33 kV Cable Connector Failures due to Shunt Reactor Switching by Means of Vacuum Circuit Breaker – A Thorough Investigation & Mitigation Analysis

K. Velitsikakis, B.C. van Maanen, P.A.A.F. Wouters, P. La Seta, K. Trunk

***Abstract*—Switching of (small) inductive currents by means of vacuum circuit breakers may lead to multiple re-ignitions. This is the result of the ability of the interrupter's quenching capability, which generates steep overvoltages that can stress the equipment insulation. Should no mitigation measures be applied, the equipment is exposed to a high risk of failure. In this paper, the findings and conclusions of a such a failure investigation and mitigation analysis are presented, referring to multiple cable connector failures in 33 kV shunt reactor installations in the Netherlands.**

***Keywords*: vacuum circuit breaker, re-ignitions, shunt reactor switching, overvoltages, RC surge suppressor, RC snubber**

I. Introduction

TenneT is the Transmission System Operator in the Netherlands and in big part in Germany. In the Dutch system, TenneT owns and operates the offshore grids -up to and including the gas insulated substations on the offshore platforms- that facilitate the connection of two 1400 MW windfarms to the 380 kV system on land. More specifically, one to the Zeeuwse Kust Landstation (ZKL) in the Borssele area and one to the Hollandse Kust Zuid (HKZ) station in the Maasvlakte area. In the coming years, new offshore windfarms are planned to be connected to the 380 kV land stations Hollandse Kust Noord (HKN) and West (HKW) respectively. At the ZKL station, there are four 400 MVA auto-transformers, each one connected to a 220 kV export cable. Also, each auto-transformer is equipped with a 33 kV tertiary winding, where one 65 MVAr shunt reactor, one 32.5 MVAr capacitor bank and one earthing/auxiliary transformer are connected. All connections between the auto-transformer and the 33 kV switchgear, as well as between the switchgear and the components are realized by means of relatively short cables. Vacuum circuit breakers are used for the switching of these components. Since February 2020, five double connectors of the cables connected to the shunt reactors have dielectrically failed.

In general, vacuum circuit breakers (VCB) constitute a high-performance and high-reliability economical solution in Medium Voltage applications [1]. However, due to the characteristics of the VCBs it is expected [2-6] that the switching of small inductive currents can lead to multiple re-ignitions and virtual current chopping. These electromagnetic transient (EMT) mechanisms result in overvoltages that are characterized by very short rise-times (high dV/dt values) and, potentially, by elevated amplitudes. Consequently, a component's insulation can be dielectrically stressed, causing its accelerating ageing or even failure. Similarly, the high frequency surges, which are generated due to the multiple re-ignitions, form a serious risk for the integrity of a power transformer or a shunt reactor, by exciting inter-winding resonances.

Based on the above, a thorough investigation was conducted to identify a possible root-cause of the failures. The investigation activities included -among others- review of relevant system event lists and fault recorder data, EMT analysis in ATP on the VCB switching and on-site transient measurements. As a next step, an additional EMT analysis was performed to a) study the effectiveness of RC surge suppressors on mitigating the VCB multiple re-ignitions and b) define the effective range of values and the location of the RC component.

In this paper, the findings and conclusions of the complete failure investigation process and mitigation analysis are presented. More specifically, a detailed description of the system under study as well as operational aspects are given. Next to that, the EMT model, its validation and the analysis results are discussed. Furthermore, a description is given on the set-up of the on-site transient measurements and the method used for the analysis of the measurement data. The main findings and conclusions of the measurement campaign are presented as well. Last but not least, the results of the desktop study are presented with respect to the application of RC surge suppressors as a remedy against the VCB multiple re-ignitions.

II. Description Of The System Under Study

The Zeeuwse Kust Landstation at Borssele facilitates the connection of the offshore grid to the 380 kV system. Four 400 MVA 380/220/33 kV auto-transformers connect the export

K. Velitsikakis is with TenneT TSO, Utrechtseweg 310, 6800 AS, Arnhem, The Netherlands (Kostas.velitsikakis@tennet.eu)
B.C. van Maanen is with DNV, The Netherlands
P.A.A.F. Wouters is with Eindhoven University of Technology, The Netherlands
P. La Seta and K. Trunk are with Siemens PTI, Germany
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cables to the main transmission grid. Each of the four 33 kV installations of the tertiary windings consists of the following components, as shown in the single line diagram of Fig. 1:

- Short cables between the transformer terminals and the 33 kV switchgear (Table I).
- One 65 MVAr shunt reactor of the fixed design, I_n = 1137 A; the reactor is connected to the 33 kV switchgear by means of short cables.
- One 32.5 MVAr capacitor bank, I_n = 626 A, that is connected to the 33 kV switchgear by means of short cables.
- One 400 kVA earthing/auxiliary transformer that is connected to the 33 kV switchgear by means of short cables.
- Each component is switched by means of a 40.5 kV vacuum circuit breaker.

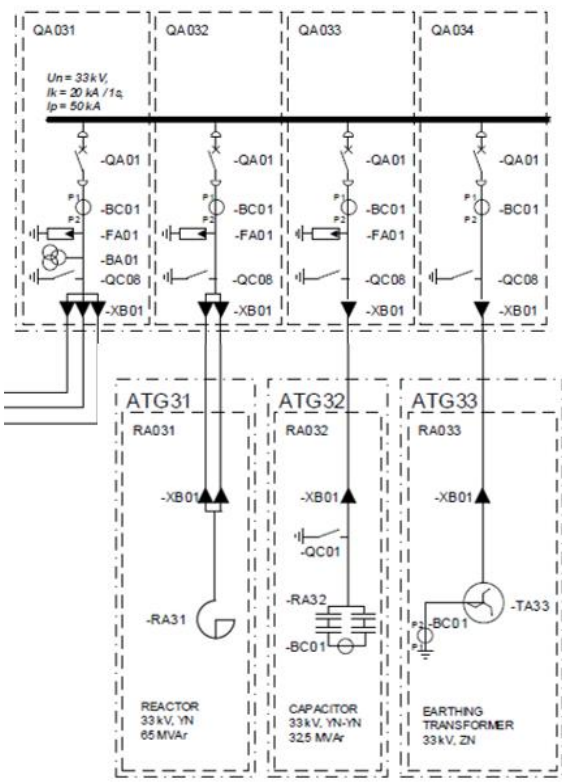

Fig. 1. Single line diagram of the 33 kV tertiary installation

TABLE I
33 KV CABLES – MAIN INFORMATION

Connection	Cross Section [mm^2]	No. cables per section	Length [m]
Trfm – Swgr	800	3	60-80
Swgr – Rctr	630	2	40-45
Swgr – Cptr	630	1	50
Swgr – Earth. Trfm	240	1	30

The operating status of the shunt reactor and the capacitor bank is defined by the so-called "MVAr controller" scheme that is implemented at the ZKL station. More specifically, the two components are -independently from each other- switched according to the level of power generated by the offshore wind park. Consequently, the switching frequency of the shunt reactor and the capacitor bank strongly depends on the fluctuations of the generated power in the offshore wind park. Tables II and III summarize the operating status of the shunt reactor and of the capacitor bank as well as the switching actions defined by the MVAr controller.

TABLE II
SHUNT REACTOR & CAPACITOR BANK OPERATING STATUS CONTROL SCHEME

Generated power [pu]	Shunt reactor status	Capacitor bank status
[0…0.35]	*IN*	*OUT*
[0.35…0.52]	*IN*	*IN*
[0.52…0.8]	*OUT*	*OUT*
[0.8…1.0]	*OUT*	*IN*

TABLE III
SHUNT REACTOR & CAPACITOR BANK SWITCHING ACTIONS

Generated power [pu]	Shunt reactor status	Capacitor bank status
0.35 → 0.36	*Remains energized*	*To be energized*
0.52 → 0.53	*To be de-energized*	*To be de-energized*
0.8 → 0.81	*Remains de-energized*	*To be energized*
0.81 → 0.8	*Remains de-energized*	*To be de-energized*
0.53 → 0.52	*To be energized*	*To be energized*
0.36 → 0.35	*Remains energized*	*To be de-energized*

III. CABLE CONNECTOR FAILURE INVESTIGATION

For the connection of the short cables to the auto-transformer and the shunt reactor terminals, double cable connectors are utilized, as shown in Fig. 2. It total, 24 of these connectors have been in operation in the four tertiary installations. Since February 2020, five connectors have failed, all located at the cable ends connected to one of the four shunt reactors. The failures occurred at three out of the four shunt reactor installations and at a different phase each time. Therefore, failure investigations were conducted, that included on-site and laboratory inspections of the failed units. During the laboratory inspections, electric activity marks were found, which were deemed indicative for presence of high electric field stresses in the connectors. Moreover, for three connector failures, the analysis of the event list and of the fault recordings indicated that the overcurrent protection of the shunt reactor was triggered after the reactor had been energized. Based on these facts, the initial hypothesis was formed stating that the dielectric failures of the cable connectors could have been the result of overvoltages due to the switching actions in the 33 kV tertiary installations. Therefore, further actions were taken to support the above hypothesis. Firstly, a detailed EMT analysis was deemed necessary to a) calculate the overvoltages at the reactor terminals when energizing the shunt reactor and the capacitor bank and b) study the re-ignition behavior of the VCB when de-energizing the shunt reactor under normal operating conditions. Secondly, a series of on-site transient measurements was performed in September 2021, aiming to record the transient overvoltages during the switching of the shunt reactor and of the capacitor bank.

Fig. 2. Failed double cable connector at the 65 MVAr shunt reactor terminal

A. *EMT analysis – Overvoltages due to energization*

For the transient analysis purposes, the 33 kV tertiary installation, including the auto-transformer, was modelled in detail in ATP. The rest of the 380 kV and 220 kV grids were represented by simplified power frequency Thevenin equivalents (R_1, X_1, R_0 and X_0 representation) of 10 kA and 2 kA respectively, referring to a low short circuit power system condition. The auto-transformer, shunt reactor and capacitor bank were modelled according to the test report data (Tables IV and V) [7]. The short cables were modelled according to their geometrical configuration; the Bergeron model was considered with a parameter calculation frequency at $f_{Bergeron}$=500 kHz [8]. The target frequency was selected according to the main oscillation frequency during a re-ignition, as captured in the transient measurements. The same oscillation frequency was initially estimated by means of hand calculations, based on the LC circuit that is created between the source- and load-side circuit of the breaker during re-ignition conditions. For the surge arrester model (U_r=36 kV), the complete voltage-current characteristic was provided by the manufacturer and used, as given in Fig. 3 [9-10].

For the calculation of the switching overvoltages within the 33 kV tertiary installation, all possible energization switching actions were simulated, as expected by the operation of the MVAr controller. For each energization case, parametric switching was performed, by varying the switching instant on the power frequency cycle with a step of 1 ms. It needs to be noticed that no time discrepancy was considered between the circuit breaker poles upon switching. Table VI summarizes the maximum peak phase-ground overvoltage values, as calculated for all simulated cases. According to IEC [11] and for U_m = 36 kV, the components insulation withstand is defined by the Lightning Impulse Withstand Level (LIWL) and the Short Duration Withstand Voltage (SDWV) respectively. In order to account for switching overvoltages, a converted Switching Impulse Withstand Level ($SIWL_{converted}$) was defined, by applying a conversion (k_c) and a safety factor (k_s=1.15). The conversion factor depends on the type of insulation, i.e., GIS, liquid (k_c=1.1) or solid insulation (k_c=1.0).

The simulation results showed that the switching overvoltages due to the energization maneuvers did not exceed the defined $SIWL_{converted}$ level.

TABLE IV
SHUNT REACTOR & CAP. BANK INPUT DATA

$L_{Reactor}$ [mH]	53.33
P_{Losses} [kW]	113.7
$C_{Bushing-Gr}$ [nF]	6.5
$C_{Cap.Bank}$ [μF]	95.1

TABLE V
AUTO-TRANSFORMER INPUT DATA

Power rating [MVA]	400/400/72
Voltage rating [kV]	380/220/33
Winding connections	Ad5
$I_{no-load}$ [%]	0.137
$P_{no-load}$ [kW]	77.1
u_{Pr-Sec} [%]	14.54
U_{Pr-Ter} [%]	9.02
$U_{Sec-Ter}$ [%]	5.76
C_{Pr-Ter} [nF]	15.05
$C_{Sec-Ter}$ [nF]	15.05
C_{Ter-Gr} [nF]	25.47

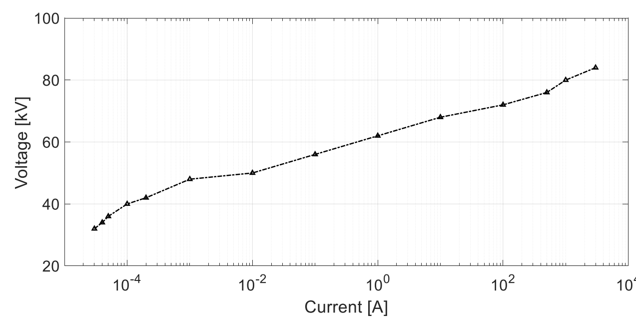

Fig. 3. Surge arrester V-I characteristic

TABLE VI
MAXIMUM PEAK SWITCHING OVERVOLTAGES DUE TO ENERGIZATION

Component under energization	$SIWL_{converted}$ [kV_{peak}]	Ph-Gr [kV_{peak}]
Shunt reactor	134.4	35.0
Capacitor bank	134.4	57.6
Shunt Reactor & Capacitor bank	134.4	53.5

B. EMT analysis – Overvoltages due to the VCB multiple re-ignitions

For the analysis of the VCB re-ignition behavior, it was deemed necessary to model in detail the breaker's opening and closing logic. The following input parameters were considered: a) the maximum chopping current level, b) the dielectric withstand characteristic of the gap under contact separation, c) the breaker quenching capability and d) the arcing time. The VCB model did not include the arc resistance. According to [12], the voltage drop across the arc will be small and it is expected that it will not have a significant impact on the calculated voltage transients. The required input data was provided by the breaker manufacturer and as such, it is regarded as confidential. The VCB re-ignition logic was defined according to [12] and it was developed in MODELS [13] based on the following conditions:

Conditions for opening the breaker

1. The breaker is closed AND
2. The current flowing through the breaker is equal to or lower than the defined current chopping level AND
3. The derivative of the high frequency re-ignition current is lower than the defined quenching capability of the breaker.

Conditions for closing the breaker

1. The breaker is open AND
2. The voltage across the breaker contacts exceeds the defined dielectric withstand.

Figures 4 and 5 provide a graphical explanation of the breaker's re-ignition logic. When the TRV across the breaker contacts exceeds the dielectric withstand of the instant gap-distance, a re-ignition occurs. The voltage across the contacts becomes zero and the control signal "VCB status" becomes equal to 1 (Fig. 5). Under re-ignition conditions, a high frequency current flows through the breaker with high di/dt values and it is superimposed on the power frequency load current. This current is interrupted when its slope becomes lower than the breaker's quenching capability and when its amplitude becomes equal to or lower than the defined chopping level. Following the current interruption, a TRV appears again across the breaker contacts. Multiple re-ignitions will occur until the recovery of the dielectric strength of the gap is higher than the resulting TRV (Fig. 4).

The re-ignition behavior of the VCB is strongly dependent on the arcing time. The spread of the values is stochastic and can vary within a given range per switching action. For the purposes of the investigation analysis, a deterministic approach was chosen over a parametric calculation, by considering a relatively short arcing time of t_{arcing}=200 μs. Table VII summarizes the simulation results for the two switching cases considered. In both cases, multiple re-ignitions were calculated; the phase-ground peak overvoltages did not exceed the defined $SIWL_{corrected}$.

TABLE VII
RE-IGNITIONS & OVERVOLTAGES DUE TO SHUNT REACTOR SWITCHING

Component under de-energization	No. re-ignitions	dV/dt [kV/μs]	Ph-Gr [kV_{peak}]
Shunt reactor	28	102	40.9
Shunt Reactor & Capacitor bank	32	177	60.0

C. Transient measurement analysis

In September 2021 and for a period of three weeks, transient measurements were conducted in one of the shunt reactor fields. Aim of these measurements was to capture the transient overvoltages within the 33 kV tertiary installation, when switching the shunt reactor and the capacitor bank. The measurements were based on the principle that the cable acts as a capacitive sensor. More specifically, an overvoltage on the cable conductor leads to a capacitive current to ground.

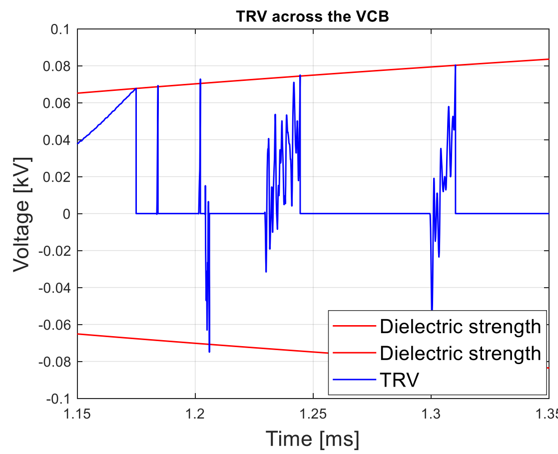

Fig. 4. TRV across the – still moving – breaker contact (zoom-in)

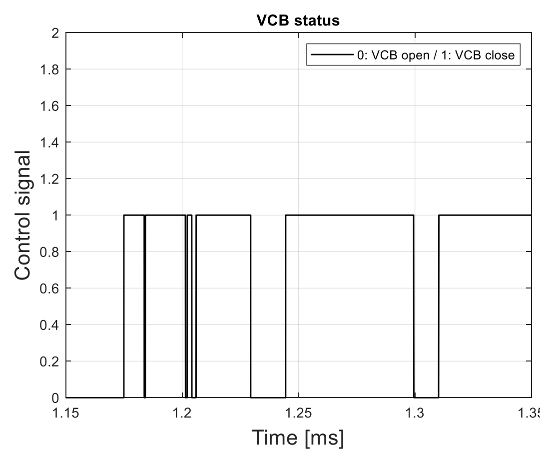

Fig. 5. VCB status control signal

This current was measured by means of a high frequency current transformer (HFCT) [14] that was placed around the cable earth screen at the VCB side (Fig. 6). This set-up worked under the condition that the cable at the shunt reactor side was single-sided earthed. The measured current represented the time derivative of the voltage waveform. The signal from the HFCT was transferred along a 10 m coaxial measuring cable, characteristically terminated, to a setup containing "integrators". These integrators restore the original voltage waveform and at the same time external high frequency interference is attenuated [15-16]. The overall frequency range covered by the setup reaches up to the low MHz levels. Trigger signals for transient events were based on the recorded phase voltages, after filtering out the lower frequency part of the signal. This was achieved with a high-pass filter with a cut-off frequency at approximately 5 kHz. Another channel measured a 50 Hz reference signal provided by a differential probe connected to a wall socket. This signal enabled the comparison of the momentary power frequency phase angles of the transient events observed in different measurements. Due to the limited available space within the MV cabinet, the HFCTs were placed near to the phase conductors. Consequently, a significant coupling occurred due to the neighboring 50 Hz currents. In order to completely eliminate the 50 Hz components, a numerical 2nd order high-pass filter (500 Hz) is applied, leaving the high frequency signal unaffected.

During the three-week measuring period, the shunt reactor was switched off 10 times. The measurement analysis showed that:

- multiple re-ignitions occurred in 5 of the 10 switching actions (Table VIII and Fig. 7);
- after the first re-ignition, very short rise times occurred (<1 µs) and the associated steepness values exceeded the 100 kV/µs, as calculated in the EMT analysis;
- the main oscillation frequency of the re-ignited voltages was approximately 500 kHz (Fig. 8), as calculated in the EMT analysis;
- multiple prestrikes occurred when energizing the shunt reactor.

TABLE VII
RE-IGNITIONS & OVERVOLTAGES DUE TO SHUNT REACTOR SWITCHING

No. measurement	No. re-ignitions	Ph-Gr [pu]
1	0	1.0
2	21	1.8
3	0	1.0
4	13	2.2
5	0	1.0
6	21	1.9
7	0	1.0
8	15	3.1
9	0	1.0
10	15	Unknown(1)

(1) Re-ignition occurred at the phase without a HFCT, only two were available at the time of the transient measurements

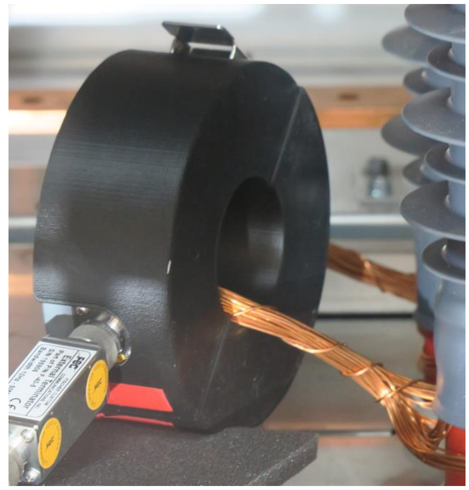

Fig. 6. HFCT placed around the cable earth screen

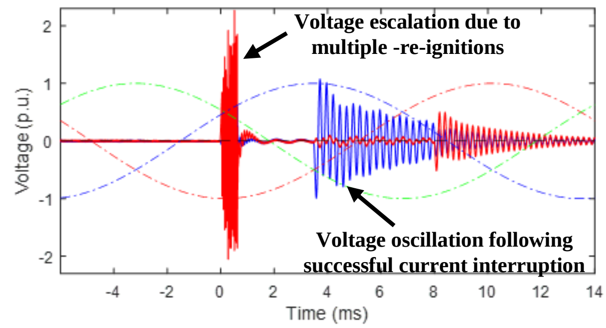

Fig. 7. Recording of measurement No. 8

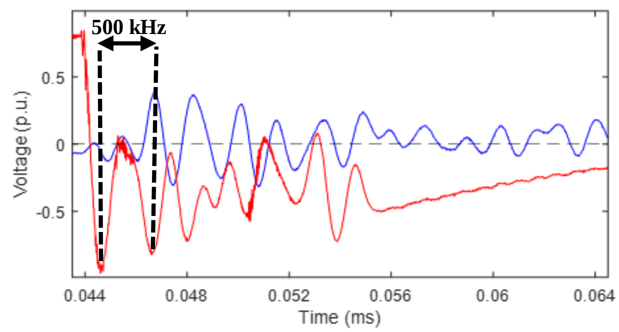

Fig. 8. Recording of measurement No. 8 (zoom-in)

IV. MITIGATION ANALYSIS BY MEANS OF RC SURGE SUPPRESSORS

The desktop and the transient measurement analyses confirmed the initial hypothesis of the failure investigation and lead to the conclusion that the multiple re-ignitions in the vacuum circuit breaker and the resulting repetitive steep overvoltages were regarded as the "most probable" root-cause of the cable connector failures. As a result, correction actions were deemed necessary to mitigate the VCB multiple re-ignition behavior. RC surge suppressors form a proven and effective solution [17-19] for limiting the number of re-ignitions. In ideal tuning conditions, the RC surge suppressors can limit the VCB to a single re-ignition.

An EMT parametric study was performed in the Siemens PSS SINCAL software tool, where the 33 kV tertiary installation was modelled in detail, similarly to the ATP model, as described in the sections III-A and III-B respectively. Two possible options were considered with respect to the location of the RC surge suppressor, as shown in Fig. 7:

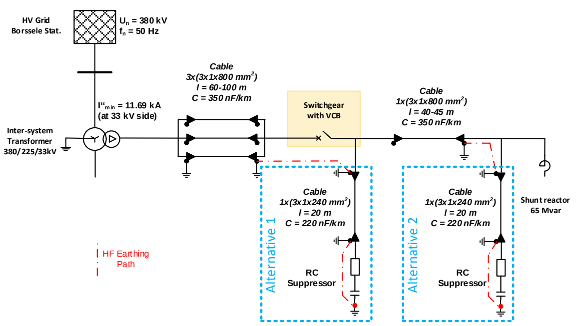

Fig. 7. Possible locations of the RC surge suppressors

Due to the space limitations both at the outdoor shunt reactor cell as well as indoors, it was decided to consider the RC surge suppressor of the integrated resistor design. In this case, the resistor and the capacitor are enclosed in one compartment, resulting in a compact design. For the latter, a resistor thermal limit of 200 W/ph was considered. The resistor steady state losses are the result of the capacitor current and of possible presence of harmonics. For the latter, a factor of 1.3 was assumed, as given in equation (1) below.

$$P_{Losses} = R \cdot (1.3 \cdot I_C)^2 = R \cdot (1.3 \cdot U_m \cdot 2 \cdot \pi \cdot f \cdot C)^2 \quad (1)$$

where R is the resistor value
C is the capacitor value
U_m is the maximum system voltage phase-ground, 20.8 kV in this case

For the parametric calculations, the resistor value was varied between 5 and 40 Ohm in steps of 2.5 Ohm. The capacitor value was varied in steps of 25 nF from 100 nF up to a value that did not result in exceedance of the defined losses limit. The simulation analysis aimed to the definition of an effective range of R and C values, which would be applicable a) to all 33 kV shunt reactor installations in all offshore grid projects and b) for all expected switching actions defined by the MVAr controller scheme. Moreover, three values were assigned to the VCB arcing time (100, 500 and 950 µs) to account for very short up to relatively long arcing times. All these resulted in a set of 24 cases, each one having a total of 186 simulations. As graphically shown in Fig.9, the parametric analysis concluded that a capacitor value of C=325 nF and a resistor value of R=25 Ohm resulted in an RC surge suppressor design that limited the VCB re-ignitions in acceptably low numbers for all studied variations.

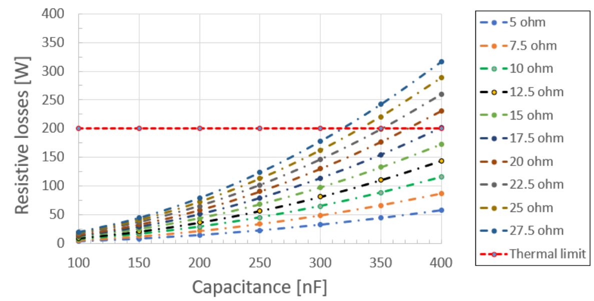

Fig. 8. RC surge suppressor thermal losses

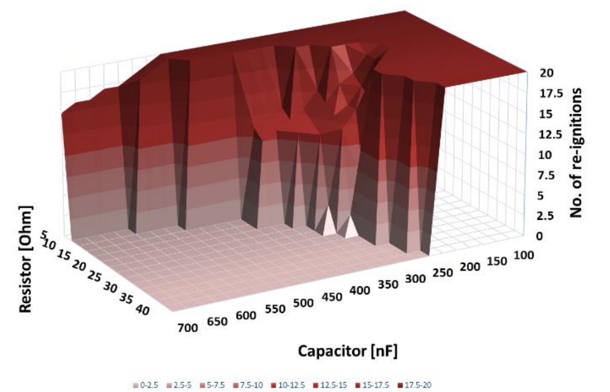

Fig. 9. RC surge suppressor – Parametric analysis results

V. Conclusions

Switching of (small) inductive currents by means of vacuum circuit breakers may lead to multiple re-ignitions. This is the result of the ability of the interrupter’s quenching capability, which generates steep overvoltages that can stress the equipment insulation. Should no mitigation measures be applied, the equipment is exposed to a high risk of failure.

Since February 2020, five double connectors of cables have dielectrically failed in the Zeeuwse Kust Landstation in the Netherlands. These cable connectors were connected to the terminals of 65 MVAr shunt reactors of the 33 kV installations. Failure investigations were conducted that included on-site and laboratory inspections of the failed units. The initial hypothesis stated that the dielectric failures of the cable connectors could have been the result of overvoltages due to the switching actions in the 33 kV tertiary installations. Therefore, a detailed EMT analysis was performed to a) calculate the overvoltages at the reactor terminals when energizing the shunt reactor and the capacitor bank and b) study the re-ignition behavior of the VCB when de-energizing the shunt reactor under normal operating conditions. In addition, a series of on-site transient measurements was performed in September 2021, aiming to record the transient overvoltages during the switching of the shunt reactor and of the capacitor bank. Both analyses indicated that multiple re-ignitions occur when de-energizing the shunt reactor under normal operating conditions. The measurements captured up to 21 re-ignitions in a switching action; the associated rise times were in the order of hundreds of ns. As a result, correction actions were deemed necessary to mitigate the VCB multiple re-ignition behavior. A detailed EMT parametric analysis that aimed to the definition of an effective range of R and C values of a surge suppressor. Based on the analysis results, a capacitor value of C=325 nF and a resistor value of R=25 Ohm were selected for an RC surge suppressor design that limited the VCB re-ignitions in acceptably low numbers for all studied variations.

VI. Acknowledgment

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