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Dielectric, Switching and System Requirements under Out-of-Phase Conditions, during Synchronisation and under Comparable Stresses.

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On behalf of CIGRE WG A3.13

SUMMARY

Recent developments in electrical networks can increase the probability of out-of-phase switching and dielectric stresses being applied to open circuit-breakers, due to asynchronous systems at both sides. This report presents a systematic study of TRV-stresses associated with generator separation and system separation. TRV peak values are higher than required in the Standards, even for relatively small out-of-phase angles (75° to 90°), and the dielectric stresses are high with respect to the short-duration power frequency withstand voltages across a circuit-breaker open contacts, especially taking into consideration the external insulation under pollution and ageing processes. To the opinion of the authors, the Standards should be revised to give users clear and adequate guidance on the assessment and specification of TRV-values and dielectric withstand requirements under out-of-phase conditions.

KEYWORDS

Out-of-phase, synchronisation, TRV, RRRV, First-Pole-to-Clear Factor (fpcf), longitudinal dielectric stress

1. INTRODUCTION

Within CIGRE SC A3 "High-voltage Equipment", WG A3.13 "Changing Network Conditions and System Requirements" has investigated the impact of developments in electrical networks upon conventional high voltage apparatus. The major relevant trends identified are:

1) increasing implementation of distributed generation
2) increasing distances of bulk power transmission
3) increasing application of power electronics (generation, transmission, distribution and load).

One of the phenomena studied is the increased probability of out-of-phase conditions. Operating of systems closer to their limits may lead to steady-state, transient and dynamic stability problems and the problems are exacerbated by the increasing complexity of the power systems: large distances between load and power generation centres, regional concentrations of wind farms and associated power transmission and reserve problems, the changed nature of distribution grids and a trend to consider island operation of parts of the (distribution) system.

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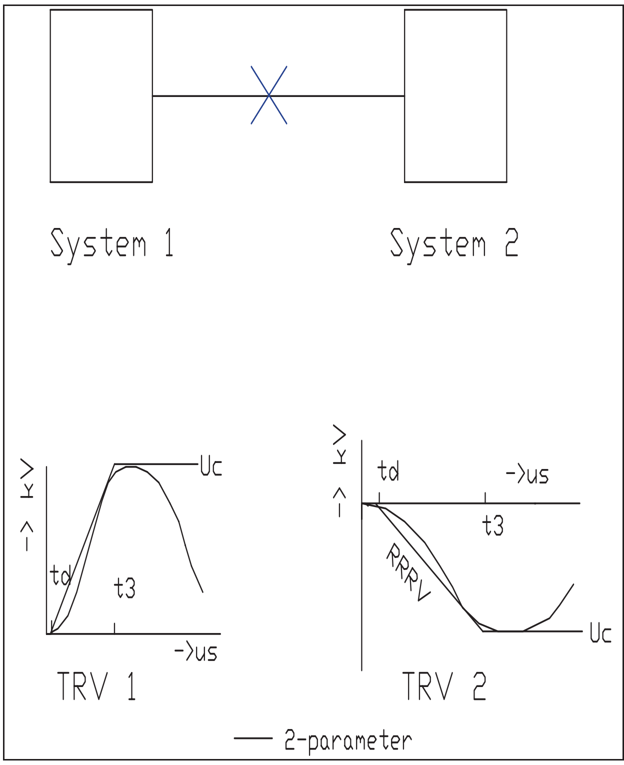

Fig. 1 Longitudinal stresses across the first-pole to clear out-of-phase

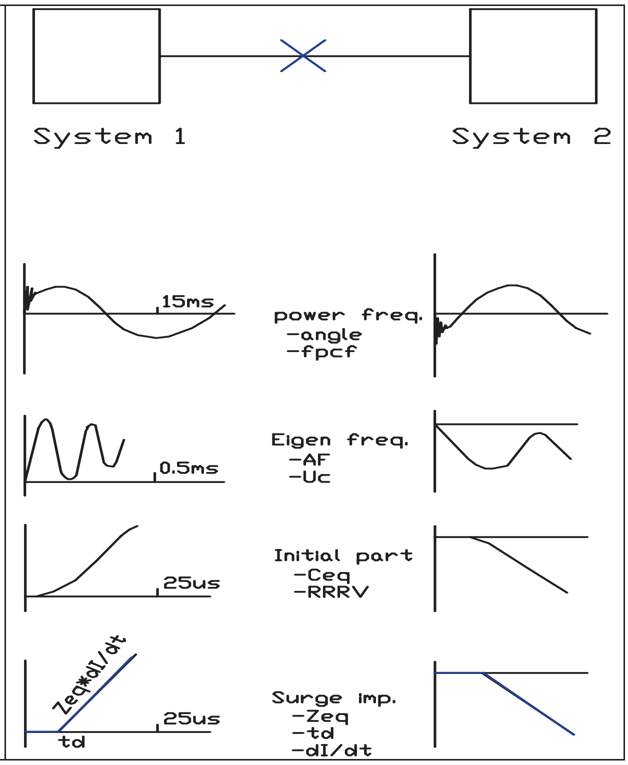

Fig. 2 Characteristics of the RV and TRV

The stresses on HV equipment, especially circuit-breakers (figure 1), under out-of-phase conditions and during synchronisation of generators and networks have been investigated and are presented in the following sections. Present Standards [1][2][3][4] define out-of-phase TRV (transient recovery voltage) and RRRV (rate of rise of recovery voltage) conditions on the basis of parameters including out-of-phase angle (ψ), out-of-phase current (I_{oop}), recovery voltage (RV), natural frequency, damping and amplitude factors (AF) and travelling wave behaviour. Figure 2 shows schematically the different time domains which are relevant for the TRV-studies and reference [5] presents the relation between the different parameters in 3-phase systems. The out-of-phase test duty leads to the highest TRV-peak requirements for circuit-breakers.

WG A3.13 will publish more detailed information in two CIGRE Technical Brochures during 2007.

2. SYSTEM CONSIDERATIONS

The circumstances that may lead to system separation, either singly or in combination, include:

- transient instability (slow fault clearing, false synchronisation of large network elements or large power plants)
- voltage instability (inadequate reactive power and/or voltage regulation, poor or adverse tapchanger control)
- small signal instability (amplification of power swings due to negative damping)
- frequency instability (system inability to react to sudden load/generation unbalances)
- cascade trippings (multiple lightning, weather conditions, overloading, vegetation growth, temporary overvoltages)
- protection mal-operation
- false synchronisation of a single generator.

Large increases in distributed generation, including many windmills and windmill parks, and multiple power transfers across longer distances, increase the probability of occurrence of many of these events as detailed in the following examples:

- medium voltage networks typically have fault clearing times which exceed the maximum clearing time for continued stability of small generating plants equipped with synchronous generators
- the optimal control of reactive power supply and voltage regulation by small generators has not been established yet
- windmills are very sensitive for wind variations, especially under high wind conditions, which may result in co-incident tripping of many units
- small cogeneration plants (e.g. for greenhouses) are operated in large groups without consideration of wider network requirements
- systems are more commonly operated up to, or even beyond, their loading capabilities
- (small) generators are tripped and synchronised more regularly than ever before
- certain distributed power generation technologies cannot provide inertial energy required for the immediate dynamic response to sudden load/generation unbalances. This reduces the average inertia constant of the whole system and hence reduces the margin to the dynamic stability
- it is important that dispersed generators remain connected to the network during voltage and/or frequency deviations caused by faults and other disturbances as specified for the large conventional synchronous generators, thus contributing to ride through system disturbances with their active and reactive outputs and their inertia
- on the other hand, the growing use of dispersed generation increases the probability of out-of-phase conditions.

All these trends lead to the conclusion that out-of-phase conditions have to be studied more carefully than in the past. A better understanding of the effects and consequences of out-of-phase conditions and of the present and future probabilities of occurrence is necessary.

3. OUT-OF-PHASE PHENOMENA

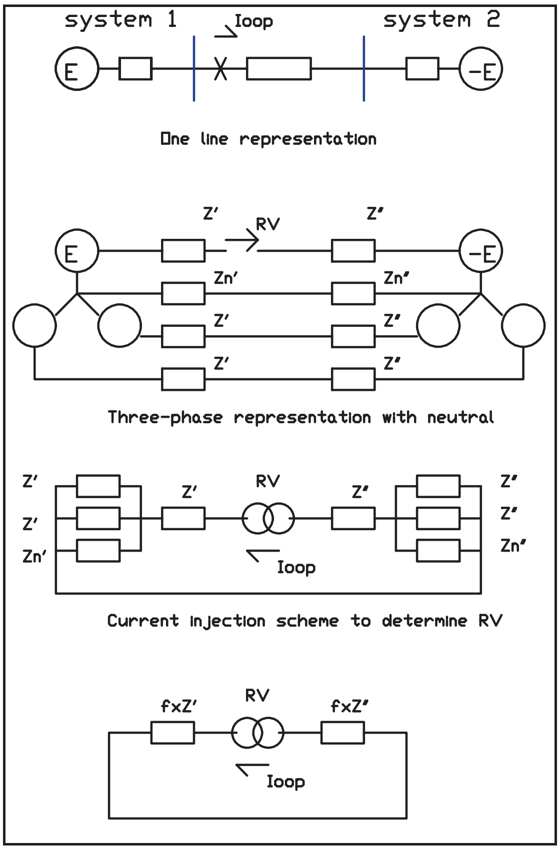

Fig. 3 Out-of-phase RV with f = total fpcf

In common with the recently published Guide for Application of IEC 62271-100 and IEC 62271-1 [15], two out-of-phase cases are considered here:
(*i*) generating units that separate from the network
(*ii*) major systems that separate.
Whilst the focus of the above mentioned Guide is to explain the values given in the Standards, a more fundamental approach is taken here with emphasis on the behaviour of system topologies not directly considered in the Standard.

3.1 Case (i)

Out-of-phase switching may be applicable to a generator circuit-breaker at the MV-terminals of a generator, as specified in IEEE Standard C37.013 (1997) [10], or to a generator circuit-breaker at the HV side of the step-up transformer, normally specified as a general purpose circuit-breaker to IEC 62271-100 or ANSI/IEEE C37.04/06/09. In both situations, as shown in figure 4, the total RV is caused by the disappearance of the voltage drop across the reactances of the generator, the step-up transformer and the system and the overall fpcf: RV = I_{oop} * fpcf * (Xd" + Xtr + Xs). The overall fpcf is a combination of the fpcf (depending on the neutral treatment Zn) of the systems at both sides of the circuit- breaker and can be deduced from the double Neptune-scheme as shown in figure 3.

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The largest voltage drop will generally be across the generator sub-transient reactance. The transformer reactance is in the range from 0.1 to 0.15 pu whilst many modern generators have a sub-transient reactance in the range 0.18 – 0.27 pu; lower values (0.12 – 0.15 pu) were typical in old 2-pole turbine generators. The system reactance is typically five (or more) times smaller than sub-transient generator plus transformer reactance. Further, the natural frequency of the generator windings is 2 to 3 times lower than the natural frequency of the transformer windings. System frequencies usually have the lowest values defined primarily by the travelling waves of the shortest OH-lines. In terms of surge impedances and local capacitances, the generator will offer the lowest surge impedance (in the range of several tens to less than 100 Ohms) with the highest capacitance (typically 0.1 μF) and the transformer the highest surge impedance (thousands of Ohm) with the smaller local capacitances. The system's surge impedance does not exceed 300 - 400 Ohm with local capacitances comparable with the capacitance of a transformer (thousands of pF).

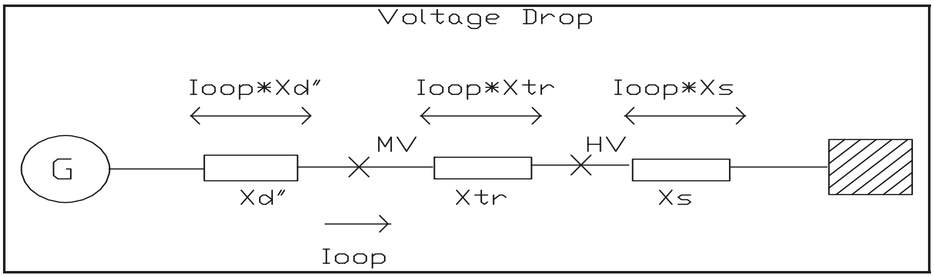


Fig. 4 Generator circuit- breaker RV

Seen from the HV-side of a step-up transformer (winding configuration: YN-D), it is assumed that the earth fault factor and therefore the first-pole-to clear factor (fpcf) are very low: k=Z0/Z1 is 0.7 to 0.9. With k being about 0.8 the fpcf becomes 0.92, and the second and last pole clearing factors are larger than the fpcf [5]. On the other hand, as shown in figure 3, the total fpcf is to be considered and not the individual fpcf at each side of the circuit-breaker. For k=0.8 at the generator-transformer side and a fpcf of 1.1 at the net-side, the total fpcf is 0.94 to 0.96, depending on the ratio of normal sequence reactance at the generator/transformer side versus the normal sequence reactance at the network side.

With a fpcf of 1.3 at the net-side, the total fpcf becomes 1.06 for a sub-transient generator/transformer reactance which is five times the reactance at the net side. To derive the total RV, this total fpcf has to be multiplied with the out-of-phase voltage which depends on the out-of-phase angle. In this example, the total RV for full phase opposition will reach a value of 2.12 pu, with 5/6 of the voltage appearing at the step-up transformer side of the circuit-breaker and the remaining 1/6 appearing at the network side, in addition to the pre-clearing voltage of 4/6 pu. So, at the step-up transformer side the terminal voltage of the first clearing pole jumps from 0.67 pu to – 1.10 pu (Δ = 1.77 pu) and at the other terminal from 0.67 pu to 1.02 pu (Δ = 0.35 pu). For smaller out-of-phase angles ψ, the total RV, the two parts of the RV and the voltage jumps are smaller in proportion to sin(½ψ).

At the generator-transformer side the amplitude factor (over-swing) will be quite large (for instance 80%: amplitude factor 1.8), as the losses will be relatively low (X/R ratio of 50 or more) and the generator side capacitance large. A significant depression of the voltage at the generator terminals and therefore of the recovery voltage at the HV-side of the transformer can be expected [16], figure F.1 of [1]. This phenomenon leads to a considerable reduction of the voltage at the HV circuit-breaker, typically resulting in a residual voltage of 80% to 90%; i.e. a sub-subtransient source voltage of 0.8 to 0.9 pu, in the first few hundred μs after clearing the out-of-phase current. The effect is larger at larger currents but is not observed for generators with fully laminated poles and a damper winding [16].

The amplitude factor of the RV is determined by the natural frequencies of each side of the circuit-breaker and normally the natural frequencies differ substantially such that the components of the transient recovery voltage at both sides of the circuit-breaker swing independently and their crests do not coincide.

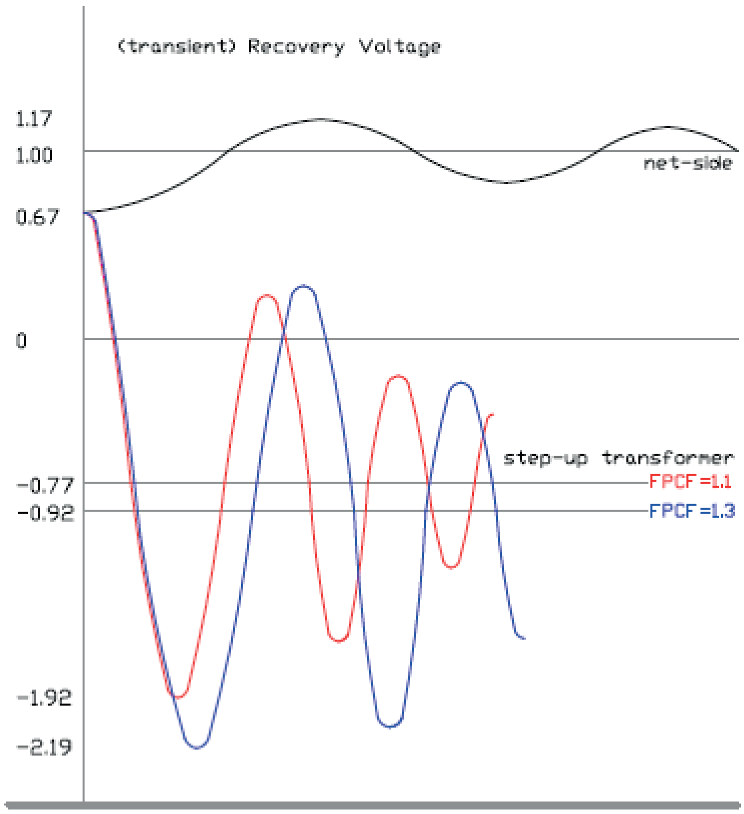


Fig. 5 Out-of-phase Recovery Voltage. Case (i)

Shortly before clearing the voltage at both terminals of the circuit-breaker pole is defined by:
Vcb = Es + (Eg-Es) * Xs/(Xd"+Xt+Xs), where Vcb is the circuit-breaker terminal voltage, Eg is the source voltage at the generator side and, Es is the source voltage at the net side. If Eg = -1.0 pu, Es = +1.0 pu (full phase opposition) and Xd"+Xt = 5*Xs then Vcb = 0.67 pu. The net side RV will swing from 0.67 pu to about 1.0 pu (see former page and figure 5). With an over-swing of the voltage jump corresponding to an amplitude factor of 1.5, a peak value of 1.17 pu is reached.

The transformer side will swing from 0.67 pu to -0.92 pu (assuming net side fpcf of 1.3 and 10% depression) with an amplitude factor of 1.8, thus giving a peak value of – 2.19 pu. For a net-side fpcf of 1.1 (and 10% depression), the voltage will jump at the transformer side from 0.67 pu to - 0.77 pu; with an amplitude factor of 1.8, a peak value of -1.92 pu is reached.

In order to estimate the crest value of the total TRV, the assumption is made that the peak at one side coincides with the power frequency recovery voltage at the other side. In this case,

1. the peak at the net side 1.17 pu coincides with –0.92 pu (resp. –0.77 pu) at the step-up transformer side, summing up to a TRV peak value of 2.1 (resp. 1.9 pu)
2. the peak at the step-up transformer's side -2.19 pu (resp. -1.92 pu) coincides with 1.0 pu at the net side, summing up to 3.2 pu (resp. 2.9 pu).

These peak values are higher than 2.5 pu, as specified in IEC 62271-100 for systems with fpcf = 1.3.

In figure 5, the wave-shapes on both sides of the first clearing pole are schematically given assuming full phase opposition. Reducing the out-of-phase angle will shift Vcb from 0.67 pu towards 1.0 pu, thus decreasing the over-swing at the net side but increasing the over-swing at the step-up transformer side. Moreover, due to the lower out-of-phase current the generator will show less depression and this leads to a higher residual voltage.

At an out-of-phase angle of 90º the out-of-phase voltage is 1.41 pu. Assuming no depression, a reactance ratio of 5, k = 0.80 at the step-up transformer-side and fpcf = 1.3 at the net side, it can be calculated that the peak-value of the TRV is 2.5 pu: a value which is recognised in the Standards. In other words, for these specific assumptions, the Standards do not address out-of-phase angles in excess of 90º.

In a system with a floating neutral, or equipped with Peterson coils, the fpcf = 1.5 and the maximum RV will be 3.0 pu. The total TRV for the same example case can reach 4.55 pu at full phase opposition. Without depression, an out-of-phase angle of 75º gives a RV of 1.83 pu and a peak value of the TRV of 3.1 pu which is close to 3.13 pu as given in the Standards (for systems with fpcf of 1.5).

For a circuit-breaker at the MV-side of the step-up transformer, the IEEE/ANSI Standard C37.013 [10] is applicable. In this Standard an out-of-phase angle of 90° has been taken as the basic assumption to specify the TRV requirements. It has to be mentioned however that many utilities specify an angle of 180°; see for instance [8].

3.2 Case (ii)

When, during out-of-phase conditions, the equilibrium point (virtual short-circuit point) is somewhere on the OH-line that connects the two systems going out of synchronism, protection systems will trip the circuit-breaker. Whilst it is possible to install advanced and complicated out-of-phase blocking systems to delay the tripping command until the beating out-of-phase angle is small, this is uncommon and switching can normally occur over a wide range of out-of-phase angles. The TRV across the first clearing pole is determined by the system parameters on the busbar side of the circuit-breaker and by the line parameters at the line side. As the largest impedance will be on the line side, the largest voltage excursion will also appear at the line side.

The out-of-phase current is, to a large extent, dependent on the out-of-phase angle and the length of the OH-line. Due to the traveling wave effects, the TRV at the line side will exhibit a triangular shape and its peak value can be calculated as twice the wave traveling time along the OH-line multiplied by the RRRV (rate of rise of the recovery voltage). The traveling time is proportional to the line length, but the RRRV shows a decreasing trend with increasing line length due to the decrease in out-of-phase current (I_{oop}). Specifically RRRV = fpcf * Zeq * dI_{oop}/dt where Zeq is the equivalent surge impedance. Due to the influence of the source impedances of both systems, the amplitude of I_{oop} is not inversely proportional to the line length. Therefore, the peak value of the line side TRV will still increase with an increasing line length. This effect, however, becomes smaller for OH-lines with longer lengths.

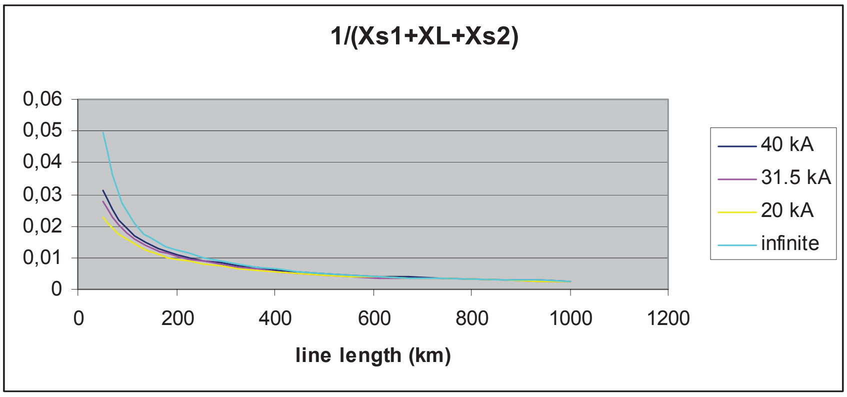


Fig. 6 Total admittance as function of line length

Figure 6 shows the total admittance of both systems and the interconnecting line as a function of the line length, for different (but arbitrarily chosen to be equal at both sides) source impedances of the systems; i.e. for 420 kV systems with a short-circuit power equivalent to short-circuit currents of 40 kA, 31.5 kA and 20 kA in comparison to infinite short-circuit powers.

In addition to the line side TRV, the busbar side TRV should be added. As I_{oop} is defined to be 25% of rating in the Standards and is often less than this in reality (15%), the system side TRV can be estimated to be 25% (15%) of the TRV associated with, for instance, T100. The peak value is then less than 0.37 pu (0.22 pu). For an OH-line with a length of 100 km, the return traveling time will be roughly 650 µs, close to T2, as defined for T100. For a 420 kV/40 kA circuit-breaker, the peak value of the total TRV will be close to 4.1 pu for I_{oop} = 25% and 2.5 pu for I_{oop} = 15% of the rated short-circuit current.

In figure 7, the TRV peak values (line side) as a function of line length are shown for the example above (figure 6). The out-of-phase currents are based on full phase opposition. As the TRV peak value at the line side is proportional to I_{oop}, it is also proportional to sin (½ψ).

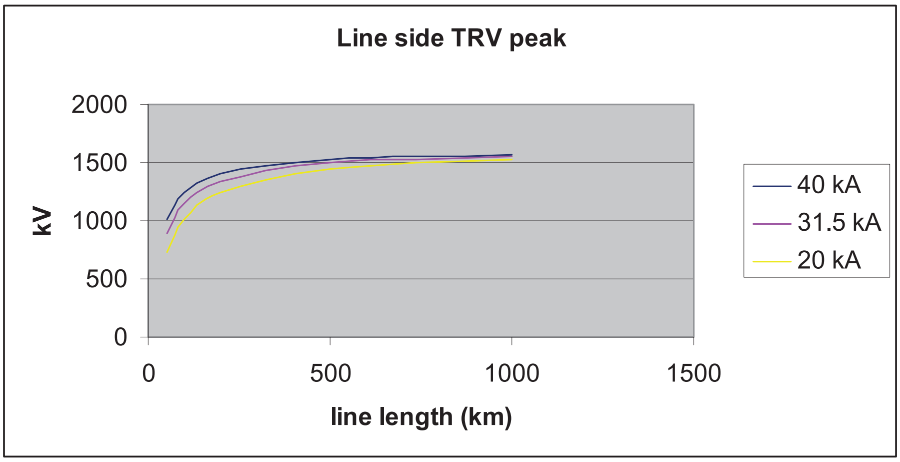


Fig. 7 Line side TRV peak value as function of length in a 420 kV-network

It can be concluded that the TRV peak values can be considerably higher than specified in the Standards (857 kV @ 1335 µs for a rated voltage of 420 kV), even when taking into account smaller out-of-phase angles. For instance with a line length of 200 km and source impedances corresponding to a short-circuit current of 20 kA, an out-of-phase angle of 120º will still give a line side peak value of 1075 kV. Combined with a system side RV of roughly 100 kV this results in a total TRV peak of 1175 kV. A line length of 100 km under the same conditions will give 875 kV at the line side and 975 kV in total. The IEC peak value of 857 kV is reached at out-of-phase angles as small as 75º and 90º for 200 km and 100 km lines respectively.

Calculations and simulations for real networks show out-of-phase TRV peak values as high as 3.3 to 3.5 pu [9] or even 3.9 pu [19] for very extended networks (hundreds of km, low currents) and 3.0 to 3.5 pu for meshed networks (hundred or less km, relatively high currents).

4. DIELECTRIC STRESSES ACROSS OPEN CONTACTS

During synchronization the longitudinal voltages applied to open contacts vary from zero to 2 pu in a periodic, beating pattern for periods of seconds or minutes. In case of frequent synchronisation, clause 2.3.2.4 of IEC 60071, part2 [13] recommends consideration of the occurrence of an earth fault during synchronisation (at one side!), thus leading to higher longitudinal voltages: up to 2.5 pu for a short time.

Clause 2.3.2.5 of [13] recommends careful examination of the probability of simultaneous occurrence of circumstances that lead to temporary overvoltages. Examples include an earth fault with consequential line tripping firstly at load side, load rejection with high overvoltage causing an earth fault, load disconnection under heavy pollution conditions, or a failure of a circuit-breaker to trip a line fault with a generator still feeding the earth fault. In such cases a careful system study is required.

Clause 2.3.2.2 of [13] indicates that full load rejection will lead to temporary overvoltages, which are normally less than 1.2 pu for moderately extended systems but which could reach values up to 1.5 pu for large extended networks and even more in case of (ferro)resonance. (Ferro)resonance, however, should be avoided and mitigation measures are suggested (cl. 2.3.2.3 and 2.3.2.6). The longitudinal overvoltages across the circuit-breaker open terminals are equal to the temporary overvoltages when the rejected load was of a static nature. But, in case of generators the longitudinal overvoltage can reach values up to 2.5 pu and in very extended systems even more. A power frequency longitudinal overvoltage as high as 2.5 pu is also given in clause D.1.3.2. of IEC 60694 [11].

With regard to the dielectric requirements under synchronising operations simultaneously with a substantial transient or temporary overvoltage, clause 4.2 of IEC 62271-100 [1] indicates that the standard requirements may be insufficient and the application of the requirements as specified for disconnectors across open contacts is recommended. In clause 4.2 of IEC 60694 [11] different requirements for the longitudinal withstand voltage across open contacts for the safety function (eg. disconnectors) and for the working function (eg. circuit-breakers) are specified for rated voltages ≤ 245 kV. The values given in column (2) of the tables 1a and 1b [11], applicable for rated voltages ≤ 245 kV, are used for the specification of the longitudinal requirements of circuit-breakers, while the values given in column (3) are used for the longitudinal requirements for disconnectors. For rated voltages ≥ 300 kV, the values of column (3) of the tables 2a and 2b are specified for the 1min power frequency type test across open contacts of both circuit-breakers and disconnectors, however the values of column (2) are accepted for routine tests. In the following table the power frequency short-duration withstand voltages are reported for some rated voltages for comparison, including the withstand voltages in pu. For rated voltages ≤ 245 kV, the highest class of insulation has been taken from table 1a, and for ≥ 300 kV the values given in table 2a:

Rated voltage (kV)	(2) 1min withstand (kV) +)	(2) 1min withstand (pu) +)	(3) 1min withstand (kV) Δ)	(3) 1min withstand (pu) Δ)
24	50	3.61	60	4.33
72,5	140	3.34	160	3.82
145	275	3.28	315	3.76
245	460	3.25	530	3.75
420	520	2.14	610	2.52
550	620	1.95	800	2.52
550 º	710	2.24	890	2.80
800	830	1.80	1150	2.49

º from table 2b: additional rated insulation levels in North America.
+) Specified for longitudinal insulation of circuit breakers with rated voltage ≤ 245kV
Δ) Specified for longitudinal insulation of disconnectors (all rated voltages) and of circuit breakers with rated voltage ≥ 300kV

IEC-Standard 62271-203 "Gas-insulated metal-enclosed switchgear for rated voltages above 52 kV" [17] (the previous Standard 60517), makes reference to these tables in IEC 60694 but for the highest rated voltages different short-duration power frequency withstand voltages are specified:

Rated voltage (kV)	(2) 1min withstand (kV)	(2) 1min withstand (pu)	(3) 1min withstand (kV)	(3) 1min withstand (pu)
420	650	2.68	815	3.36
550	710	2.24	925	2.91
800	960	2.08	1270	2.75

External and internal flashovers across the open contacts of EHV circuit-breakers have occurred in operation during synchronizing of generating units (due to contamined wet insulators in live tank circuit-breakers, due to failure of grading capacitor in dead tank breakers, etc.) or during the dead time before line automatic re-closure. These events generally cause a busbar fault, and also explosions of circuit-breaker poles. It is therefore necessary to specify the circuit-breakers to withstand with a reasonable margin the over-voltages liable to occur during these manoeuvres and to preserve this capacity in operation.

Some reported cases of circuit-breaker failures during synchronizing of generating units have been caused by flashovers on contaminated and wet external insulation of the interrupting chambers of live tank circuit-breakers, by failure of the grading capacitor in parallel with one of the contacts, or by inadequately specified power-frequency withstand voltage of circuit-breakers across open contacts eroded by aging or by other reasons. Rare flashovers across the open contacts of line circuit-breakers during the dead time before the automatic re-closure have been reported to be caused by multiple lightning strokes in absence of surge arresters or of special protective air gaps at the open line terminal [18]. Figure 8 shows a special protective gap shaped such as to minimize the influence of polarity and wave shape of LIs and SIs on flashover voltage and to provide a time to flashover shorter in the gap than in the protected open circuit-breaker. For decades, in Italy, there is very good service experience with the application of these special protective gaps.

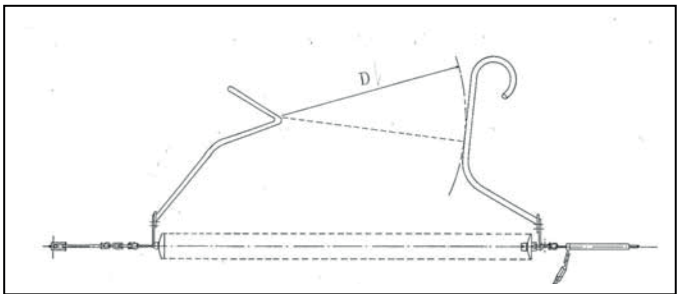


Fig.8 Special protective spark gap fitted in the line anchor insulator strings to substation gantry; D = 1700 mm° for 380 kV lines; D = 800 mm for 150 kV lines.

° SI 50% flashover voltage=1040 kV(3 pu)

In live tank circuit-breakers the external insulation between terminals is not energized when the circuit-breaker is closed. It is recommended that for the external insulation across open contacts of live tank circuit-breakers used for synchronizing, the withstand voltages as specified to column (3) of the tables 1a, 1b, 2a and 2b of IEC 60694 [11], should be withstood in a type test under wet test conditions and also under representative artificial pollution conditions.

All the dispersed statements in the Standards support the view point that with respect to out-of-phase conditions and synchronisation, circuit-breakers longitudinal dielectric withstand should be specified to column (3) rather than column (2) for all rated voltages.

5. OTHER CONDITIONS LEADING TO HIGH TRV PEAK VALUES

When clearing single or multi-phase faults distant from the substation on an OH-line (instead of at a short distance, as with short-line faults), the well-known triangular wave-shape of the TRV at the line side will rise to high values, depending on the wave travelling time from the circuit-breaker terminal up to the location of the fault and back. This phenomenon is known as long line fault (LLF) and has been discussed in [14]. As the time to the peak value of the TRV is rather long, it is comparable with the TRV for out-of-phase switching. Peak values of 2.4 pu have been reported [14] and LLF is a subject of study for CIGRE WG A3.19.

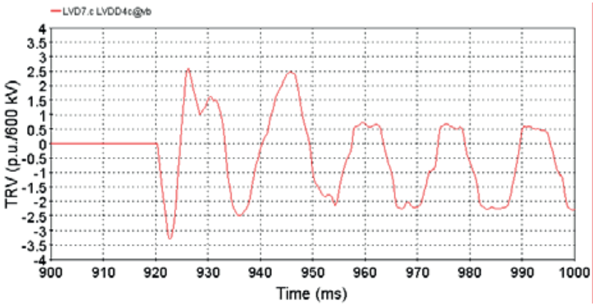
Clearing faults in series compensated OH-lines leads to TRV values in excess of the values specified in the Standards, due to the charging voltage on the series capacitor banks. Peak values of the TRV as high as 4.6 pu (420 kV-system in Turkey) and 4.8 pu (800 kV system in Canada) could be expected without certain countermeasures. By means of special MOSA with a low SSPL (switching surge protective level) of 1.57 pu, Hydro Québec manages to reduce the TRV peak value to 3.2 pu. In Turkey, MOV parallel to the arcing chambers of circuit-breakers have been applied successfully. Depending on the requirement of re-synchronisation by the circuit-breaker, the TRV peak can be reduced to 2.5 pu or 3.0 pu. These solutions lead nevertheless to TRV peak values comparable with or beyond those given before for out-of-phase conditions.

Although there is no real application of half-wave length lines (HWLL, 3000 km at 50 Hz; 2500 km at 60 Hz), a number of studies on over-voltages and TRVs have been performed for this interesting technology for long distance bulk power transmission. Simulations show that clearing faults in HWLL will lead to TRV peak values as high as 3.2 pu, again comparable with the TRV peak values mentioned before for out-of-phase clearing [9].

Another switching phenomenon giving high TRV values is the de-energization of unloaded OH-lines under high TOV (temporary overvoltages) conditions [15]. For the 800 kV system of Hydro Québec TRV peak values of 3.3 pu to 3.5 pu have been reported under such conditions; see figure 9b. [9]

Out-of-phase switching on series compensated OH-lines has not been addressed yet, but it is evident that the electrical charge on the series capacitors will add to the peak value of the TRV. Unfortunately, right at the moment of current clearing the voltage across the series capacitors is at maximum value, unless the capacitors have been by-passed by the self-triggered or forced triggered spark gaps. The situation is similar to clearing short-circuit currents. In modern series capacitors metal-oxide varistors are installed in parallel to the capacitor bank. Such varistors limit the voltage across the capacitor banks. Moreover special surge arresters connected phase-to-ground or varistors across the arcing chambers of the circuit-breakers are applied, thus limiting the total TRV peak value at clearing short-circuit currents and out-of-phase currents as well. The countermeasures for limiting the peak value of the TRV at clearing short-circuit currents are also effective at clearing out-of-phase currents; see figure 9a. [9]

a) Max. TRV stress due to out-of-phase clearing



b) Max. TRV stress due to de-energization of unloaded line under high TOV (p.u./600 kV)

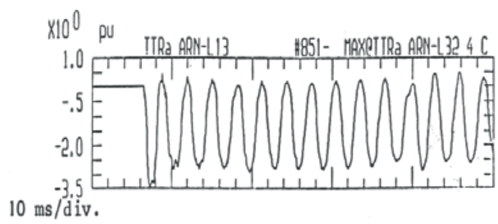


Fig. 9: Maximum TRV stresses due to out-of-phase clearing and de-energization of unloaded line under high TOV

6. CONCLUSIONS

- The Standards showed to be based on an out-of-phase angle substantially less than 180º, despite the fact that in many cases the angle will be random, ranging up to 180º. For generator circuit-breakers and special applications users already ask for out-of-phase angles of 180º.
- The RV in the Standards [1][4] is 2.0 or 2.5 pu respectively for systems with an effectively earthed neutral or a non-effectively earthed neutral with a TRV of 2.5 and 3.13 pu respectively.
- Both IEEE and IEC specify the RRRV of the TRV for out-of-phase switching to be lower than the RRRV specified for T100, whereas higher values occur in the systems. The RRRV for out-of-phase switching is considered to be covered by T30 (multi-part testing).
- Standardised TRV is based on system conditions in the absence of an earth fault. For situations with frequent out-of-phase switching and synchronisation, the Standards recommend to specify actual TRVs in the system (taking into account tripping and blocking relays for out-of-phase conditions when applied) and to adapt the requirements for the longitudinal dielectric strength accordingly.
- Under rather normal system conditions (no earth fault, no temporary overvoltages), full phase-opposition switching of a generating plant at the HV-side leads to TRV peak values in the range of 2.9 to 3.2 pu in systems with effectively earthed neutral and higher values for systems with un-earthed neutral. The peak values of the TRV as specified in the Standards, cover out-of-phase angles up to 90º or, in case of systems with unearthed neutral, even less (75º).
- For out-of-phase switching of OH-lines, calculations show peak values of the TRV from 2.5 pu (100 km length, I_{oop} = 15%) to 4.1 pu (100 km length, I_{oop} = 25%) and even beyond for longer line lengths, under full phase opposition. The Standards cover out-of-phase angles up to 90º (line length < 100 km) or up to 75º (line length < 200 km).
- During synchronisation, a longitudinal power frequency withstand test voltage larger than 2.0 pu, preferably 2.5 pu or even 3.0 pu, is a reasonable requirement for circuit-breakers used for that purpose. The related auxiliary components, such as grading capacitors, MOVs, insulating materials, external insulation, should be equally specified and tested.

- Under out-of-phase switching conditions the first-pole-to-clear factor is determined by the neutral status of the systems at both sides of the circuit-breaker, as shown by the double Neptune-scheme. Depression of the generator source voltage has to be taken into account, unless the rotor is equipped with fully laminated poles and a damper winding.
- False synchronisation, mal-operation of protection equipment and erroneous switching operations by operators [7], may lead to considerable damage. Re-strikes at clearing out-of-phase currents with large out-of-phase angles will also lead to comparable consequences. Developments in modern networks lead to a higher probability of the phenomena described: distributed generation leading to large power transfers, systems separation on overloaded OH-lines, large power swings due to tripped generation, etc.

7. RECOMMENDATIONS

- Utilities have to look carefully for such situations and, when applicable, put forward the appropriate requirements to the protection of involved equipment and switchgear.
- The present Standards do not give users clear and adequate support in specifying TRV-values for out-of-phase conditions, for clearing of fault currents flowing through series capacitors and for dielectric withstand requirements under synchronisation conditions. The requirements should be revised or more guidance should be incorporated to improve understanding.
- Since increased TRV requirements may lead to increased costs of circuit-breakers, enhanced out-of-phase requirements should be limited in their application or countermeasures to limit TRV should be used [9].

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