Load range extension methods for lightning impulse testing with high voltage impulse generators

Klaus Schwenk, Michael Gamlin
Haefely Test AG, Basel, Switzerland
E-mail: schwenk.klaus@haefely.com

Abstract: The test circuit parameter limitations for lightning impulse testing according to the IEC 60060-1 standard in regards of front time and overshoot are identified and discussed. The different load range extension methods for lightning impulse testing with impulse voltage generators are introduced, their pros and cons are discussed and underlined by examples. Possible limitations for power transformer testing due to internal resonance's and reflections caused by the power transformer winding design are explained. The new revision of the IEC 60060-1 standard will introduce a new lightning impulse evaluation method by means of the k-factor. The impact of the revised lightning impulse evaluation on the load range extension efficiency is shown.

INTRODUCTION

Equipment for high-voltage transmission systems has to be tested with lightning impulses according to the applicable IEC standard to proof their capability against lightning overvoltages.

The tolerance for the front time T_1 of a lightning impulse 1,2/50µs is ±30%. Therefore the maximum allowed front time is 1,56µs, the overshoot β is limited to 5% [1]. During lightning impulse testing with high capacitive test objects these two parameters limit the load range of a lightning impulse test circuit.

The front time T_1 of a lightning impulse is proportional to the product of the total front resistance R_S and the series connection of the test capacitance and the impulse generator capacitance.

High capacitive test objects require a low series resistance value and vice versa to meet the front time tolerance. Each impulse voltage test circuit has an inherent inductance L_S due to the dimensions of the circuit components and the connections between them. The sum of all these inductances L_S generates oscillations close to the peak of the lightning impulse voltage which have to be damped by the front resistor R_S. The approximate series resistance needed to damp oscillations sufficiently can be calculated according Equation (1)

$$R_S \geq 1.4 \cdot \sqrt{L_S \cdot \frac{C_S + C_T}{C_S \cdot C_T}} \qquad (1)$$

The higher the total circuit inductance L_S is the higher the front resistance has to be and the more limited is the possible load range. The ratio between internal and external inductance is approx. 2:1.

The contribution of a maximum possible reduction of the internal generator inductance compared to the total loop inductance would be in the range of typically 10%. Therefore a load range extension by reducing any generator inductance is assiduous and very limited.

A much more efficient approach to increase the load range of an impulse test circuit is to use either a series or a parallel compensation. The compensation methods do not reduce the total inductance L_S but they compensate the oscillations on the impulse wave shape by additional passive elements.

PARALLEL COMPENSATION

Fig 1 shows the equivalent electrical diagram of an impulse circuit with parallel compensation.

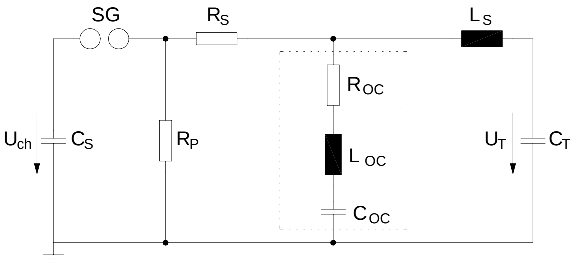

Fig 1: Equivalent impulse circuit diagram with parallel compensation

C_S: total capacitance of the impulse voltage generator,
U_{ch}: total charging voltage,
R_S: total front resistor,
R_P: total tail resistor,
L_S: total loop inductance including the impulse voltage generator,
C_T: total test capacitance (consisting of test object, divider chopping gap, etc.),
U_T: applied test voltage,
R_{OC}, L_{OC} and C_{OC}: elements of the parallel compensation.

The parallel compensation is an absorption circuit which short circuits at resonant frequency f_{Res} the series resonance circuit consisting of L_S and the series connection of C_S and C_T. With the Equation (2) for the resonant frequency the elements L_{OC} and C_{OC} can be calculated as follows.

$$f_{Res} = \frac{1}{2 \cdot \pi \cdot \sqrt{L_{OC} \cdot C_{OC}}} \qquad (2)$$

Figure 2 shows the voltages at the components of the parallel compensation as well as the voltage without compensation based on a 2600kV, 260kJ impulse generator with a capacitance C_T of 5.2nF and a total inductance L_S of 98.8µH.

The inductance L_{OC} and C_{OC} could be realized in a single component which is placed at the top of the capacitance C_{OC}.

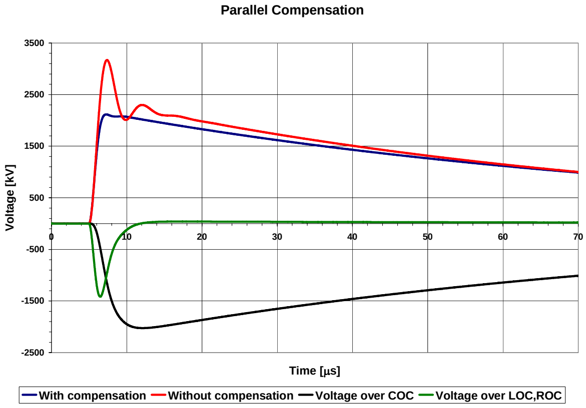

Fig. 2: Voltages with and without parallel compensation.

The front time T_1 without compensation is 1.74µs, the overshoot β is 35%. With compensation the front time T_1 is 1.55µs and no overshoot occurs, the output voltage is 2115kV. The series resistor is with 90Ω in both cases the same.

SERIES COMPENSATION

The patented series compensation method was indroduced by Haefely Test AG under the name "Overshoot Compensation" (OC) in 1997 [2].

The series compensation arrangement consists of a compensating capacitor C_C in parallel with a resistor R_C and an inductance L_C. The necessary inductance L_C is not a separate component but the inherent self inductance of the resistor R_C. The series compensation is connected in series with the impulse generator (see figure 3).

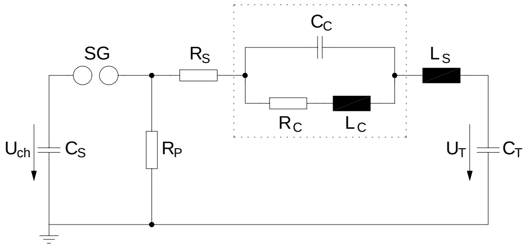

Fig. 3: Equivalent impulse circuit diagram with series compensation

The series compensation and the capacitance C_T build up a low-pass filter. The higher frequencies of the front of an overshooting impulse are more damped than the lower frequencies of the tail. The damping by the low-pass filter reduces the applied voltage at C_T during the impulse front. Figure 4 shows the voltages at the compensation components with the same conditions as with the parallel compensation but with a capacitance C_T of 5.7nF.

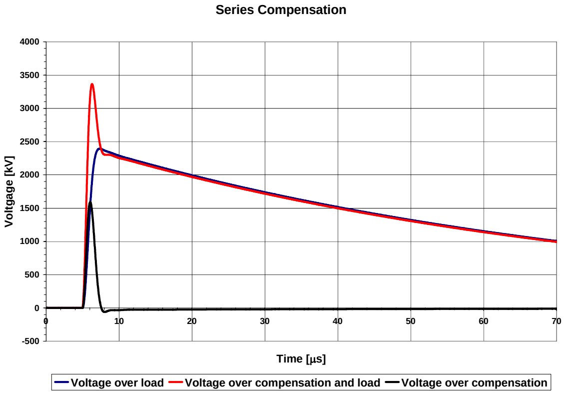

Fig. 4: Voltages at series compensation

The voltage over the series compensation and the test objects shows still the overshoot but the high-frequency part of the voltages now drops across the series compensation. The voltage across the test object is the difference between these two voltages and the overshoot got compensated. The series compensation does not influence the tail of the impulse voltage.

With a series compensation a front time T_1 of 1.55µs, an overshoot β of 2.1% at an output voltage of 2393kV is achieved. The series resistor is with approx. 19Ω much lower that with parallel compensation.

The series compensation can be designed as an external component or can be integrated into the stages of an impulse generator. An internal solution is reasonable for generators with enough connecting slots for the series compensation components within the generator. No additional mechanical changes have to be done at the generator. Fig. 5 shows the solution of an internal series compensation for a Haefely generator and fig. 6 shows the series compensation within a non Haefely generator.

Fig. 5: Example for an internal series compensation within a Haefely generator

Fig. 6: Example for an internal series compensation within a non Haefely generator

The external series compensation consists, depending on the voltage, of one or more capacitors in series with one or more resistors in parallel. The capacitors and resistors are mounted vertically on an insulator with a mobile base frame. A very easy connection between generator and test object is possible. Figure 7 shows the realisation of an external overshoot compensation.

The load range extension of a series compensation is approx. 2-3 times the value of a generator without compensation.

Fig. 7: External overshoot compensation

The figures 8 and 9 show the results when testing a power transformer without and with a series compensation.

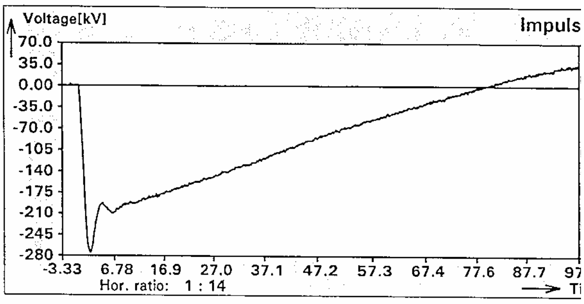

Fig. 8: Impulse test without series compensation

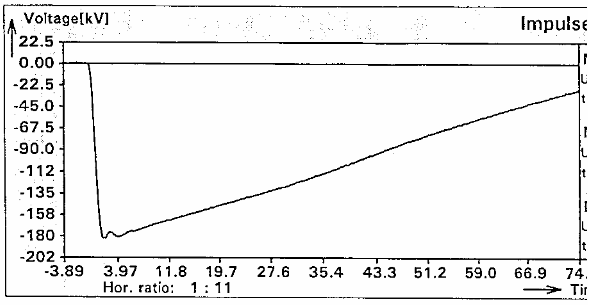

Fig. 9: Impulse test with series compensation

In figure 8 the front time is 1.68µs and the overshoot is 20%, both values extend the allowed tolerances. With the series compensation the front time is 1.47µs and the overshoot at the peak of the wave is less than 5%.

COMPARISON OF THE TWO COMPENSATION METHODS

The series compensation (SC) has got several advantages against the parallel compensation (PC):

- Higher load range C_T and higher efficiency due to a higher achievable output voltage U_T under comparable conditions.
  Figure 10 shows the output voltage C_T with SC and PC for a 2400kV, 240kJ impulse generator with an total inductance L_S of 91.2µH.

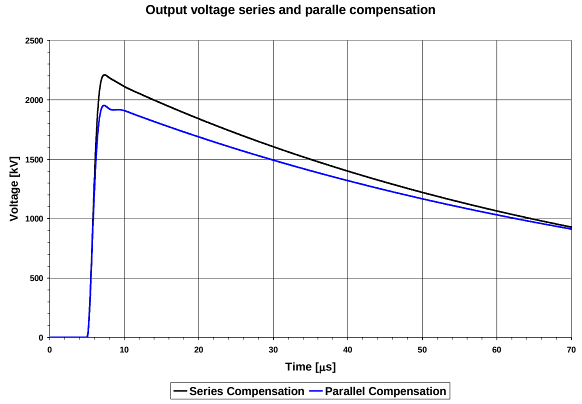

Fig 10: Output voltage SC and PC

The maximum load range for the SC is 6.18nF whereas with the PC only 5.65nF can be achieved. The output voltage U_T of 2210kV with the SC is higher than with the PC (1952kV). For testing the same capacitance C_T with the same output voltage U_T with a PC a generator with a charging voltage of 2900kV and an enegry of 225kJ would be required.

In general the maximum testable capacitance C_T with SC is about 7 to 10% higher than with PC. The achievable output voltage U_T with SC is about 13% higher than with PC (see table 1).

- The necessary capacitance value for the PC is approx. 3.5 times higher than for the SC. This results in a higher weight for the capacitor. For a full lightning impulse the voltage drop over the capacitance of the SC is approx. 66% of the maximum output voltage, whereas the voltage drop over the capacitance of the PC reach almost 100% of the maximum output voltage.
- The PC is an additional load which reduces the efficiency of the impulse generator. It might be happen that additional parallel resistors are necessary to adjust the tail time because of the high capacitance value of the PC.
- The SC needs a significantly lower front resistance R_S to adjust the front time. The required front resistance R_S for the PC is approx. 3-5 times higher, which also reduces the efficiency of the generator.
- If the external SC consists of several capacitances (especially for higher voltages) a reduced connection together with a reduced series connection of the impulse generator is possible. This can be achieved by short-circuiting of one or more capacitors. The advantage of the reduced connection is a higher SC capacitance and therefore an increased maximum load range compared to the non reduced SC. For an internal SC the usage of a reduced SC is also possible, whereas for a PC a reduced connection is not possible.

Generator voltage [kV]	1000	1200	1400	1600	1800	2000	2200	2400	2600
Generator energy [kJ]	100	120	140	160	180	200	220	240	260
Total inductance L_S with compensation[µH]	38	45.6	53.2	60.8	68.4	76	83.6	91.2	98.8
Max load C_T with SC [nF]	13.8	12	10.5	9.27	8.2	7.4	6.74	6.18	5.7
Capacitance C_C of SC [nF]	6.9	6	5.25	4.63	4.1	3.7	3.4	3.1	2.85
Max output voltage U_T with SC [kV]	916	1100	1300	1469	1656	1837	2026	2210	2393
Max load C_T with PC [nF]	13.5	11.2	9.65	8.6	7.5	6.8	6.15	5.65	5.2
Capacitance C_{OC} of PC [nF]	24.3	20.3	17.4	15.5	13.5	12.2	11	10.2	9.4
Max output voltage U_T with PC [kV]	806	972	1152	1299	1466	1628	1792	1952	2115

Table 1: Possible load ranges with SC and PC

- Both compensation methods are adjusted to a specific circuit inductance $L_{S,\ max}$ and test capacitance $C_{T,\ max}$. If the test configuration deviates from these optimal parameters then the impulse wave shape differs at the peak from the ideal form. An adjustment of the compensation components to the new values of L_S and C_T is difficult. But it is nevertheless possible to generate an lightning impulse according the standard. Figure 11 shows the peak of the impulse wave shapes of the SC and PC for the following cases:
  1) the test capacitance C_T is 20% lower than $C_{T,\ max}$
  2) 2) the test capacitance C_T and the inductance L_S are 20% lower than $L_{S,\ max}$ and $C_{T,max}$.

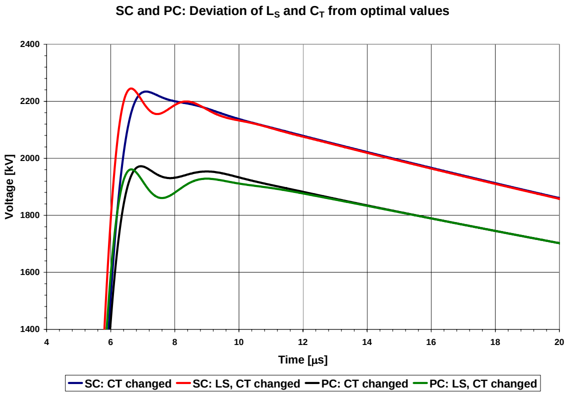

Fig. 11: Influence of the deviation of L_S and C_T

All wave shape parameters of the curves in figure 11 are within the IEC tolerances. Nevertheless the distortion of the waveforms with the SC is less significant than those with the PC. In general an alternation of the total inductance L_S has a higher negative impact on the wave shape than an alternation of the test capacitance C_T.
In case of a too low inductance L_S an additional external inductance can be added. This could be done by an air coil or by a longer high voltage lead.

LIMITS OF THE COPENSATION METHODS

Both described methods, the series and the parallel compensation, are based on the idea to compensate the oscillation caused by the inherent total inductance L_S of the impulse circuit and the series connection of the generator capacitance C_S and test object capacitance C_T. Thereby, the test capacitance C_T is considered as a concentrated element.

Since complex designed power transformers can not be considered as a pure capacitance but as a complex network of capacitances, resistors, inductances and mutual inductances more sophisticated models are necessary to describe their transient behavior [3].
This complex power transformer design might have the following impact on both compensation methods:

- Oscillations caused by resonances within the transformer winding can not be compensated from the series or parallel compensation. (see figure 12).

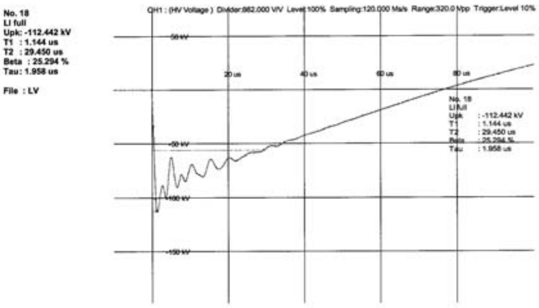

Fig. 12: Resonance in a transformer winding

Transformer windings might have different kind of resonance's [4]. The disturbing resonances may occur in the windings if the applied lightning impulse excites natural frequencies of the winding. This might result in oscillations on the impulse wave shape.

- Running time effects within the winding might lead to an increased front time which can not be influenced by changed front resistor values. Reflections might e.g. occur at the neutral point of a transformer or at design changes within the winding (interleaved design to non interleaved design). This effect might have an impact on the wave shape (no smooth impulse wave shape). This phenomenon can also not be influenced from a series or parallel compensation.

The two compensation methods are not designed to eliminate these phenomenona, because they can not be influenced by external elements. Nevertheless in these cases significant improvements of the wave shape can be achieved by reducing the negative impact of the total loop inductance L_S (see figure 13 and 14).

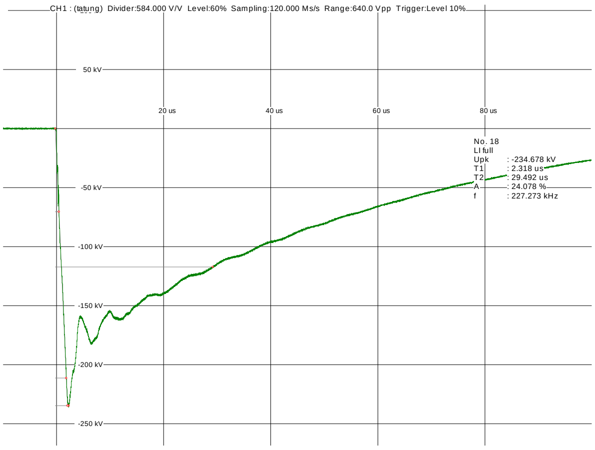

Fig. 13: Transformer without series compensation

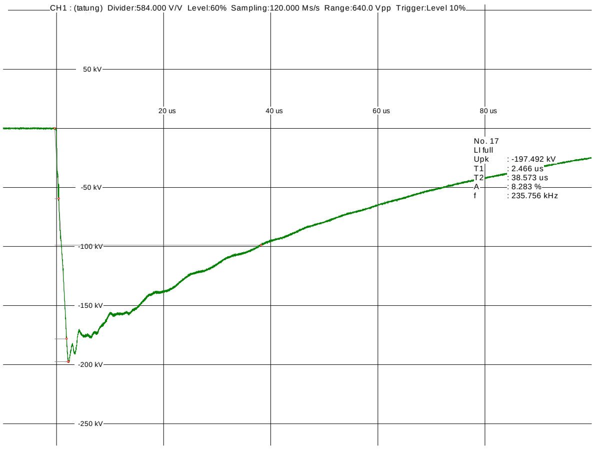

Fig 14:   Transformer with series compensation

Figure 13 and 14 show a lightning impulse on a 161kV, 60MVA 3phase transformer with reflections and running time effects within the transformer as well as oscillations due to the big loop inductance L_S. The front time could not be influenced significantly but the oscillations due to L_S could be reduced with the series compensation from 24% to approx. 8.3%.

NEW k-FACTOR METHOD AND OVERSHOOT

Due to the introduction of the k-factor method for the lightning impulse evaluation in the revised IEC 60060-1 it is likely that the permitted overshoot value will be increased [5]. Values between 10 % to 20 % are in discussion. Although with an increased overshoot value a significant load range extension by a factor of approx. 2-3 can be achieved by the series compensation method.

CONCLUSION

The maximum allowed front time T_1 and overshoot β for lightning impulses according to IEC 60060-1 limits the maximum capacitance to be tested with an impulse generator. The main reason for the overshoot β is the inherent total test circuit inductance L_S.

Efficient load range extensions in the range of a factor 2-3 can achieved by additional compensating circuits.

The introduced patented series compensation method shows a better performance than the parallel compensation method due to the following advantages:

- Up to 10% higher maximum load range under similar conditions.
- Up to 13% higher output voltage efficiency.
- Higher load range by the usage of the series compoensation in a reduced connection in case the impulse generator is operating in a reduced series connection compared to the non reduced SC.
- Lower capacitance value in the range of a factor 3.5 necessary for the series compensation than for the parallel compensation which results in a lower weight.

In case of a complex power transformer design some performance limitations might have to be accepted. Nevertheless significant wave shape improvement also in these cases are possible by the compensation of the inherent total loop inductance L_S.

REFERENCES

[1] IEC 60060-1 (1989) High voltage test technique part 1, General definitions and test requirements

[2] J. Wolf, G. Voigt: A new solution for the extension of the load range of impulse generators, 10th ISH Montreal, 1997

[3] A. Kühner: Dreidimensionale FEM-Modelierung eines Hochspannungsleistungstransformators zur Untersuchung ihres transienten Verhaltens, Dissertation University Karlaruhe, 1999

[4] W. J. McNutt, T. J. Blalock, R.A. Hinton: Response of transformer windings to system transient voltages, IEEE Transactions on power apparatus and systems, volume PAS-93, March 1974

[5] M. Gamlin: Implementation of the k-factor for the lightning impulse evaluation by means of digital FIR filtering, 14th ISH Beijing, 2005.