

# Transient Recovery Voltages During the Switching Under Out-of-Phase Conditions

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**Abstract** – Out-of-phase synchronising occasionally occurs in power stations, one of the main reasons being wiring errors leading to particular out-of-phase angles of 60°el., 120°el. or 180°el. The relevant standards IEEE Std C37.013 for generator circuit-breakers and IEC 62271-100 for high-voltage circuit-breakers consider only a maximum out-of-phase angle of 90°el. From the well-defined TRV (transient recovery voltage) parameters for system-source faults and generator-source faults also the TRV parameters for out-of-phase conditions can be deduced. This is done for three examples and the calculated TRV parameters are compared to those given in IEEE Std C37.013. For a 90°el. out-of-phase angle the rates of rise of TRV fit rather well; the calculated peak values are however smaller and the calculated out-of-phase switching currents are larger than given in IEEE Std C37.013. This standard does not at all cover the conditions at an out-of-phase angle of 180°el.. The situation seems to be still worse with IEC 62271-100 for high-voltage circuit-breakers.

**Keywords** – power station, out-of-phase conditions, generator circuit-breaker, high-voltage circuit-breaker, transient recovery voltage

## I. INTRODUCTION

Out-of-phase synchronising occasionally occurs in power stations [1, 2, 3]. The main reasons for out-of-phase synchronising are wiring errors made during commissioning or during maintenance when connecting voltage transformers and synchronising equipment. These wiring errors lead to particular out-of-phase angles, i.e. multiples of 60°el. E.g. polarity errors at a voltage transformer cause synchronising at 180°el. out-of-phase angle; phase connection errors lead to 60°el. and 120°el. out-of-phase angles.

Besides these particular out-of phase angles any value may be caused by inadequate settings of the synchronising equipment, e.g. due to an incorrect value of the closing time of the circuit-breaker.

The above mentioned aspects apply especially to generator circuit-breakers (located between the generator and the step-up transformer) but also to circuit-breakers at the high-voltage terminals of step-up transformers. All these circuit-breakers have to have the capability to interrupt out-of-phase currents. The corresponding breaking currents and TRV (transient recovery voltage) ratings are laid down in IEEE Std C37.013 [4] for generator circuit-breakers and in IEC Publication 62271-100 [5] for high-voltage circuit-breakers.

In [4] the breaking currents under out-of-phase condi-

tions are defined as 50% of the rated short-circuit breaking current of the circuit-breaker and in [5] as 25%. The TRVs in both standards are based on an out-of-phase angle of 90°el. only, which seems to be arbitrary.

On the other hand the conditions regarding switching of short-circuit currents are well-founded and very precisely defined.

In [4] two kind of terminal faults are distinguished:

- system-source fault (fault between the generator circuit-breaker and the generator)
- generator-source fault (fault between the generator circuit-breaker and the step-up transformer)

and corresponding TRV parameters have been assigned to these cases.

It seems to be logical that the two short-circuit cases should be consistent with the out-of-phase switching case since according to Figure 1 exactly the same components are involved, namely the generator, the generator circuit-breaker, the step-up transformer and the high-voltage system, and the same frequencies apply. This means that from the TRVs at short-circuit cases a) and b) the TRV for out-of-phase conditions can be deduced.

It is the purpose of this paper to check by means of a few typical examples whether this consistency exists.

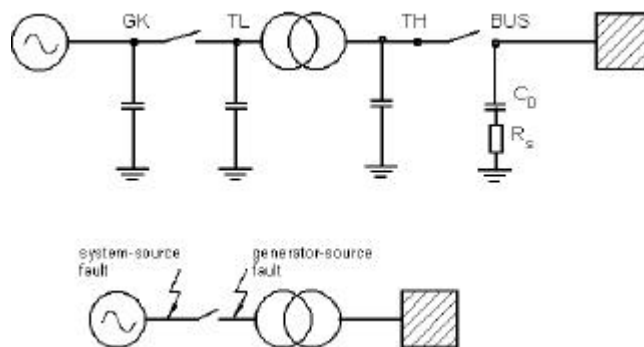


Fig. 1: Synchronising at MV side of step-up transformer

## II. TRVs FOR SYSTEM-SOURCE AND GENERATOR-SOURCE FAULTS

In power stations the system-source fault (fault between the generator circuit-breaker and the generator) normally yields the highest short-circuit current due to the small leakage impedance of the step-up transformer and the generally considerably smaller short-circuit impedance of the high-voltage system (referred to medium-voltage side of

the step-up transformer). This is more pronounced at smaller MVA ratings of the step-up transformer.

The TRV parameters for this case (Table 5 of [4]) are very severe regarding the steepness (due to high natural frequency of transformers) and the steepness increases with transformer rating.

Compared to this the generator-source fault (fault between the generator circuit-breaker and the step-up transformer) shows a smaller current and a less critical steepness of the TRV which rises too with the MVA rating of the generator (Table 6 of [4]). The smaller steepness of the generator-side TRV is mainly caused by the large winding capacitance of generators.

As a first step 3 typical and realistic transformer and generator data sets with system-source short-circuit currents of 80, 100 and 130kA at a rated voltage of 25.3kV have been chosen (Table I). The corresponding generator-source short-circuit currents are 64, 80 and 104kA.

Table I: Data for TRV analysis

Case	1	2	3
$V_{\text{rated}}$ [kV]	25.3	25.3	25.3
$S_{\text{Generator}}$ [MVA]	480	600	780
$I_{\text{sc, generator-source}}$ [kA]	64	80	104
$x_d'$ [p.u.]	0.171	0.171	0.171
TRV rate [kV/ $\mu\text{s}$ ] <sup>1)</sup>	2.0	2.0	2.0
$E_2$ -crest voltage [kV] <sup>1)</sup>	46.6	46.6	46.6
$T_2$ [ $\mu\text{s}$ ] <sup>1)</sup>	27.3	27.3	27.3
$S_{\text{Transformer}}$ [MVA]	480	600	780
$I_{\text{sc, system-source}}$ [kA]	80	100	130
$u_{\text{sc}}$ [p.u.]	0.1369	0.1369	0.1369
TRV rate [kV/ $\mu\text{s}$ ] <sup>2)</sup>	5.0	5.0	5.5
$E_2$ -crest voltage [kV] <sup>2)</sup>	46.6	46.6	46.6
$T_2$ [ $\mu\text{s}$ ] <sup>2)</sup>	10.9	10.9	9.9

<sup>1)</sup> according to Table 6 of [4]

<sup>2)</sup> according to Table 5 of [4]

From Tables 5 and 6 of [4] the corresponding TRV rates of rise,  $E_2$ -crest voltages and  $T_2$  are calculated and shown in Table I, too. It is to be noted that these TRV ratings correspond to the first pole to clear a three-phase grounded fault. The components connected to the other side of the three-phase grounded fault do not play any role for the TRV, in contrary to a three-phase ungrounded fault which would show a higher steepness of the TRV.

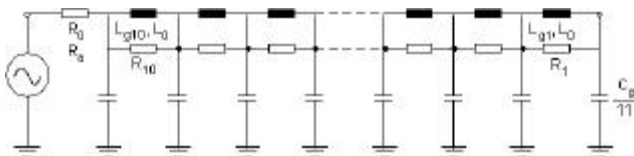
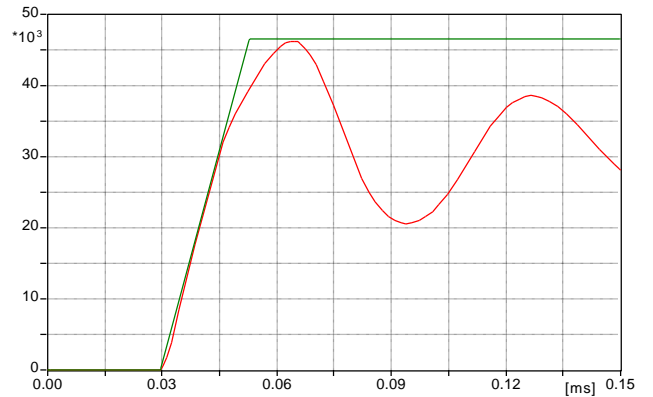


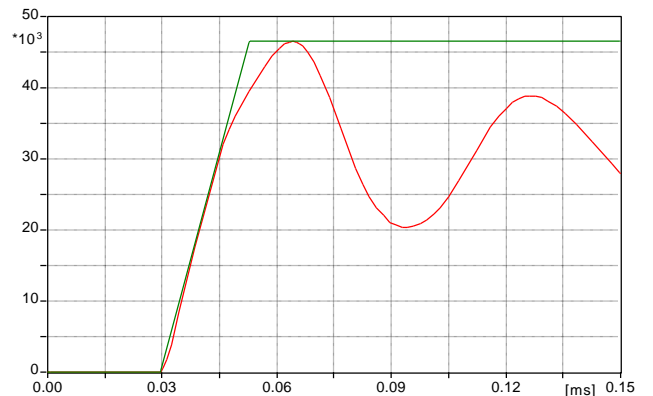
Fig. 2: Model for generator

A three-phase generator model (Figure 2) providing the correct generator-source short-circuit current has been established consisting of 10 positive and zero sequence in-

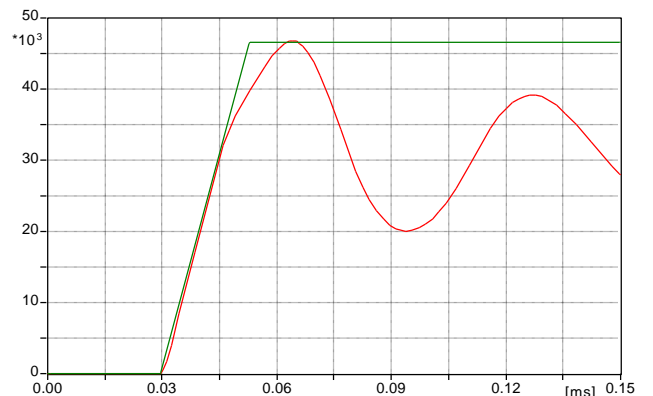
ductances, paralleled by resistance elements and 10 capacitance-to-ground elements (all per phase). For calculating the TRV shapes the Alternative Transients Program [6] has been used. The inductance elements determine the short-circuit current. The capacitance and resistance elements have been adapted to result into the required TRV shape for the first pole-to-clear in case of an interruption of a three-phase ground fault.



a) TRV for case 1 (envelope acc. to Table 6 of [4])



b) TRV for case 2 (envelope acc. to Table 6 of [4])



c) TRV for case 3 (envelope acc. to Table 6 of [4])

Fig. 3: TRV shapes for generator-source fault

Figures 3a), b), and c) show the simulated TRV shapes for the generator-source fault. The generator model used does not claim to represent the generator correctly in the

total frequency range but it shows a perfect behaviour regarding the TRV during three-phase fault conditions. The model has been deduced from measured TRVs of generators. It should be noted that even the bend during the first rise of the TRV typical for three-phase grounded faults is correctly reproduced by this model (Figure 4); the TRV of ungrounded faults would show a straight line up to the peak.

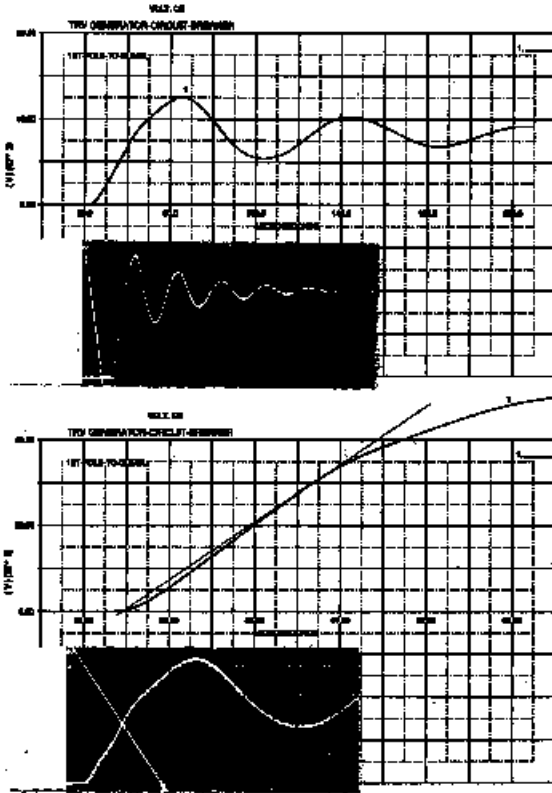


Fig. 4: Comparison between measured and calculated TRV

The corresponding model for the step-up transformer is shown in Figure 5. It consists again of 10 modules per phase, in this case 10 series connected single-phase transformers paralleled by resistors at the medium-voltage side, capacitances to ground both at the high- and medium-voltage side and coupling capacitances between the high-voltage and the medium-voltage side. The impedance of the high-voltage system has been considered to be included in this scheme. Actually the high-voltage system feeding the step-up transformer will have a considerably smaller natural frequency than the transformer leading to an equivalent circuit with two natural frequencies. This has been taken into account by a modest amplitude factor of 1.5 for the single frequency circuit specified in [4], Table 5. Hence it seems to be justified to include the impedance of the high-voltage system in the transformer model. The high-voltage side neutral of the step-up transformer of vector group Yd is grounded.

The parallel elements of Figure 5 have been adapted to provide the correct TRV shapes like for the generator-source fault.

Figures 6a), b), and c) show the simulated TRV shapes for the system-source fault.

Similarly as for the generator model it must be emphasised that this transformer/system model is valid only for a restricted frequency range, namely up to the frequencies associated with TRVs at short-circuit interruptions.

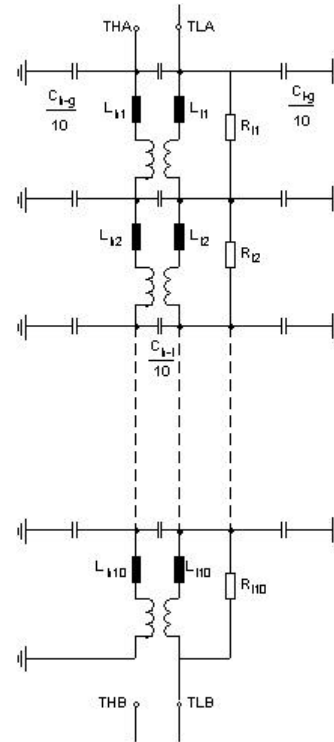


Fig. 5: Model for step-up transformer

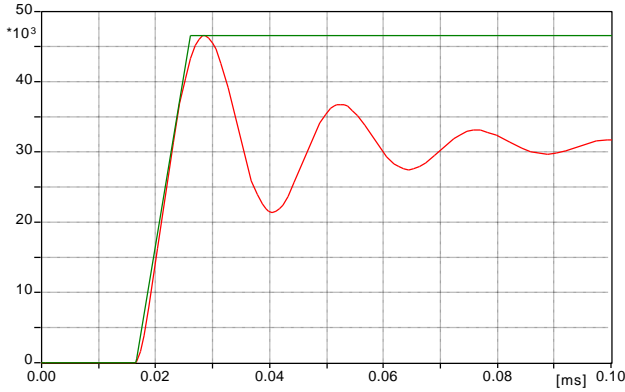
### III. CURRENTS AND TRVs FOR OUT-OF-PHASE CONDITIONS AT MV SIDE OF STEP-UP TRANSFORMER

It is obvious that for out-of-phase current switching the same models must be valid since the only condition changed is the angle of the voltage and the absence of a short-circuit. For a 180°el. out-of-phase angle the TRV plots for the 3 cases are shown in Figures 7a), b), and c), respectively, and the corresponding evaluation is given in Table II.

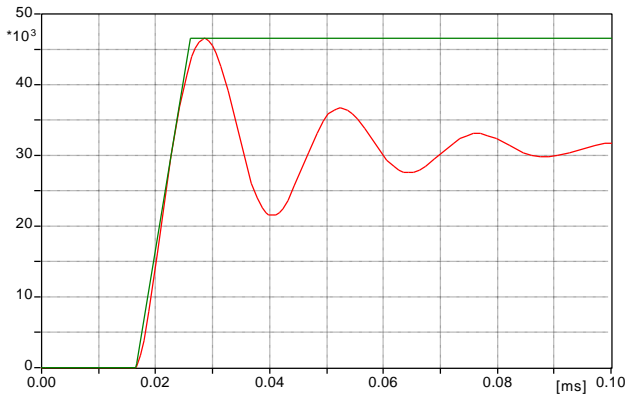
Table II: Out-of-phase switching - comparison of TRV

Case	1	2	3
TRV data according to [4], Table 9			
TRV rate [kV/μs]	4.7	4.7	4.7
E <sub>2</sub> -crest voltage [kV]	65.8	65.8	65.8
Out-of-phase current [%]	50	50	50
TRV data calculated for 180°el. out-of-phase angle			
TRV rate [kV/μs]	6.7	6.5	7.0
E <sub>2</sub> -crest voltage [kV]	85.7	85.8	84.1
Out-of-phase current [%]	89	89	89
TRV data calculated for 90°el. out-of-phase angle			
TRV rate [kV/μs]	4.5	4.4	4.8
E <sub>2</sub> -crest voltage [kV]	60.6	60.7	59.4
Out-of-phase current [%]	63	63	63

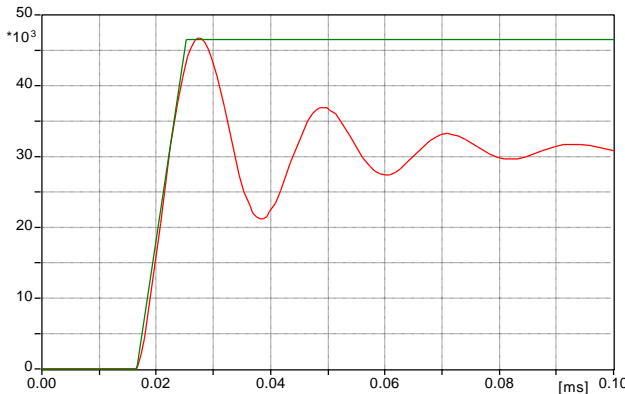
As to be expected far more severe TRV parameters result than those given in Table 9 of [4]. It is interesting to note that the out-of-phase current in this case is 89% of the system-source short-circuit current, i.e. it is quite close to the rated short-circuit current of the generator circuit-breaker.



a) TRV for case 1 (envelope acc. to Table 5 of [4])



b) TRV for case 2 (envelope acc. to Table 5 of [4])

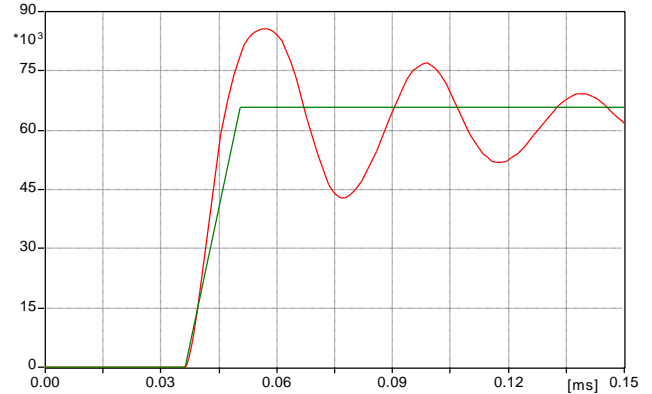


c) TRV for case 3 (envelope acc. to Table 5 of [4])

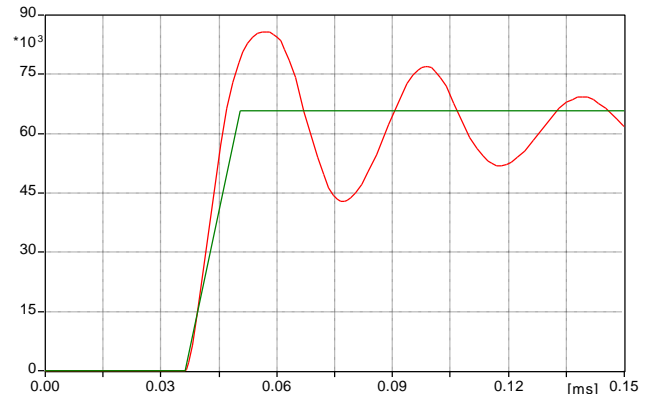
Fig. 6: TRV shapes for system-source fault

For the case given in [4], i.e. an out-of-phase angle of  $90^\circ$ el., the out-of-phase current is  $1/\sqrt{2}$ -times smaller. The TRV shapes are proportional to those of Figures 7a), b), and c) again with a proportionality factor of  $1/\sqrt{2}$ . In Table II also the results of the simulation for a  $90^\circ$ el. out-of-

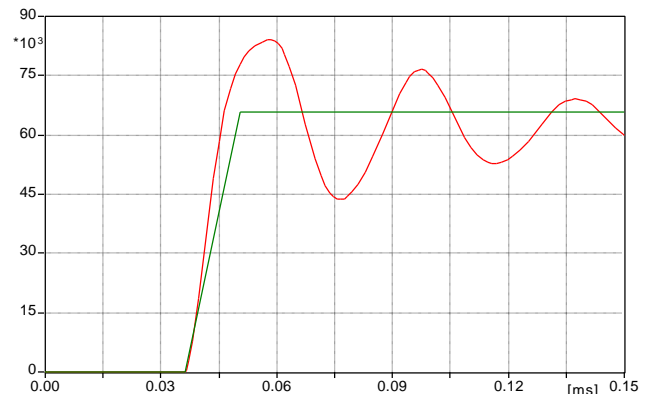
phase angle are compared to the TRV parameters given in [4]. The steepnesses fit quite well, the voltage peaks of the simulations are smaller however. This is caused by the difference in the natural frequency of the generator and the step-up transformer and should be taken into account in a future revision of [4].



a) TRV for case 1 (envelope acc. to Table 9 of [4])



b) TRV for case 2 (envelope acc. to Table 9 of [4])



c) TRV for case 3 (envelope acc. to Table 9 of [4])

Fig. 7: TRV shapes for  $180^\circ$ el. out-of-phase condition

#### IV. TRVs FOR OUT-OF-PHASE CONDITIONS AT HV SIDE OF STEP-UP TRANSFORMER

Analogous to the case of the generator circuit-breaker the TRV requirements for the circuit-breaker at the high-

voltage terminals of the step-up transformer may be deduced. The same synchronising errors can occur at this location, hence a 180°el. out-of-phase angle is possible as well. The corresponding scheme is shown in Figure 8.

The highest short-circuit current through the circuit-breaker is normally delivered by the system (fault between the high-voltage circuit-breaker and the step-up transformer) which corresponds to test duty TD100 and TRV-requirements according to Tables 1b, 1c and 1d of [5]. For rated voltages of 100kV and above the rate of rise of the TRV is given as 2kV/μs and the TRV shape as a four-parameter curve with a peak value of  $1.4 \cdot 1.3 \cdot \sqrt{2} U_n / \sqrt{3}$ .

A generator-source fault (fault between the high-voltage circuit-breaker and the high-voltage system) comprises in this case the generator impedance and the transformer impedance leading to a substantially smaller short-circuit current than for the system-source fault. This case is covered by the test-duties TD10 and TD30 of [5], i.e. short-circuit currents of 10% and 30% of the rated short-circuit breaking current.

The corresponding TRV parameters are laid down in Tables 14a and 14b of [5]. Especially high rate of rise values and high amplitude factors are assigned to test duty TD10; they are meant to represent the high natural frequencies and the low damping of transformers. These high rate of rise values and even higher amplitude factors would also prevail in case of out-of-phase switching, since the voltage drop mainly appears across the generator and the step-up transformer.

The out-of-phase breaking current according to [5] is 25% of the rated short-circuit breaking current which is fairly in line with the considerations above. In contrast to this the TRV parameters for out-of-phase conditions given in [5] are extremely modest (1.54kV/μs in the voltage range =100 kV) and do not seem to be adequate.

Basically the same procedure as described in Section III could be applied for the determination of the TRV parameters for out-of-phase switching with high-voltage circuit-breakers.

Due to a multitude of cases and combinations to be considered such an analysis is beyond the scope of this paper.

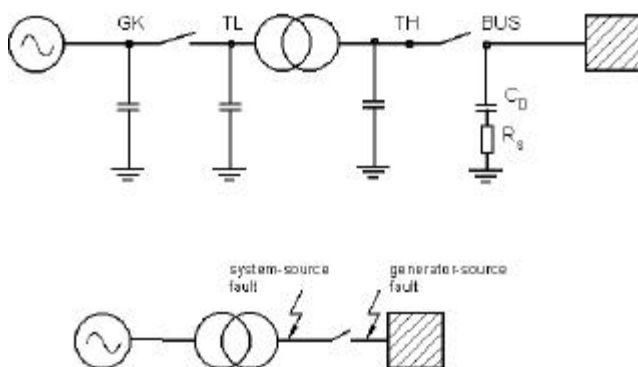


Fig. 8: Synchronising at HV side of step-up transformer

## V. CONCLUSIONS

The TRV requirements of IEEE Std C37.013 [4] regarding out-of-phase switching have been analysed based on three examples. The following conclusions may be drawn from the results obtained:

- The out-of-phase TRV parameters and switching currents specified in [4] are restricted to an out-of-phase angle of 90°el. From the point-of-view of possible wiring errors causing synchronising faults this angle seems to be arbitrary and inadequate. The most severe case is an out-of-phase angle of 180°el..
- Since the TRV parameters for system-source faults and generator-source faults are well defined in [4], the corresponding TRV parameters for out-of-phase switching follow necessarily from that data.
- For the three examples appropriate models have been chosen to represent the TRV behaviour of the system source faults and the generator-source faults. TRV calculations for these models at 90°el. out-of-phase conditions show a good fit with [4] regarding steepness; the peak value is only about 90% of [4] however. At 180°el. out-of-phase angle the steepnesses and peak values are  $\sqrt{2}$ -times higher than at 90°el..
- The out-of-phase switching current specified in [4] amounts to 50% of the short-circuit breaking current. The examples show higher values of 63% at 90°el. and 89% at 180°el..
- Based on these findings it seems to be advisable to revise the out-of-phase switching requirements given in [4].

Similar considerations apply to IEC 62271-100 [5]. This standard applies to high-voltage circuit-breakers, i.e. in the case considered to the circuit-breaker at the high-voltage terminals of the step-up transformer. The required out-of-phase switching current of 25% of the short-circuit breaking current fits with practical data. The TRV requirements however seem to be far too low regarding steepness as well as amplitude.

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