Ironing out resonance

Ferroresonance prevention in MV voltage transformers

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Every engineer knows the phenomenon of resonance. Without it, there would be no musical instruments, no radio-based communication and many natural phenomena, ranging from the astronomical to the sub-atomic would not occur. The occurrence is not always benign: Oscillations can reach amplitudes for which the system was not designed, leading to damage and failure. In 1940 the Tacoma Narrows Bridge in the USA collapsed spectacularly as the result of undamped resonance. Resonance is also a frequent cause of malfunction in electronic systems.

Fortunately, the frequencies at which resonance occurs can be influenced by design. The calculation of resonance gets trickier for non-linear effects: When the magnetic flux in a core (of for example, a transformer) exceeds a certain value, resonance becomes much more difficult to predict. Such occurrences are frequent in the voltage transformers (VT) that transform high and medium voltage levels into low voltage for instrumentation or protection purposes.

The rated power of voltage transformers (VTs) is usually very low due to their metrological, rather than power supply function. Nominal primary currents in the transformer winding are typically of the order of single milliamps (at several up to tens of kilovolts).

The so-called ferroresonance phenomenon can occur when VTs are connected phase to ground in an ungrounded network. Currents can occur that exceed nominal values by orders of magnitude, risking damage to the VTs.

The ferroresonance phenomenon

The resonance of a circuit containing an inductance and a capacitance is a well known physical phenomenon. The simplest forms of this are the parallel and the series resonant circuits 1.

In the series circuit, the equivalent impedance is the sum of the impedances of the individual components:

$$Z(\omega) = j\omega L - j\frac{1}{\omega C} + R_s$$

In the parallel resonant circuit the equivalent admittance is the sum of the admittances of the individual components:

$$Y(\omega) = j\omega C - j\frac{1}{\omega L} + \frac{1}{R_P}$$

The resonance pulsation is

$$\omega_r = \frac{1}{\sqrt{LC}}$$

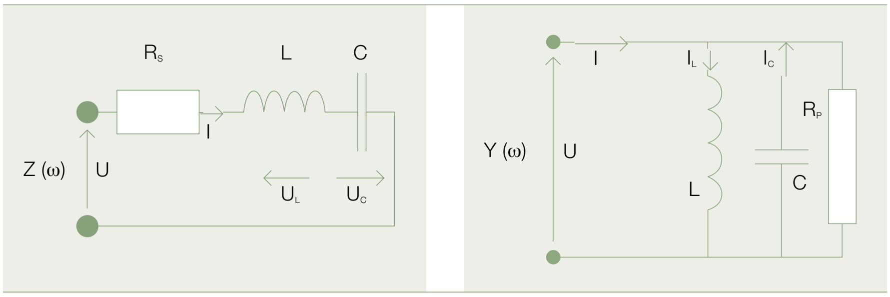
in both cases. At and near to this frequency in the series circuit, voltages across the capacitor and the inductance can reach values that exceed the source voltage significantly. In the parallel circuit, it is the currents through these components that are similarly amplified. Such extreme values can damage the equipment if no remedial action is taken.

For known values of L and C, the resonant frequency can be predicted. Resonance-related hazards can be avoided by maintaining an appropriate safety margin from the power-supply frequency.

1 Series and parallel linear resonant circuits.

Series resonant circuit

Parellel resonant circuit



In the so-called ferroresonance phenomenon, however, resonance frequencies are more difficult to predict. The phenomenon occurs when the magnetic core of an inductive device is saturated, making its current-flux characteristic non-linear 2. Because of this non-linearity, resonance can occur at various frequencies.

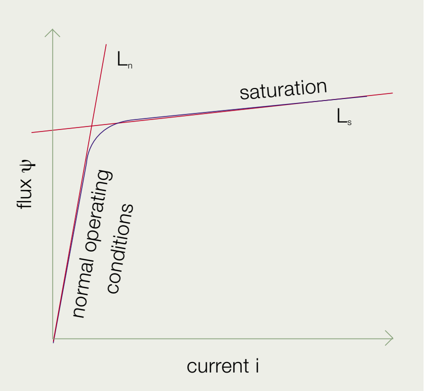
In practice, ferroresonant oscillations are initiated by momentary saturation of the core of the inductive element as a a result of switching operations, for example. The effects of such resonance are further aggravated if damping is insufficient.

Currents can occur that exceed nominal values by orders of magnitude, risking damage to the VTs.

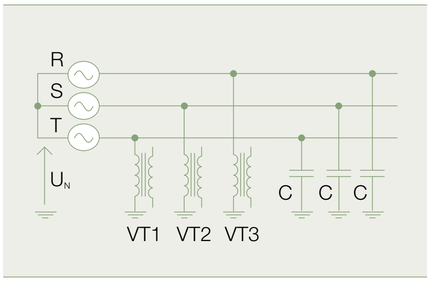
In many cases of non-transient resonance involving a saturated inductive element, some nodes in the equivalent network circuit are electrically floating (or connected to the fixed potential points through very high impedances). Such a situation is illustrated in the network of 3.

Although ferroresonance can also be initiated in other situations (eg, capacitive coupling between parallel lines, ferroresonance between the VT and the power transformer's internal capacitance or single-phase disconnection in grounded networks) the configuration shown in 3 reflects a typical unearthed distribution system with single-pole VTs.

2 Non-linear characteristic of an inductive component with a saturable magnetic core.



3 Ungrounded MV network with three single-phase voltage transformers connected phase-to-ground.



4 The result of the ferroresonance in unprotected VT.

Despite first publications on the ferroresonance phenomenon appearing at the beginning of the 20th century, no reliable criteria on the risk of ferroresonance have been formulated to this day. No universally applicable mitigation methods exist other than a damping resistor connected to the open-delta auxiliary windings of the three individual VTs.

The compact design of modern voltage transformers and the high quality of the magnetic material (low losses) makes damping difficult.

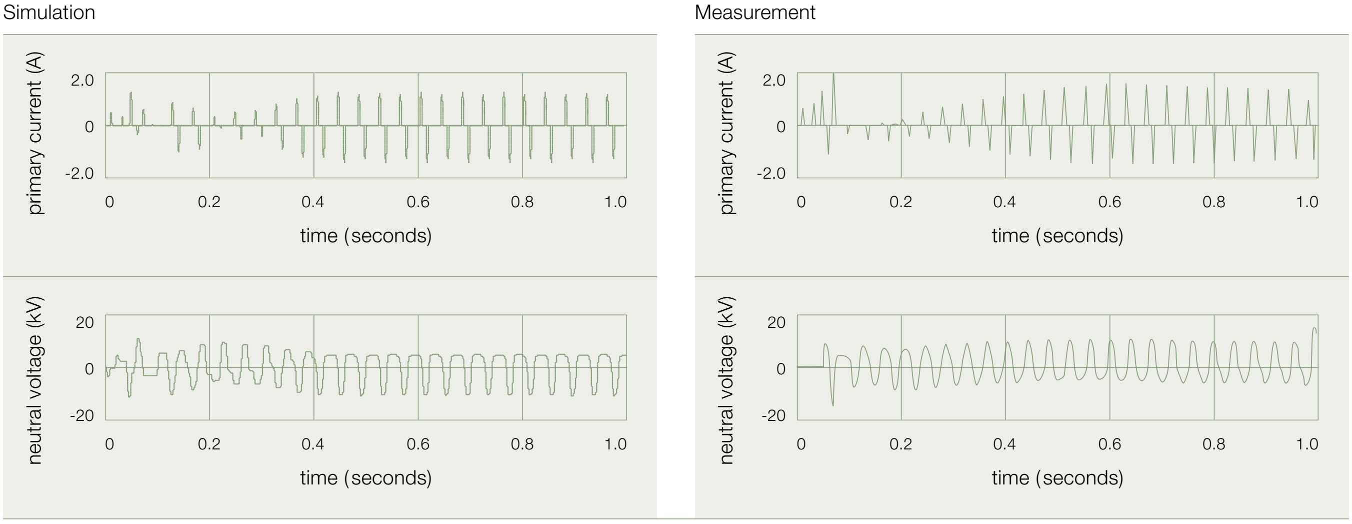
Risk to equipment

Under normal operating conditions, the primary currents in the MV voltage transformers are typically well below 10mA. In ferroresonance, the core of the VT operates in the deep saturation region and primary currents can reach amp values. The two order of magnitude difference between normal and ferroresonant conditions leads to thermal damage to the primary winding if not appropriately damped 4.

The compact design of modern voltage transformers and the high quality of the magnetic material (low losses) makes damping difficult. The resistive load must have a low value to dissipate sufficient oscillation energy. Too small a value, however, draws too much power from the VT when a sustained zero-sequence voltage occurs (eg, due to a ground fault that is not cleared), and so overloads the VT thermally. Selecting the right resistance is therefore crucial.

5 Simulated and experimentally obtained primary VT current and neutral voltage for capacitance C within the hazardous range.

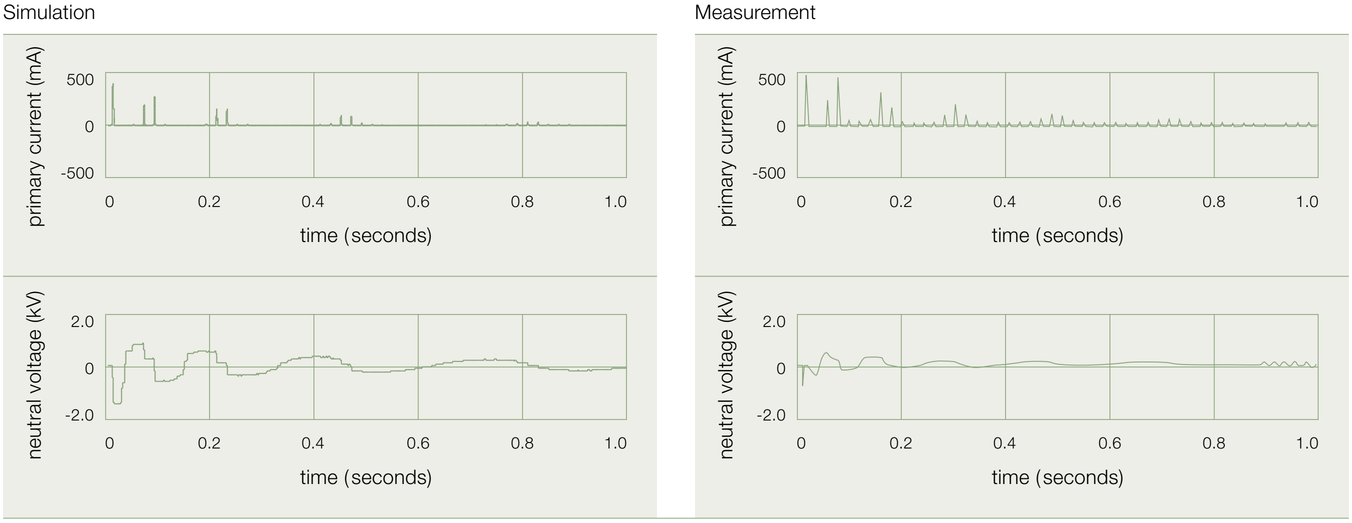
System voltage 20 kV/$\sqrt{3}$, C=70nF/phase


Simulation

Measurement

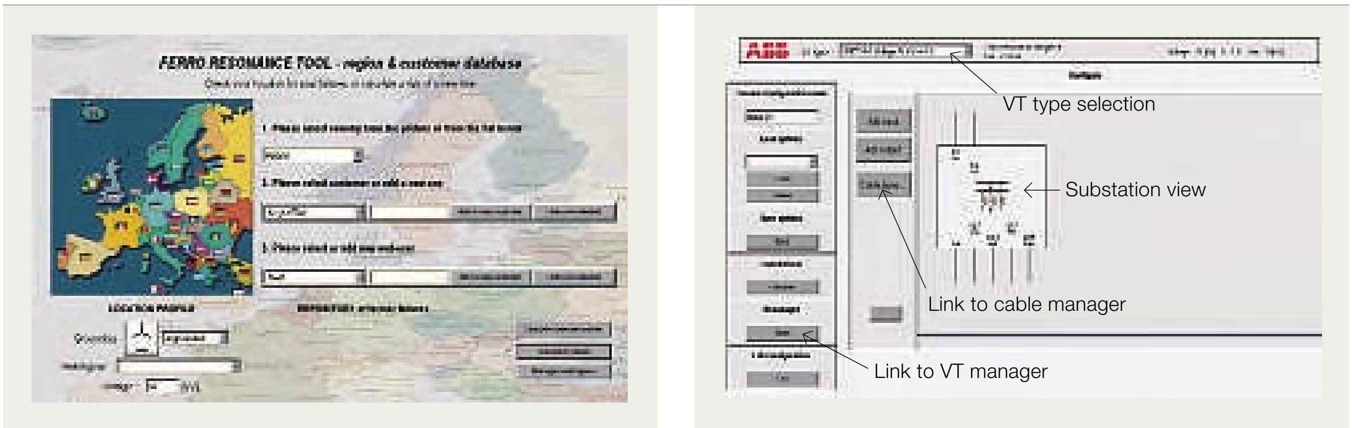
6 Simulated and experimentally obtained primary VT current and neutral voltage for capacitance C above the hazardous range.

System voltage 20 kV/$\sqrt{3}$, C=240nF/phase


Simulation

Measurement

7 FerroTool for potential ferroresonance risk identification for particular network VT configuration.



Analysis of potential ferroresonance

To analyze the network conditions for which ferroresonance is initiated in particular VT types, simulations were performed using dedicated transient simulation software (PSpice, ATP/EMTP). Simulating transient responses to switching events involved making models of various VT types, based on magnetic parameters. These models were inserted into an equivalent network model with ungrounded voltage sources and line-to-ground capacitances. A worst-case analysis of the unloaded network was performed to determine the capacitance range in which hazardous ferroresonance occurs. Including the auxiliary windings and damping resistors in the models helped identify the optimal resistor values.

FerroTool contains a database mapping VTs to their parameters, including hazardous capacitance ranges and suggested damping resistances.

Simulation results were verified experimentally. 5 shows a switching response with ferroresonant oscillation and 6 shows a response without.

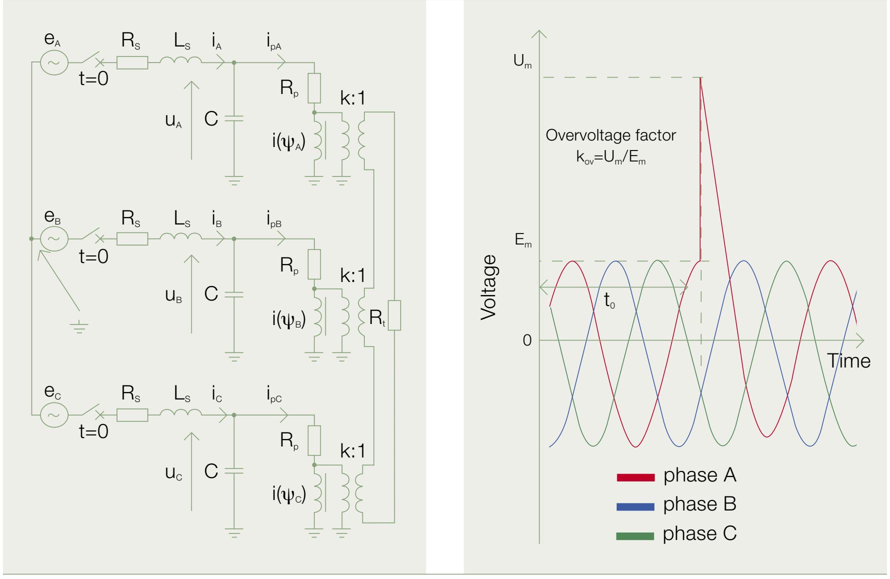
FerroTool and FerroSim

The simulations identified the hazardous capacitance range and the maximum damping resistance for different VT types and voltage levels. To make full use of these results in practical applications, software tools were implemented for the fast identification of potential ferroresonance. FerroTool 7 contains a database mapping VTs to their parameters, including hazardous capacitance ranges and suggested damping resistances. The tool calculates equivalent capacitance values for substations based on the line characteristics to permit fast analysis of the risk of ferroresonance.

Computer simulations and experiments show that in many cases the resistance needed to damp ferroresonant oscillations is very small. Such a resistor would, however, draw too much current from the VT in the case of a network asymmetry.

FerroTool is supported by the FerroSim dedicated software for simulating a network response to switching transients 8. As the topology of the circuit is predefined, the user interface is kept very simple 9.

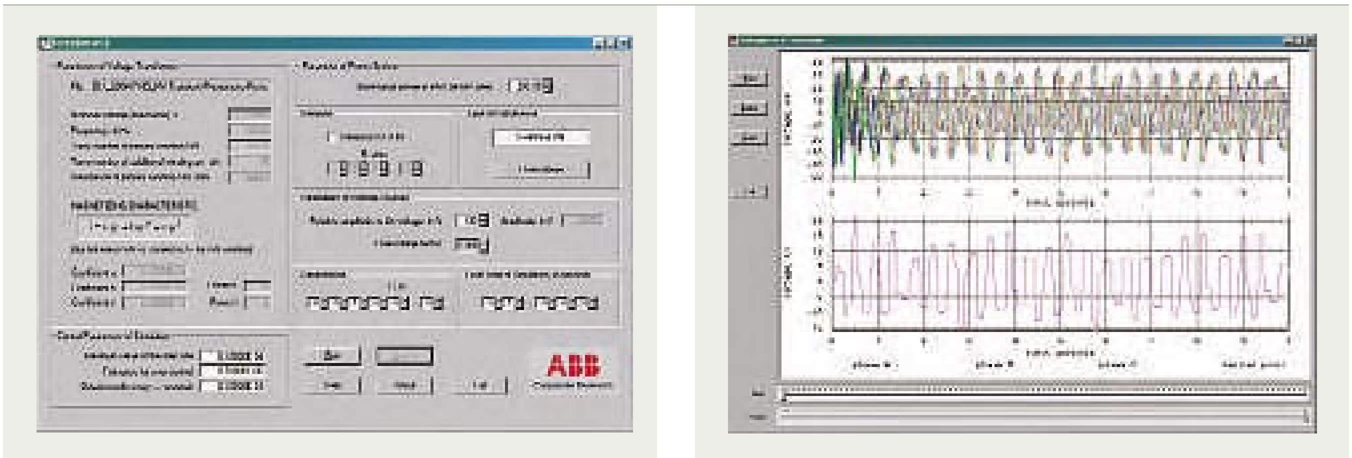
8 Predefined circuit model and stimulus.



VT Guard: New ferroresonance prevention concept

Computer simulations and experiments show that in many cases the resistance needed to damp ferroresonant oscillations is very small (<20 W).

9 User interface of the FerroSim and exemplary results showing the primary VT currents and the neutral voltage.



Such a resistor would, however, draw too much current from the VT in the case of a network asymmetry. A new and unique protection approach has been developed by ABB: A two-terminal element named VT Guard takes the place of the conventional linear resistor.

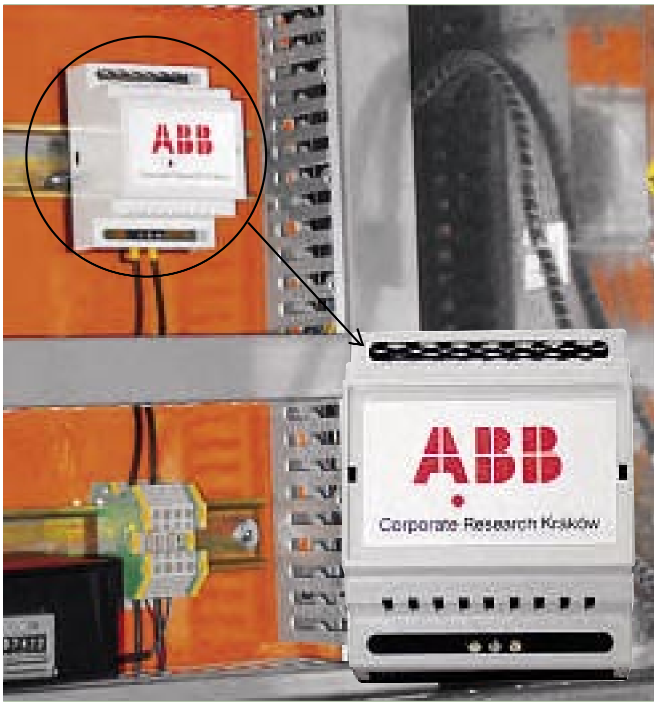
The VT Guard protects against thermal overload and can be used for practically any type of IEC-standard inductive MV voltage transformer.

When zero-sequence voltage occurs due to a natural system unbalance under normal operating conditions, the device acts as a very high resistance and so does not drain power from the VTs. When the zero-sequence voltage exceeds a predefined threshold level, however, the device's ohmic value drops sufficiently to dampen oscillations within a small number of cycles. A device has been created that efficiently dampens ferroresonant oscillations without overloading VTs. The device is very compact and can be mounted on a standard DIN-rail in the secondary equipment cabinet 10.

Conclusions

Inductive voltage transformers operating in ungrounded networks must always be protected against ferroresonance. Ferroresonant oscillations exceeding the nominal values by orders of magnitude pose a serious risk to VTs. Resistive damping is not always viable because the low ohmic value this requires overloads the VT. ABB's novel solution is a self-adjusting load which practically eliminates the risk of thermally overloading of VT in case of non-transient faults in the system. The VT Guard can be used for protecting practically any type of IEC-standard inductive MV voltage transformer.

10 Pilot installation of the VT Guard.



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