Surge-Transferred Overvoltages in Earthing/Auxiliary Transformers

Fabian Koehler, Andrew Bremner, David Allan

***Abstract*—This paper describes an investigation into surge-transferred overvoltages in earthing/auxiliary transformers connected to wind farm HV transformers. The investigation contains a transient analysis of a wind farm grid connection cable network with an EMT simulation approach. The transformer in question is modelled with a resonance circuit and verified with measured sweep frequency analysis curves. The simulation results show that overvoltages produced during HV cable switching result in 6 p.u. overvoltages in the open-circuited LV terminal box. Furthermore, the mitigation method of LV connected load banks is explored. Finally, measurements of the determined solution for mitigation of the resonance are presented.**

***Keywords*: Cable, transformer, resonance, overvoltage.**

I. Introduction

TRANSIENT interactions between transformers and the network they are connected to are well understood for both switching operations and fault events. In this context, one particular onerous phenomenon is a transformer resonance, which can produce exceptionally high overvoltages, especially for the condition of an unloaded secondary side. Many studies have shown that network conditions such as

- ground fault initiation on the far end of a cable connected to a transformer,
- energisation of a transformer together with a short cable to a busbar,
- energisation of a transformer together with a short cable to a network with parallel cables and
- energisation of a transformer together with a short cable to a network with parallel identical cable-transformer configurations

can lead to these resonant overvoltage conditions [1], [2]. In contrast to the above, in this paper, an uncommon network configuration for a transformer resonant condition is reported and discussed.

During trial operation and inspection of a new wind farm (WF) grid connection, evidence of flashovers in earthing transformer (ET) LV connection boxes were found. An evaluation of the switching logs and alarm signals suggested, that these occurred during the energisation sequence of the WF connection. An investigation was carried out to determine the problem and find a workable solution.

Examination of the ETs showed normal oil analysis results, no internal mechanical damage to windings, no degradation of insulation or internal flashover within the tank, which concluded that transferred overvoltages are the cause of the LV connection box flashovers. As this particular network configuration is not yet reported in the literature to feature a possible overvoltage resonant condition, but is widely used in the connection of WFs, the objective of this paper is to report on the network investigation and findings.

The paper first summarises the network models and derivation of models, which are needed for an EMT simulation. In contrast to other transformer modelling approaches, which use sophisticated models based on measurements of the transformer transfer function, such as transmission line model based approaches [3], black-box models [4], or models based on detailed winding modelling such as reduced order models [5] or transformer white box models [6], in this work a lumped circuit model, as outlined in [7], tuned to available sweep frequency response analysis (SFRA) measurements is applied.

Secondly, the EMT simulations are presented, which comprises frequency-impedance scans to determine the network resonant points and the EMT results including a possible mitigation method for damping transferred transformer resonance overvoltages.

Finally, recorded measurement results of switching operations of the investigated network are presented and a comparison drawn with the simulation model to show the effectiveness of the proposed mitigation solution.

II. Network Model

For the investigation of overvoltages an EMT model of the network is constructed in PSCAD/EMTDC. An overview of one of the grid connections is provided in Fig. 1(a). In normal operations, the grid transformer (GT) is energised together with the 630mm^2 cables and the ET (Fig. 1(b)). The ET is open-circuit in the LV connection box. The wind farm 33kV busbar is energised via a two step switching operation. First the grid supply point (GSP) circuit breaker (CB) is closed, which energizes the 33kV 500mm^2 cables (Fig. 1(c)). Second, the WF 33kV cable array breakers are closed, in which energisation of wind farm cable arrays is carried out in arbitrary order. Wind turbine transformers associated with one array are energised in sequential order with delays to avoid overvoltage conditions.

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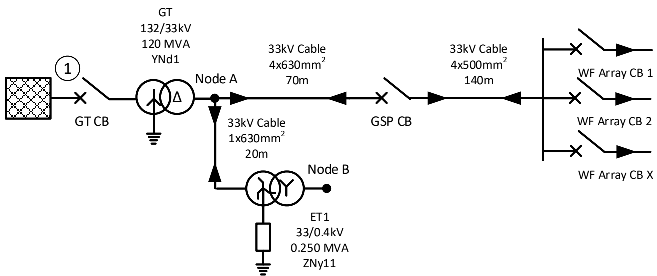
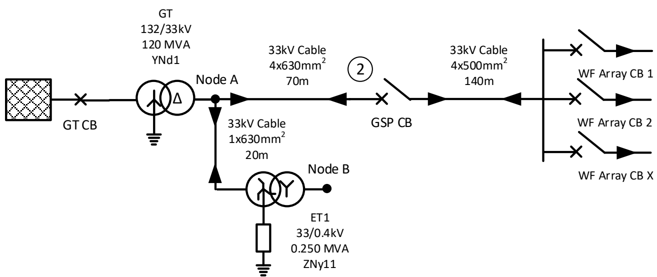
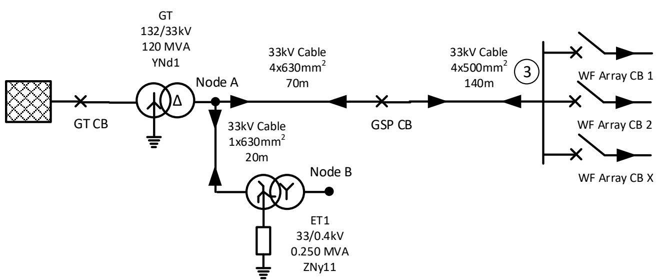


(a) Network Configuration 1



(b) Network Configuration 2



(c) Network Configuration 3

Fig. 1. Overview of investigated network

A. Network Equivalent

The wider external grid connected to the GT is represented with a Thevenin equivalent including zero-sequence impedance and a capacitance network. A summary of the data for minimum short-circuit power at the grid connection point is provided in Table I alongside the impedance scan results for one phase at the 132kV node without the windfarm connection, in Fig. 2. Due to the wider external transmission network connections, which feature long HVAC cables, the first system parallel resonant point is located at the 11th harmonic.

TABLE I
SUMMARY OF NETWORK EQUIVALENT DATA

Resistance $R_{1/2}$ (Ω)	Reactance $X_{1/2}$ (Ω)	Resistance R_0 (Ω)	Reactance X_0 (Ω)
0.76	7.71	2.54	17.16

B. Cables

Both the 630mm^2 and 500mm^2 cables are modelled with the frequency-dependent phase model with sheaths directly earthed via 1Ω, representing the earth mats of the substations. A summary of the data is provided in Table II.

C. Grid Transformer

The grid transformer is modelled with a standard T-circuit including saturation effects in the simulation software. The relevant input parameters are provided in Table III.

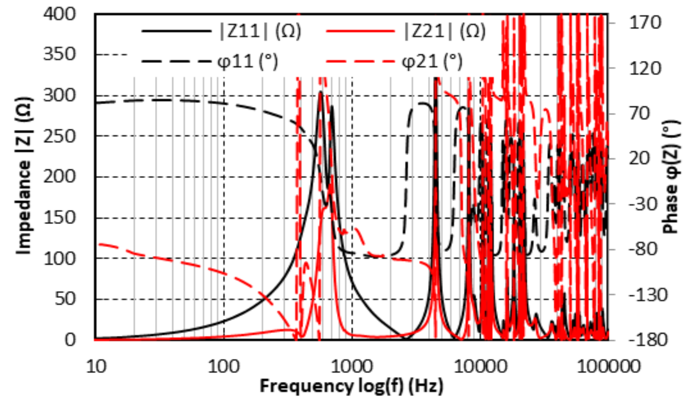


Fig. 2. Phase impedance scan results at the 132kV node (network configuration 1) without WF connection

TABLE II
SUMMARY OF CABLE DATA

Cable Type	500mm^2	630mm^2
Conductor Radius (m)	0.01355	0.015
Insulation Radius (m)	0.02155	0.024
Sheath Radius (m)	0.02515	0.0265
Outer Radius (m)	0.02775	0.030
Capacitance (μF/km)	0.32	0.35
DC Resistance R_{DC} (Ω/km)	0.037	0.047

TABLE III
SUMMARY OF GT DATA

Rated Power (MVA)	120
Rated Voltage HV (kV)	132
Rated Voltage LV (kV)	33
Vector Group	Yd1
Leakage Reactance (pu)	0.2118
Eddy Current Loss (pu)	0.000228
Copper Loss (pu)	0.003125
Knee-Point Voltage (pu)	1.23
Air Core Reactance (pu)	0.43

D. Earthing/Auxiliary Transformer

The earthing/auxiliary transformer is modelled with three-winding transformer elements and concentrated winding series and line to earth capacitances, as depicted in Fig. 3. This approach is valid to represent the first internal transformer resonant point, as stated in [7].

TABLE III
SUMMARY OF EARTHING/AUXILIARY DATA

Rated Power (kVA)	250
Rated Voltage HV (kV)	33
Rated Voltage LV (kV)	0.415
Vector Group	ZNy11
Leakage Reactance Zig-LV (pu)	0.0747
Leakage Reactance Zag-LV (pu)	0.02177
Leakage Reactance Zig-Zag (pu)	0.0352
Resistance Zig/Zag-N (Ω)	3.93
Resistance LV-N (Ω)	0.006
Knee-Point Voltage (pu)	1.12
Air Core Reactance (pu)	0.032
HV star-point earthing resistor (Ω)	21
Capacitance Core-Zig (pF)	150
Capacitance Zig-Zag (pF)	750
Capacitance Zag-LV (pF)	1000
Capacitance LV-Earth (pF)	40
Capacitance Zig (pF)	2750
Capacitance Zag (pF)	3850

To match the earthing transfer model's first resonant point to the available sweep frequency response analysis (SFRA) [8] results from the ET manufacturer, the SFRA test setup is modelled in PSCAD/EMTDC for the case of LV terminals and LV neutral short-circuited and HV phase B and C open-circuited. Since the single-phase SFRA measurements are carried out for HV phase A to neutral without the neutral earthing resistor connected, a frequency-impedance scan is performed for phase A in the simulation software with the neutral earthed.

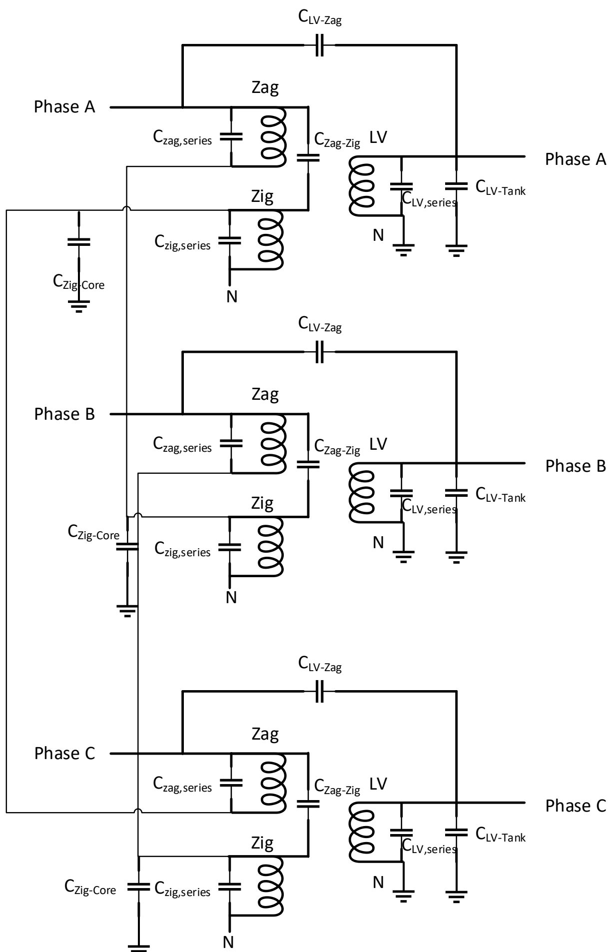


Fig. 3. Circuit model of the Earthing/Auxiliary Transformer

In Fig. 4, the result of the frequency-impedance scan in PSCAD/EMTDC is shown, which features two parallel resonant points, at approximately 4 kHz and 7.4 kHz respectively. Results only show one self- and mutual impedance due to the symmetry of the impedance matrix. In contrast to the simulation model, the second resonant point in the SFRA measurements is located at 11 kHz, which shows the limitation of the modelling approach. The transformer's reactive behaviour changes from inductive to capacitive at both the resonant points, which matches the SFRA measurement results. The SFRA measurements provided by the manufacturer are only available in dB (gain) and phase values. Therefore, frequency-impedance scan values from PSCAD/EMTDC are divided by the DC/zero Hz value to obtain the gain, as stated in the SFRA device manual. The amplitude of the gain approximately matches the SFRA measurement results, but the initial gain at 100 Hz is 30 dB lower in the SFRA measurements. These differences are attributed to the modelling limits of the lumped circuit modelling approach.

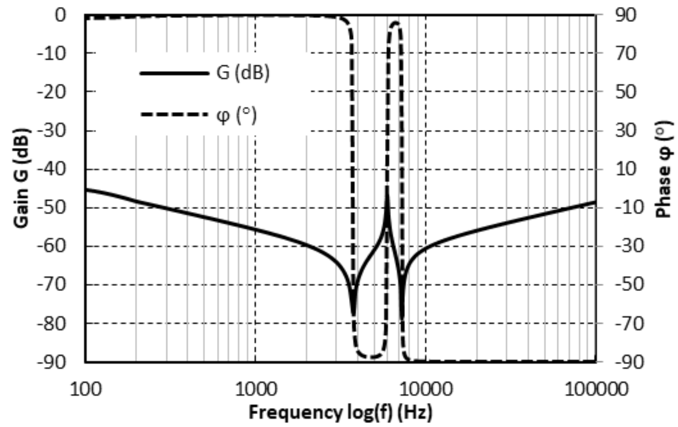


Fig. 4. Simulation results of simulated SFRA scan of Earthing/Auxiliary Transformer for HV phase A to neutral N, LV terminals short-circuited

III. Results

A. Frequency-Impedance Scans

To assess the possible resonance points in the network, frequency-impedance scans are carried out for the network configurations 2 and 3 in Fig. 1(b) and (c) at Node A.

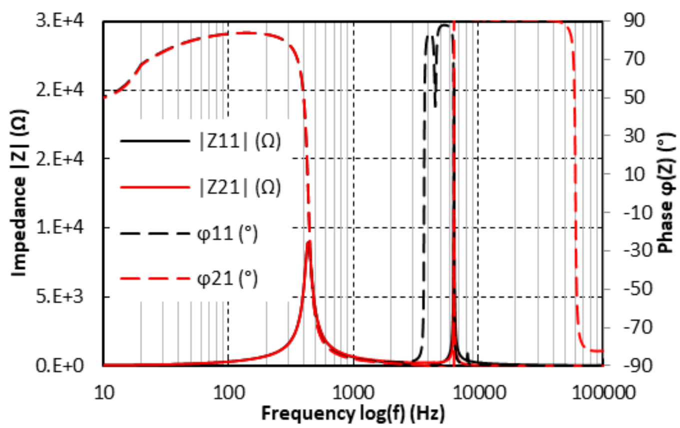


Fig. 5. Impedance scan results at node A (network configuration 2)

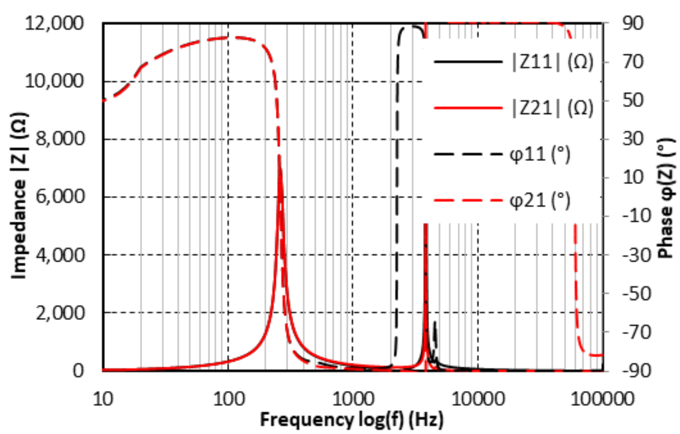


Fig. 6. Impedance scan results at node A (network configuration 3)

The frequency-impedance scans in Fig. 5 and Fig. 6 show that the main resonant point for GT energisation at the 33kV side is located at approximately 6.5 kHz, which is a network resonant point. A lower frequency resonant point exists at approximately 4 kHz, which matches the internal resonant point of the ET. Furthermore, the dip in the phase at 650 Hz originates from the resonant point of the long HVAC cables connected at the 132kV bus (see Fig. 2). The additional section of 33 kV cable introduced during the WF GSP energisation in configuration 3 shifts the network resonant point on the 33kV network to a lower frequency, in this case matching the internal ET resonant point. Due to the impedance matrix symmetry only one self- and mutual coupling impedance is plotted.

B. EMT Simulation Results

The EMT simulations are carried out for the switching sequence to transition from

- network configuration 1 to 2, energisation of the GT transformer including earthing/auxiliary transformer and the 630mm^2 cables and
- network configuration 2 to 3, energisation of the 500mm^2 cables from GSP to WF.

For both the GT and the GSP to WF cable energisation a statistical switching method is applied. For simplicity, in the following only the determined worst-case is presented and discussed.

1) GT Energisation

The simulation results of the point-on-wave switched GT energisation are plotted in Fig. 7 for measurements at the 33kV Node A as well as the ET LV terminals, node B (see Fig. 1(b)).

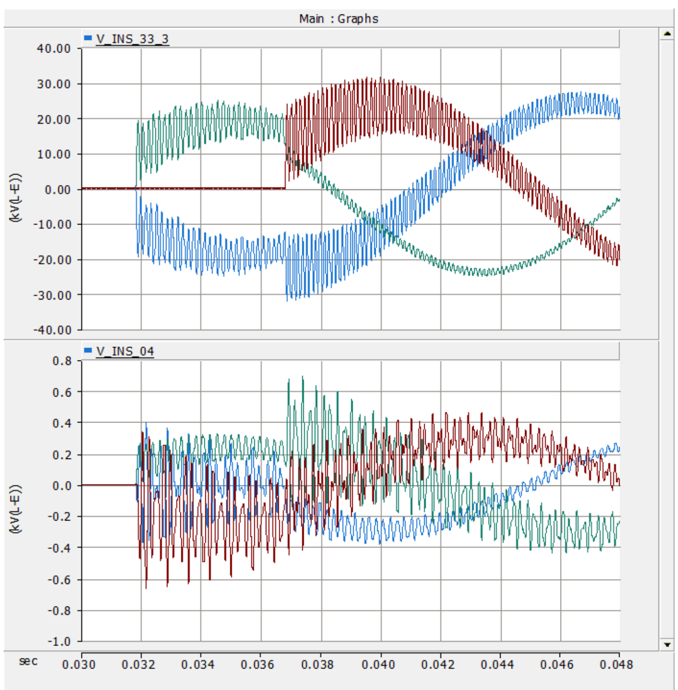


Fig. 7. Simulation results of network configuration 2, energisation of GT including ET and 630mm^2 cables

The simulation results show a 6.5kHz transient overlaying the power-frequency voltage, which originate from the 630mm^2 cables, matching the resonant point in Fig. 5.

2) GSP to WF Cable Energisation

The three-pole simultaneous energisation of the 500mm^2 cables from the GSP to the WF is plotted in Fig. 8. for measurements at the 33kV Node A as well as the ET LV terminals, node B (see Fig. 1(c)).

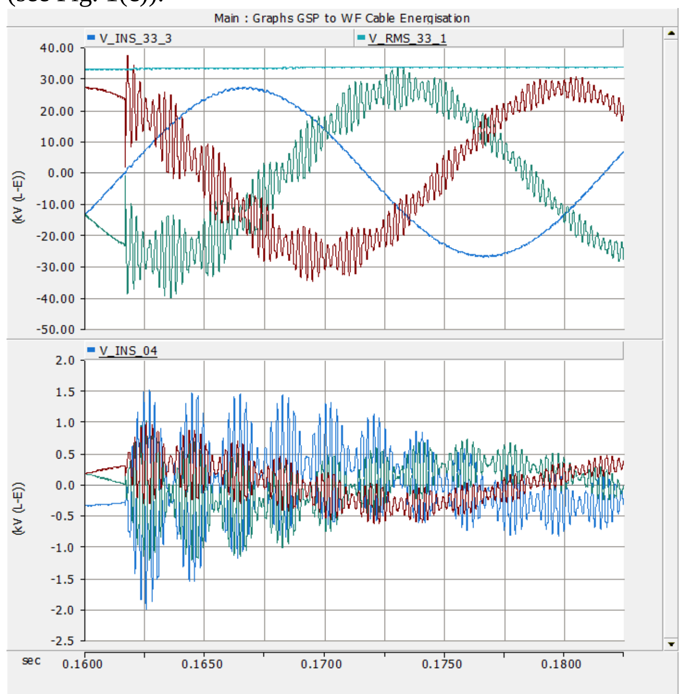


Fig. 8. Simulation results of network configuration 3, energisation of GSP to WF 500mm^2 cables

The simulation results in Fig. 7 show both a 4 kHz transient overlaying the power frequency-voltage, corresponding to the resonant point in the frequency-impedance scan results and a beat voltage phenomenon, characteristic for a transformer resonance. The resulting line-earth overvoltages at the ET LV terminals exceed 6 pu, which may lead to flashovers in the LV connection box.

3) GSP to WF Cable Energisation with ET LV connected Load Bank

To suppress or avoid the overvoltages created by the transformer resonance, IEC [9] recommends either a change of the system configuration or adding damping resistors. IEEE [10] recommends among others the connection of either resistor-capacitor snubber devices or load to unloaded/open circuits.

In this paper, a variable load bank is investigated, where load can be set in 5kW steps. The results of a simulation with a 50kW and 100kW load bank connected to the ET LV terminals are shown in Fig. 9 and Fig. 10. The 30m LV cable between the ET LV and the load bank is neglected.

The simulation results clearly show the effectiveness of the load bank to suppress the beat voltage due to transformer resonance, both at 50 kW and 100kW. The 4 kHz transient originating from the 500mm^2 cable energisation is still present, resulting in a maximum overvoltage of 1.84pu and 1.5pu for 50kW and 100kW load bank, respectively.

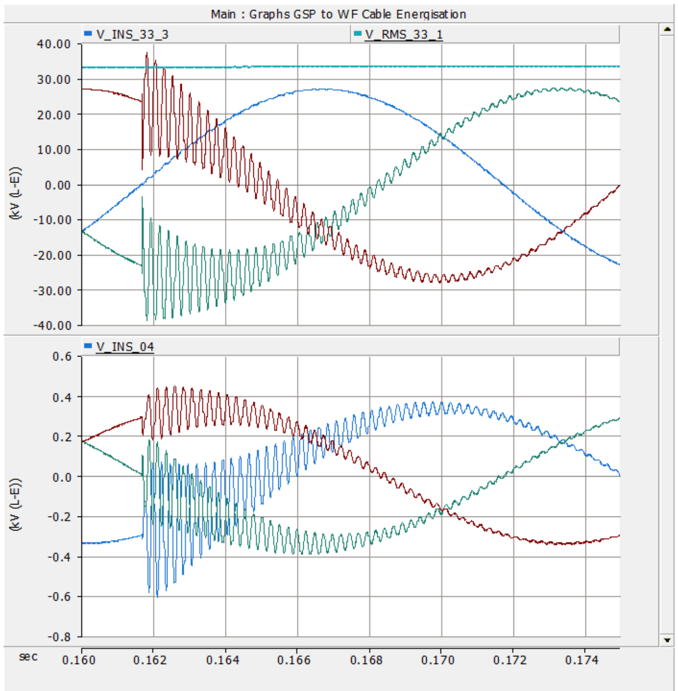


Fig. 9. Simulation results of network configuration 3, energisation of GSP to WF 500mm² cables with 50kW load bank connected to ET LV

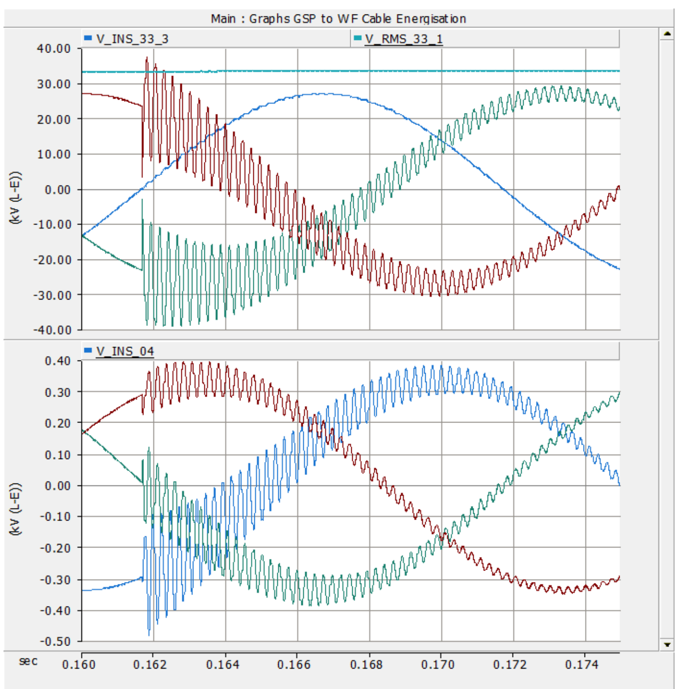


Fig. 10. Simulation results of network configuration 3, energisation of GSP to WF 500mm² cables with 100kW load bank connected to ET LV

IV. Measurement Results

Corresponding to the EMT simulations, load banks are installed at the LV terminals of the ET and measurements carried out to prove the solution. Measurements are carried out with an Outram PM7503 directly connected to the ET LV bushings. In Fig. 11 the corresponding measurement results are shown for GT energization corresponding to the transition from network configuration in Fig. 1(a) to Fig. 1(b). Load banks are only switched on after the GT and ET are energized. Therefore, no load bank damping is involved in this switching event.

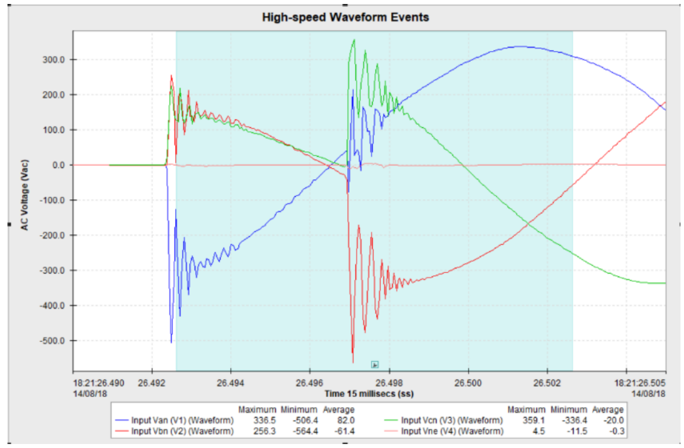


Fig. 11. Measurement results of network configuration 2, energisation of GT including ET and 630mm² cables, measurements on LV of ET

The measurements show a 6 kHz oscillation, approximately matching the simulation results with 6.5 kHz. Due to the GT being energised with a point-on-wave device the measurements in Fig. 11 show a second switching event (pole 2/3, red/green trace) 5ms after energization of the first pole (blue trace).
In Fig. 12 and 13 the corresponding measurement results for the GSP to WF cable energisation with 50kW and 100kW load bank are shown.

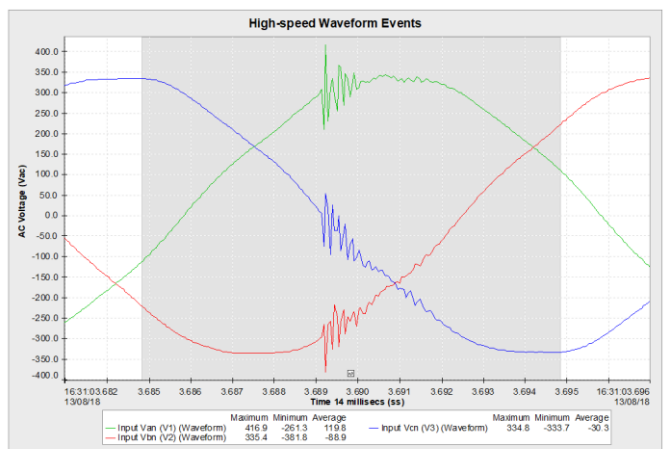


Fig. 12. Measurement results of network configuration 3, energisation of GSP to WF 500mm² cables with 50kW load bank connected to ET LV

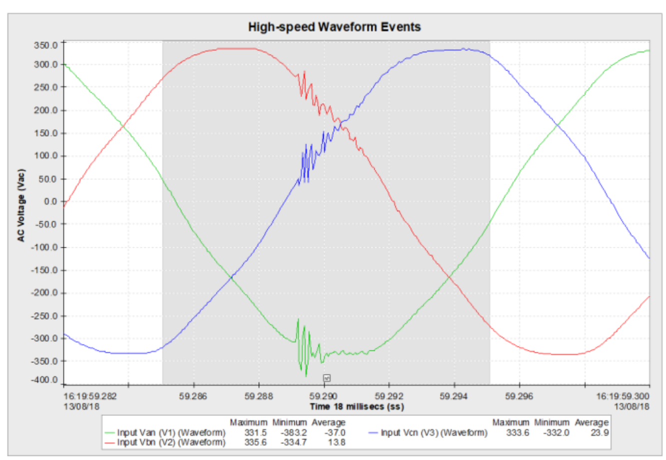


Fig. 13. Measurement results of network configuration 3, energisation of GSP to WF 500mm² cables with 100kW load bank connected to ET LV

Similar to the GT energisation measurements, the transient oscillation frequency is slightly lower than in the simulations with approximately 3.75 kHz. The effect of the lower load, lower damping and higher overvoltage at the LV terminals of the earthing transformer is also visible in the measurements. Overall no notable overvoltages are observed with the load connected to the ET LV side.

V. Conclusions

This paper investigates a transformer resonance of an unloaded earthing/auxiliary transformer in an unusual network configuration for these resonance issues. Unlike in other investigations, where the transformer in question is modelled with a detailed black or white box model derived from measurements of the transfer functions of each winding, the transformer is modelled with lumped elements to match available SFRA measurements. This type of modelling is based on the transformer internal geometric winding arrangement and features limitations in terms of modelling of the first transformer resonant point only.

Frequency-impedance scans of the simulated network configuration already show the existence of a possible transformer resonance due to the match of an internal transformer resonant point and network resonant point.

The performed simulations show that there exists a resonance phenomenon between the transformer and the network it is connected to. The simulated resonant condition leads to transferred overvoltages in excess of 6 pu on the open-circuited LV terminals in the studied configuration with the simplified modelling approach. Furthermore, the mitigation method of a load bank connected to the LV side of the ET is investigated, which shows that the resonant condition can be mitigated with this measure.

Following the results of the simulations, load banks were installed at the LV side of the ET and measurements carried out during switching operations. The measurements obtained during transformer and cable energization show that the LV connected load bank damps out the resonant condition and thus prevents excessive overvoltages from occurring.

A comparison of the simulation and measurement results shows some differences, especially in the damping and the peak overvoltages. These can be attributed to the following reasons:

- higher real system damping than in the simulations due to parasitic inductances and capacitances as well as contact resistances, etc. not being modelled in the simulations,
- differences in 33kV cable modelling and real cable system installed as well as cable length,
- neglect of 30m LV cable between ET LV and load bank, which adds additional damping and
- lumped circuit modelling approach of the ET resonance point.

Following the above it can be concluded that the lumped circuit modelling approach of the ET's first resonance point and comparison with available SFRA measurements produces a transformer resonance beat voltage phenomenon and severe overvoltages but is not detailed enough to accurately reproduce the measurement results. Consequently, the lumped circuit approach is a fast modelling approach to investigate resonant conditions, where limited transformer data is available, but not sophisticated enough to be utilized for load bank sizing.

VI. References

[1] B. Gustavsen, "Study of Transformer Resonant Overvoltages Caused by Cable-Transformer High-Frequency Interaction," *IEEE Transactions on Power Delivery*, vol. 25, no. 2, pp. 770 - 779, 2010.

[2] R. Musil, G. Preininger, E. Schopper and S. Wenger, "The Resonance Effect of Oscillating System Overvoltages on Transformer Windings," *IEEE Transactions on Power Apparatus and Systems*, Vols. PAS-101, no. 10, 1982.

[3] M. Popov, L. van der Sluis and R. Smeets, "Evaluation of surge-transferred overvoltages in distribution transformers," *Electric Power Systems Research*, vol. 78, p. 441–449, 2008.

[4] B. Gustavsen, "Wide Band Modeling of Power Transformers," *IEEE Transactions on Power Delivery*, vol. 19, no. 1, 2004.

[5] F. de Leon and A. Semlyen, "Reduced Order Model for Transformer Transients," *IEEE Transactions on Power Delivery*, vol. 7, no. 1, 1992.

[6] B. Gustavsen and A. Portillo, "A Damping Factor-Based White-Box Transformer Model for Network Studies," *IEEE Transaction on Power Delivery*, 2018.

[7] R. K. Senobari, J. Sadeh and H. Borsi, "Frequency response analysis (FRA) of transformers as a tool for fault detection and location: A review," *Electric Power Systems Research*, vol. 155, pp. 172-183, 2018.

[8] CIGRE WG 33.02, "CIGRE Technical Brochure 39: Guidelines for Representation of Network Elements when calculating Transients," 1990.

[9] BS EN IEC 60071-2:2018, "Insulation co-ordination - Part 2: Application guidelines," 2018.

[10] IEEE PC57.142/D1.7, "A Guide To Describe The Occurrence and Mitigation Of Switching Transients Induced By Transformer And Breaker Interaction," no. draft, 2004.

[11] PD IEC TR 60071-4:2004, "Insulation co-ordination — Part 4: Computational guide to insulation co-ordination and modelling of electrical networks," BSi, 2004.