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Impulse Voltage Test of Power Transformers

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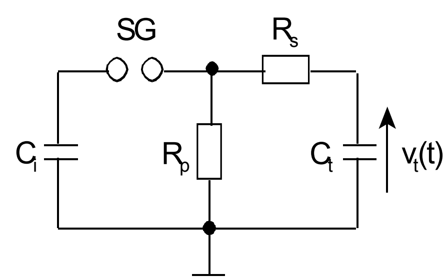
Abstract

During the Lightning Impulse (LI) test of transformer windings with a low impedance it is difficult to ensure a minimum time to half-value of 40 µs in accordance with IEC 60076-3 and IEC 60060-1. This is caused by the oscillating discharge determined by the impulse voltage test generator capacitance and the transformer impedance. In most cases using special adapted circuits can solve the problem.

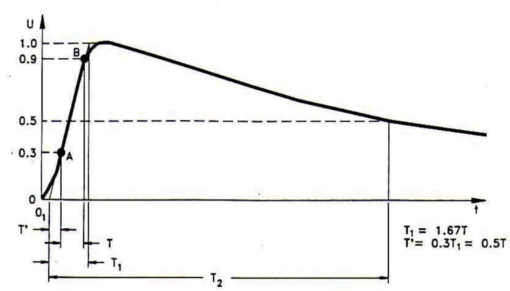
1. Impulse voltage test generator with capacitive load

For the LI testing of basic arrangements but also of different electrical components a purely capacitive load can be assumed. The impulse voltage shape generated by an impulse voltage test generator based on the MARX multiplier circuit can be described by two exponential functions with different time constants. Whereas the LI front time T_1 according to IEC 60060-1 [1] is essentially determined by the resistance of the front resistor R_s located in the impulse voltage test generator and the load capacitance C_t, see fig. 1, the time to half-value T_2 is determined by the impulse capacitance of the impulse capacitor C_i and the resistance of the tail resistor R_p being part of the impulse voltage test generator. According to IEC 600060-1 there are the following time parameters and tolerances for the standard LI 1.2/50:

Front time	T_1 = 1.2 µs + 30 %
Time to half-value	T_2 = 50 µs + 20 %



a) C_i Impulse capacitance
C_t Capacitance of the load (including voltage divider)
R_p Tail resistor
R_s Front resistor
SG Switching spark gap



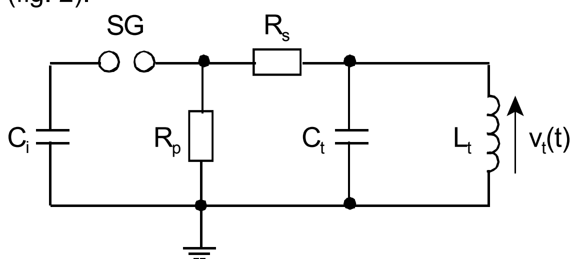
b)

c)
$$v_t(t) = V \times K \times \left(e^{-\frac{t}{\tau_2}} - e^{-\frac{t}{\tau_1}} \right) \quad (1)$$

Fig. 1: LI test at a capacitive load
a) Principal circuit
b) Standard LI 1.2/50 (IEC 60060-1) with time parameter T_1 and T_2
c) Equation for the voltage shape

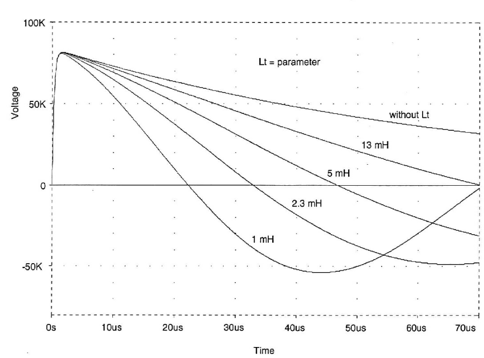
2. Impulse voltage test generator with inductive load

In most of the cases power transformers cannot be assumed as a purely capacitive load for the LI testing. Usually the LI test voltage is applied to one winding terminal of the transformer to be tested, whereas all other terminals are connected with the earth. Hereby, not only the input capacitance of the transformer winding acts as the load for the impulse voltage test generator but also its impedance to all other short-circuited windings. The principal circuit (fig. 1) must be extended by the transformer inductance L_t that is connected in parallel to the test capacitance C_t (fig. 2).



a)

C_i	Impulse capacitance
C_t	Capacitance of the load (including voltage divider)
L_t	Inductance of the load
R_p	Tail resistor
R_s	Front resistor
SG	Switching spark gap



b)

c) $$v_t(t) \approx V * \left[K_1 * e^{-\delta t} * \cos(\omega t - \varphi) - K_2 * e^{-\frac{t}{\tau}} \right] \quad (2)$$

Fig. 2: LI test at an inductive/capacitive load
a) Principal circuit
b) Voltage shape depending on the inductance factor L_t
c) Equation for the voltage shape

Thereby the inductance L_t of the load becomes smaller with decreasing impedance voltage $v_{imp\%}$, with decreasing rated phase-to-phase voltage $V_{P\text{-}P}$ and with increasing power P_{tot} of the transformer winding to be tested. Therefore the lowest values of the inductance L_t have to be considered by testing the low-voltage side windings for power transformers. For a three-phase winding in a star connection the following equation can be applied:

$$L_t = \frac{v_{imp\%} * V_{P-P}^2}{100 * \omega * P_{tot}} \quad (3)$$

$\omega = 2 \pi f$

L_t	Inductance (stray inductance) of the winding to be tested
$v_{imp\%}$	Impedance voltage of the winding to be tested
$V_{P\text{-}P}$	Rated phase-to-phase voltage of the three-phase winding to be tested
P_{tot}	Rated total power of the three-phase winding to be tested
f	Rated frequency

With decreasing inductance L_t the impulse capacitance C_i of the impulse voltage test generator is not only discharged via the tail resistor R_p, but also via the low inductance L_t of the winding to be tested. Thereby the time to half-value T_2 of the LI is reduced and the aperiodic discharge of the impulse capacitance turns to a damped oscillating cosine shape. This is permitted in principle acc. to IEC 60076-3 [2]. However, the lower tolerance limit for the time to half-value of $T_{2\ min}$ may not remain under 40 µs (= 50 µs - 20 %). At the other side the amplitude of opposite polarity of the LI voltage d_{max} should not exceed 50 %. To fulfil these both requirements the impulse voltage impulse voltage test generator must have a minimum required impulse capacitance $C_{i\ req}$, which can be calculated closely as following:

$$C_{i\,req} \geq 2 * \frac{T_{2\min}^{\;2}}{L_t} \quad (4)$$

with $T_2 = 40$ µs

Hence it follows with equation (3):

$$C_{i\,req} \geq 2 * \frac{T_{2\min}^{\;2} * 100 * \omega * P_{tot}}{v_{imp\%} * U_{P-P}^{\;2}} \quad (5)$$

Though the requirement for a minimum impulse capacity $C_{i\ req}$ of the impulse voltage test generator is necessary but it is not sufficient to meet the requirements $T_{2\,min} \geq 40$ µs (IEC) and $d_{max} \leq$ 50 %. Moreover, the oscillating circuit formed by the impulse capacitance C_i of the impulse voltage test generator and the winding inductance L_t must have a certain characteristic damping. This is mainly determined by the front and tail resistors (R_s, R_p) located in the impulse voltage test generator. If the damping is to low, a minimum time to half-value $T_{2min} \geq 40$ µs can be reached, but the amplitude of opposite polarity d is more than 50 %. For a higher damping the requirement for the amplitude of opposite polarity $d \leq 50$ % can be fulfilled, but the time to half-value may remain smaller than 40 µs, see fig. 3. In the case that the impulse capacitance of the impulse voltage test generator C_i is not greater than the minimum required impulse capacitance $C_{i\ req}$ according to equation (5), the adjustment of the damping of the test circuit must be done very exactly. The margin for the adjustment, i.e. for the sufficient circuit damping, becomes greater the more the impulse capacitance of the applied impulse voltage test generator C_i exceeds the minimum required impulse capacitance $C_{i\ req}$ according to equation (5).

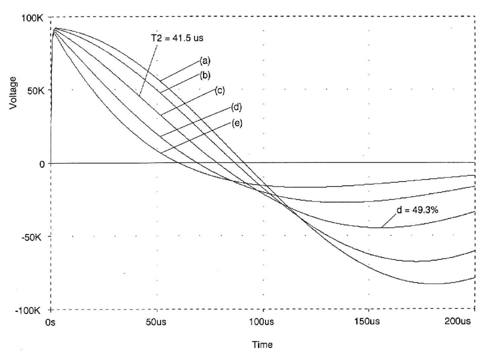


Fig. 3: LI test of power transformers with different damping of the test circuit
(a), (b): Damping to low - the amplitude of opposite polarity d of the LI is to high (d > 50%)
(c): Optimal damping ($T_2 > 40$µs, d < 50%)
(d), (e): Damping to high - T_2 is to short ($T_2 < 40$µs)

3. Resistive earthing of winding terminals

If the requirements acc. to equation (5) can not be fulfilled for the LI test of a power transformers with an existing impulse voltage test generator, IEC 60076-3 allows for the following exceptions:

a) A shorter time to half-value than $T_2 = 40$ µs can be agreed between the manufacturer and the customer of the transformer
b) Winding terminals being not directly exposed to the test voltage, can be earthed via termination resistors

The resistance of the termination resistors has to remain under 500 Ohm. Furthermore, it has to made sure that the voltage which will occur at the resistively earthed winding terminals will not exceed 75 % of the rated LI withstand voltage of these windings. With this method it is often possible to extend the operating range of an impulse voltage test generator considerably. Nevertheless, it must be noted that hereby, the impulse voltage stress of the tested windings may considerably deviate from the voltage stress for direct earthing. It has to be agreed between customer and manufacturer which exception is accepted.

Fig. 4: Impulse Voltage Test System IP 360/3600 G (360 kJ, 3600 kV) with impulse voltage divider and chopping multiple spark gap, with a stage energy of 20 kJ being used for the LI test of power transformers up to 765 kV

4. Projection of an impulse voltage test generator for the LI test of power transformers

The main technical data of the transformers to be tested, like the circuitry and the arrangement of the windings, their rated voltage, rated power, impedance voltage and not at least the rated frequency determine essentially the total charging voltage and the stage energy of an impulse voltage test generator for the LI test.

The total charging voltage of the impulse voltage test generator should lie for LI testing 30 % … 60 % above the highest required LI test voltage. In many cases the value of 30 % is sufficient for routine tests. If development tests are to be carried out, a total charging voltage, which lies 60 % above the highest rated LI test voltage, is recommended.

If the exception “earthing via termination resistors” is not considered, the required impulse capacitance $C_{i\ req}$ can be calculated for each winding voltage level acc. to equation (5). Taking into consideration the different circuitry options of the impulse voltage test generator (parallel connection of stages, partial operation) and the above aspects regarding the total charging voltage the stage charging energy can be calculated in principle for each possible test case.

Normally a stage energy of 5 … 10 kJ per 100-kV-stage and a stage energy of 10 … 20 kJ per 200-kV-stage will be sufficient. Whereas the lower values apply to transformers with lower power, the higher values apply to transformers with higher power (fig. 4). Often, impulse voltage test generators for power transformer testing have an energy of 15 kJ per 200-kV-stage, see fig. 5.

5. Extension of the loading range of impulse voltage test generators

Often it is required to test transformer with such a high power, for which the existing impulse voltage test generator has not been originally meant. In such cases it is necessary to utilise all reserves of the existing impulse voltage test generator.

5.1. Increasing the effective impulse capacitance

The following generally known measures can be taken:

a) Running the impulse voltage test generator in partial operation, i.e. with the minimum number of stages, being necessary to reach the required test voltage level.
b) Switching a certain number of generator stages respectively in parallel and connect this parallel stages in series to reach the required test voltage.

5.2. Increasing the parallel resistors

If the time to half-value remains only a few below the permitted lower limit $T_{2\ min}$ = 40 µs, it is possible to reach a value of $T_2 \geq 40$ µs by increasing the tail resistors R_p. Usually the tail resistors meant for switching impulse voltage can be applied. A further increase of the resistance of the tail resistors R_p above the resistance value for the SI generation does not have any result.

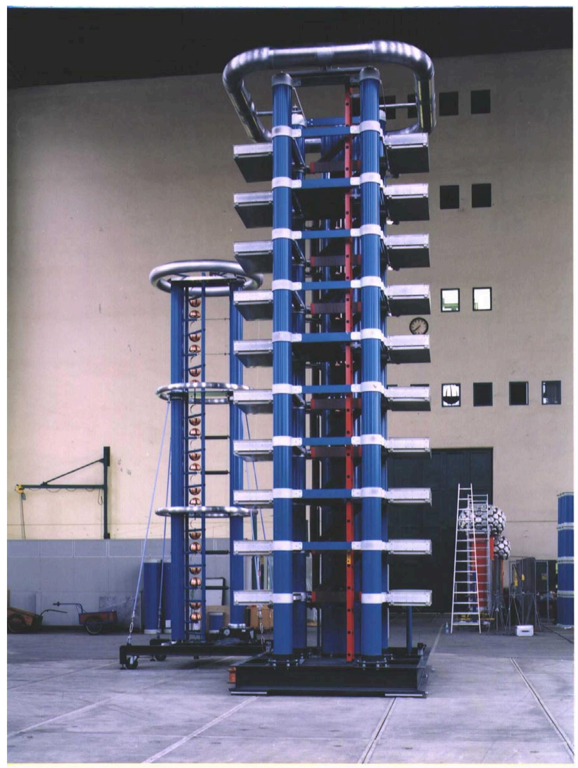


Fig. 5: Impulse Voltage Test System
IP 150/2000 G (150 kJ, 2000 kV) with impulse voltage divider and chopping multiple spark gap, with a stage energy of 15 kJ being used for the LI test of power transformers up to 245 kV

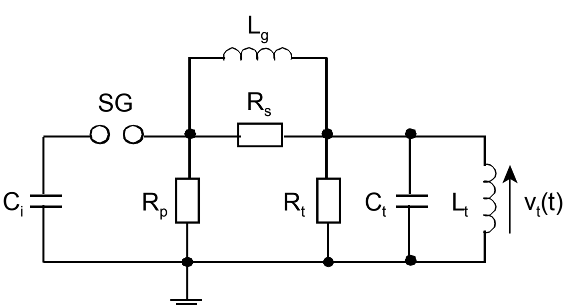
5.3. Decreasing the damping of the test circuit

As already mentioned in chapter 2, if the circuit damping is to high, a time to half-value of $T_2 \geq 40$ µs is not reached even with a sufficient impulse

capacitance of the impulse voltage test generator ($C_i \geq C_{i\,req}$), see fig. 3.
The front and tail resistors in the impulse voltage test generator are mostly responsible for that damping.
The damping caused by the tail resistors R_p can be considerably eliminated by their increase, as already recommended in chapter 5.2. . For a further reduction of the damping the resistance of the front resistor R_s has to be reduced. This would cause a shorter front time T_1 of the LI. To keep the front time T_1 unchanged, the capacitance of the load has to be increased corresponding to the reduction of the resistance of the front resistor R_s. This is easily realised by connecting an additional capacitor in parallel to the transformer winding to be tested.
Unfortunately, the effect of this method is limited, because a reduction of the resistance of the front resistor R_s will lead to oscillations on the front of the LI voltage soon, which may exceed the permitted limit for the overshoot of 5 % /1/.

5.4. Application of the "Glaninger-circuit"

The disadvantage of oscillations on the voltage front after a reduction of the front resistor R_s is completely avoided with a circuit invented by GLANINGER [3]. Hereby the front resistor responsible for the voltage front remains unchanged but it is bridged by an additional inductance formed by an air-coil (fig. 6).



C_i	Impulse capacitance
C_t	Capacitance of the load (including voltage divider)
L_g	Glaninger-coil
L_t	Inductance of the load
R_p	Tail resistor
R_s	Front resistor
R_t	Resistor in parallel to the load
SG	Switching spark gap

Fig. 6: Test circuit with Glaninger-circuit (L_g and R_t) for LI testing of power transformers with extremely low impedance

The Glaninger-coil must have an inductance value ca. 100 … 200 µH, to be ineffective for the fast impulse front and to bridge the front resistor R_s during the much longer impulse tail. So he front of the LI impulse remains unchanged and the tail is extended. Consequently an additional resistor R_t has to be switched in parallel to the load inductance L_t, to form a true voltage divider consisting of R_s//L_q and R_t//L_t.

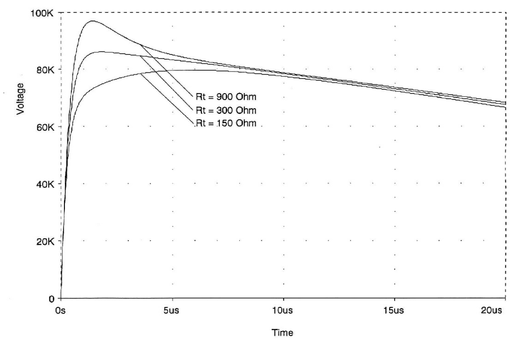


Fig. 7: LI test of power transformers by using the Glaninger-circuit, adjustment of the voltage shape at the voltage crest by means of an additional resistor R_t (optimal adjustment R_t = 300 Ohm for this example)

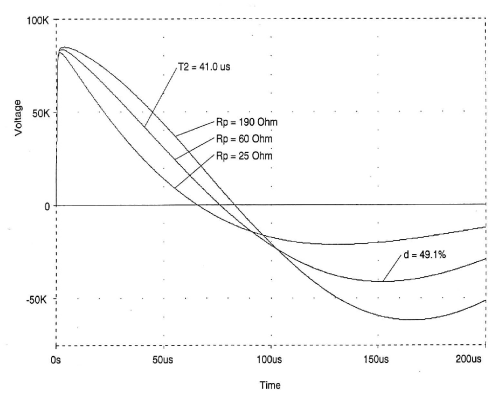


Fig. 8: LI test of power transformers by using the Glaninger-circuit, adjustment of the time to half-value T_2 and the amplitude of opposite polarity d by means of the tail resistor R_p (optimal adjustment R_p = 60 Ohm for this example, $T_2 >$ 40 µs, d < 50 %)

With a Glaninger-circuit the front time T_1, the time to half-value T_2 and the amplitude of opposite polarity d of the LI test voltage can be set almost independently, i.e. T_1 with the tail resistor Rs, T_2 and d with the resistors R_p und R_t (fig. 7 and 8). A variation of the Glaninger-coil inductance is as a rule not necessary. The Glaninger-circuit enables for LI testing the most effective adaptation of the impulse voltage test generator and the transformer to be tested. An existing impulse voltage test generator can be utilised optimally.

6. Conclusion

The testing of power transformers with LI test voltage acc. to the IEC standards presupposes special knowledge of the interaction between the impulse voltage test generator and the inductive load. For example, there exists a close connection between the main data of the transformer to be tested and the required impulse capacitance of the impulse voltage test generator. There are also requirements related to the damping characteristic of the test circuit to utilise an existing impulse voltage test generator optimally. Some basic aspects and circuitries were described in this paper.

References

[1] IEC 60060-1 (1989-11), High-voltage test techniques. Part 1: General definitions and test requirements

[2] IEC 60076-3 (2000-03), Power transformers Part 3: Insulation levels, dielectric tests and external clearances in air

[3] Glaninger, P.: Stoßspannungsprüfung an elektrischen Betriebsmitteln kleiner Induktivität. ISH Zürich, 1975, Beitrag 2.1-05