Challenges and Mitigations for the Energization of Large Offshore Grids in the Netherlands

K. Velitsikakis, C.S. Engelbrecht, K. Jansen, B. van Hulst

***Abstract*-- TenneT, the Dutch Transmission System Operator, is realizing the connection of large offshore wind farms to the 380 kV transmission network. Dedicated offshore grids consisting of long AC submarine cables will facilitate these connections. Such an offshore grid imposes great challenges to the TSO that are related to power quality aspects, e.g. amplification of background harmonics and harmonic emissions, as well as to insulation coordination aspects, e.g. temporary overvoltages. In addition, the energization procedure of the offshore grid should be operated in such a way that the defined compliance criteria are not violated. This paper presents the results of the detailed energization study of an offshore grid, as performed in EMTP/ATP. The application of pre-insertion resistance as remedial measure was deemed necessary to mitigate possible violation of the compliance criteria.**

***Keywords*: Offshore grid, energization, current zero-miss, temporary overvoltages, TOVs, EMTP/ATP**

I. Introduction

In the Netherlands, there is a drive to increase the contribution of renewable sources to the total energy supplied into the Dutch energy grid. According to the future planning, a large portion of this energy will be generated by large offshore wind farms (OWF) in the North Sea. TenneT is currently realizing the offshore electrical infrastructure to connect several OWFs to the onshore grid (project "Grid at Sea") and, more specifically, to the West part of the country. As a general scheme, each offshore AC collection platform will have an installed capacity of 700 MW and it will be connected to the 380 kV transmission system by means of two 220 kV_{AC} export cables. Figure 1 illustrates the 380 kV substations (Borssele, Maasvlakte, Beverwijk) that will form the connection points for each of the three OWFs, as well as the approximate distance of the offshore platforms to the coast.

International guidelines [1] and studies [2-7] have shown that long AC cable connections at the transmission level introduces new low resonance frequencies in the profile of the network harmonic impedance close to the 2^{nd} or 3^{rd} harmonic. Network contingencies could result in a resonance shift towards 100 Hz; such an onerous resonance condition could be excited by switching events in the system that include power transformers and could lead to temporary overvoltages (TOVs). The latter imposes an important challenge to the energization procedure of an offshore grid consisting of long AC export cables. Additionally, during the energization procedure of an offshore grid, issues could arise related to compliance with power quality requirements (e.g. fast RMS voltage variations) and to the reliability of the system (e.g. current zero-miss).

This paper presents the challenges met, when studying the energization process of the offshore grid to be connected to the Maasvlakte substation. Furthermore, the selection approach for applying mitigation measures to avoid possible non-compliance with the criteria set by TenneT is presented. The study was performed based on detailed electromagnetic transient models developed in EMTP/ATP to represent the offshore grid and a significant part of the transmission network [8].

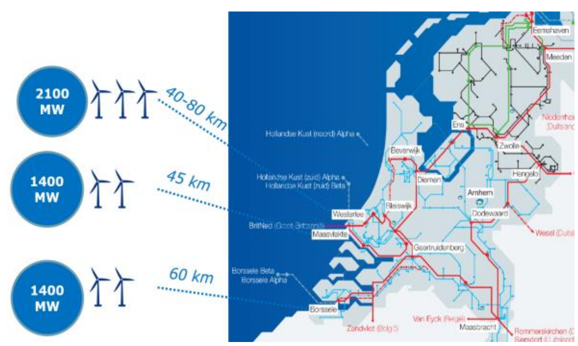

Fig. 1. Connection points of three offshore grids to the 380 kV Dutch transmission system

II. Description of the System

The offshore grid towards the wind area called "Hollandse Kust South", will be connected to the Maasvlakte 380 kV substation. The installed capacity of the OWFs will be 1400 MW and it will be collected by the 66 kV inter-array cables, which will be connected to two offshore platforms. Four 220 kV_{AC} export cables will connect the offshore platforms to the Grid at Sea landing point station; each export cable will be compensated by means of a shunt reactor at the 220 kV onshore side. At the landing point station, each string will be connected to a 400 MVA 380/225/33 kV autotransformer. At the tertiary winding of each onshore auto-transformer, both a 65 Mvar shunt reactor and a 32.5 Mvar capacitor bank will be connected. These units will provide additional reactive power support within the offshore grid, depending on the generated wind power levels.

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The 380 kV landing point station will be connected to the Maasvlakte 380 kV substation via two 380 kV_{AC} underground cables 4.2 km long each. A simplified single-line diagram of the offshore grid and the landing point station is illustrated in Figure 2, where the length of each export cable is shows as well.

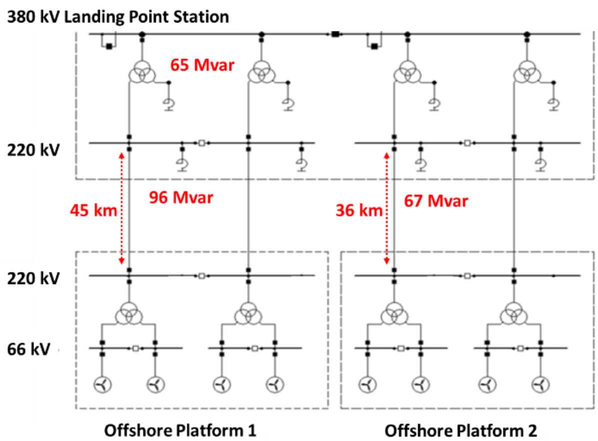

Fig. 2. Single-line diagram of the offshore grid

The EMTP/ATP network model represented in detail the offshore grid up to the offshore transformers, i.e. the 66 kV inter-array cables and the wind turbines were not considered in the model. Moreover, a significant part of the 380 kV and 150 kV transmission system was modelled; Figure 3 illustrates a simplified representation of the transient model.

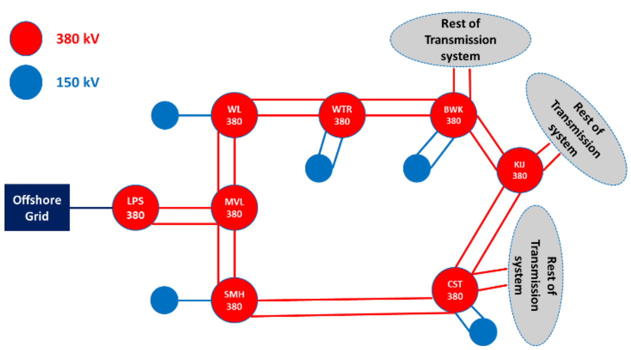

Fig. 3. Simplified representation of the transmission system modelled in EMTP/ATP

III. ENERGIZATION PROCEDURE & COMPLIANCE CRITERIA

For the energization procedure of an offshore grid, TenneT defines the criteria, as summarized in Table I. Each action in the switching sequence should comply with these criteria, otherwise proper mitigation options should be applied.

TABLE I
COMPLIANCE CRITERIA DURING THE ENERGIZATION PROCEDURE OF AN OFFSHORE GRID

ΔU_{RMS} [%]	TOVs	$t_{current-zero-miss}$ [ms]
≤ 3.0	-	≤ 60

A. Limitation of RMS fast voltage variations

According to the Dutch Grid Code, each switching event in the transmission system should not cause RMS fast voltage variations that exceed the limit of ΔU = 3% of the system's nominal voltage. The fast voltage variations refer to either voltage dips, e.g. due to a transformer energization, or voltage swells, e.g. due to the energization of a long cable section.

B. Temporary overvoltages (TOVs)

As discussed in [2], the connection of the offshore grid to the 380 kV transmission grid introduces a low resonance frequency in the harmonic impedance of the network, as calculated at the Point-of-Common-Coupling (PCC). This resonance already occurs when the first string is connected to the PCC and it lies between the 2nd and 3rd harmonic (Figure 4). Under system contingencies, i.e. weak network conditions, the resonance shifts to lower frequencies, while the impedance amplitude increases (Figure 5). When such a low harmonic resonance is triggered due to a switching event close to the PCC, it could lead to TOV conditions. Especially, events that include the switching of power transformers at or close to the PCC, e.g. "virtual" transformer re-energization after fault clearance, could introduce a significant increase in TOV levels, both at the 380 kV PCC and at all voltage levels along the offshore grid. The TOVs could stress the High Voltage components in various ways, e.g. ageing, dielectric failure, surge arrester thermal runaway, etc., and therefore, their evaluation is deemed necessary for each action of the energization switching sequence. The assessment method and its limits, as presented in [9], were applied in this case.

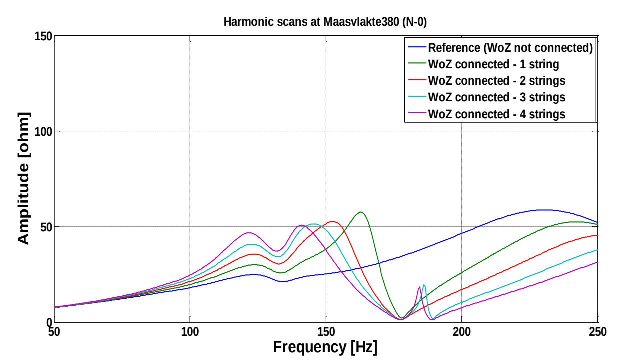

Fig. 4. Harmonic impedance scans at the PCC: N-0 contingency with zero (blue), one (green) up to four (purple) export cables in service

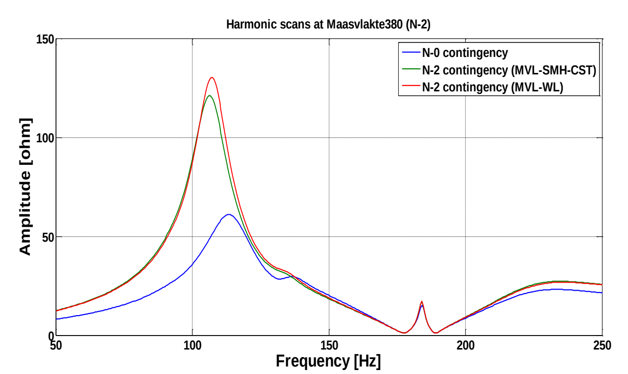

Fig. 5. Harmonic impedance scans at the PCC: N-0 VS N-2 contingencies

C. *Current zero-miss*

The current zero-miss could occur during the simultaneous energization of a cable and its shunt compensation reactor, under the condition that the compensation level is equal to or higher than 50% [10]. Due to their approximate phase opposition, the capacitive current of the cable and the inductive current of the shunt reactor compensate each other. Consequently, a DC component without zero-crossings occurs in the current flowing through the circuit breaker under operation. The energization at the voltage zero is regarded as the most onerous switching instant, resulting in the highest DC component and, thus, in longer zero-miss durations.

The current zero-miss might last for long durations, e.g. up to several seconds. The latter could lead to unsuccessful operation of circuit breakers during fault conditions or cause saturation problems to current transformers and affect by this way the reliability of the system's protection. When studying the energization process of the offshore grid and, more specifically, the simultaneous energization of the export cable and its compensation reactor, current zero-miss conditions could occur. The latter is graphically shown in Figure 6. Consequently, the evaluation of the current zero-miss durations is regarded necessary, when studying the energization process of the offshore grid. Table II presents the compensation levels of the export cables, referring to the nominal tap position of the shunt reactors.

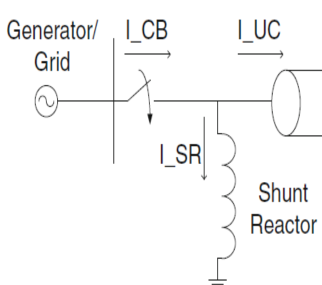

Fig. 6. Simplified representation of the energization of a shunt compensated cable

TABLE II
COMPENSATION LEVELS OF THE EXPORT CABLES

Length [km]	Cable reactive power [Mvar]	Shunt reactor rating [Mvar]	Compensation level [%]
45	150.5	90	64
36	120.5	67	56

D. *Energization study approach*

As shown in Figure 7, there are six circuit breakers in each string of the offshore grid:

- CB_1 at the 380 kV side of the auto-transformer at the landing point station.
- CB_2 at the 33 kV tertiary.
- CB_3 at the 33 kV tertiary responsible for the switching of the 65 Mvar shunt reactor.
- CB_4 at the 33 kV tertiary responsible for the switching of the 32.5 Mvar capacitor bank.
- CB_5 at the 220 kV side of the landing point station responsible for the switching of the export cable and the shunt reactor.
- CB_6 at the 220 kV offshore platform responsible for the switching of the offshore transformer. CB_6 was considered to be equipped with a Point-on-Wave (PoW) controller.

For the first string to be energized, all possible step-by-step sequential switching options (Figure 8) were studied and evaluated against the defined criteria. This approach allowed to identify onerous switching operations that would result in the violation of any of the criteria. These operations should be either avoided or properly mitigated. In the latter case, proper remedies were studied in detail to investigate their effectiveness on mitigating the problem(s).

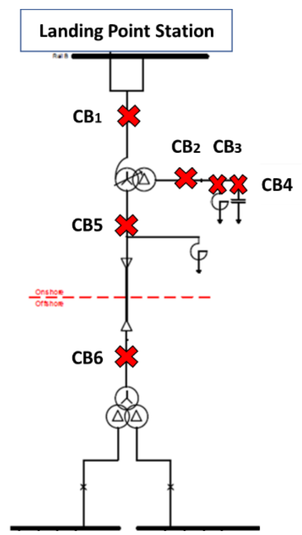

Fig. 7. Circuit breakers in an offshore string

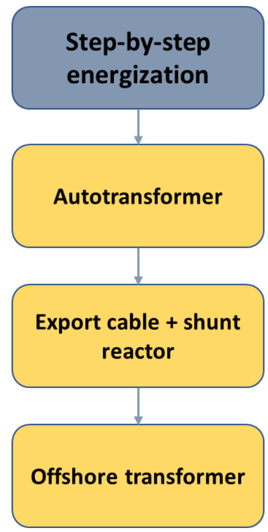

Fig. 8. Step-by-step energization sequence

IV. STUDY RESULTS & MITIGATIONS

A. *Step-by-step energization*

Table III qualitatively presents the evaluation of the simulation results for each switching case of the step-by-step energization.

TABLE III
STEP-BY-STEP ENERGIZATION OF THE OFFSHORE GRID'S FIRST STRING

Energization of the auto-transformer		
ΔU_{RMS} [%]	TOVs	$t_{current\text{-}zero\text{-}miss}$ [ms]
√	√	√
Simultaneous energization of the export cable and the shunt reactor		
ΔU_{RMS} [%]	TOVs	$t_{current\text{-}zero\text{-}miss}$ [ms]
√	√	X
Energization of the offshore transformer		
ΔU_{RMS} [%]	TOVs	$t_{current\text{-}zero\text{-}miss}$ [ms]
X	√	√

The above results indicated that the step-by-step energization of an offshore string violated the defined criteria and, therefore, the further study of mitigation options was deemed essential.

Figures 9 and 10 present the current of Phase A, as measured at CB_5, when simulating the simultaneous energization of the export cable and the shunt reactor. In the first case, the 65 Mvar reactor at the 33 kV tertiary was not energized, in the second case this reactor was considered already in service. The difference in the total compensation level of the export cable resulted in longer current zero-miss duration in the second case.

Figures 11 and 12 present the RMS voltage of Phase A, as measured at Maasvlakte380, when simulating the energization of the offshore transformer via CB_6. In the first case, the ideal PoW switching was considered, where each phase was switched in on the voltage peak. In the second case, the statistical behavior of the PoW switching was considered, which could result in a deviation around the target instant on the power frequency voltage wave. Due to the pole scatter around the target instant, the resulting transformer inrush current was higher compared to the first case, as shown in Figures 13 and 14. The latter resulted in higher RMS voltage dips at the 380 kV substation, which exceeded the 3% limit value.

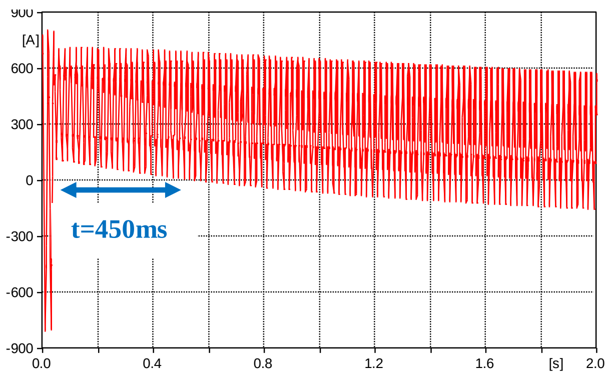

Fig. 9. Current zero-miss – 33 kV reactor not energized

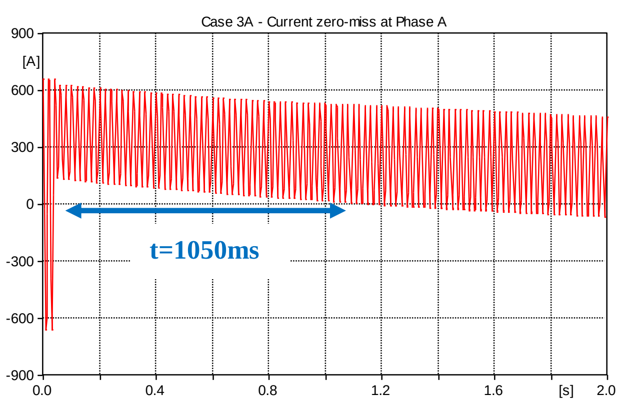

Fig. 10. Current zero-miss – 33 kV reactor already energized

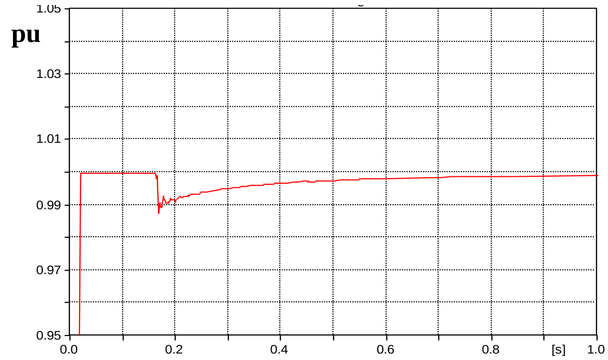

Fig. 11. Ideal PoW energization of the offshore transformer – RMS voltage at Phase A of the PCC

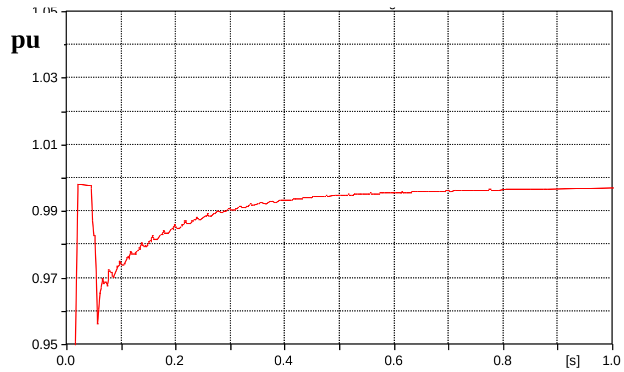

Fig. 12. Non-ideal PoW energization of the offshore transforme – RMS voltage at Phase A of the PCC r

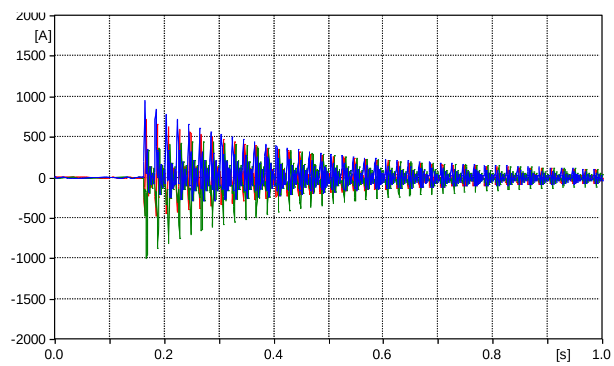

Fig. 13. Ideal PoW energization of the offshore transformer – Phase currents at the CB_6 circuit breaker

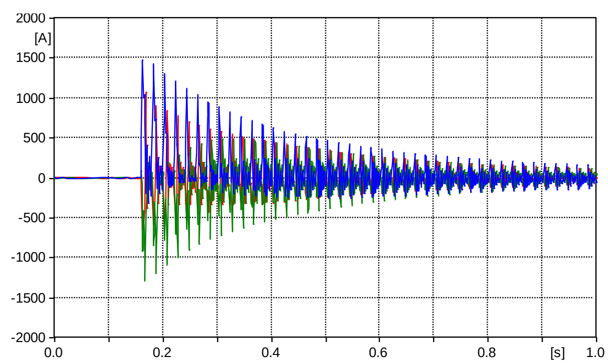

Fig. 14. Non-ideal PoW energization of the offshore transformer – Phase currents at the CB_6 circuit breaker

B. Energization in one step

As a next step, the energization of the first string in one step was studied. For this case, the application of a pre-insertion resistance (PIR) at the 380 kV circuit breaker, i.e. CB_1, was considered as an effective remedial against the violation of any of the criteria. More specifically, the pre-insertion resistance limits the current zero-miss to short durations [11] as well as the transformer inrush current, which could result in excessive RMS voltage dips at the PCC. The concept of the PIR (Figure 15) is based on the following:

- The circuit breaker CB_1 closes at $t=t_{switch}$ and energizes the PIR in series with the offshore string up to and including the offshore transformer;
- The parallel switch closes at $t=t_{switch}+100$ms, bridging by this way the PIR.

A detailed parametric analysis was performed to study the effectiveness of the PIR in limiting the current zero-miss duration. The analysis considered two variations related to the operating condition of the 65 Mvar reactor at the auto-transformer 33 kV tertiary. In the first case, CB_2 and CB_3 were closed and the reactor was energized with the rest of the string. In the second case, CB_2 and CB_3 were open. In Figure 16, the current zero-miss duration is presented in relationship to the value of the PIR for both cases. When CB_2 and CB_3 are closed, a resistance equal to or higher than 200 Ohm is required to limit the zero-miss to durations shorter than 60 ms. On the other hand, when CB_2 and CB_3 are open, a resistance value of 50 Ohm is sufficient to limit the zero-miss duration to acceptable levels.

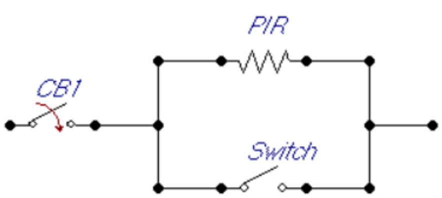

Fig. 15. PIR concept

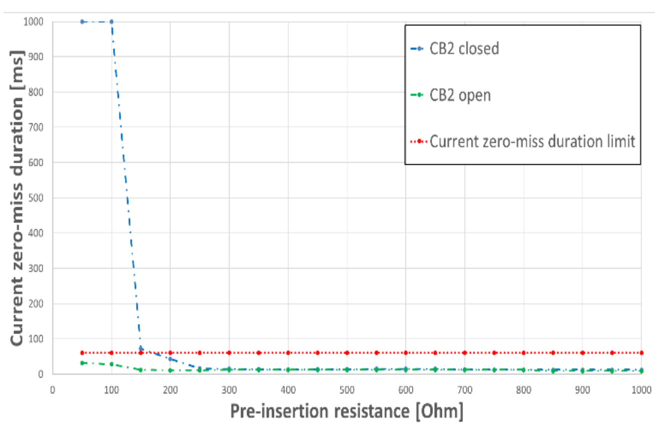

Fig. 16. PIR parametric analysis results

C. Energization of the offshore grid

Based on the above analysis, a pre-insertion resistance of 200 Ohm was selected for the energization of each string of the offshore grid. Table IV qualitatively presents the evaluation of the simulation results for each string to be energized in one step, in a consecutive procedure. Figures 17-19 present the time-domain simulation results for the first string to be energized.

TABLE IV
ENERGIZATION OF THE OFFSHORE STRINGS

	ΔU_{RMS} [%]	TOVs	$t_{current\text{-}zero\text{-}miss}$ [ms]
String No.1	√	√	√
String No.2	√	√	√
String No.3	√	√	√
String No.4	√	√	√

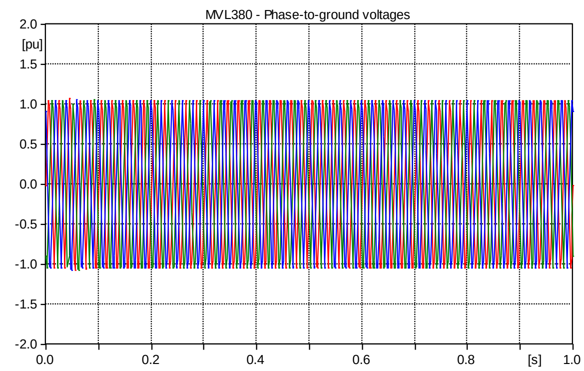

Figure 17. Phase-to-ground voltages at the PCC

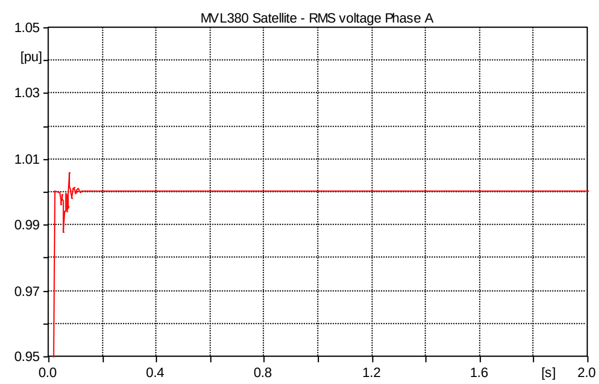

Figure 18. RMS voltage of Phase A at the PCC

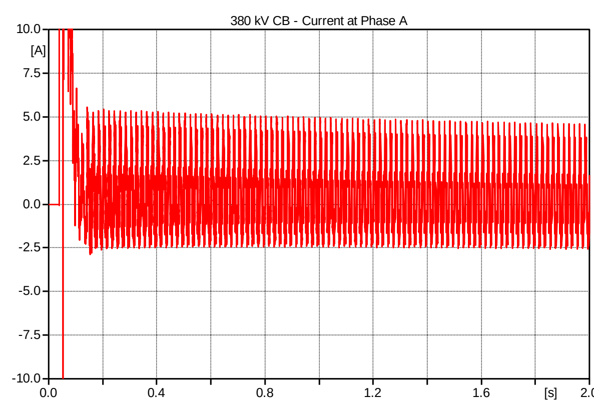

Figure 19. Current of Phase A at the 380 kV circuit breaker (CB_1)

V. CONCLUSIONS

In the Netherlands, TenneT is realizing the connection of large offshore wind farms to the 380 kV transmission grid. Dedicated AC offshore grids will facilitate the connection of the OWFs. Such connections impose great challenges, especially related to power quality aspects, e.g. amplification of background harmonics and harmonic emissions, as well as to insulation coordination aspects. Moreover, the energization procedure of such an offshore grid should comply with the criteria defined by the Transmission System Operator. Therefore, detailed electromagnetic transient (EMT) studies are deemed necessary during the planning stage to define a) the switching sequence to be followed during the energization procedure and b) the need for proper mitigation actions, when violation of any of the criteria occurs.

In this paper, the results of the EMT study on the energization procedure of the offshore grid to be connected to the Maasvlakte 380 kV substation are presented. For the purposes of the study, a detailed transient network model was developed in EMTP/ATP, which represented a significant part of the 380 kV and 150 kV Dutch transmission system. The applied approach considered the analysis of the step-by-step energization of the first string to be energized. The latter allowed to identify the switching actions that would lead to the violation of any of the defined criteria. The energization of each string in one step by means of a pre-insertion resistance at its 380 kV circuit breaker was regarded as an effective remedial to mitigate issues related to RMS fast voltage variations at the PCC, prolonged current zero-miss durations and temporary overvoltages due to possible excitation low harmonic resonances.

VI. References

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