



Surviving a strike

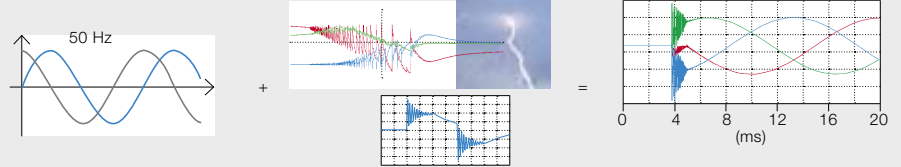
ABB helps distribution transformers survive rapid voltage transients

WOJCIECH PIASECKI, MAREK FLORKOWSKI, MAREK FULCZYK, PAWEŁ KŁYS, EGIL STRYKEN, PIOTR GAWĄD – A lightning strike is not a pleasant experience under any circumstances. For electrical equipment it is not just the voltage peak that can cause damage, but also the sudden and rapid voltage rise. In some cases the voltage transients are far steeper than those that occur in typical situations covered by common standards – they can surge by megavolts in the space of microseconds. The insulation covering the windings of transformers and motors is not normally designed for such

transients and can suffer permanent damage if no additional protection is used. Studies show that despite each piece of equipment being designed to withstand typical surges, as many as 35 percent of total dielectric failures in power equipment may be caused by such surges [1]. One solution is to totally redesign equipment to better cope with such transients. A simpler approach involves adding a component that protects the equipment from surges without affecting normal everyday operation. ABB has developed precisely such a component.

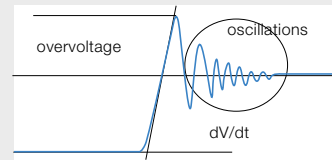
Transients in power networks are consequences of:

- External events (eg, lightnings)
- Events within power networks (switching, faults)



Fast and very fast transients affect the equipment by:

- Overvoltages
- High dV/dt
- High frequency oscillations



Transients in power networks result in overvoltages and oscillations superimposed on the phase voltages and currents.

The high-frequency components in the spectrum of a voltage surge → 1 result in a highly non-uniform voltage distribution. This causes local stresses on the insulation system, going far beyond those encountered during normal operating conditions. Furthermore, the complicated internal structures of electric apparatus can act as multiresonant circuits. High frequencies can therefore additionally cause local amplification. The resulting stresses on the insulation system can significantly compromise the equipment's lifetime, and often leads to internal short circuits.

The voltage impulse the insulation material can withstand strongly depends on the impulse rise time. This is normally taken into account when choosing insulation for electric motors. Of special concern is dry type insulation on rotating electric machines when these machines are fed by drives that use solid-state switching devices at high frequency. Manufacturers of such machines often provide guidelines regarding the limits of surge voltage amplitudes and corresponding front times. Of special concern are surges whose rise time is typically below $1\mu s$ [2], resulting in a nonlinear initial voltage distribution along the winding. This initial uneven voltage distribution produces high-voltage insulation

stress and can lead to breakdowns, corona and partial discharges → 2.

The increasing demand for a higher withstand level is also observed in distribution transformers. This is being met by nonconventional designs of windings that are increasing both design and manufacturing costs. Of special concern are transformers exposed to frequent atmospheric discharges. Operators of such networks often request compliance with a highly demanding norm, requiring the testing of transformers with a steep-fronted impulse. The Finnish standard SFS 2646 prescribes a voltage rise (dV/dt) of $2 MV/\mu s$ [3]. This norm requires that the transformer should be protected against overvoltages by a spark gap in its proximity. As a spark gap is relatively slow to react, the voltage at the transformer terminals may (under test conditions) rise to levels largely in excess of the basic insulation level (BIL) determined by the operating voltage of the equipment. In addition, the high dV/dt of the waveform results in a highly nonlinear initial voltage distribution in a conventional winding, leading to local overstressing of the insulation system → 3. Experimental results confirm this and indicate that a spark gap may not provide sufficient protection for distribution transformers [4] of standard design.

The common solution is to apply a special winding design comprising additional elements (electrostatic screens) equalizing the initial potential distribution. Such a solution helps avoid local overstressing of the insulation by high dV/dt values, but it adds complexity to both the design and the manufacturing process of the transformer. Furthermore, the peak overvoltage nevertheless reaches the transformer winding and thus the insulation must be dimensioned to withstand overvoltages in excess of the standard BIL.

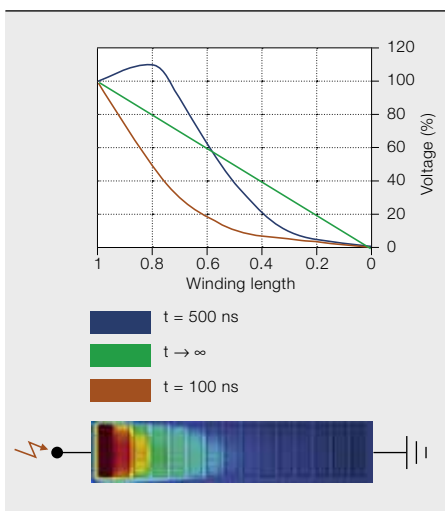
SmartChoke – series-impedance-based protection

ABB has developed an alternative to such a special transformer design by providing a series-connected filtering element (referred to as a choke) upstream of the protected equipment. The basic principle of the series element is to provide an appropriate impedance-frequency characteristic → 4. This makes the

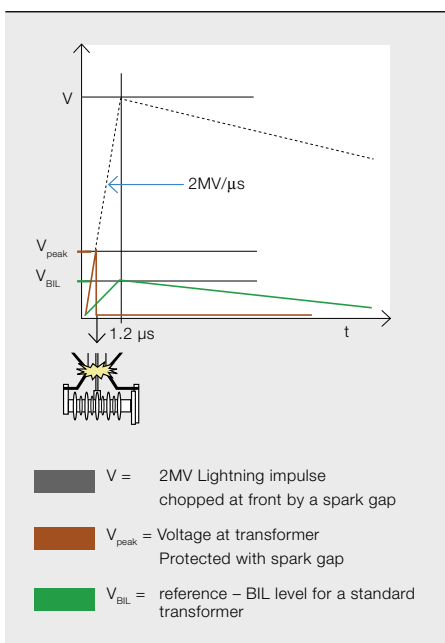
Of special concern are surges, whose rise time is typically below $1\mu s$, resulting in the initial voltage distribution along the winding being nonlinear.

device practically transparent at 50 or 60 Hz while suppressing very high frequency components.

2 Initial, nonlinear distributions of electrical potential along the transformer winding

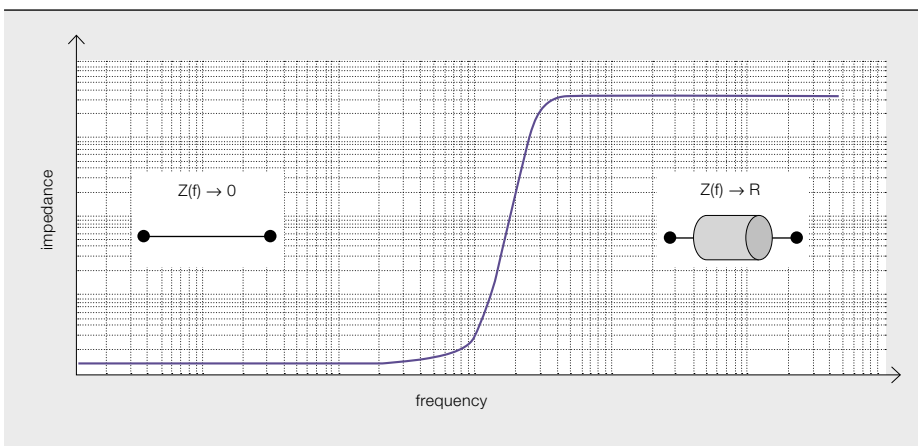


3 Impact of a front-chopped lightning surge on a transformer



The standard BIL waveform (green line) is a reference.

4 Idealized representation of the frequency characteristic of the impedance of the series choke



Experiments have demonstrated the effectiveness of this method in reducing the dV/dt resulting from transients associated with reignitions and prestrikes in a circuit breaker. The externally installed series choke element combined with a small shunt capacitor reduced dV/dt to a safe level and also eliminated the high-frequency oscillations that would otherwise have followed such a transient [5].

The successful mitigation of switching-induced dV/dt transients raised the question of whether a similar approach could be used to mitigate the lightning-induced chopped dV/dt transients to which pole-mounted distribution transformers are frequently exposed. Furthermore, ABB sought to integrate the device within the transformer itself.

The series choke element can be regarded as an alternative to specially designed winding described above that uses electrostatic screens for the equalization of potential distribution at high frequencies. The series choke element forms a low-pass filter when combined with the self capacitance of a transformer (at high frequency the transformer winding's characteristic can be represented by its surge capacitance). This capacitance varies depending on the type and size of the device. For oil-filled transformers it can be between a single and a few nanofarads per phase.

The frequency response of such a filter can then be optimized by appropriate selection of the R and L parameters. It must furthermore be ensured that the choke behaves correctly under normal operating conditions and is able to withstand the short-circuit test.

Depending on the relation between the R , L , and C values, the circuit response can be either aperiodic, or it can additionally contain oscillatory components. If the resistance value is lower than the critical value R_c , the periodic terms are equal to zero and the output voltage is a combination of exponential functions.

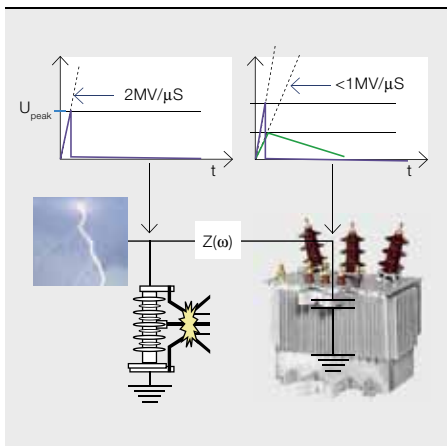
Therefore, selecting an appropriate value for the damping resistance is extremely important in order to achieve the highest possible reduction in dV/dt , while still preventing overshoots and oscillations of the voltage downstream of the choke element → 5.

In this approach, the capacitance C is the equivalent phase-to-ground capacitance of the transformer. Since, as mentioned above, the limits of this capacitance are known for a given class of transformer, the optimization of the R

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5 Concept of series device protecting the distribution transformer against high dV/dt



6 Transformer bushing with integrated SmartChoke filter

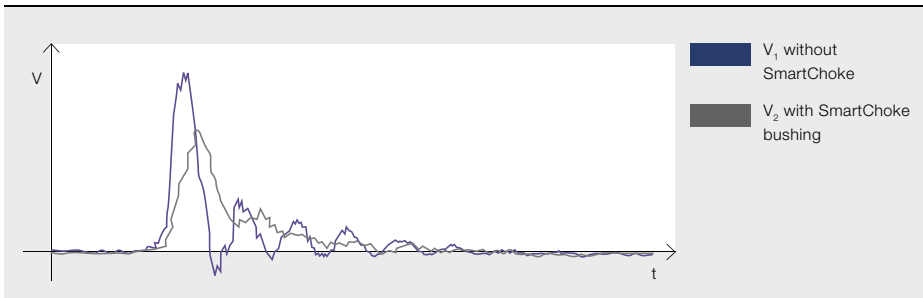


and L values can be achieved to cover all typical transformers of a certain category. Considering the idealized situation of → 3, in which a 2 MV lightning impulse is chopped with a spark gap, the unprotected equipment (eg, pole-mounted transformer) would experience the phase-to-ground voltage at a peak above 270 kV (characterized by a dV/dt of 2 MV/μs). With the series choke element installed upstream of the protected device, the dV/dt is not only lower, but the peak value of the voltage surge reaching the transformer is also reduced.

SmartChoke-protected transformer

The described series choke element concept has been implemented in new ABB distribution transformers, giving them a superior protection against high

7 Experimentally measured reduction in the overvoltage and dV/dt



Selecting an appropriate value for the damping resistance is extremely important in order to achieve the highest possible reduction in dV/dt.

8 SmartChoke-protected, high dV/dt resistant transformer by ABB

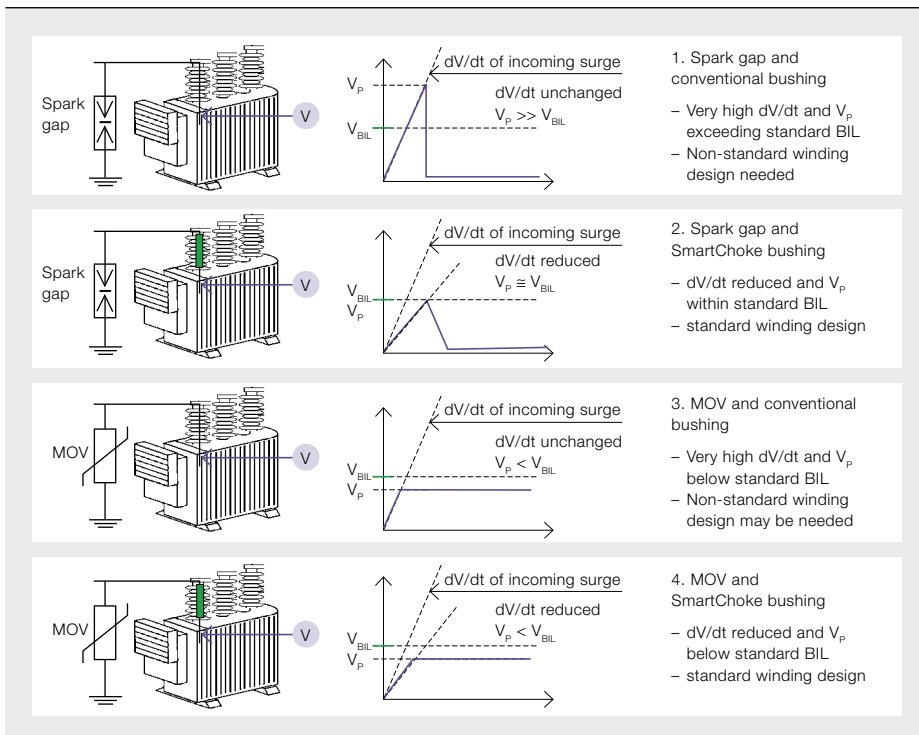


dV/dt transients. The SmartChoke element is integrated within the transformer bushing → 6 and thus the filtering of the high dV/dt transient takes place before it reaches the winding.

The parameters of the choke element embedded within the epoxy-cast transformer bushing are selected so that the same bushing can be used to protect all typical sizes of distribution transformers working in pole-mounted substations in distribution networks.

Experiments performed have shown that a reduction in dV/dt exceeds a factor of two with respect to the standard transformer bushing. A significant reduction in peak overvoltage was also observed → 7.

A transformer featuring the SmartChoke bushing → 8 has been certified according to the SFS 2646 standard at the HV



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laboratory of the Helsinki University of Technology in Espoo, Finland. It was demonstrated that the transformer using a standard winding design and that has protective chokes embedded in the bushings as well as a 2×40 mm spark gap could be safely exposed to a $2 \text{ MV}/\mu\text{s}$ lightning impulse.

Successful protection

The use of a choke upstream of the equipment to be protected has been shown to represent an attractive alternative to complex redesigning of the equipment itself. Although chokes reduce dV/dt and consequentially also the peak value of the front-chopped wave, it should be pointed out that the primary function of the protective device is the reduction in dV/dt of a transient caused by a lightning surge. It is therefore complementary to the standard overvoltage protection provided, for example, by protective spark gaps or metal oxide arresters → 9.

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Title picture

Lightning strikes are a cause of steep voltage transients that can damage electrical equipment.