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TECHNICAL REPORT

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inside

Instrument transformers –
Part 102: Ferroresonance oscillations in substations with inductive voltage transformers

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

INSTRUMENT TRANSFORMERS – PART 102: FERRORESONANCE OSCILLATIONS IN SUBSTATIONS WITH INDUCTIVE VOLTAGE TRANSFORMERS

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IEC 61869-102, which is a technical report, has been prepared by IEC technical committee 38: Instrument transformers.

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
38/440A/DTR	38/445/RVC

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all the parts in the IEC 61869 series, published under the general title *Instrument transformers*, can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

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INTRODUCTION

During the last twenty years ferroresonance oscillations in substations with inductive voltage transformers according to IEC 61869-3 or with combined transformers according to IEC 61869-4 were discussed in the international Cigré working groups and in IEEE committees in the US.

The results were published in Cigré [1] technical report or IEEE [2] publications.

The reasons for these publications were the more frequent occurrence of ferroresonance oscillations in substations. As a consequence of the price pressure on the operating authorities and the component manufacturers such as instrument transformers, power transformers and grading capacitors for high-performance circuit breakers have led to an increasingly higher exploitation of the system and components.

This trend results in:

a) the shift from normal rated voltage U_{pr} in the direction of the maximum permitted highest voltage for equipment U_{m} (IEC 60071-1 [3]);

b) increasing the flux density $\vec{\hat{B}}$ by reducing the cross-section of the core of the inductive voltage transformer;

c) the reduction of the substation capacitance by using new components (e.g. MV and HV instrument transformers) leads to an increase of the excitation-voltage for the non-linear circuits;

d) reduction of the actual burden in the substation by using digital meters and relays with burden of approximately 1 VA, while still specifying the high nominal burden (50 VA to 400 VA) for the inductive voltage transformer. However, even these higher burdens are often not sufficient to prevent ferroresonance oscillations.

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PART 102: INSTRUMENT TRANSFORMERS – 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*

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3 Introduction to ferroresonance oscillations

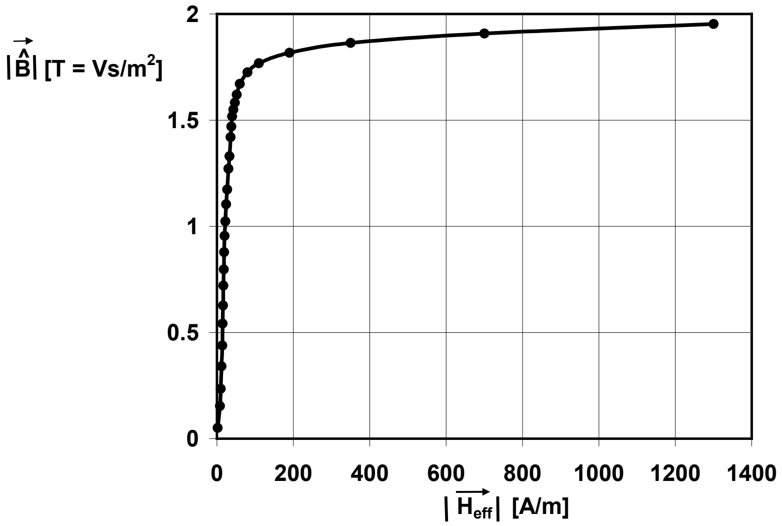
3.1 Definition of ferroresonance

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 $\vec{B}_{\mathrm{S}}$. If inductive voltage transformers are magnetised over their saturation flux density, the relationship between the magnetic field strength $\vec{H}_{\mathrm{eff}}$ 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.



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Key

$\left\lvert\hat{\vec{B}}\right\rvert$	Peak value of flux density in the iron core
$\left\lvert\vec{H}_{\text{eff}}\right\rvert$	Effective value of magnetic field strength in the iron core

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

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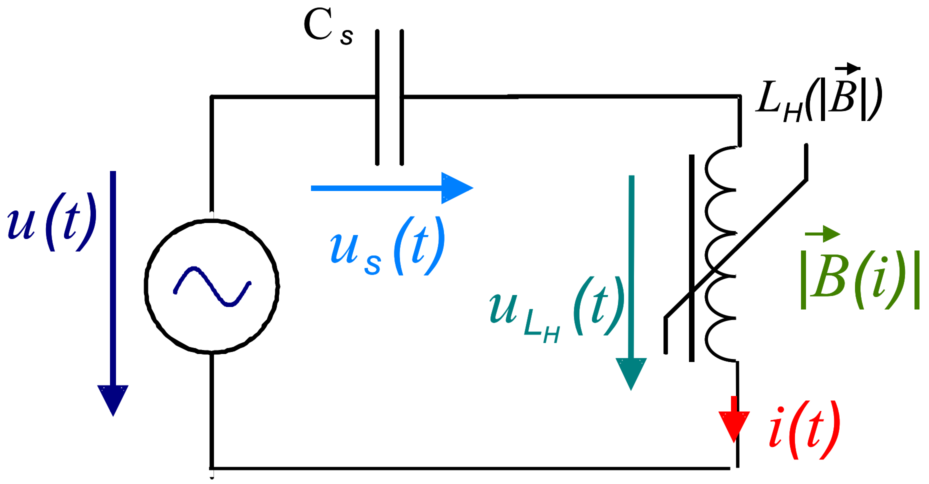
Figure 1 – Example of a typical magnetisation characteristic of a ferromagnetic core



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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
$\left\lvert\vec{B}\right\rvert(i(t))$	Flux density as function of the current i(t)
$L_H(\left\lvert\vec{B}\right\rvert)$	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.

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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.

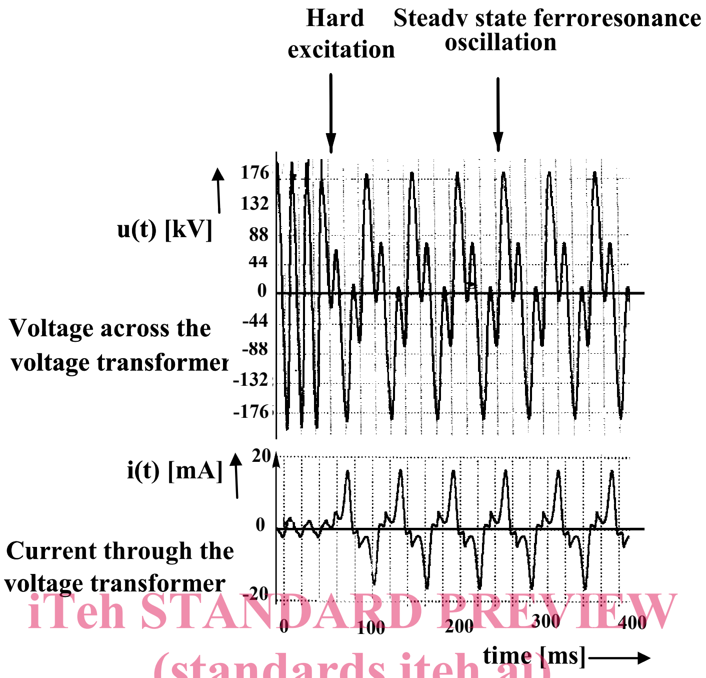
However, ferroresonance is in most cases caused or "triggered" as a result of a switching transient through which the core becomes saturated ("hard excitation").

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.



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

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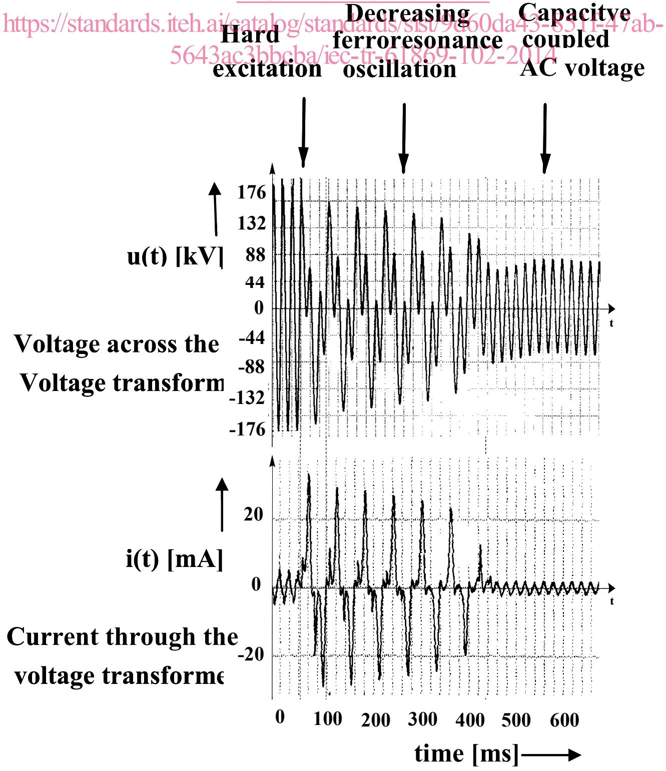

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b) Single-phase decreasing ferroresonance oscillations, type 2c according to Table 1

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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.

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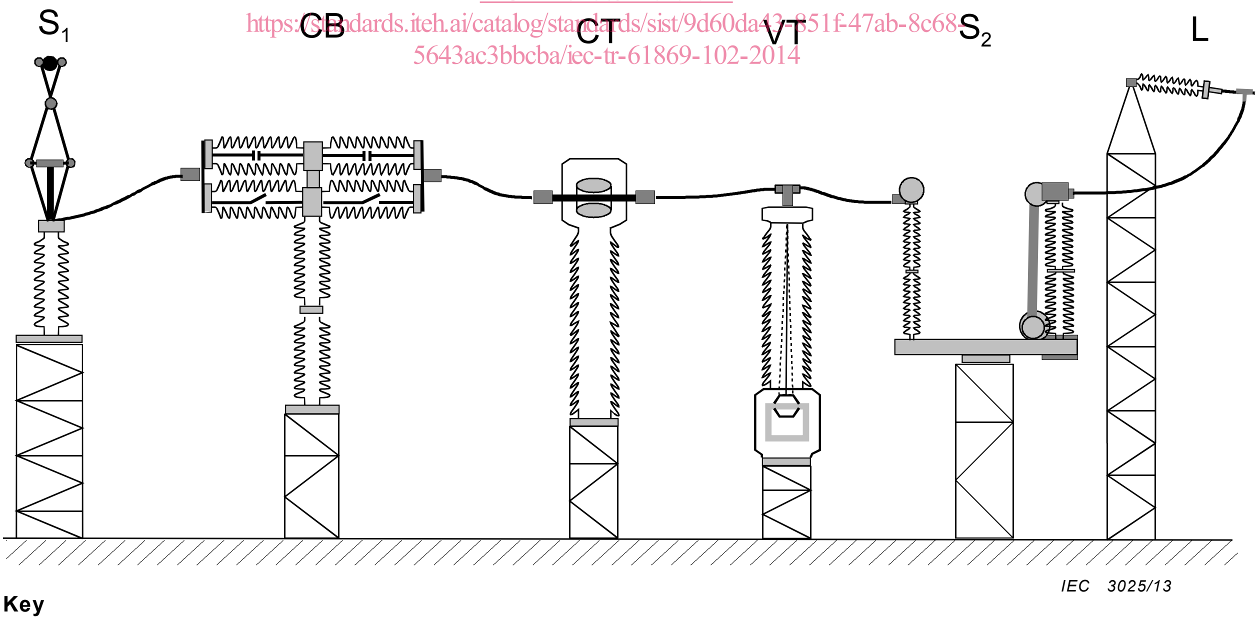


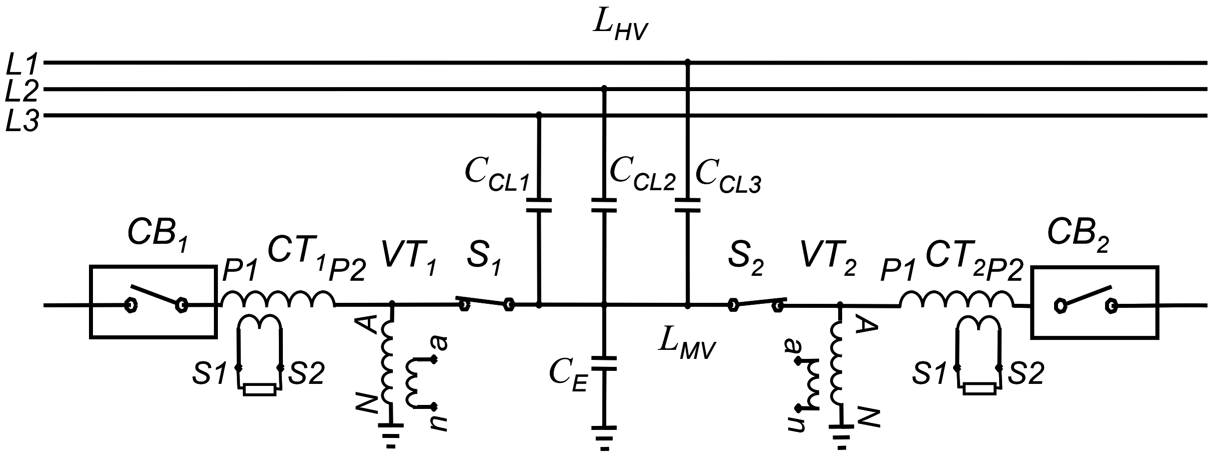
Key

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

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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.