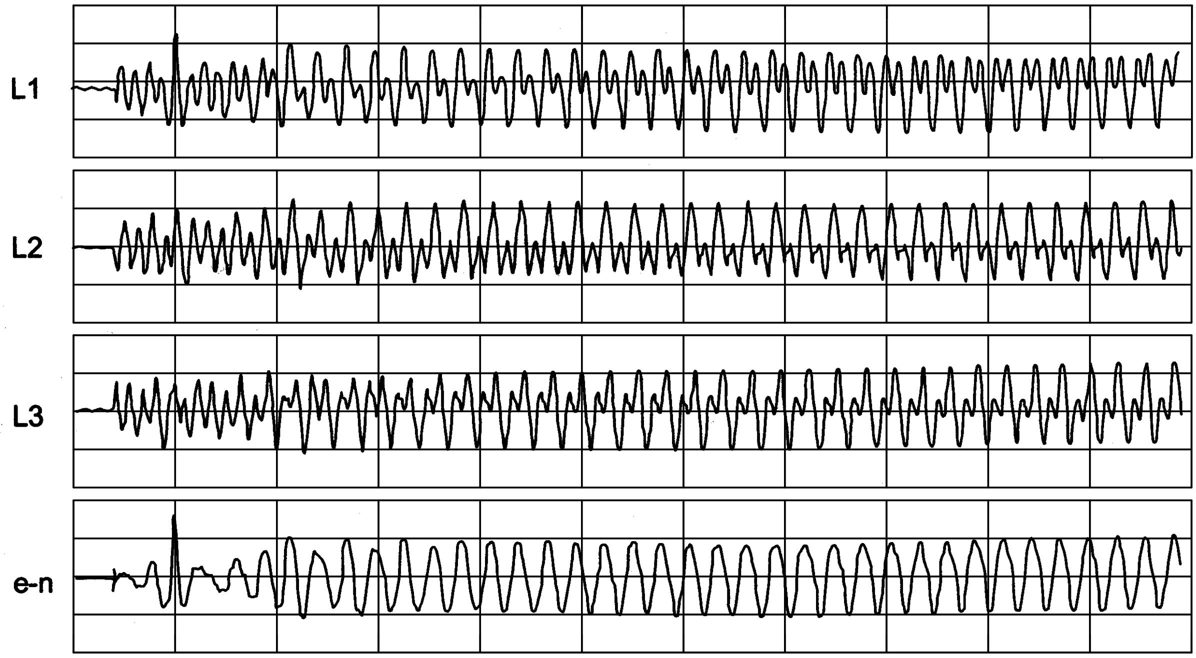
Reproduced from [6].

Figure 12 – Domains in the capacitance *C* and line voltage *U* where different modes of second sub-harmonic ferroresonance oscillations are obtained for a given resistance *R* of 6,7 Ω in Bergmann's test set

The observed basic oscillations in substations are mostly sub-harmonics of the network frequency. Sub-harmonics to the order of 2, 3, or higher will occur.

4.4.5 Typical oscillogram of three phase ferroresonance

Once this progression has been excited the oscillation will remain in the steady state in the network configuration without change. A typical oscillogram of a three phase ferroresonance is shown in Figure 13. While in all three phases a mixture of the basic voltage and the ferroresonance together with the beating is visible, in the open delta winding, a fairly regular subharmonic voltage with 25 Hz and a very small additional subharmonic (beat) can be observed.



Reproduced from [14], with the permission of Ritz Instrument Transformers/D .

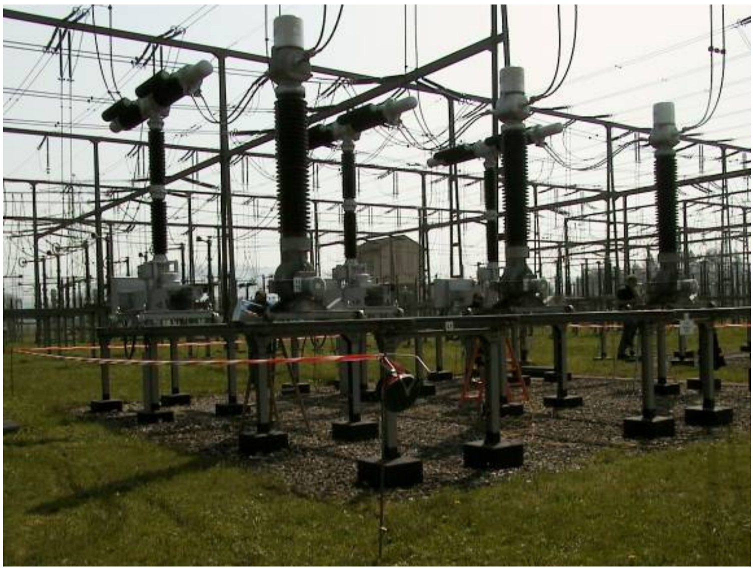
Figure 13 – Fault recorder display of a three-phase ferroresonance oscillation

The voltage traces of the three phases L1 to L3 are displayed along with the voltage trace of the neutral e-n. The ferroresonance oscillation frequency deviates slightly from the second subharmonic 25 Hz (at power frequency 50 Hz). Therefore the peak values of the ferroresonance voltage are drifting slowly from phase to phase. The three line voltages L1, L2, L3 and the neutral e-n voltage is triggered by energizing of the power transformer (see Figure 7).

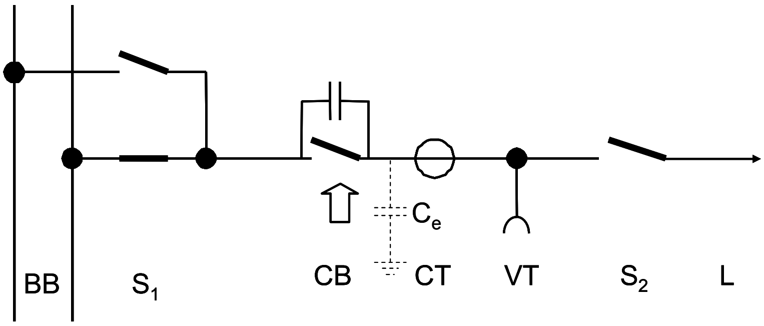
5 Examples of ferroresonance configurations

5.1 Single-phase ferroresonance power line field in a 245 kV outdoor substation

This first example demonstrates a frequently occurring situation in air insulated substation feeder bays, where single-phase ferroresonances can occur (Figure 14) in practice during test and commissioning, but generally not during normal operation. Depending on the magnetization characteristic of the voltage transformer and the effective capacitances in the feeder bay (grading capacitance of the circuit breaker and the earthing capacitance), ferroresonance oscillations can occur when opening the circuit breaker, if the line disconnector is already open and thus only a small earthing capacitance exists (Figure 14b)). In this case the voltage transformer is only connected with the operating voltage of the substation by the grading capacitor of the circuit breaker. This configuration is a typical ferroresonance circuit.



a) the 245 kV part of the substation GM Mettlen/CH



b) Schematic of the described switching configuration

Key

BB Busbar

S_1 Busbar disconnector, closed

CB Circuit breaker, triggering event is the opening of the breaker

CT Current transformer

VT Voltage transformer

S_2 Line disconnector, open

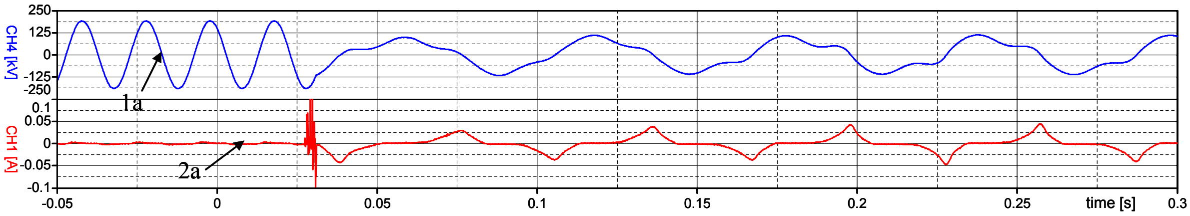
L Outgoing lines

Reproduced from [13], with the permission of ewz/CH.

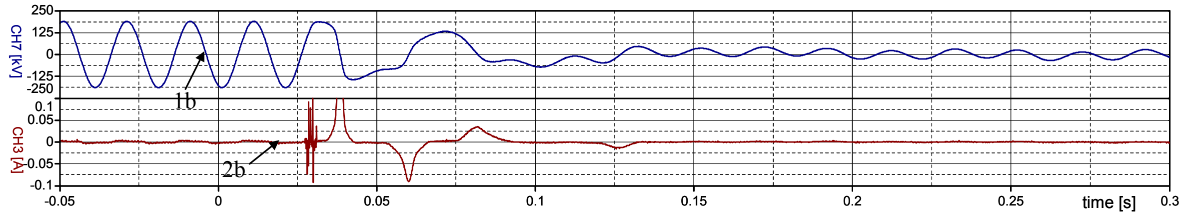
Figure 14 – Switching fields in the 245 kV substation in which single-phase ferroresonances occur

For this case, Figure 15 shows oscillograms of the measured inductive voltage transformer secondary voltages and the currents through the inductive voltage transformer's high voltage windings of one phase after the opening of the circuit breaker. In the first case (Figure 15a)), a steady state ferroresonance oscillation occurs. In the second case (Figure 15b)) the ferroresonance oscillations is decreasing.

Weather a steady state oscillation occurs or not depends on the circuit parameters (magnetisation characteristic of the voltage transformer, capacitors, etc.) and most often also on the switching angle (see Annex A).



a) Steady state ferroresonance oscillations, frequency $16^{2}/_{3}$ Hz; switching near the voltage maximum



b) Non-steady state, decreasing ferroresonance oscillation, transient waveform (between 0,03 and 0,15 s); switching near zero crossing of voltage (between 0,15 s and 0,3 s the coupled a.c. voltage can be seen)

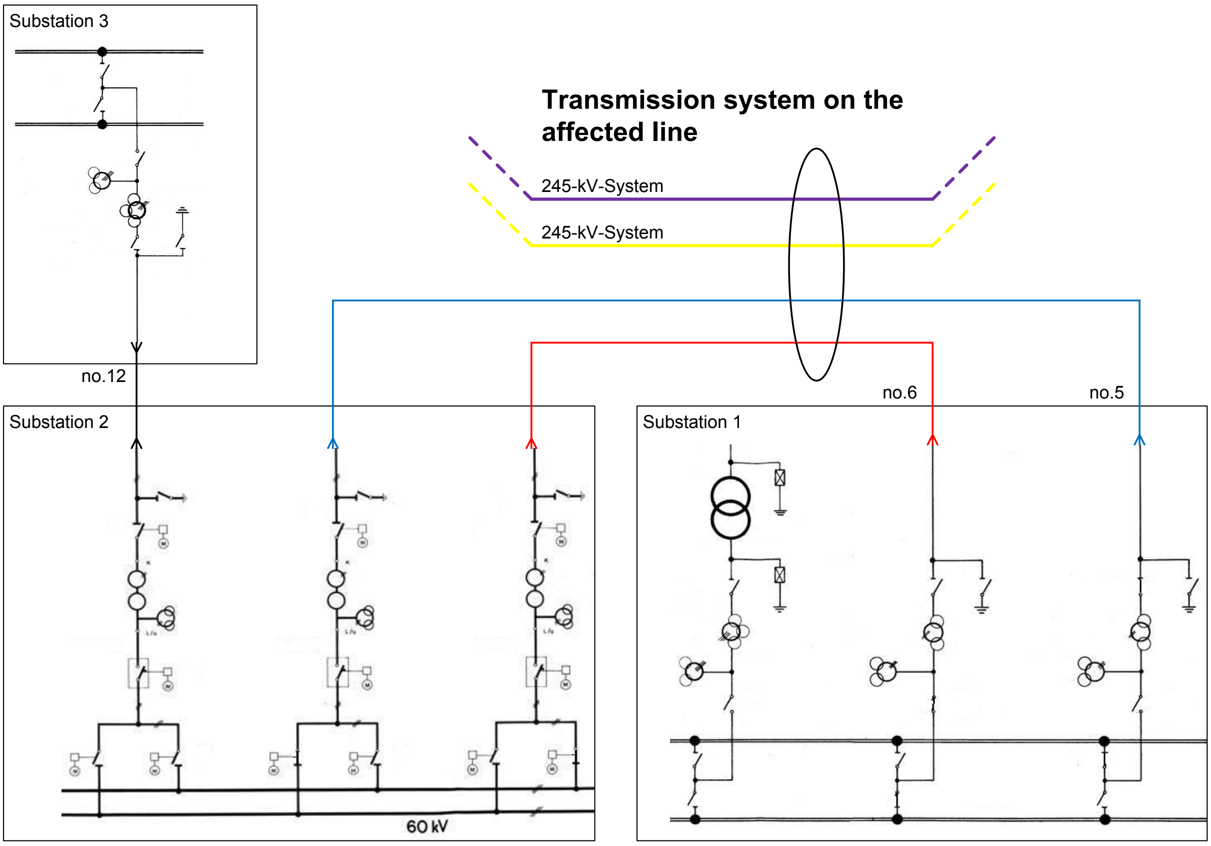
The upper curve (1a/1b) shows the primary voltage measured at secondary winding of the inductive voltage transformer, the lower curve (2a/2b) shows the current through the primary winding of the inductive voltage transformer.

Reproduced from [13], with the permission of ewz/CH.

Figure 15 – Examples of oscillations of single-phase ferroresonance when switching off the circuit breaker in Figure 14

5.2 Single phase ferroresonance oscillations due to line coupling

Another ferroresonance case corresponds to the coupling situation between parallel power lines as illustrated in Figure 5 and 6 b). In the following example (Figures 16 to 18), in the 60 kV network ferroresonance oscillations occurred in a disconnected power line phase to which voltage transformers were connected on both sides.



Reproduced from [13], with the permission of ewz/CH.

Figure 16 – Single-phase schematic of the network situation on the 60 kV voltage level in the area of substations 1, 2, and 3

Line no. 12 was shut down and earthed for maintenance work in substation 2 and substation 3. As a result, there was no load on the transformer in substation 1. Therefore it was shut down for maintenance work through the transformer bay.

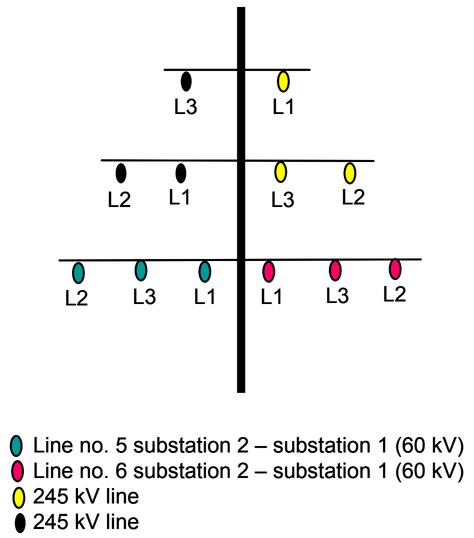
During this condition line no. 5 was de-energised but still connected to the busbars at both sides. It began to oscillate at phase L1 at a frequency of $16^{2}/_{3}$ Hz.

Line no. 6 remained in operation and was thus not affected by the ferroresonance oscillations.

Figure 18 shows a corresponding oscillogram of the three phases of line no. 5. On all three phases, a 50 Hz coupling from the 245 kV system situated on the same tower (see Figure 17) on line no. 5 was detected. At phase L1 there were obviously coupling capacitances and earthing capacitances present which, together with the magnetic characteristic of the voltage transformer, met the conditions for ferroresonance oscillations. This was not the case with the other two phases.

From the records of the disturbance recorder, the presence of ferroresonance oscillations was detected on line no. 5 between substations 1 and 2. The line was immediately earthed, preventing damage to the voltage transformers and the burdens.

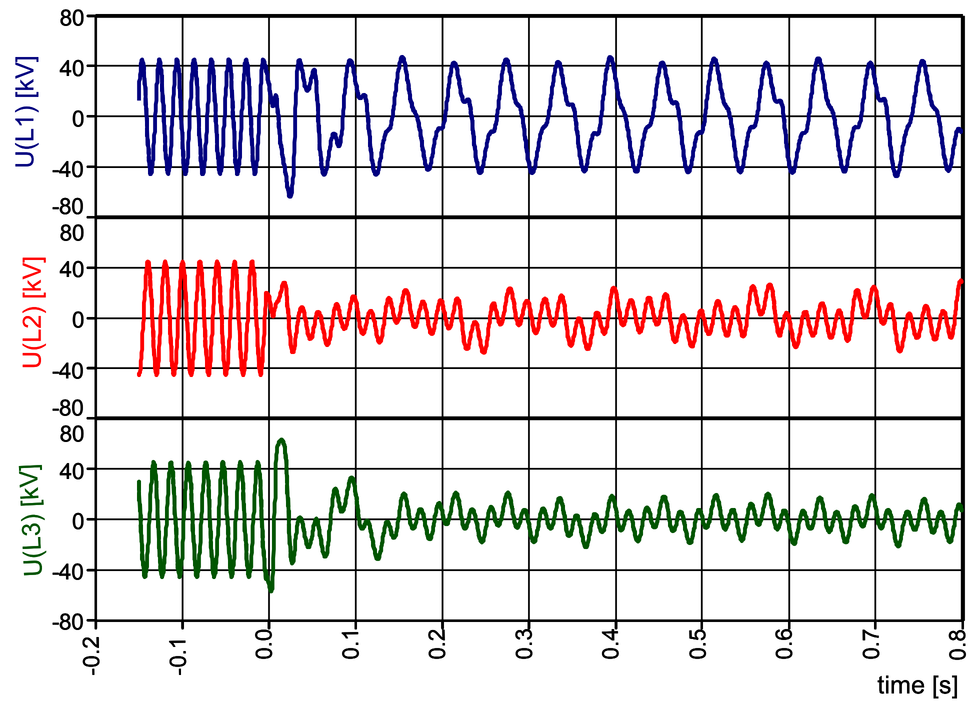
A similar ferroresonance case resulting from capacitive coupling on a deactivated power line led in various cases to significant damages, for example see [12].



Reproduced from [13], with the permission of ewz/CH.

Figure 17 – Tower schematic of the common stretch of overhead lines between substations 1 and 2

On the tower schematic in Figure 17, the 60 kV line no. 5 and no. 6 are parallel to the two 245 kV lines.



Reproduced from [13], with the permission of ewz/CH.

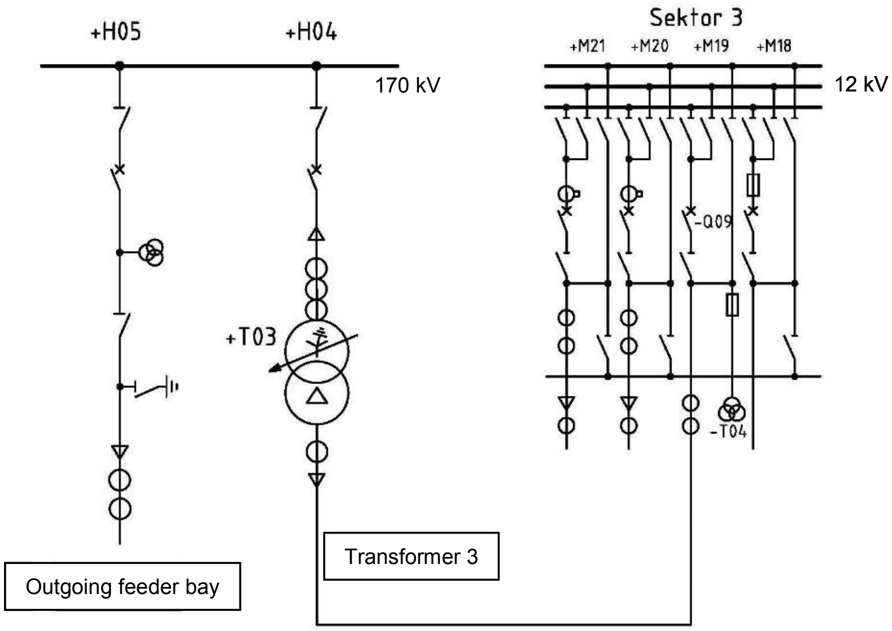
Figure 18 – Ferroresonance oscillations recorded in line no. 5 at Substation 2

The voltage at phase L1 (Figure 18) shows a clear ferroresonance oscillation at a frequency of $16^2/_3$ Hz.

The voltages at phases L2 and L3 (Figure 18) show a capacitive coupling with 50 Hz (from a 245 kV system), with $16^2/_3$ Hz (from L1).

5.3 Three-phase ferroresonance oscillations

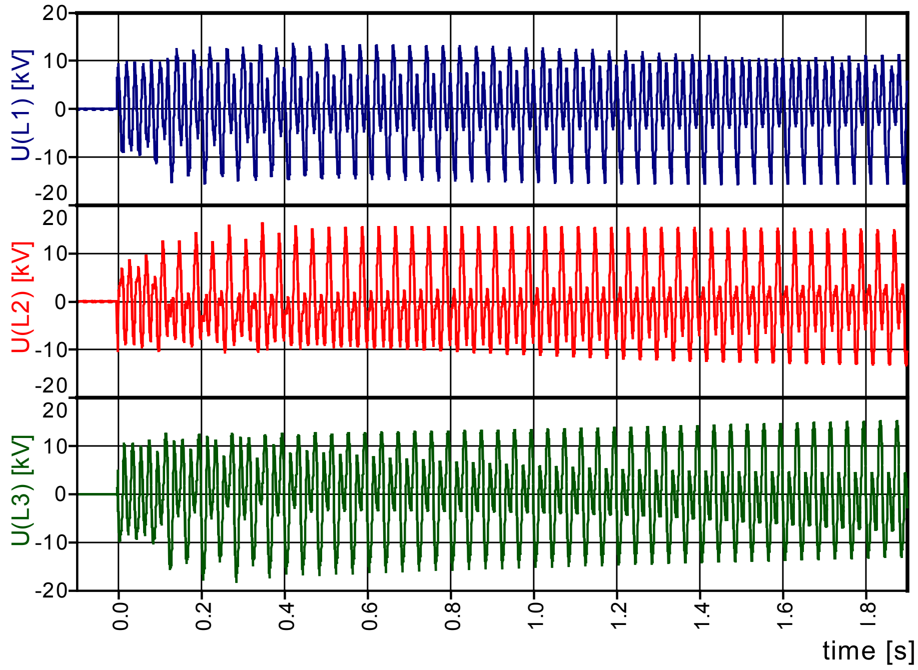
The substation shown in Figure 19 performs a transformation from the level of the high voltage network (operational voltage 170 kV) to the distribution voltage level (12 kV) of the medium voltage network.



Reproduced from [13], with the permission of ewz/CH.

Figure 19 – Single-line diagram of the 170-kV substation (left) and the 12-kV substation (right); where during switching operation three phase ferroresonance oscillations occurred

A fault recorder was put into service in the 12 kV transformer bay "+M19" (feed from Transformer 3). During commissioning tests of the fault recorder, the 170 kV transformer bay "+H04" was switched on, which feeds sector 3 over transformer bay "+M19". Circuit breaker Q09 in field "+M19" remained open and the recorded waveforms shown in Figure 20 via the inductive voltage transformer T04. These were identified as a manifestation of ferroresonance.



Reproduced from [13], with the permission of ewz/CH.

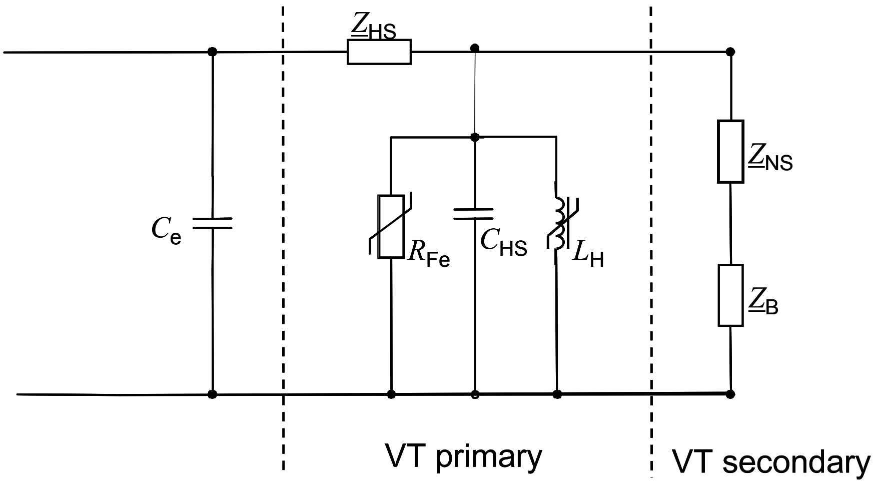
Figure 20 – Oscillograms of the three-phase voltages at inductive voltage transformer T04 (Figure 19)

The basic frequency of the ferroresonance oscillations lies close to the second network subharmonic of 25 Hz which is superimposed by 50 Hz signal. The deviation of the ferroresonance oscillations from 25 Hz (second subharmonic of 50 Hz), leads to a beat with a very low frequency [13]

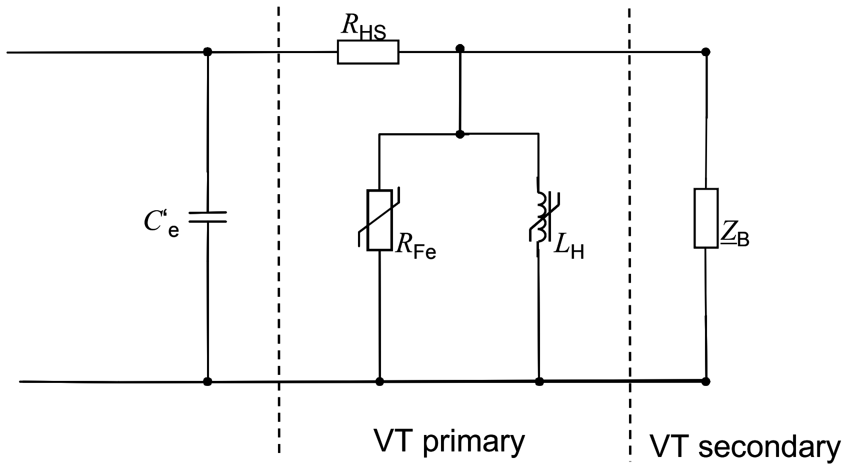
Due to the ferroresonance oscillations, the voltage transformers were subjected to a thermal overload due to the increased current in the primary windings. The damaged inductive voltage transformers were replaced. In order to avoid future three-phase ferroresonance oscillations, a damping impedance was inserted into the open delta winding.

6 Inductive voltage transformer (key parts)

The general schematic circuit of an inductive voltage transformer is represented in Figure 21 a). However, as shown in Figure 21 b) a simplified voltage transformer model can be used to investigate the ferroresonance behavior. The hysteresis of the core determines the non-linear inductance L_H and the iron losses of the VT with the nonlinear resistance R_{Fe}.



a) VT-schematic circuit



b) Simplified VT-circuit for ferroresonance studies

Key

C_e	Earth capacitance
C_{HS}	Capacitance of the HV-winding of voltage transformer
C'_e	Total earth capacitance $C'_e = C_e + C_{HS}$
R_{Fe}	Non-linear resistance representing the iron losses of the inductive VT
R_{HS}	Resistance of the high voltage winding
L_H	Non-linear main inductance of the HV-winding of the inductive VT
$\underline{Z}_B$	Impedance of the burden of secondary winding 1 (load impedance and inductance)
$\underline{Z}_{HS}$	Impedance of the HV winding (resistance and stray inductance)
$\underline{Z}_{NS}$	Impedance secondary winding 1 (resistance and stray inductance)

Figure 21 – Schematic circuit of voltage transformer and the simplification for ferroresonace studies

Additional losses are given by the burden $\underline{Z}_B$ of measuring and protection relays connected to the secondary winding of the VT. However state of the art of modern electronic metering and protection equipment has almost zero burden and can therefore often be neglected. Together with the additional power losses in the network these losses are determining, whether an oscillation stays transient or turns into a steady state ferroresonance oscillation.

The leakage inductance L_{HS} and the ohmic resistance R_{HS} of the primary winding are represented by the impedance $\underline{Z}_{HS}$.

The leakage inductance of the primary winding as well as the impedance $\underline{Z}_{NS}$ of the secondary winding can be neglected. The capacitance of the high voltage primary winding can be added to the phase to earth capacitance of the system.

Under normal steady state operating conditions the applied voltage and therefore the magnetic flux density of the magnetic core is constant.

The corresponding excitation current is up to some mA depending on the design of the magnetic circuit, for example whether it consists of a magnetic circuit with or without an air gap (see Clause 11).

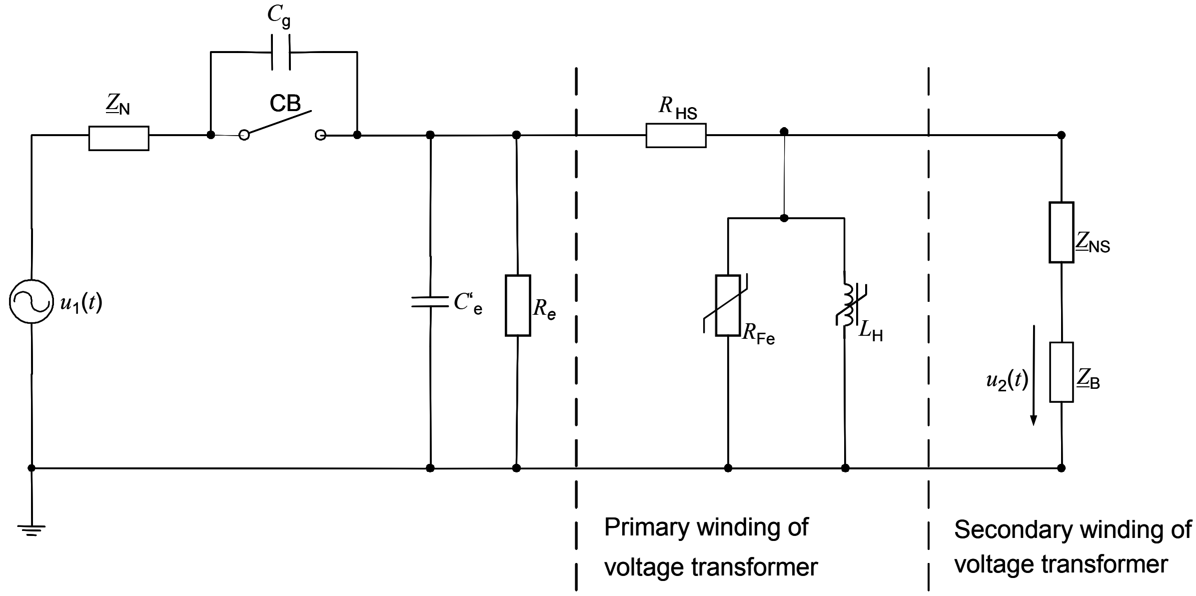
Transients in the power network for example caused by circuit breaker switching can saturate the voltage transformer and trigger a ferroresonance oscillation. The result of the saturation effect is a much lower VT reactance with a corresponding higher excitation current.

7 The circuit of the single-phase ferroresonance configuration

7.1 Schematic diagram

Figure 22 shows the circuit for the simulation approach to single-phase ferroresonance. The reduction of this schematic diagram to a series resonance circuit as shown in Figure 2, which can often be found in the literature, is helpful as a qualitative description for understanding the ferroresonance phenomenon. This simplification without losses cannot be used for simulation and mathematical treatment of the non-linear system.

Accordingly it is especially important to pay attention to the treatment of non-linear elements and the proper transformation of the initial conditions before switching operation. With the currently available computing capacities, it is not necessary to simplify the circuit.



Key

CB	Circuit breaker
C'_e	Total earth capacitance of circuit
C_g	Grading capacitance of circuit breaker CB
R_e	Summary of phase-earth insulation resistances (insulating resistance internal to transformer, non-linear leakage resistance, e.g. on account of currents in contaminated surfaces, corona currents and currents from metal oxide leakage
R_{Fe}	Non-linear resistance representing iron core losses
L_H	Non-linear main inductance
$u_1(t)$	Primary phase to earth voltage
$u_2(t)$	secondary voltage
$\underline{Z}_B$	Impedance of the load resistance of secondary winding 1 (load resistance and inductance)
R_{HS}	Resistance of the primary winding
$\underline{Z}_N$	Network impedance
$\underline{Z}_{NS}$	Impedance of secondary winding (resistance and leakage inductance)

Reproduced from [14].

Figure 22 – Circuit for the analysis of single-phase ferroresonance oscillation

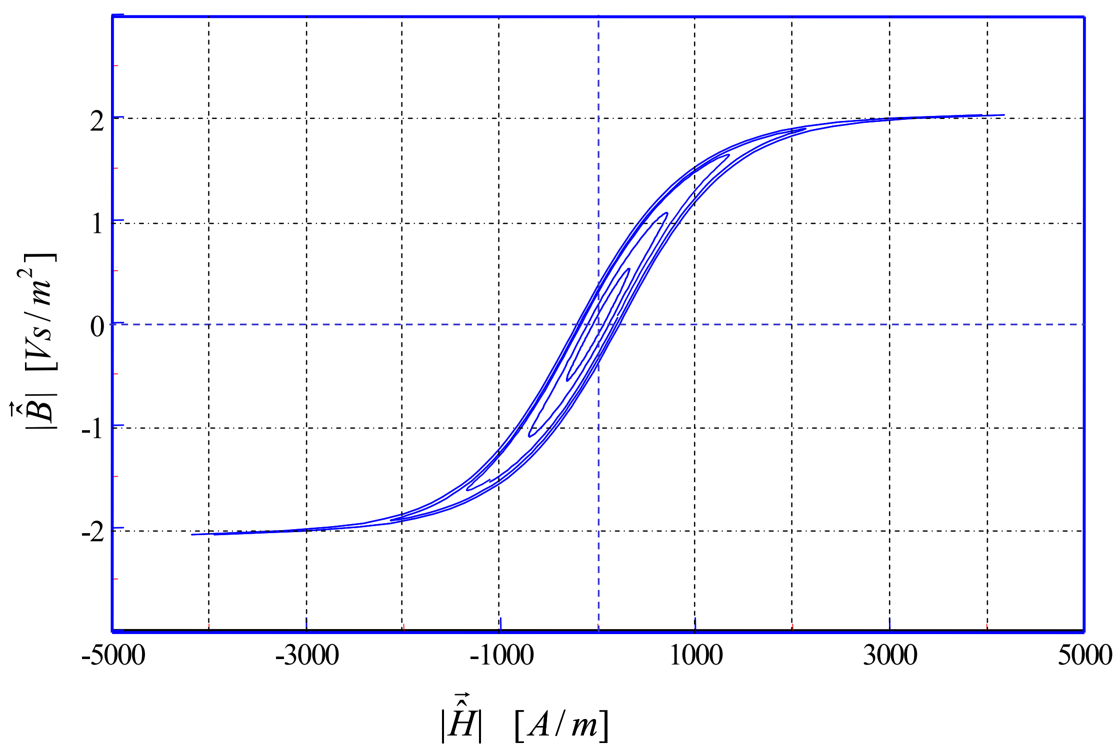
In addition to choosing a suitable schematic diagram, it is important for the simulation and the calculation to choose the correct initial conditions, and appropriate characterisation of the circuit elements. The non-linear elements, i.e. the magnetisation curve of the voltage transformer and the circuit losses play an important role for the ferroresonance simulation.

7.2 Magnetisation characteristic

Figure 23 shows a typical hysteresis curve of an inductive voltage transformer. The results of simulations showed that even small changes to the circuit parameters, as well as to the magnetisation characteristic, can lead to completely different results. For this reason, it is important for the analysis to follow as much as possible the real magnetisation curve, well into the saturation area.

From material properties calculated magnetisation curves can often deviate considerably from measured curves. Thus, measurement most often represents the most exact option for determining the magnetisation characteristic. Suitable methods have to be used to measure the magnetisation curve.

Nevertheless, even when performing a measurement, parasitic influences shall be thoroughly considered. Since we are only interested in the magnetic behaviour of the main inductance, capacitive effects will distort the measurement results. These parasitic capacitive influences will occur when the measurements are performed on the assembled voltage transformer. To avoid this effect it is recommended to measure the magnetizing characteristic on the iron core only.



Reproduced from [14], with the permission of Trench Germany.

Figure 23 – Example of a hysteresis curve of a voltage transformer core measured at 50 Hz

Furthermore it is necessary to ensure that the saturation behaviour will be available up to sufficiently high excitation $\vec{H}(t)$. The shape of the magnetisation curve suitable for simulation is the representation of magnetic flux density $\vec{B}(t)$ as a function of the excitation $\vec{H}(t)$.

7.3 Circuit losses

Another important variable that influences the precision of the analysis and simulation results are the losses in the ferroresonance circuit. These losses influence whether the oscillation becomes steady-state or not. The circuit in Figure 22 contains the various equivalent loss components.

The losses occurring in the inductive voltage transformer itself are contained on the one hand in impedance $\underline{Z}_{HS}$ of the high-voltage winding. On the other hand, the non-linear resistance R_{Fe} represents the losses due to the hysteresis in the core. Losses occurring on account of connected loads are represented by burden impedance $\underline{Z}_{B}$.

Further sources of losses in the switchgear, such as leakage current of insulators, current through metal oxide arresters or corona discharges are summarized in resistance R_e parallel to the earth capacitance C_e. While the voltage transformer losses may be known from the manufacturer's specifications, the other losses are different from substation to substation. They are a function of temporary influenced variables such as weather and degree of contamination, and mostly unknown.

Depending on the type and design of the equipment, the value of resistance R_e can certainly vary over several orders of magnitude. Typical values for a 420 kV air insulated substation range from several MΩ up to several GΩ. Due to the basic design the losses in gas-insulated switchgear are significantly lower compared to air-insulating switchgear.

8 Necessary information for ferroresonance investigation

8.1 General

Prior to the network analysis in respect to their ferroresonance behaviour the existing configuration shall be transferred to a circuit for simulation. To check the ferroresonance behaviour by high voltage laboratory tests the test set up has to include the voltage transformer, the circuit breaker, all capacitances and resistors. To check the ferroresonance behaviour by computer simulation the parameters of all relevant circuit elements shall be known.

The simulation results strongly depend on the realistic assumption values of the input data.

8.2 Single phase ferroresonance

Single phase ferroresonance network configurations can be described with the circuit according to Figure 6.

The following data in Table 2 (reproduced from [10]) shall be provided:

Table 2 – Parameters

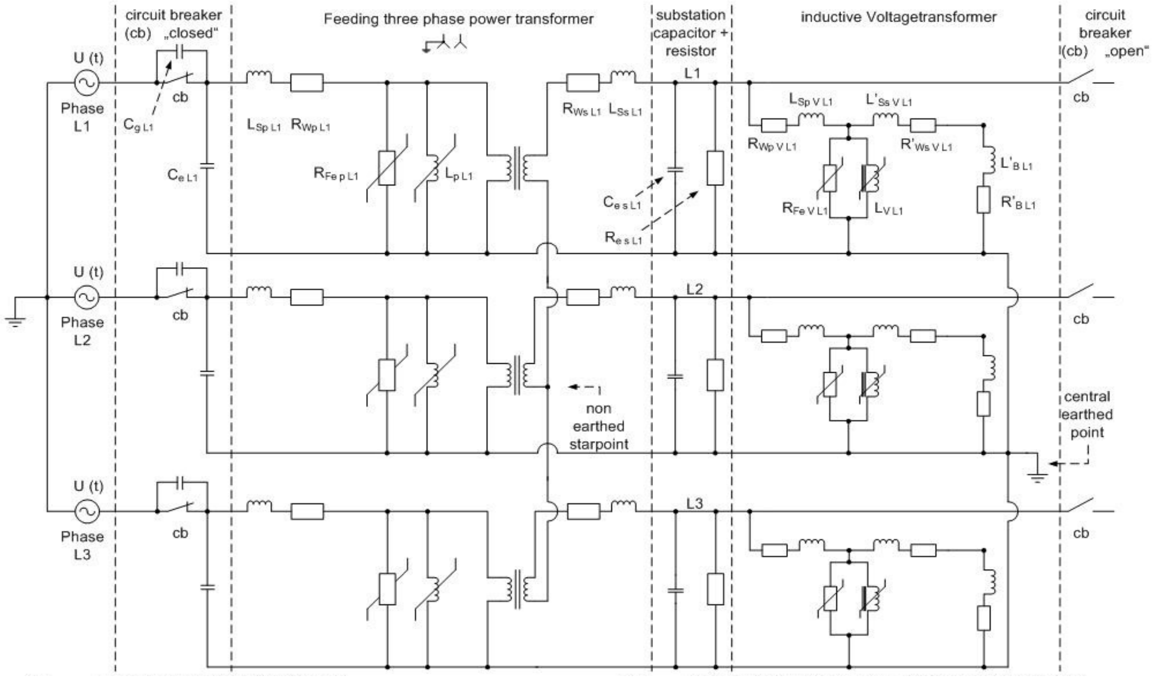
Parameter	Element	available from	Remark
Maximum system voltage	Network	Utility	
Earthing [a]	Network	Utility	Referred to the investigated configuration
Grading capacitance C_g per Circuit Breaker	Circuit breaker	Circuit breaker manufacturer	E.g. two chambers of 700 pF in series correspond to 350 pF
Number of relevant circuit breakers	Network	Switchgear manufacturer or utility	Connected to VT
Coupling capacitances to the other phases	Network	Switchgear manufacturer or utility	Only for more accurate simulation result
Coupling capacitances of adjacent lines	Network	Switchgear manufacturer or utility	Necessary for studies of de-energized lines
Phase to earth capacitance C_e	Network	Switchgear manufacturer and utility	CT, VT, Busbar, line
Power losses in the network R_e, if available	Network	Switchgear manufacturer and utility	Mostly unknown parameter
VT Specification	Voltage transformer	Switchgear manufacturer or utility	Burden and accuracy requirements
Actual connected burden	Voltage Transformer	Switchgear manufacturer or utility	E.g. digital secondary equipment has a burden of practical 0 VA

Parameter	Element	available from	Remark
Magnetizing curve	Voltage transformer	VT manufacturer	
Iron losses	Voltage transformer	VT manufacturer	
Impedance of primary winding	Voltage transformer	VT manufacturer	
Damping device	Voltage transformer	VT manufacturer and utility	Type and parameter of damping device
Switching procedure and configurations	operation	Switchgear manufacturer and utility	
[a] solidly earthed, isolated or resonant earthed system, high impedance earthed			

These data shall be provided for all relevant network configurations and switching conditions during normal operations, and also commissioning, testing and maintenance.

8.3 Three phase ferroresonance

The circuit for three phase ferroresonance oscillations is shown in Figure 24.



Reproduced from [15], with the permission of Siemens Switzerland.

Figure 24 – Schematic diagram for three phase ferroresonance oscillation

In this example the power transformer is realized with three single phase transformers.

In contrast to single phase ferroresonance configurations all parameters describing the individual phases and additionally all parameters describing the inductive and capacitive coupling of the three phases are required for simulation, for example coupling via power transformer and coupling capacitances. In addition, data about the type and parameters of the power transformer are necessary.

9 Computer simulation of ferroresonance oscillations

9.1 General

As for any other physical problem dealing with non-linear elements there is no general self-consistent analytical solution for the mathematical representation of ferroresonance oscillations. Therefore numerical methods are required. Besides simulation, which determines the time-dependent solution for a discrete configuration other methods are also available which show the existence domains of the various ferroresonance modes without having to determine the time-dependent solutions. The disadvantage of the latter is that they are difficult to handle in practice, and that they cannot provide any information about the expected current and voltage waveforms and their respective amplitudes. Simulation, on the other hand, does provide this information. However, this only applies for the specific configuration under investigation, and does not provide any general result. Several loops of calculation might be required for various configurations. Subclauses 9.2 to 9.5 explain the essential circuit parameters and their significance in view of the simulation result using the example of single-phase ferroresonance.

9.2 Electrical circuit and circuit elements

Figure 22 shows the electrical circuit for the calculative approach to single-phase ferroresonance. The reduction of this circuit on a series resonance circuit according to Thevenin theorem as shown in Figure 2 is helpful as a qualitative description for understanding the ferroresonance phenomenon but cannot be applied for non-linear elements and the simulation of the transient ferroresonance behaviour [10]. Additionally to the choice of a suitable electrical circuit, it is of great importance for simulation results to use the right initial conditions before switching, and properly characterize the individual elements of the circuit. The representation of the non-linear elements, i.e. the magnetisation curve of the voltage transformer and the representation of circuit losses play a specific role for the simulation.

Since the fundamental frequency of the network for example 50 Hz or 60 Hz is the highest observed frequency in practice for ferroresonance oscillations all circuit elements as capacitance, inductance and resistive elements can be represented by lumped elements.

All circuit elements relevant for the simulation of single phase ferroresonance oscillations are described in the key of Figure 22.

For more detailed simulations additional capacitive coupling from adjacent phases and/or phases of adjacent voltage systems shall be applied. Please note that Figure 6 b) exemplary shows the coupling from one phase only. A capacitance matrix considering the mutual coupling of all phases shall be considered for the simulation.

9.3 Circuit losses

The relevant circuit losses are described in detail in 6.3.

Another source of losses is the burden connected to the VT secondary winding. The burden consists of all connected devices, for example protection relays, measuring meters, and if needed a ferroresonance damping device. Since there is only little burden for modern electronic relays power losses can be neglected in this case.

9.4 Examples of simulation results for single phase ferroresonance oscillations

9.4.1 General

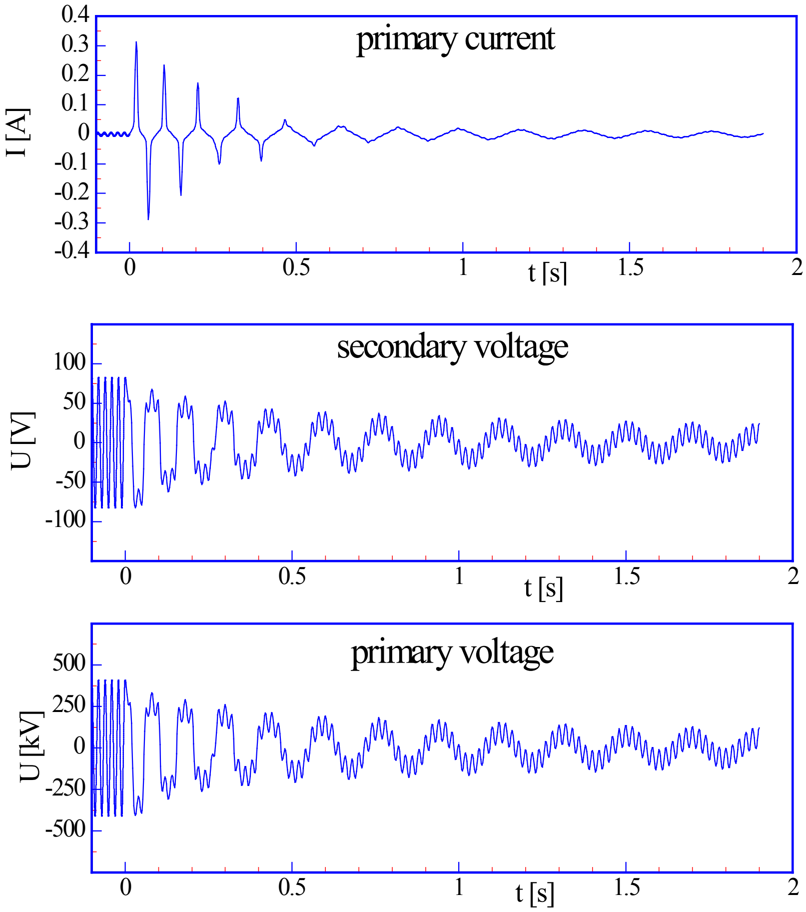
Depending on the circuit parameters, essentially 4 different modes of ferroresonance can be distinguished. In the calculation examples, the line bay is de-energized by the circuit breaker at the maximum voltage $u_1(t=0)=\hat{U}$ of the selected phase.

- Case 1: non-steady-state decreasing ferroresonance oscillation
- Case 2: steady-state ferroresonance oscillation at network frequency.
- Case 3: steady-state subharmonic ferroresonance oscillation.
- Case 4: steady-state chaotic ferroresonance oscillation.

All cases of steady state ferroresonances (cases 2 to 4) lead to high current in the primary winding of the inductive voltage transformer and therefore to overheating.

9.4.2 Case 1: Transient, decreasing ferroresonance oscillation

Any switching operation inevitably leads to a compensation process due to the change of the network conditions after circuit breaker switching. However, the resulting decaying oscillations are not critical for the voltage transformers.



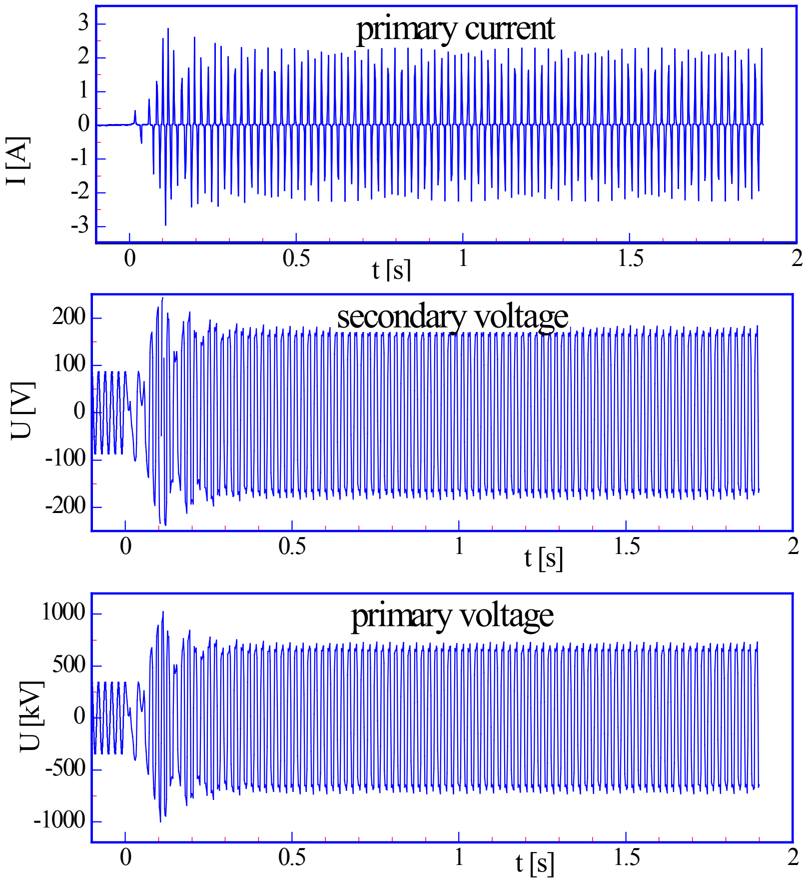
The frequency is decreasing with the decreasing of the saturation.

Reproduced from [14], with the permission of Trench Germany.

Figure 25 – Transient decreasing ferroresonance oscillation with the fifth subharmonic 50/5 Hz (10 Hz)

9.4.3 Case 2: Steady-state ferroresonance oscillation at network frequency

In the case of a steady-state ferroresonance oscillation, the circuit losses are not sufficient to damp the oscillation (Figure 26). In this ferroresonance mode, the oscillation can result in high over-voltages at network frequency, depending on the values of the capacitances of the circuit. These over-voltages can lead to breakdown in the switchgear. Alternatively the high current in the primary winding of the inductive voltage transformer leads to overheating.



Reproduced from [14], with the permission of Trench Germany.

Figure 26 – Steady state ferroresonance oscillation with network frequency

9.4.4 Case 3: Steady-state subharmonic ferroresonance oscillation

The most often observed ferroresonance modes are subharmonic oscillations whereby only odd subharmonics can exist (see Clause A.4). The voltage arising during this ferroresonance oscillation is lower than for the ferroresonance with network frequency due to the lower frequency of the subharmonic mode. For the lower frequency, the saturation of the core occurs at lower voltages. This results in high current through the primary winding and leads to overheating. The example in Figure 27 shows an oscillation of 10 Hz (fifth subharmonic).

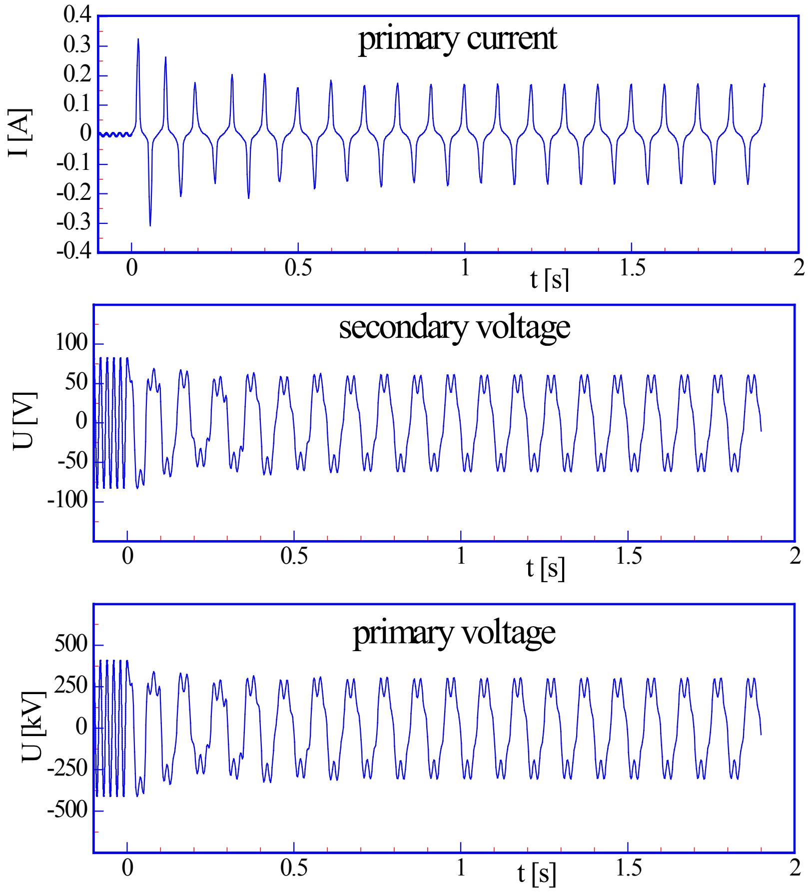


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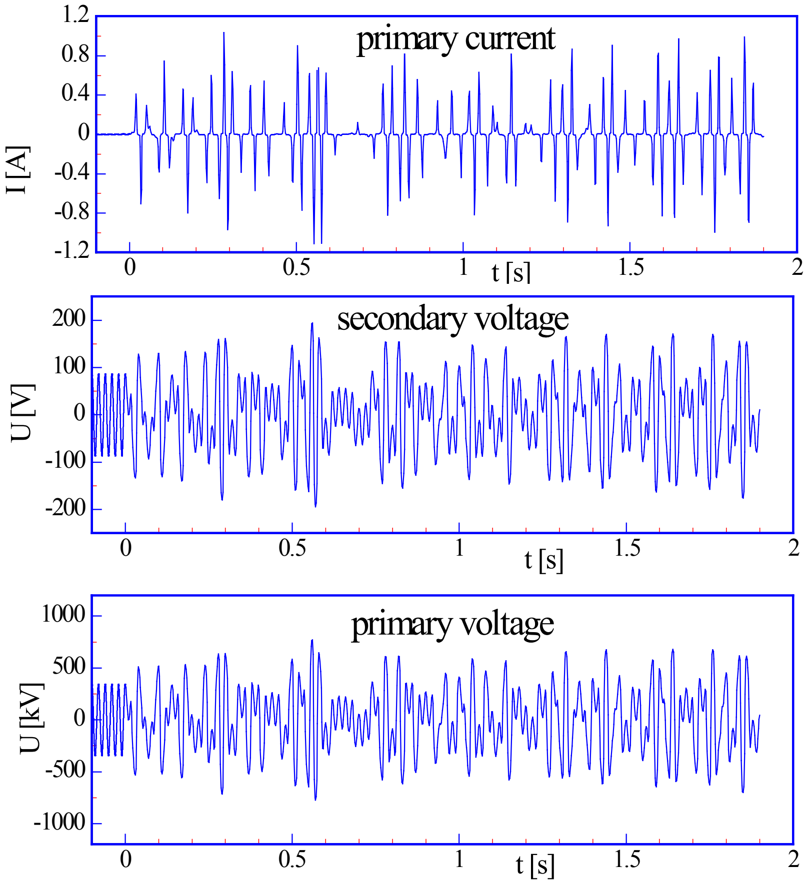
Figure 27 – Steady state ferroresonance oscillation with 10 Hz

9.4.5 Case 4: Steady-state chaotic ferroresonance oscillation

In rare cases, also chaotic oscillation waveforms with no defined frequency can occur (Figure 28). In this case, the resulting voltages can again turn out to be much higher than for the subharmonic waveform and the high current through the primary winding can lead to overheating.



Reproduced from [14], with the permission of Trench Germany.

Figure 28 – Steady state chaotic ferroresonance oscillation

9.5 Simulation of three phase ferroresonance

For three phase ferroresonance phenomena the coupling of the three phases is the most relevant effect. However the mutual coupling between different phases is mostly an unknown parameter and shall be determined by sophisticated studies. Moreover, as shown by the electrical circuit, the characteristics of the power transformer shall also be considered for the simulation. For this the magnetizing characteristics as well as ground and stray (mutual) capacitances shall be known. In practice these values are not available especially when considering three phase power transformers. Besides the capacitive coupling also magnetic coupling and the mutual influence on the magnetic behaviour of the three phases in the power transformer shall be considered.

Therefore in practice qualification of inductive voltage transformers is done by field tests or by a combined method with measurement and simulations.

If simulations are made, they are used to analyse network configurations where ferroresonances phenomena occurred to develop mitigation methods. For this the parameters of the equivalent circuit are adopted to the experimentally obtained voltage and current signals. Afterwards it is possible to transfer these parameters to modified network configurations, for example changed VT-design to develop mitigation methods for decreasing ferroresonance oscillation by simulation.

10 Experimental investigations, test methods and practical measurements

10.1 General

Measurements of electrical signals can be taken within an installation containing inductive voltage transformers to determine whether ferroresonance oscillations could occur in the event of specific switching operations. Usually, the important question is whether or not the occurring oscillations will lead to harmfully high currents in the primary winding of the inductive voltage transformer. For a basic analysis, as for verification of calculation models, measurements are taken with simultaneous recording of several voltage and current signals, and then compared with the theoretically calculated waveforms [17].

Because leakage currents at insulating surfaces in high voltage substations may significantly attenuate or prevent ferroresonance oscillations, experimental investigations in air insulated switchgear shall be performed only under dry weather conditions.

The measurements shall be performed on all three phases simultaneously for both single phase and three phase ferroresonance oscillations.

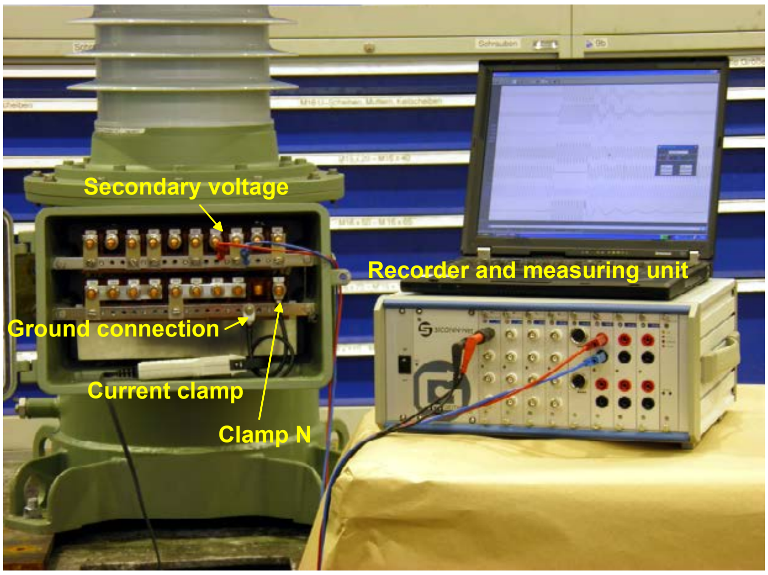
10.2 Single-phase ferroresonance oscillations

Measurements are usually taken during switching tests in order to investigate whether ferroresonance oscillations occur in certain configurations. The most sensitive variable for detecting ferroresonance is the current through the primary winding of the inductive voltage transformer. In order to measure this current, which in normal operation amounts to a few mA, two alternative methods can be used:

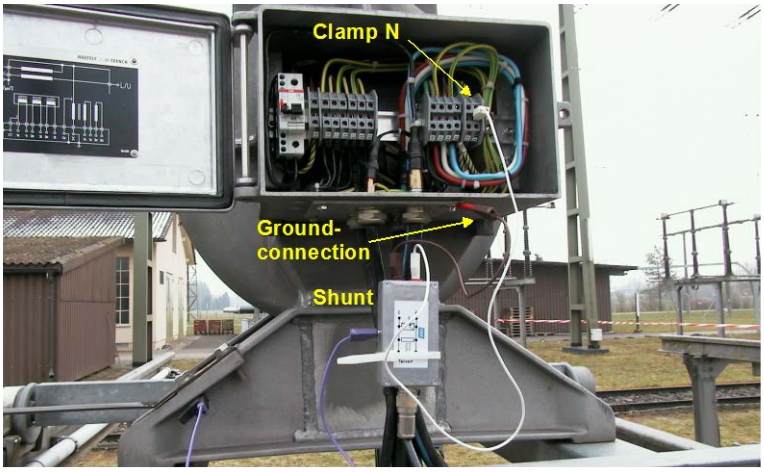
1) A current clamp is installed around the earth connection of the high voltage winding (see Figure 29a). In this case the transmission behaviour of the current clamp shall be checked regarding the frequency range from 0 Hz to 10 kHz.
2) A measuring shunt of typically 10 Ω is introduced between the HV winding earth terminal N and earth. The measuring cables shall be twisted and shielded (see Figure 29b).

The earth connection of the primary winding shall never be opened during operation, since high voltage will otherwise arise at the terminal N. As well for this reason, the resistor shall be dimensioned for the maximum possible current through the primary winding. An overvoltage protection element between the earth terminal and the earth-side terminal of the primary winding N shall be installed as a safety measure.

In the case of ferroresonance, the peak values of the current through the primary windings will be between 20 mA and a few hundred mA. Only in extreme cases will they be to the order of 1 A.



a) current measurement with current clamp

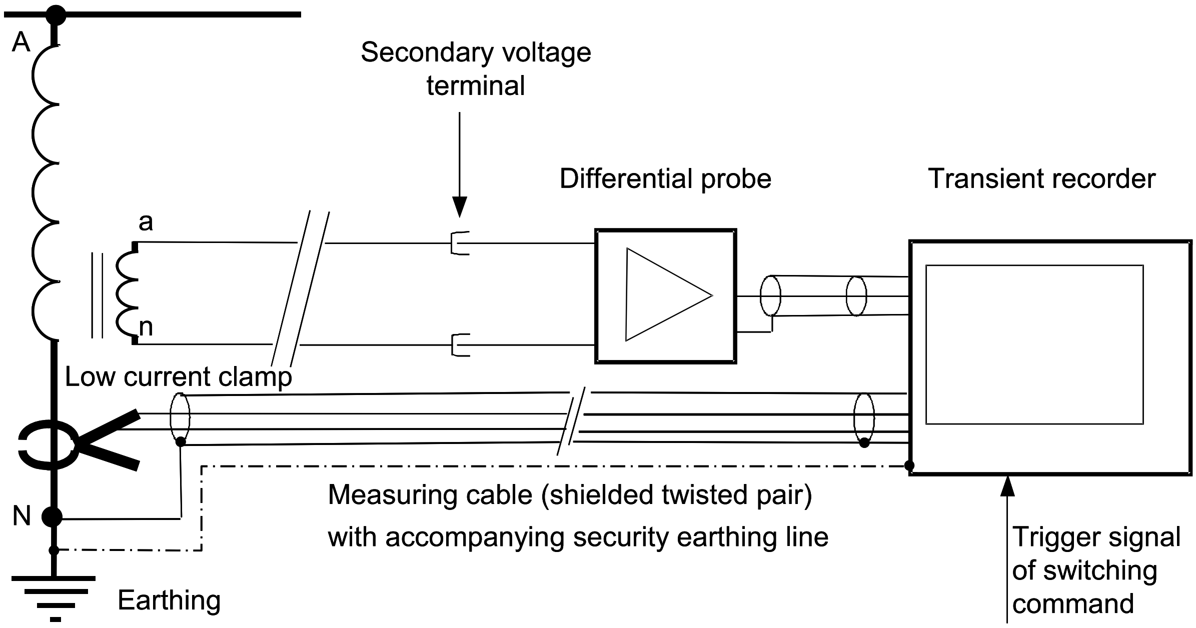


b) current measurement with shunt

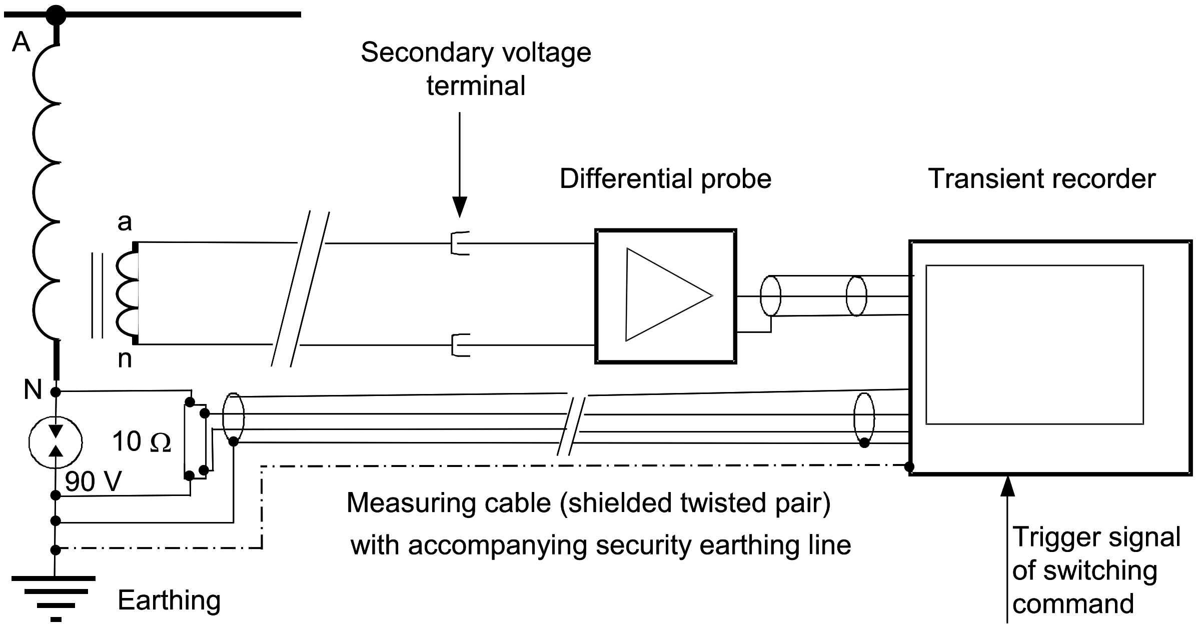
Reproduced from [14], with the permission of FKH Zürich/CH.

Figure 29 – Example of the connection of a measuring resistor for capturing the current signal through the voltage transformer's primary winding at terminal N (see connection diagram in Figure 30)

Figure 30 a) and b) show the measuring connections on a voltage transformer's terminal box. The current through the primary winding of the voltage transformer will always provide clear indications of any existing ferroresonance oscillations.



a) current measurement with current clamp



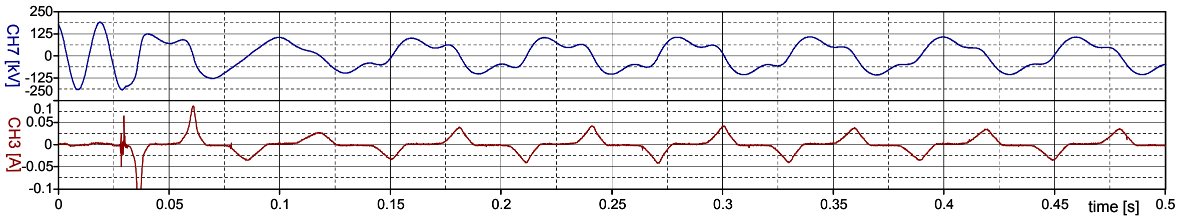
b) current measurement with shunt resistor

Reproduced from [14], with the permission of FKH Zürich/CH.

Figure 30 – Current measurement through voltage transformer's primary winding and the voltage at the secondary winding

For a detailed experimental analysis of the ferroresonance behaviour for example the verification of computer simulations, multi-channel measurements are required (including the source voltage, the secondary voltage of the inductive voltage transformer, the current through damping devices if existent and further signals).

If only voltages are measured (Figure 31, upper oscillogram curve), it is usually not possible to clearly distinguish between oscillations without core saturation and those with saturation (ferroresonance) and with dangerous high currents in the primary winding. The degree of saturation can be seen from the amplitude of the narrow current peaks (see Figure 31, lower oscillogram curve).



Example of a measured steady-state single-phase ferroresonance oscillation with the third subharmonic 50/3 Hz = $16^2/_3$ Hz in a 220 kV AIS switching bay.

Upper curve: Voltage across the voltage transformer burden referred to the primary side measured at the secondary side.

Lower curve: Current through the voltage transformer's primary winding.

Reproduced from [14], with the permission of GM Mettlen.

Figure 31 – Measurement of a single-phase ferroresonance oscillation

In the above example (Figure 31) the circuit breaker was operated in the voltage peak. This is regarded as worst case condition. The voltage curve results in a 16 $^2/_3$ Hz (thirdsubharmonic) signal. The current through the primary winding, which is normally in the order of 1 mA, reaches in the beginning more than 100 mA and stays at 50 mA peak under the steady-state conditions. Both curves show that the inductive voltage transformer performs steady-state ferroresonance oscillations. The primary winding can be overheated by the current through the winding during ferroresonance oscillations.

10.3 Three-phase ferroresonance oscillations

Measuring of three-phase ferroresonance is generally considered too complex to be done in a manufacturer's or other laboratories. The three voltage transformers are therefore usually tested in the substation in the real feeder bay.

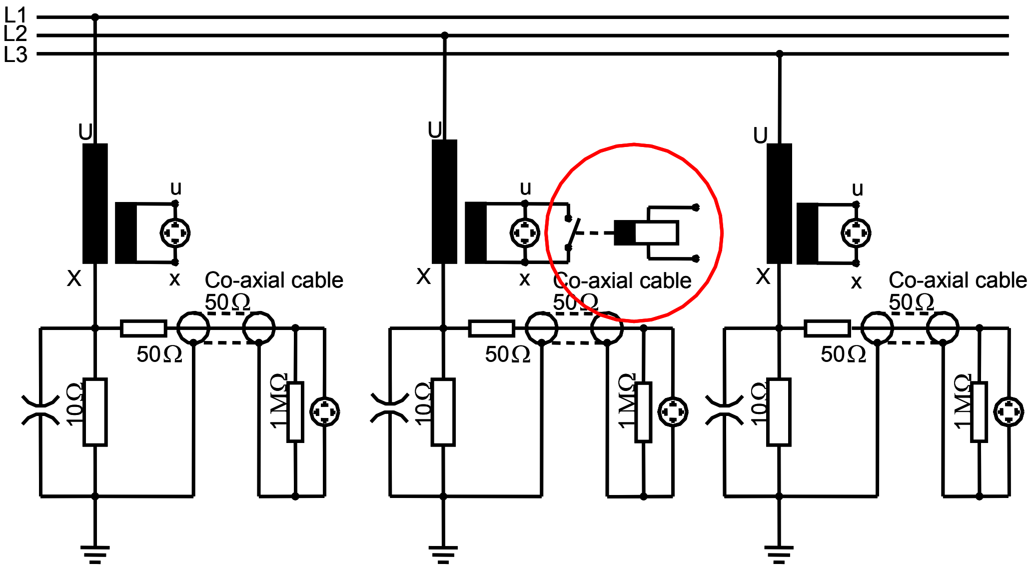
To determine whether a switching configuration is critical to three-phase ferroresonance or not, the measurement of the current through the primary winding and the voltages of the three voltage transformers of the feeder bay is important.

For this measurement the same equipment is needed as for measurement of single-phase ferroresonance described in Figure 30.

Additionally the voltage across the open delta connection should also be measured to get an indication of the resulting voltage of the non-earthed star point.

For these field tests, three-phase ferroresonance can be initiated by switching on the power transformer with the circuit breaker at the high voltage side. Every switching operation is a very strong stress for the power transformer; especially when the tap changer is in a higher position.

To protect the power transformer against damage, the ferroresonance can alternatively be initiated by a briefly short-circuit (approximately 200 ms) of the secondary voltage at one voltage transformer in the feeder bay (Figure 32).



Excitation of the oscillations on account to a secondary short circuit of a voltage transformer (red circle).

Reproduced from [14].

Figure 32 – Measurement of three-phase ferroresonance oscillations with an oscilloscope

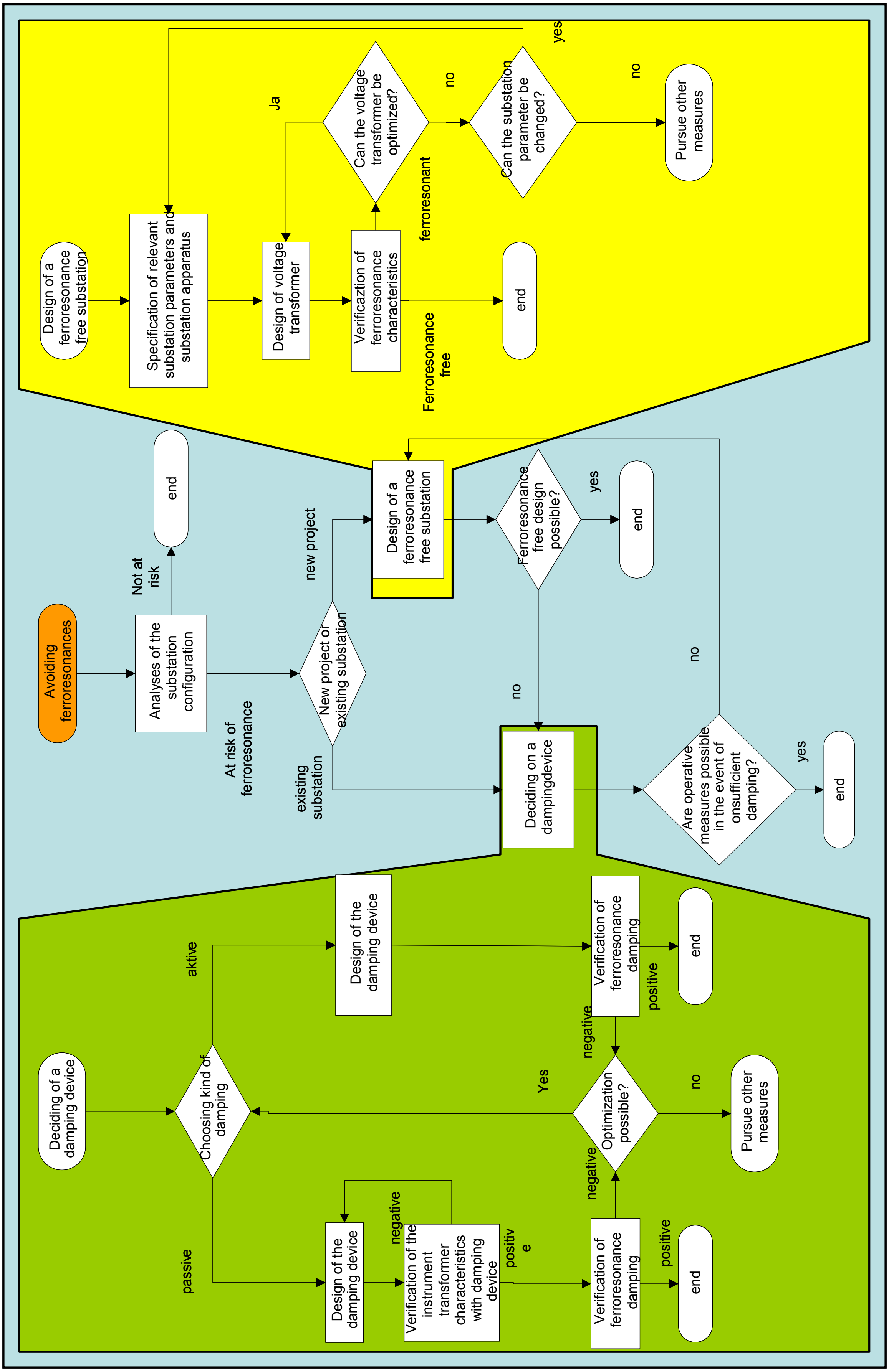
This transient short-circuit is regarded as the worst case excitation condition. With this method the ferroresonance behaviour can be tested without stressing the power transformer and circuit breaker by repeated switching transients on the primary voltage side.

This method of measuring is often successfully practised.

11 Avoidance and suppression of ferroresonance oscillations

11.1 Flow diagram

Figure 33 shows a flow diagram as an aid in analysing the situation and avoiding ferroresonance. The beginning of this process is an assessment in principle of the facility points to the risk of single-phase or three-phase ferroresonance. Here the possible critical switching conditions are identified and further measures are specified. To start with, it is important to distinguish between the procedure with respect to an existing facility (left branch of the main flow diagram in the middle) and a new switching facility (right branch).



Reproduced from [18].

Figure 33 – Flow diagram for analysis and avoidance of ferroresonance oscillations

11.2 Existing substations

Without modifications, ferroresonance oscillations can only be avoided in an existing substation using external damping device or by implementing specific operational measures. If attempts to remedy an existing problem with the aid of an external damping device are unsuccessful, it will be necessary to determine whether steady-state ferroresonances can be avoided by way of operational measures such as the elimination of critical switching conditions or switching operations, e.g. immediate activation of disconnectors for interrupting the energy coupling. If these measures are not successful, the substation configuration will have to be changed correspondingly (e.g. by reducing the grading capacitance).

11.3 New projects

For new switchgears as well as for extension and retrofitting of existing substations, the vulnerability to ferroresonance can be evaluated already in the design phase of the project. At present, the required reliability of calculated air gaps or damping devices can only be realized for single-phase configurations. In any case however, an experimental evaluation can be carried out in the affected substation itself or exemplary in a typical reference substation of the operator.

If the calculative approach indicates the sensitivity to single-phase ferroresonance, measures to avoid ferroresonance oscillations should be considered. The system can be influenced positively by modifying the design of the inductive VT (e.g. lower flux density). In case this is not possible for the original specification, the specifications of the inductive VT and the circuit breaker can be changed accordingly (e.g. reduction of grading capacitance).

If this is also not possible, an active or passive damping device can be connected to the secondary winding of the inductive VT to prevent steady-state ferroresonance oscillations.

11.4 Avoidance of ferroresonance oscillations

11.4.1 General

Avoiding of steady state ferroresonance oscillations is very important for utilities to prevent expensive damages in the substation. Switching states with possible ferroresonance oscillations should be as short as possible.

To eliminate this problem different methods are generally possible:

- in existing substations it is mostly possible to avoid ferroresonance oscillations with additional passive or active damping devices;
- for new voltage transformers the design can be improved for instance by changing the inductance and the use of air gaps or open core voltage transformers.

NOTE Voltage transformers with air gaps have for the network frequency f_R = 50 Hz / 60 Hz a linear impedance (ωL_H). With the existing ferroresonance circuit , grading capacitance, substation capacitance C_e against ground and main inductance L_H of the inductive voltage transformer this circuit is very sensitive to have ferroresonance oscillations at network frequency. The same statement is valid for open core voltage transformers. It is difficult to excite single phase ferroresonance oscillations of the subharmonic frequencies $f_3 = f_R / 3 = 16^2/_3$ Hz / 20 Hz, $f_5 = f_R / 5$ = 10 Hz / 12 Hz etc. in ferroresonance circuits with inductive measuring voltage transformer with a linear inductance L_H.

Specific solutions for single phase ferroresonance and for three phase ferroresonance are given in the following subclauses 11.4.2 and 11.4.3.

11.4.2 Single phase ferroresonance oscillations

Methods to avoid or limit the occurrence of steady state single phase ferroresonance:

- disconnect the inductive voltage transformer from the de-energised power line by open the line disconnector switches S1 and S2 (see Figure 5);

- disconnect the power coupling over the circuit breaker by opening the Busbar disconnector switch S1 (see Figure 4);
- methods to avoid ferroresonance oscillations by changing the resonance circuit: in new substations it is advisable to optimize the relevant capacitances (e.g. limiting the grading capacitor of circuit breaker).

11.4.3 Three phase ferroresonance oscillations

Methods to avoid or limit the occurrence of steady state three phase ferroresonance:

- Switching operations often can be optimized to avoid ferroresonance oscillations (e.g. switching the power transformer with the tap changer in the position for the lowest secondary voltage).

11.5 Damping of ferroresonance oscillation

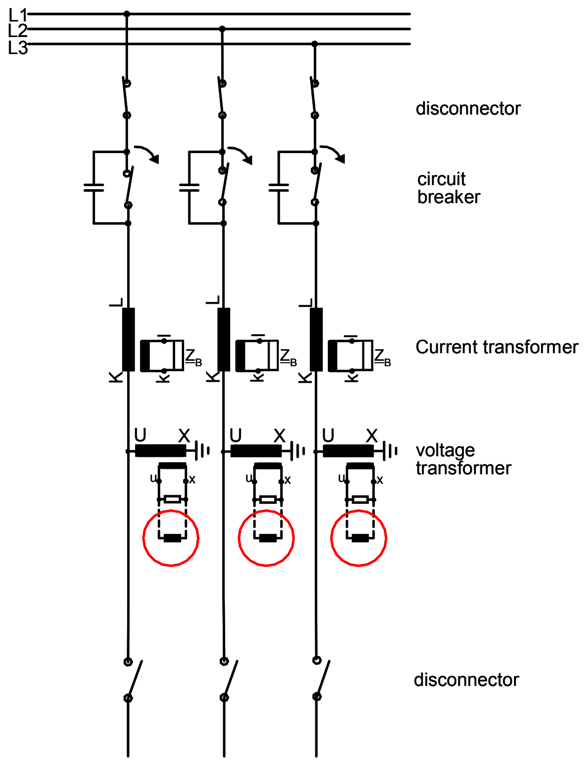
11.5.1 General

The following supplementary damping devices were successfully applied in high voltage sub stations.

Ferroresonance oscillations can occur in two different modes. Single-phase and three-phase ferroresonance have to be distinguished and to be treated in different ways.

11.5.2 Single-phase ferroresonance oscillations

For damping of single-phase-ferroresonance oscillations the damping device is connected to the secondary winding of each phase of the voltage transformer (Figure 34).



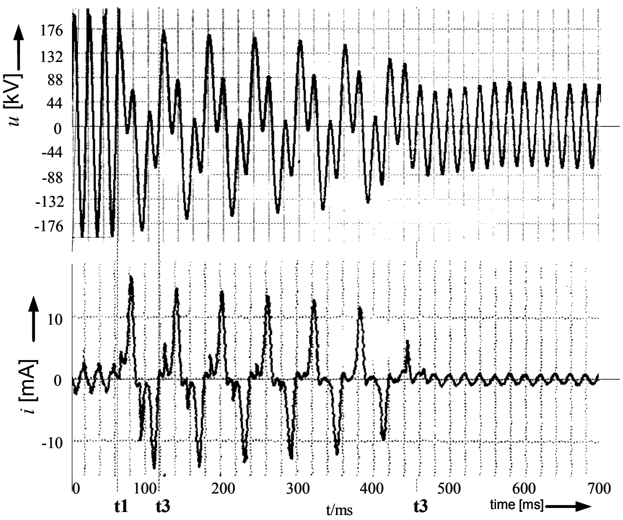
Reproduced from [18].

Figure 34 – Electrical circuit with damping device (red circles) connected to the secondary winding of the voltage transformer

The damping device can be built as:

- Resistors (linear or non-linear)
  The resistor has to be dimensioned to withstand the permanent operation conditions and additional the short time ferroresonance damping operation with adiabatic temperature rise.
- Saturable coils
  During normal operation this coil represents a low loss, during the ferroresonance oscillation the coil is going to saturation and represents high losses suitable to damp the oscillations. The dimensioning of the operational voltage of the coil shall be based on the specified voltage factor.
- Combination of resistors and coils
  During normal operation this coil and resistor represents a low loss, during the ferroresonance oscillation the coil is going to saturation and represents together with the resistor high losses suitable to damp the oscillations. The resistor is limiting the current through the coil. The dimensioning of the operational voltage of the coil and the resistor in series shall be based on the specified voltage factor.
- Coil in combination with a capacitor (tuned to the frequency of the ferroresonance)
  The coil and the capacitor are tuned to have a resonance frequency of the ferroresonance oscillation (e.g. $16^2/_3$ Hz, 10 Hz, $7^1/_7$ Hz). In case of oscillation the circuit is effectively damping them. For each frequency a separate circuit has to be connected.

An example of successful damping of single-phase-ferroresonance oscillations is shown in Figure 35.



Reproduced from [18].

Figure 35 – Example of successful damping of single-phase ferroresonance oscillations of $16^2/_3$ Hz

Advice:
With the damping device and the specified burden connected to the secondary winding, the accuracy requirements shall meet the specified values (IEC 61869-3:2011, 5.6)

It can often be successful to connect the voltage transformer with its nominal burden.

NOTE A practical solution is also to connect a damping devise in the open delta. It is mentioned that this solution will fail if all three phases show the same ferroresonance oscillations.

11.5.3 Three-phase-ferroresonance oscillations

11.5.3.1 General

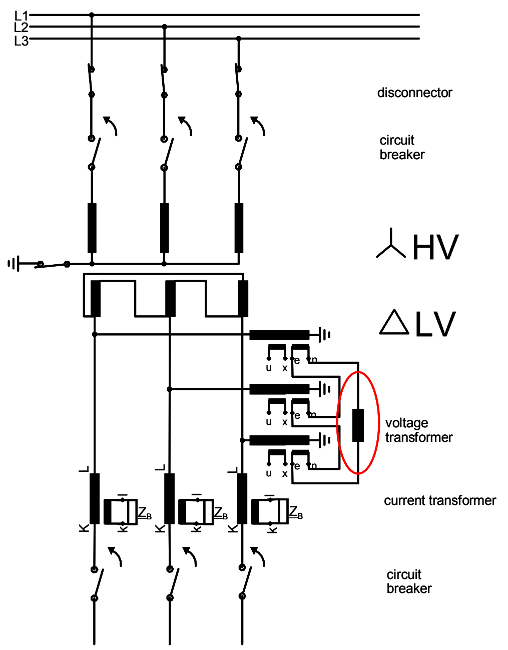
Damping of 3-phase-ferroresonance oscillations can be realised in the open delta connection of the voltage transformers in the feeder bay (Figure 36) or in the star point of the power transformer (Figure 37).

Advice:
In both cases it has to be considered that the special dimensioned damping device has to withstand phase to earth failures in the grid (1,9 Un; 8 h).

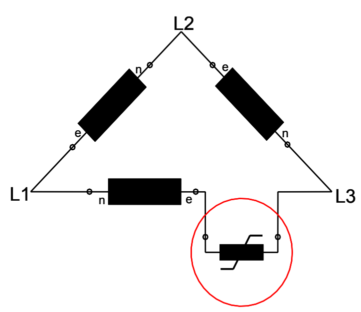
The economic efficiency, which alternative can be used is to be decided in each individual case.

11.5.3.2 Damping in the open delta connection of the voltage transformer

An often used method to damp three phase ferrresonance is to connect a special dimensioned damping device (see 10.5.1) in the open delta connection of the voltage transformer.



a) damping of a three phase oscillation system



b) open delta connection of the secondary windings

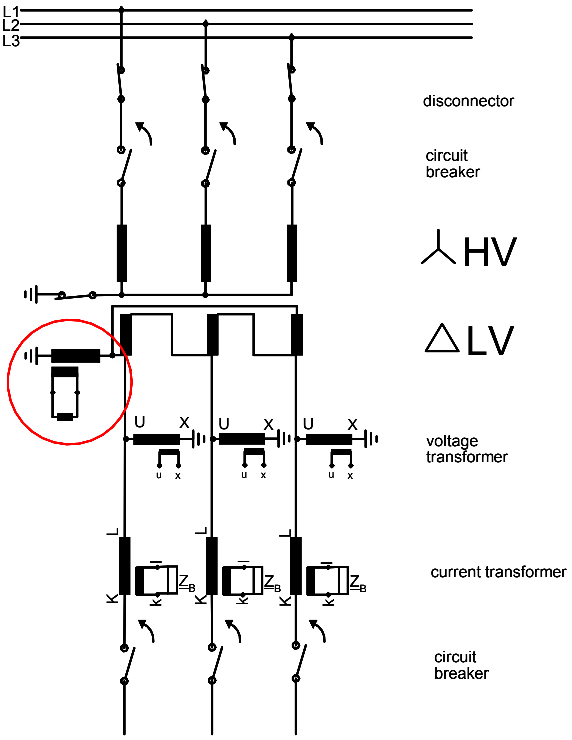
Reproduced from [18].

Figure 36 – Damping of the ferroresonance oscillation in the open delta connection of the voltage transformers in the feeder bay

11.5.3.3 Damping in the star point of the power transformer

An alternative damping measure can be used if voltage transformers in the feeder bay have no winding for open delta connection.

An additional voltage transformer is installed in the star point at the secondary side of the power transformer. Connected with a special dimensioned damping device ferroresonance oscillations can be suppressed (see Figure 37).



Reproduced from [10].

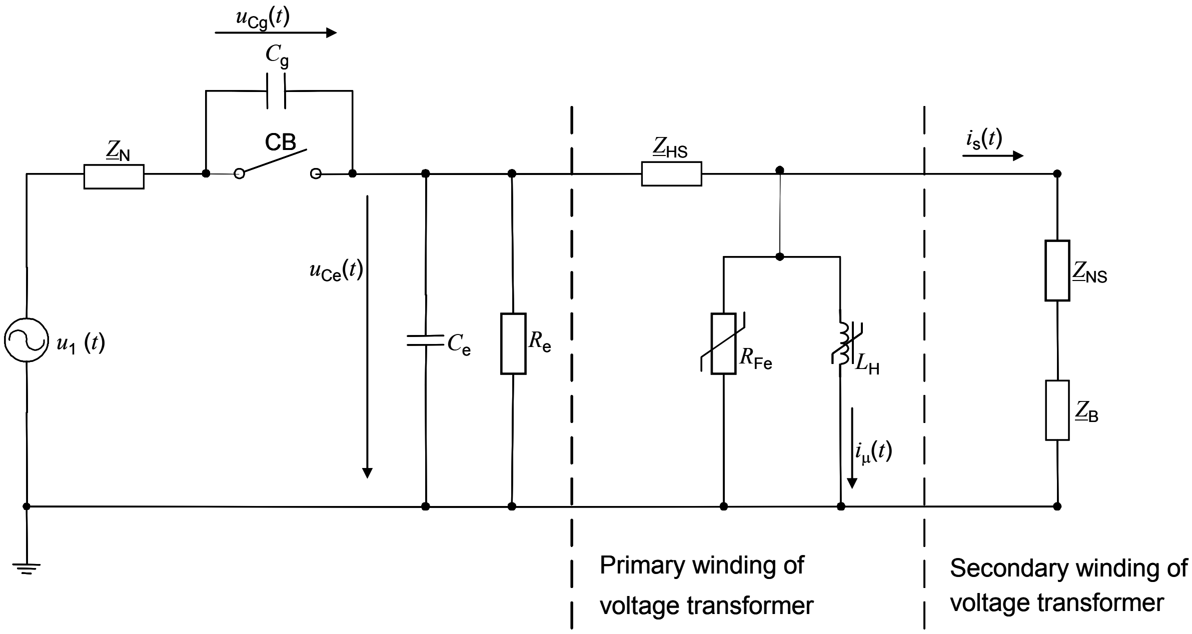
Figure 37 – Damping of ferroresonance oscillations with voltage transformer in the star point of the power transformer

Annex A
(informative)

Oscillations in non-linear circuits

A.1 Overview

The introduction of oscillations in non-linear circuits is restricted to single phase ferroresonance oscillations of the three phase networks with a solid earthed star-point connection. In Figure A.1 the simplified electrical circuit for the explanations and the calculation of single-phase ferroresonance is shown.



Key

CB	Circuit breaker
C_e	Total ground capacitance of facility (without the capacitance of the primary winding)
C_g	Grading capacitor capacitance of circuit breaker CB
$i_\mu(t)$	Current through non-linear main inductance
$i_s(t)$	Current through burden
R_e	Summary of ground-phase insulation resistances (insulating resistance internal to transformer, non-linear leakage resistance, e.g. on accountof currents in contaminated surfaces, corona currents and currentsfrom metal oxide leakage
R_{Fe}	Non-linear resistance representing iron losses
L_H	Non-linear main inductance
$u_1(t)$	Phase to ground voltage in front of the circuit breaker of the facility $\underline{Z}_B$ Impedance of the load resistance of secondary winding 1 (load resistance and inductance)
$\underline{Z}_{HS}$	Impedance of the primary winding (resistance and leakage inductance)
$\underline{Z}_N$	Network impedance
$\underline{Z}_{NS}$	Impedance of secondary winding (resistance and leakage inductance)
$u_{Ce}(t)$	Voltage across the earth capacitor C_e
$u_{Cg}(t)$	Voltage across the grading capacitor C_g

Reproduced from [10].

Figure A.1 – A simplified electrical circuit for the analysis of ferroresonance oscillation

Ferroresonance oscillations in substations are an excellent practical example to the topic of “forced oscillations in non-linear systems”. The term forced oscillations is the synonym for the sinusoidal excitation of non-linear systems with the network voltage.

$$U_1(t) = \hat{U}_1 \cdot \sin(\omega t + \varphi_S) \tag{A.1}$$

where ω is the angular frequency $\omega = 2\pi f_0$, f_0 is the network frequency and φ_S is the switching angle of the circuit breaker CB in Figure A.1.

The oscillograms in Figure 15 show the typical behaviour of a non-linear ferroresonance system, after switching operation with the circuit breaker CB.

It is evident, that the response of the system, oscillations in steady state conditions, depends on the initial values of the voltages $u_{Ce}(t = 0)$, $u_{Cg}(t = 0)$ and the currents $i_\mu(t = 0)$ (see Figure A.1), which are functions of the switching angle φ_s.

In case a) with the switching angle φ_s = 90° the initial values are: $u_{Ce}(t = 0) = \hat{U}_1$,

$$u_{C_g}(t = 0) = 0\,,\ i_\mu(t = 0) = i_{\mu 0} \text{ and } i_s(t = 0) = \frac{\hat{U}_1}{\underline{Z}_{NS} + \underline{Z}_B} \tag{A.2}$$

The storage energy in C_e, $$W_{C_e} = \frac{1}{2} C_e \hat{U}_1^2\,; \tag{A.3}$$

and in L_H, $$W_{L_H} = \frac{1}{2} L_H i_{\mu 0}^2\,. \tag{A.4}$$

With switching angle φ_s = 0° the initial values are: $u_{C_e}(t = 0) = 0$, $u_{C_g}(t = 0) = 0$, $i_\mu(t = 0) = i_{\mu 0}$ and $i_s(t = 0) = 0$

The storage energy in C_e, $W_{C_e} = 0$; and in L_H, $W_{L_H} = \frac{1}{2} L_H i_{\mu 0}^2$.

With the combination of measured oscillograms for ferroresonance oscillations in substations and the existing theory and knowledge of “forced oscillations of non-linear oscillating-systems” the following results are applicable for substations [10]:

1) An analytical solution regarding ferroresonance oscillations of the non-linear network is not possible.
2) No superimposition of transient and steady state measured and calculated voltage u_S(t) and $i_\mu(t)$ is possible.
3) Small deviations of parameters (values of the components in the schematic diagram Figure A.1) have a significant influence on the solution.
4) Numerical solutions with calculation software are a certain help for investigations regarding ferroresonance oscillations.
6) For a better technical appreciation of oscillations in non-linear systems a high number of mathematical approximation methods [19], [20] were developed, which were approved in laboratories and compared with numerical solutions.
7) In the mathematical treatment of non-linear systems the precise characterisation of the non-linear elements is crucial for a correct solution.

8) The results of experimental measurements in substations depend on the amplitude $\hat{U}_1$ of the line voltage $\hat{U}_1 \cdot \sin(\omega t + \varphi_S)$ and the switching angle φ_S (see Figure 15).

A.2 The simplification of non-linear electrical circuits with the theorem of Thévenin

The theorem of Thévenin is used for the simplification of networks for calculation and measurement. John L. Stewart's "Circuit Theory and Design" [17], clearly states that Thévenin's theorem is only applicable for linear networks. The term equivalent circuit is only used in this technical report, if the circuit is based on the application of Thévenin's theorem.

– The first IEC standardisation of capacitive voltage transformers (CVT) was integrated in IEC 60186 for inductive voltage transformers.
– In 1992 a separate standard for CVT, IEC 60044-5, was prepared.
– That standard IEC 60044-5 has been replaced in 2011 by the IEC standard IEC 61869-5.

IEC 60186, IEC 60044-5 and IEC 61869-5, standardising capacitive voltage transformers, apply Thévenin's theorem on the CVT, which is a non-linear system.

The two tests "ferroresonance" and "transient performance" can be carried out according to the three IEC standards on the complete CVT or with the "equivalent circuit".

The question is not solved, if Thévenin's theorem is also applicable to the linear part of the non-linear network.

A.3 The differential equation for ferroresonance oscillations

The following analysis is restricted to single phase ferroresonance oscillations. For this basic consideration regarding non-linear oscillations the schematic circuit in Figure A.1 is used.

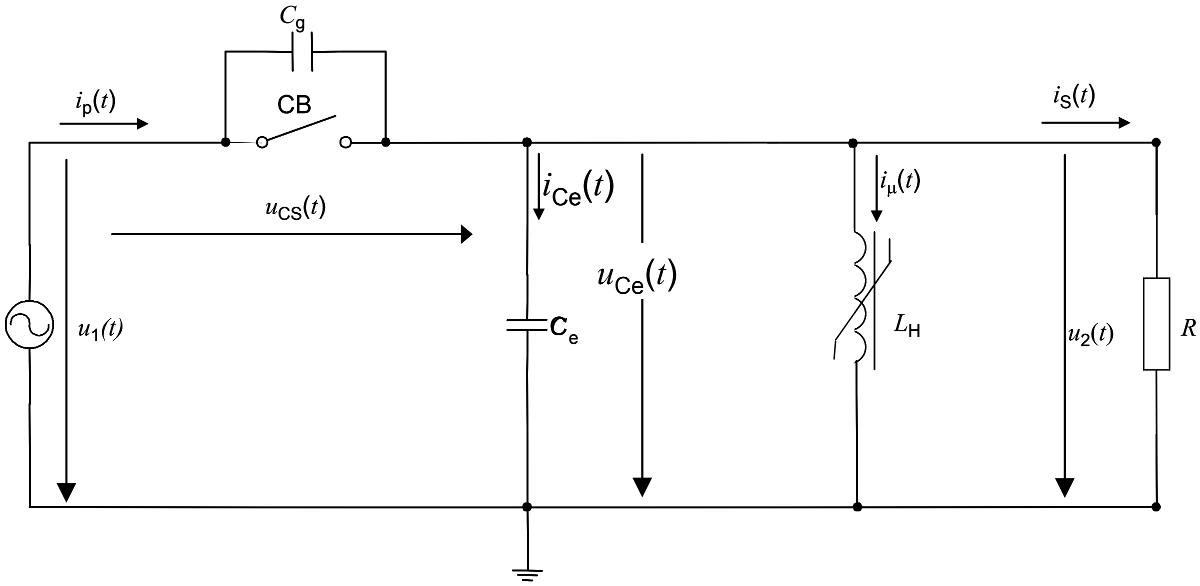
The experimental measurement of ferroresonance oscillations on models has shown, that the impedance $\underline{Z}_{HS} = R_{HS} + j\omega L_{HS}$ and $\underline{Z}_{NS} = R_{NS} + j\omega L_{NS}$ of inductive voltage transformers has only a small influence on the excitation of non-linear oscillations. For the first approximation the impedance $\underline{Z}_{HS}$ and the inductive part $j\omega L_{NS}$ are neglected.

With this simplification and shifting of R_e and the non-linear loss resistor R_{Fe} to the right side of the network, with $\underline{Z}_{NS} = R_{NS}$ and $\underline{Z}_B = R_B$, with the abbreviation

$$R = \frac{1}{\frac{1}{R_e} + \frac{1}{R_{F_e}} + \frac{1}{k^2(R_{NS} + R_B)}}, \text{ with } k = \frac{n_P}{n_S}, \quad \text{(A.5)}$$

(n_P is the number of turns of the primary winding and n_S is the number of turns in the secondary winding)

and a low network impedance $\underline{Z}_N = 0$ and a negligible primary impedance $\underline{Z}_{HS}$ the modified schematic diagram from Figure A.1 is plotted in Figure A.2:



Reproduced from [10].

Figure A.2 – Diagram for the derivation of non-linear differential equation of second order

The indications of ferroresonance are the waveforms of the primary voltage

$$k \cdot u_2(t) = \frac{n_P d\phi(t)}{dt} \tag{A.6}$$

and the current $i\mu(t)$ through the primary winding. $u_2(t)$ is measured on the secondary terminals of the inductive voltage transformer (see Clause 10).

The unknown quantity of the differential equation is

$$u_{C_e}(t) = \frac{d(n_P \cdot \phi(t))}{dt} = \frac{d\psi(t)}{dt}. \tag{A.7}$$

In the following the derivation of the differential equation is valid for steady state conditions with open circuit breaker. The following equation follows from Figure A.2:

$$\hat{U}_1 \cdot \sin(\omega t + \varphi_S) = \frac{1}{C_g}\int i_P dt + \frac{d\Psi}{dt} \tag{A.8}$$

$$i_{C_e}(t) = C_e \frac{d}{dt}(\frac{d\Psi}{dt}) \tag{A.9}$$

where $\Psi = n_P \cdot \Phi$.

The magnetisation curve is approximated with three terms of an infinitive series. For symmetry reasons only odd exponents occur

$$i_\mu(t) = A_1 \cdot \Psi(t) + A_3 \cdot \Psi^3(t) + A_5 \cdot \Psi^5(t) \tag{A.10}$$

With the dimensions of A_1 [A/Vs], A_3 [A/(V^{3}s^3)], A_5 [A/(V^{5}s^5)]

$$i_S(t) = \frac{1}{R} \cdot \frac{d\Psi}{dt} \tag{A.11}$$

$$i_P(t) = i_{C_e}(t) + i_\mu(t) + i_S(t) \tag{A.12}$$

The differential equation is given:

$$\frac{d^2\Psi}{dt^2} + \frac{1}{R(C_g + C_e)} \cdot \frac{d\Psi}{dt} + \frac{A_1}{C_g + C_e} \cdot \Psi + \frac{A_3}{C_g + C_e} \cdot \Psi^3 + \frac{A_5}{C_g + C_e} \cdot \Psi^5 = \frac{C_g}{C_g + C_e} \cdot \hat{U}_1 \omega \cos(\omega t + \varphi_1) \tag{A.13}$$

The name of this differential equation, without the term $A_5(\Psi^5)$ is the extended Duffing-Equation with damping term $\frac{1}{R(C_g + C_e)} \cdot \frac{d\Psi}{dt}$ [21]. (A.14)

A.4 Oscillation frequencies in ferroresonance systems

Measurements of single-phase ferroresonance oscillations in substations have indicated, that only the following frequencies were observed, if the excitation is the network frequency f_0:

a) Network oscillation frequency: f_0/1 = 50 Hz (60 Hz)

b) Subharmonic oscillation frequencies: f_0/3 = 16 2/3 Hz (20 Hz)

c) Subharmonic oscillation frequencies: f_0/5 = 10 Hz (12 Hz)

The solutions S_1(t), S_3(t), S_5(t) …. S_{2n+1}(t) of the non-linear differential equation (A.13) in case of forced oscillations with the network frequency f_0 = 50 Hz (60 Hz) are described in [10]. In a simple block diagram (see Figure A.3) forced oscillations of the non-linear system is plotted

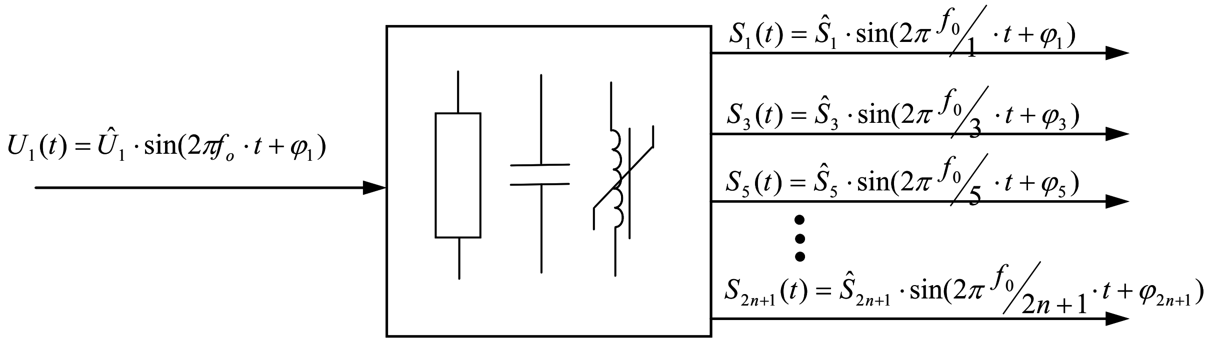


Figure A.3 – A non-linear oscillation system

Questions regarding the stability of the steady state oscillation solutions $S_1(t)$, $S_3(t)$,… $S_{2n+1}(t)$ and their combinations are described in [10].

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1 Withdrawn.

2 Withdrawn.

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