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Switching of elevated electromagnetic and electrostatic induced currents in multi-circuit, multi-voltage HVAC transmission lines

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***Abstract*—This paper presents a future-proof switching procedure for the switching of increasing electrostatic (e.s.) and electromagnetic (e.m.) induced currents with a line side earthing switch. The induced currents are becoming much higher than stated by IEC-standards due to increasing line current and the use of combined (un-transposed) overhead lines. Notorious are overhead lines with different voltage levels combined at single pylons. This adapted switching procedure becomes even more important due to the increasing amount of Gas Insulated Switchgear (GIS) being introduced in the grid.**

Keywords— electrostatic and electromagnetic induced current switching, combined overhead lines, energy transition, transposition

I. Introduction

TenneT TSO operates the Dutch onshore 110 kV, 150 kV, 220 kV and 380 kV grid. Due to the energy transition the operation of the grid is changing tremendously, requiring changes in the grid structure and operational procedures.
The trend of increasing the nominal current, refraining from transposing and shortening the distance between the circuits results in several issues that needed further study and operational adaptations, being:

1) Personal safety: high voltages and currents in de-energized circuits may jeopardize line workers.
2) Protection: There is a risk of protection malfunction such as failure to operate or unexpected operation.
3) Voltage unbalance: grid code limits may be exceeded. [1]
4) Earthing switches: Induced currents and voltages in EHV and HV overhead lines may exceed the capabilities of these components.

This paper concerns the switching of the increased induced current by the line side earthing switches.

II. The Issue – The Introduction of Compact Combined Overhead Line Configurations

In total TenneT is confronted with the following issues:

- Due to space restrictions, circuits at different voltage levels (HV and EHV) are combined at single towers as shown in figure 1.
- The combined line configuration is as compact as possible to reduce the magnetic field at ground level.
- The distance between the phases and between the different circuits are reduced.
- For the transport of off-shore wind energy longer distances need to be bridged.
- The currents for the transport of the off-shore wind energy are much higher than for normal operation (Highway versus Ring road).
- Un-transposed phases due to the construction of the pylons with the phases positioned above each other.

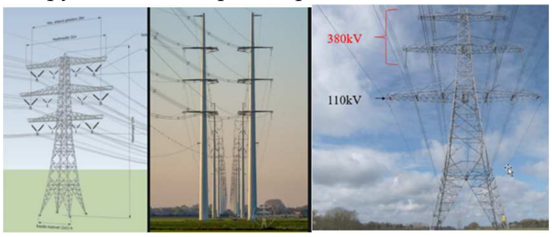

Figure 1: Three types of pylons applied in case of combined circuits: a) Moldau type lattice pylon, b) Wintrack pylon (TenneT design), c) Danube (Donau) type lattice pylon

III. Electrostatic and Electromagnetic Induced Current Switching with the Line Side Earthing Switch

A. Why combined overhead lines

In case of a pylon with two 380 kV circuits and two 150 kV circuits at close distance both the required land space and the magnetic field will be reduced. However, as a disadvantage these systems have higher mutual coupling, which results in higher induced currents (at higher induced voltage) on the earthing connections. This affects the switching of the line side earthing switches when one of the connections must be earthed (at both sides), for working in the substation (bay) or in the overhead line. For the to be built connections between Rilland and Tilburg, the amplitudes of these induced currents and voltages have been calculated and verified with earlier measurements in other Dutch connections.

B. Switching of electrostatic and electromagnetic induced current switching

Consider, for simplicity, two single phase overhead lines in parallel, A and B. Line A is in service at a voltage of 380 kV, with a load current of 2000 A. Line B is switched off and is not earthed yet. Line B is then capacitively charged (electrostatic (e.s.) induced) and attains a certain (capacitively induced) voltage. If the earthing switch at one side closes, it will close on this capacitive induced voltage and a capacitive current will flow through the earthing switch. The current level depends on the length of the lines in parallel. At the same time a magnetic induced voltage will be present at the open end of the line.

If the second earthing switch, at the other side of the line, closes, a loop is closed. In this loop an electromagnetic (e.m.) current is induced, which amplitude depends on the current in line A. This second earthing switch needs to close on this electromagnetic induced current.

The explanation above becomes more complex in case of more parallel circuits. In case of un-transposed lines (within TenneT-NL a common practice for combined circuits) the values of induced currents and voltages become significantly higher than the common IEC rating for earthing switches.

In case the earthing switch is not rated for this performance, the following risks might appear:

- The lifetime of the earthing switch is reduced as the (arcing) contacts age faster.
- Increased pollution due to prolonged arcing at a higher current, potentially affecting the dielectric withstand capability.
- Frightening noises when operating the earthing switches due to long arcing length and arcing time.
- Standard earthing switches are not designed and tested to carry a relatively high continuous current over a long time span.
- Especially in GIS, flashovers may occur to the enclosure, resulting in internal arcing and an unusable bay for a longer period.

C. *IEC Rating of the earthing switches*

Earthing switches have ratings for switching e.m. and e.s induced currents for the most common configurations, being one pylon with two circuits of equal voltage level and regular transposition, see table 1. However, these ratings do not consider un-transposed and/or multi-voltage systems.

Rated voltage[1] [kV]	Electromagnetic coupling (inductive coupling)		Electrostatic coupling (capacitive coupling)	
	Rated induced current [A]	Rated induced voltage [kV]	Rated induced current [A]	Rated induced voltage [kV]
170	80	2	3	9
420	160	10	18	20

Note: given values are for class B (the higher rating)

Table 1: Highest induced current and voltage ratings, class B according to IEC 62271-102 [2] for earthing switches.

Therefore, the induced voltages and currents in case of multi-voltage overhead lines were calculated, to substantiate the necessary precautions to be taken. The calculations were based on the Moldau-type configurations (see figure 1a). However, the conclusions and advised precautions need to be introduced for other configurations, such as Wintrack-type (see figure 1b) multi-voltage systems, as well.

IV. The calculations

Simulations were made based on the planned connection between Rilland and Tilburg, for which Moldau-type pylons (see figure 1a) are to be used with circuits at 380 kV (outside) and at 150 kV (inside). No intermediate substations at 380 kV are planned and at 150 kV several substations are planned in which a transposition can be arranged. Following the realistic locations for transposition, these calculations were based on non-ideal transposition at 380 kV (3 sections, 14,3 km (20,8%), 34,5 km (50,4%), 19,7 km (28,8%)), and at 150 kV with 13 proposed transpositions, mainly in the intermediate substations. Transposition in the sections between the substations was not taken into account.

Calculations were made based on:

- Un-transposed lines for the complete length.
- Transposed lines based on realistic transposition locations, so with unequal shares.
- A total length of 50 km.
- Continuous currents of 4000 A at 380 kV and 1925 A at 150 kV (being the maximum values).

Table 2 shows the maximum values of induced voltage and induced current in case of both no transposition at 380 kV and no transposition at 150 kV compared to both transposition at 380 kV and at 150 kV. The extreme values of induced voltage and current are shown, not always occurring in the same configuration.

	IEC rating	Calculated non-transposed, both 380 kV as 150 kV	Calculated transposed (non-ideal: RLL-GTB-TLB) and 150 kV
Source	IEC 62271-102 Tab 8, Class B	**2021-02-22** First parameter variations RS4_Rev02.pdf	**2021-04-01** RLL_TLB Findings RS3-RS4-RS5 Rev03.pdf
380 kV			
e.s.	20 kV / 18 A	12,5 kV / 2 A	4.3 kV / 35 A
e.m.	10 kV / 160 A	5 kV / 296 A	7.4 kV / 172 A
150 kV			
e.s.	9 kV / 3 A	56 kV / 9 A	2.3 kV / 14 A
e.m.	2 kV / 80 A	14 kV / 820 A	2.0 kV / 165 A

Table 2: Results of the calculation compared to IEC ratings

A. *As a brief conclusion:*

- The e.s. induced current depends on the length of the lines (capacitive charging current increases with line length). The voltage remains roughly the same (independent of the line length).
- The e.m. induced current depends on the "supplying" current in the other lines and is much higher than rated, even in case of (unequal) transposition. The induced voltage increases with the length. However, the induced current amplitude

remains roughly the same, independent of the line length (the loop increases with increasing line length and so does the inductance).

- Applying transposition reduces the induced currents and voltages.

Some further notes on the calculations:

Note 1: Also the induced current and voltage in case the three phases do not open or close simultaneously were verified. As the difference between simultaneous and non-simultaneous switching is not that high, the highest values were taken.

Note 2: The connection between Rilland and Tilburg at 150 kV will partly be using short cable sections. The effect of these cable sections has not been taken into account.

V. Validation of the Calculations

TenneT-NL already has implemented multi-voltage towers based on un-transposed Danube- and Wintrack-pylons. Already before the initiation of the calculations for the connection Rilland-Tilburg, indicative current measurements were performed at an un-transposed Wintrack-configuration (380 kV and 150 kV) and on an un-transposed Danube-configuration (380 kV and 110 kV) in the North of the Netherlands. During these measurements switching was not allowed, so only the (static) induced currents could be measured and not the induced voltage, see table 3. However, these measurements give a good indication that the calculated values are within the same order of magnitude. Therefore it was concluded that the calculated values for the induced voltage are reasonable and provide a motivation for the proposed measures.

Type of pylon	Length of parallel circuits	Measured current at 380 kV	Measured current at 110/150 kV circuits	Calculated current at 110/150 kV circuits*
Win-Track	17 km	~450 A	~33 A	~293
Danu-be	48 km	~970 A	~40 A	~165

*Table 3: Measured induced currents on Wintrack and Danube type overhead line circuits. *based on 4 kA at 380 kV*

A. Wintrack-combination

Considering no further increase of e.m.-induction in case of a longer line, and considering a load current of 4000 A at 380 kV, the estimated induced current would roughly be 330 A at 150 kV. This is less than the induced current as calculated for the Moldau-type pylon, but still much higher than rated according to IEC [2] (80 A).

B. Danube-combination

In the North of the Netherlands TenneT possesses combined systems of 48 km in length, 380 kV and 110 kV. Also there the e.m. induced current at 110 kV has been recorded. With 970 A at both 380 kV circuits, and 193 A at the other 110 kV system, an e.m. induced current of 40 A was measured at 110 kV. With 4000 A at the 380 kV circuits, the induced current would have been 165 A. During this measurement the e.s. current was recorded as well, being 2.1 A max over 48 km.

VI. Conclusions from the Calculations and Measurements

- The measured values validate the calculated values.
- The solution for switching e.s. and e.m. induced currents for Moldau-type overhead lines must be introduced for Wintrack-type combined systems as well.
- Based on standard ratings, the existing earthing switches are not suitable to switch (open and close) this higher (than rated) induced current at the higher induced voltages.
- The switching needs to be done with either the already installed and suitable circuit breaker, requiring a new switching order to be introduced, or with a suitable earthing switch that is able to switch these high induced currents and voltages (to be designed and tested). The latter is the preferred solution. However, this requires the development of new components (for TenneT-NL only) including an adapted control sequence as well.
- These measures are required for un-transposed and for transposed systems. Transposing reduces the induced current and voltage. The applied ratings are however still not fulfilled in this combined configuration.
- The earthing switches must also be able to carry a higher than rated e.m. induced continuous current.
- In the meantime, precautions shall be taken for all GIS substations, especially at 150 kV and 110 kV, for which the e.m. induced current is too high for the line side earthing switch, by:
  - Verifying the condition of these earthing switches.
  - Providing additional earthing of the particular bays by additional earthing switches or earthing rods outside the GIS, as will be explained further in this report.

Possible solutions to become future proof

A study was performed to look for the best, easiest and cheapest solution to deal with the switching of the higher induced currents and voltages, being:

1. Switch off the adjacent circuit in case of earthing a circuit. Unfortunately such planned outage is not allowed anymore as this connection Rilland-Tilburg is the highway for offshore energy into the Dutch grid. If one circuit is switched off (and earthed) the other shall remain in service.

2. Do not apply un-transposed systems, as transposition reduces the amplitude of the induced current and its induced voltage. However, regarding the e.m. and e.s. induced current switching still measures must be taken. TenneT has changed its policy and requires transposition in all new circuits.
3. Develop earthing switches that are able to switch these increased induced currents. Manufacturers are however not focused on developing such devices, especially not for GIS.
4. Request manufacturers to design earthing switches that can carry the high(er) induced current continuously. This is the easiest part of the request, as silverplated contacts normally are able to carry these increased induced currents.
5. Bypass the switching operation to a special designed by-pass switch or circuit breaker that is able to switch these higher currents.

Meanwhile TenneT owns combined multi-voltage, multi-circuit overhead lines for which the earthing switches are unsuitable.

VII. Proposed and Accepted Solution

The existing earthing switches, based on IEC-ratings, are not fulfilling the requirements for the switching of these induced currents. Also, manufacturers are not focusing on designing earthing switches suitable for these higher induced currents and voltages. Thus, especially in case of GIS, the only practical solution is the changing of the switching order and letting the existing circuit breaker do the switching.

Normally the induced currents are switched by the line side earthing switch after the circuit breaker with the line side disconnector in open position. Switching the induced current by the circuit breaker means that the settings of the control system needs to be revised. This can be done as follows, based on a normal Bay, shown in figure 2:

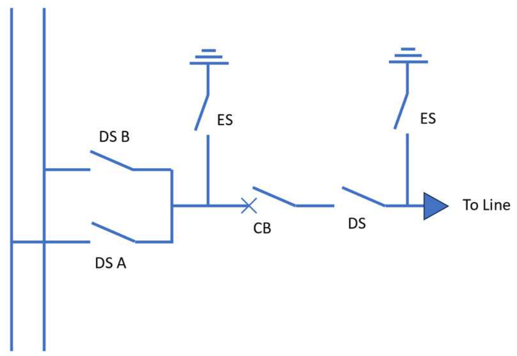

Figure 2: Single line diagram of standard bay in the Netherlands. DS = Disconnecting Switch, ES = Earthing Switch, CB = Circuit Breaker

Consider the line as being connected to the system and finally this line must be isolated and earthed:

1. Open the circuit breaker.
2. Open both busbar disconnector switches.
3. Close the earthing switch between circuit breaker and busbar disconnectors.
4. Close the circuit breaker. Now the overhead line is earthed.
5. Close the line side earthing switch in parallel with the earthing switch between circuit breaker and busbar disconnectors.
6. Open the circuit breaker, all induced current is transferred to the line side earthing switch
7. Open the line side disconnector. Now the overhead line is isolated and earthed.

VIII. Conclusion

As an advise: For simplicity of procedures it might be good to always implement above procedure in case of multi-voltage systems and the higher induced currents and voltages. However:

- AIS: some earthing switches may be able to switch these currents (e.s. and e.m induced currents or the e.s. induced current only) several times without serious damage.
- GIS: nowadays the line side earthing switch is able to close at applied voltage and able to withstand the short circuit current caused by this closing. So this type of (high speed) earthing switch will also be able to close at the induced currents. However, this type of earthing switch normally will not be able to switch off these induced currents.
- In the future, components may be replaced and new components may not be able to switch (e.g. replacing AIS with GIS). Thus, it would be good to introduce this switching by circuit breaker independent from the actual design of the particular bay.
- Although the induced current and voltage might be acceptable for now, due to the energy transition the continuous current may increase over time. Thus, also in this case introducing this switching order makes a substation future-proof.
- Combined line side earthing switches and disconnector switches shall not be applied as the proposed switching sequence is not possible with these devices.

Advise in one sentence: It is advised to apply the final method at all locations where combined systems have been or might be installed. This even counts for the most common connections with two circuits on one pylon.

References

[1] Jeroen van Waes, Frederik Groeman, Tam Mai, Kees Koreman, 'Voltage unbalance in overhead lines with EHV and HV circuits combined in the same tower.', Cigre Paris 2024, ID: 10509, unpublished

[2] IEC 62271-102:2018, 'High-voltage switchgear and controlgear – Part 102: Alternating current disconnectors and earthing switches.'