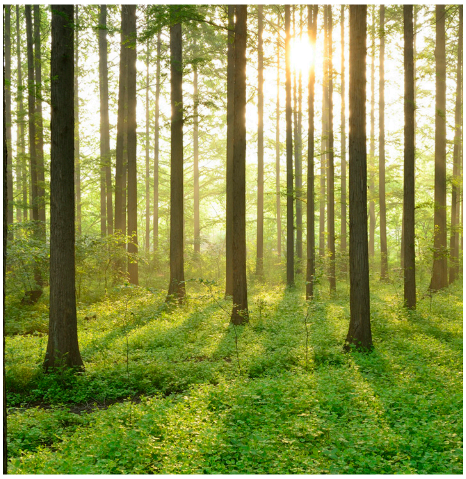
ANALYSIS OF VACUUM BREAKER GENERATED TRANSIENTS IN A 36KV WIND FARM CABLE GRID

REPORT 2018:502



VINDFORSK

Energiforsk

Analysis of Vacuum Breaker Generated Transients in a 36kv Wind Farm Cable Grid

TARIK ABDULAHOVIC

ISBN 978-91-7673-502-2 | © ENERGIFORSK November 2018

Energiforsk AB | Phone: 08-677 25 30 | E-mail: kontakt@energiforsk.se | www.energiforsk.se

Foreword

Projektet "Analysis of vacuum breaker generated transients in a 36kV wind farm cable grid" är finansierat av Energiforsk och Energimyndigheten genom programmet Vindforsk IV.

Genomslag i olika apparater och i parker med 36 kilovolts kabelnät är ett problem som både vindkraftägare och nätägare upplever. Det innebär kortslutningar som leder till ökade kostnader och till produktionsbortfall. Projektets övergripande mål är att med praktiska mätningar öka kunskapen om orsaken till problemen. Arbetet har skett i samarbete med Vattenfall med mätningar på vindkraftanläggningen "Stor-Rotliden". Speciellt har utformningen av jordningssystemet och dess konsekvenser undersökts.

Intresset för projektet har varit stort hos vindkraftägare och projektet och är ett utmärkt exempel på hur praktiska problem analyserats av kompetenta forskare från en teknisk högskola. Och där resultaten kommit till god användning hos industrin.

Projektet har utförts av Chalmers med Talrik Abdulahovic som projektledare.

Göran Dalén

Ordförande, Vindforsk IV

Sammanfattning

Detta projekt undersöks hur högfrekventa transienter i ett kabelnät påverkar anslutna komponenter. Såväl generering som propagering och apparatskydd studeras.

I projektet planeras mätningar i Stor-Rotlidens vindpark där haverier av kabelavslut vid transformatorer har förekommit. Jämfört med tidigare arbete inom detta tema så är fokus här på jordningssystemets utformning, speciellt dess högfrekvensegenskaper.

Inom tidigare Vindforsks projekt har komponentmodellering utförts, denna modellering förfinas ytterligare och resultaten hålls generella så att de kan appliceras på komponenter av olika storlekar. Analys av olika jordningssystem genomförs och faktorers betydelse för generering och propagering av transienta överspänningar fastställs. Vidare analyseras hur transienterna påverkar anslutna objekt, och vilka skydd som kan behövas.

Summary

In this project it is investigated how the high frequency transients (HF) in a cable grid influence connected equipment. Both generation and propagation as well as protection is studied.

Measurements in Stor-Rotliden's wind farm where transformer failures occurred are planned in the project. In comparison with the previous work in this field, the focus here is on the design of grounding systems (GS), especially their HF characteristics.

Component models derived in a previous Vindforsk project are improved and the results are generalized so that they can be applied to components of different sizes. Analysis of different GS is performed and the importance of different factors that influence generation and propagation of transient overvoltages is determined. Later it is analyzed how the transients influence connected components, and what protection is needed.

List of content

1 Introduction

Breaker operations in wind parks generate very fast transients that have very short rise times of about 100ns. On top of that, grounding system have a much higher impedance during such fast disturbances, especially during very fast transients. Consequently, this can result in equipment failure where the most vulnerable devices are the ones directly connected to the cable grid, such as transformers and cable terminations. Transformers are one of the most expensive equipment in electric systems and transformers replacements increase maintenance and running costs significantly.

Problems observed in Stor-Rotliden (SRL) wind park (WP) are related to auxiliary transformer failures as well as the cable termination failures. The failures off the cable terminations appeared frequently and it was required to replace failed cable terminations every year. Other wind park owners experienced identical problems in their wind parks. The problems were not present in all wind parks in Sweden. Some wind parks in southern Sweden didn’t have these problems at all. Some of the wind park owners replaced resistive cable terminations with geometric field control terminations. This solved the problem of the cable termination failures but the installation of the geometric field control terminations requires more space than the resistive cable terminations.

There is no consensus on why the cable termination failures appear. One suggestion is that a higher ground resistance may contribute to the failures since the wind parks placed in northern Sweden have a higher ground resistance.

In this project, measurements as well as simulations are used to obtain the voltage stress to which the cable terminations as well as transformers are exposed to. Grounding modelling as well as different groundings are investigated in order to determine the grounding influence on the voltage transients. Finally, the critical cases are identified and measures/future work are proposed

2 Measurements and measurement campaigns

2.1 MEASUREMENT EQUIPMENTANALYSIS OF VACUUM BREAKER GENERATED TRANSIENTS IN A 36KV WIND FARM CABLE GRID

An important part of the project was to measure transients in SRLWP. In order to capture the transients of interest, the equipment used in the measurements needs to have a very high bandwidth. Considering the expected rise times of about 100nS, the bare acceptable bandwidth minimum is 10-20MHz.

Considering the voltage measurements, the chosen voltage dividers are Northstar VD-100 that can withstand 100kV AC and 200kV BIL with 20MHz bandwidth and 10000:1 ratio. The price and the ability to withstand voltage higher than 170kV were the decisive factors. Sensors with a higher bandwidth don't exist on market.

When it comes to the current measurements, Rogowski coils were used to measure the current. CWT15R and CWT3 Rogowski coils were installed where the bandwidth of both probes is 16MHz. Later in the project, the CWT3 probes were replaced by CWT15R probes. It is worth mentioning that these are the fastest sensors available.

Installing equipment such as voltage dividers was never an easy task considering the size of the sensors. Respecting the safety standards for lightning pulse, the voltage dividers need to withstand 170kV BIL which makes them quite large. Another issue is placement of the recording computers since it is required to have a 230V power outlet to feed the power to the computer. Taking all this into account, it was chose to install the equipment directly to the low voltage bus of the 130/36 kV/kV substation transformer and in the switchgear enclosure near A11 wind turbine.

Figure 1 shows the installed voltage dividers in the substation and in the A11 enclosure. The symmetry of the divider placement could not be achieved, but we could achieve that the grounding plane was not close to the metallic parts of the sensors that shape the field and enable the high bandwidth.

Figure 1 Voltage sensors in substation and in A11

Figure 2 shows the installation of the current probes in A11 enclosure and in the substation.

Figure 2 Current sensors in A11 and in substation

There are three parallel cables in the substation and the sensors capture the current that flows in only one of them. The current is then multiplied by three in order to obtain the right current value. The placement of the coils is done in such a way so the cable passes through the center of the coil. By doing this, the correct measurements are obtained.

The oscilloscopes used in the project are USB based and require a computer for operation. The reason for choosing a USB oscilloscope is price since the requirement is to capture seven channels with at least 40MS/s; six channels are used for three phase voltages and currents and the seventh channel is used for the triggering signal. The chosen oscilloscope is Picoscope 4824 with 8 channel inputs, 12 bit resolution, 20MHz bandwidth and 80MS/s sampling. The sampling is 40MS/s in the case of 5 or more channels acquisition.

Figure 3 shows two oscilloscopes and the trigger box in the lab testing. The trigger box is just a high pass filter and passes through any disturbance that occurs on any of the three phase voltages. If a disturbance occurs in the system, the output signal of the trigger box is going to appear and is used as the triggering signal.

Figure 3 Oscilloscopes with trigger box

In order to acquire the measurements, an own LabView based program is developed. The program monitors the signals and stores the data in case of a triggering event. In addition, harmonic measurements are performed continuously in 5 minute intervals. The interval of the harmonic measurements can be varied and become as low as 1 minute.

Error! Reference source not found. shows the complete measurement system installed in the A11 enclosure.

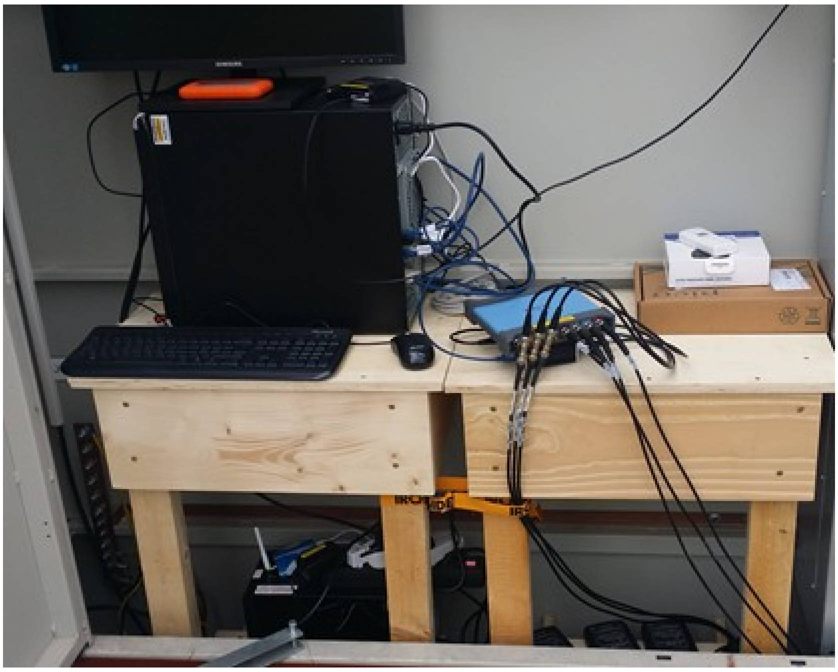


Figure 4 Measurement system in A11

The measurement system contains in addition:

- UPS system for power supply in the case of black-outs;
- 3G router for communication and data transfer;
- A remote controller for controlling the switches via internet. This system is used for hard reset of the equipment;
- Temperature/humidity measurement sensors;

2.2 MEASUREMENTS

The measurements are performed in three measurement campaigns that were held on the 11th of June 2015, 28th of September 2015 and the 8th of June 2016.

The additional campaigns were performed using additional oscilloscopes in order to achieve the minimum of 80MS/s sampling speed. The reason for that is that the first measurements showed some interesting transients of a very high frequency that were not captured well using the 40MS/s sampling speed. Therefore, two LeCroy oscilloscopes were used, where LeCroy Wavesurfer 24MSx-b was used in A11 and LeCroy Wavesurfer 3024 was used in the substation.

The list of the captured events are:

- Energizing of the substation transformer and the cable that connects the transformer to the switchgear;
- Energizing of radials A, B, C and D;
- Energizing of radial A without WT transformers;
- Disconnection of the radials;

These events were also captured automatically by the system during some other events in the wind park.

The most severe measurements were obtained during the energizing of the substation transformer. The voltage transients capture there have a frequency in order between 40-70 MHz. These events were capture using both Picoscope and LeCroy oscilloscopes. Figure 5 shows the measurement acquired in the first measurement campaign. The rise time of the voltage front is as short as the sampling time (25ns).

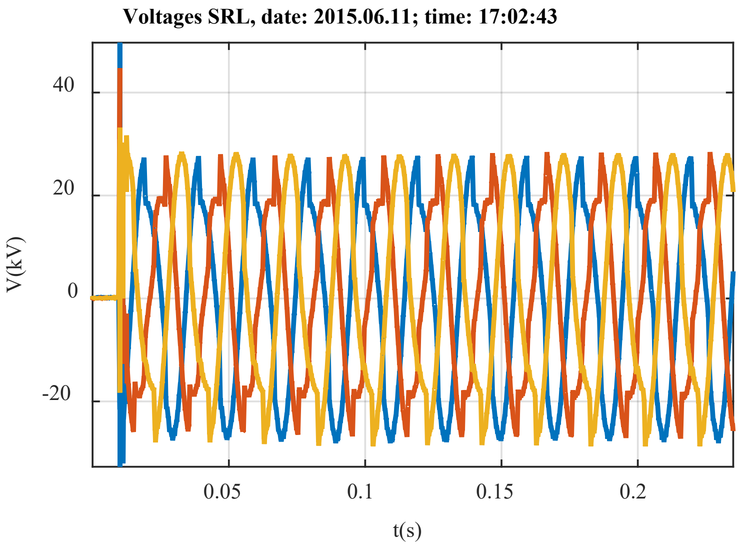


Figure 5 Substation transformer energizing – first measurements

Figure 6 shows even higher magnitude of the captured voltage revealing even higher frequency that is estimated to 70MHz. It is important to note that these very short and very fast transients appear before the secondary side voltage starts rising due to the capacitive coupling between the primary and the secondary which has rise times in order of micro seconds. The voltage divider manufacturer confirmed that the reason of fast damping is due to the probe itself and its low pass filter that filters out such transients after one period. However, according to the voltage probe manufacturer, these voltages exist and are captured well. All the three voltage dividers captured such voltages on at least one occasion. However, the reason and reasoning behind such a phenomenon is not clear and understood. What is clear is that such a voltage can damage the cable terminations on the secondary side of the transformer.

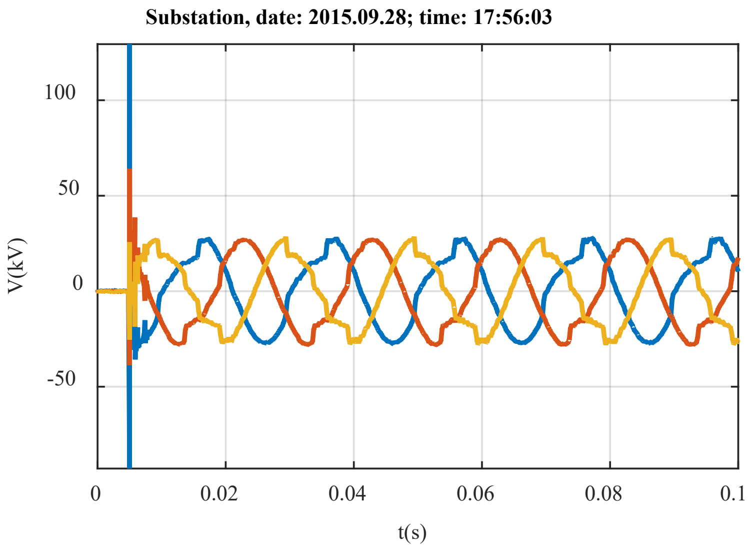


Figure 6 Substation transformer energizing – second measurements

The rest of the measurements are presented in the next chapter together with simulation results.

3 Modelling, Simulation, Verification and Analysis

3.1 MODELLING

The models of the components were improved continuously in order to improve accuracy, shorten simulation time and/or correct errors found. In addition, different types of models were used for different types of simulations. Here, the modelling that is the most relevant for transient studies is presented.

To model wind turbines, induction generators (IG) model is used for the WP generators as well as the controlled voltage source. The model using IGs is presented in Figure 7.

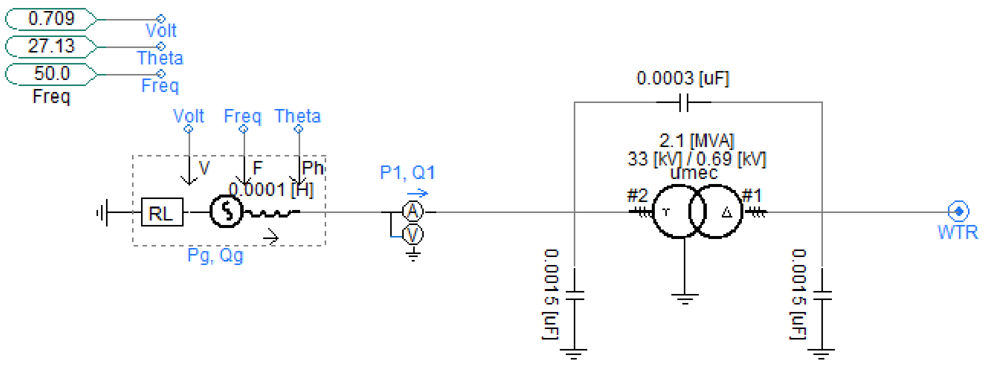


Figure 7 WT model with controllable voltage source

The substation transformer is modelled using a two winding UMEC transformer as well as a three winding classical transformer. The transformer model contains stray capacitances in order to have a good response at high frequencies. The UMEC transformer model with stray capacitances is presented in Figure 8.

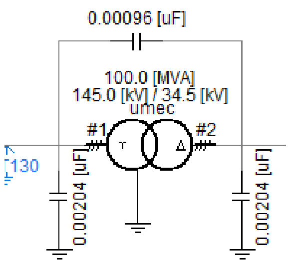


Figure 8 Substation transformer models

The saturation curve is presented using a simple knee-point and air-core reactance approach. The substation transformer has a saturation curve with knee-point of 1.2 pu and air core reactance of 0.17pu. The knee-point of WT transformers is reduced to 1.1 pu in order to achieve a higher value of magnetizing currents as seen in the measurements.

Most of the cables are modelled using the frequency dependent cable model. Even the 20m long cable in the substation is modelled using that approach. This model is used only in models where a short simulation step of 0.1us is used. The 20m cable model is shown in Figure 9. The 20m long cable consists of three cables in parallel.

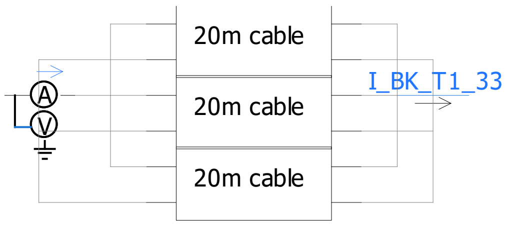


Figure 9 Frequency dependent 20m long cable

The vacuum circuit breaker (VCB) is modelled using a detailed deterministic model as used in [1]. The set of parameters are obtained from the measurements that reflect VCB behavior. The parameters that are the most important are the speed of the contacts at opening and at closing, as well as the capability to interrupt the high frequency current. These parameters are extracted from the measurements where the behavior of the VCB is dominant on the voltage waveform. One such event is energizing of radial A where prestrikes are captured, as presented in Figure 10.

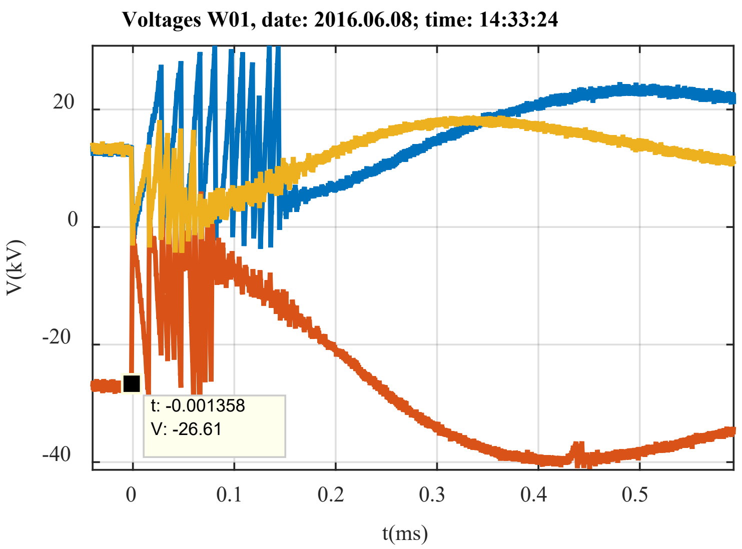


Figure 10 Prestrikes during radial A energizing

Prestrikes shown in radial A are used to tune the high frequency current quenching parameters as well as the rate of decay/rise of dielectric strength of the VCB.

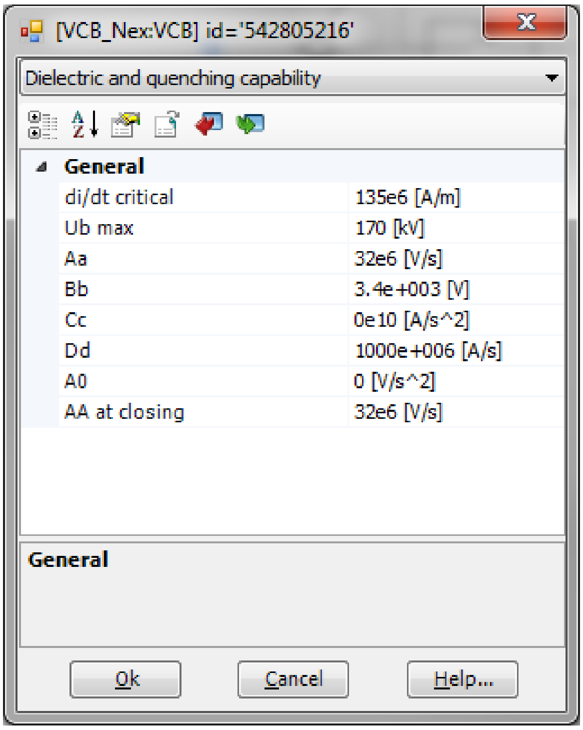


Figure 11 VCB model parameters used in SRL studies

Parameters of the new VCB are presented in Figure 11. The Cc and Dd parameters are related to the high frequency current quenching, while the other parameters are related to the dielectric withstand.

The grounding inside the park is done in such a way so the cable screens are grounded at cable termination points, as presented in Figure 12. Normally, the grounding is performed through the grounding resistance that accounts of the resistance measured at 50Hz. However, the grounding resistance is much higher at high frequencies when breakers are operated.

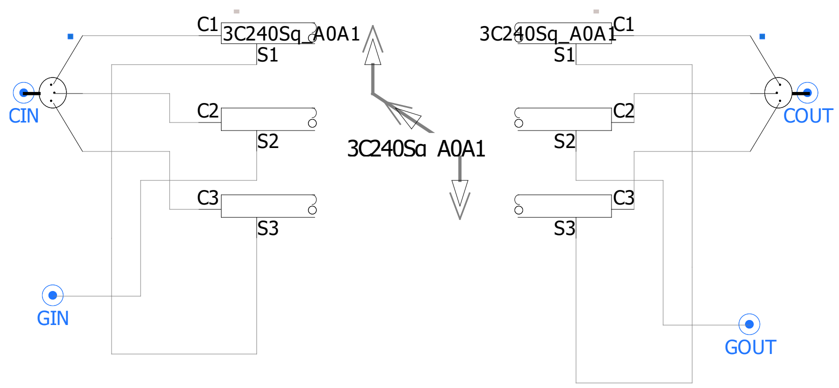


Figure 12 Grounding of cables at single nodes at cable ends

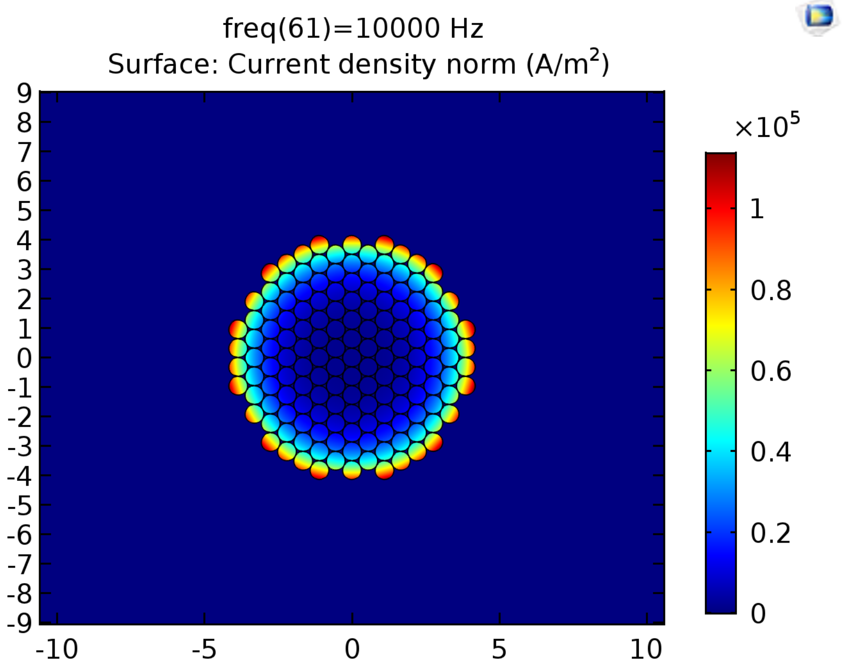


Figure 13 Current density in 50mm2 grounding wire at 10kHz

Another major step in this study is done in the grounding model where a frequency grounding model is developed. The modelling started by calculating the inductance and capacitance of a grounding wire using FEM calculations. Figure 13 shows FEM model of a 50mm2 grounding wire and the current density plot at 10kHz.

The soil resistivity is taken so the steady state 50Hz resistance corresponds to 0.55Ohm, which is the measured value. In that case, the soil resistivity is considered to be 100Ohm/m. The extracted impedance of grounding sections of different length are fitted in order to obtain impedances as analytical expressions. For this, vector fitting method by Björn Gustavsen is used [2],[3] and [4]. Figure 14 shows vector fitting result of a 200m long grounding section. The fitting is performed for all the section lengths and grounding wire cross-section areas.

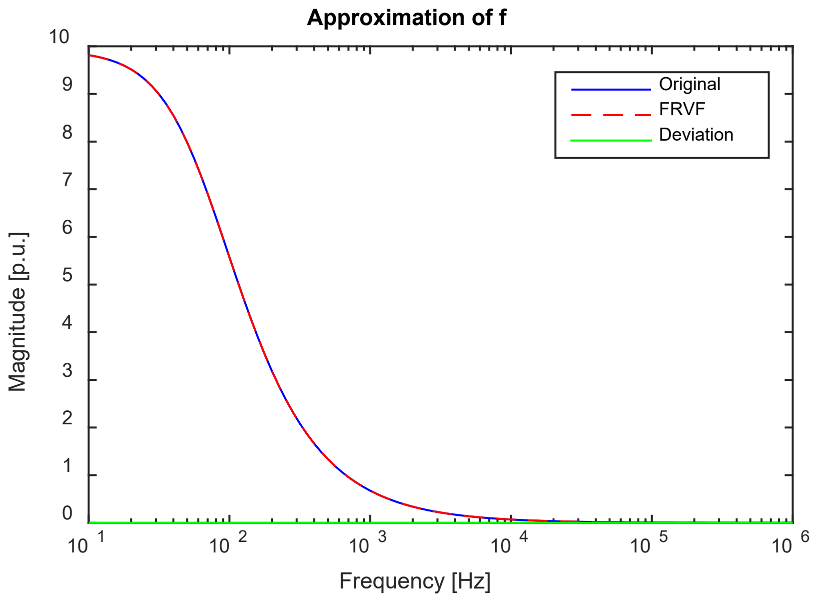


Figure 14 Vector fitting of a 200m long grounding section.

The transfer function obtained is transformed into an equivalent circuit with complex impedance equal to the transfer function obtained. This equivalent circuit is actually just an advanced PI section that gives good results at high frequency. That equivalent circuit is implemented in PSCAD. The equivalent circuit of the 200m long grounding section is shown in Figure 15.

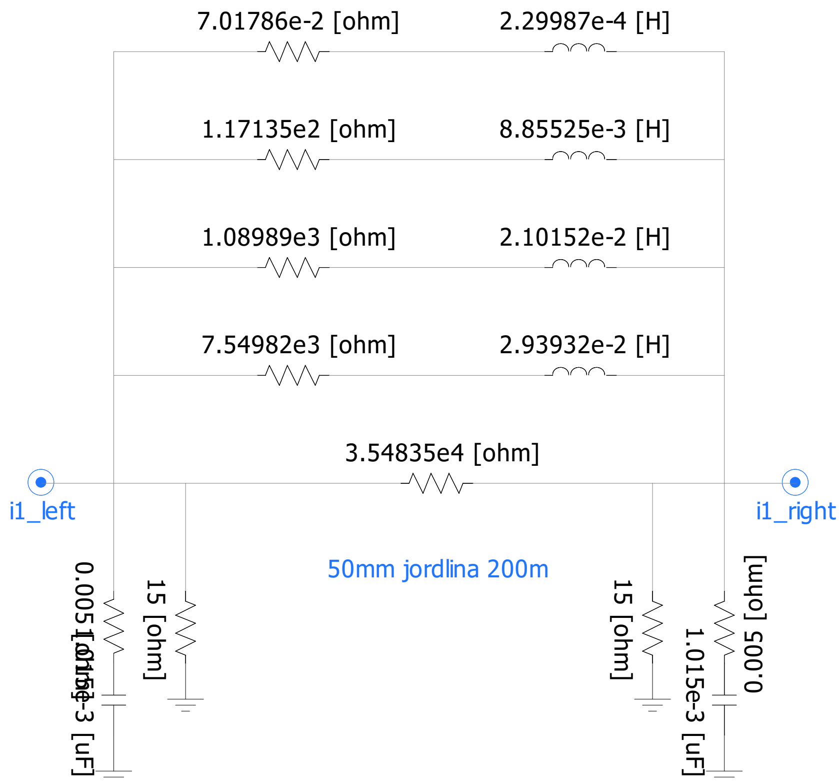


Figure 15 200m grounding line model in PSCAD

Longer grounding sections are made by connecting sections in series. The shortest grounding section model is 25m and the longest on is 200m. The shortest one is chosen to be 25m since in that case the high frequency impedance in the grounding wire direction is as high as the impedance towards the earth. By that, the realistic impedance of the wire is obtained.

3.2 MODELL VERIFICATION

Five main cases are used for model verification. These cases represent the measurement cases where the radial energizing is recorded. The reason for using these cases for verification is that they represent cases where both the low and the high frequency behavior of the WP model is going to be exposed. The layout of the SRL wind park with the PSCAD measurement points is presented in Figure 16.

Figure 16 SRL WP model

The model could be verified only in two measurement points, the low voltage side of the substation transformer, and at wind turbine A11. It is very likely that the level of remanence in the wind turbine transformers is not zero. This may influence the results significantly. However, since the level of remanence is not possible to determine, all the simulations are done with zero remanence magnetism in the transformers. Figure 17 and Figure 18 show substation voltages at radial A energizing. It can be noted that the damping of the cable model is quite poor.

However, this is as much damping as one could get from a model since a frequency dependent models are used.

3.2.1 Radial A energizing

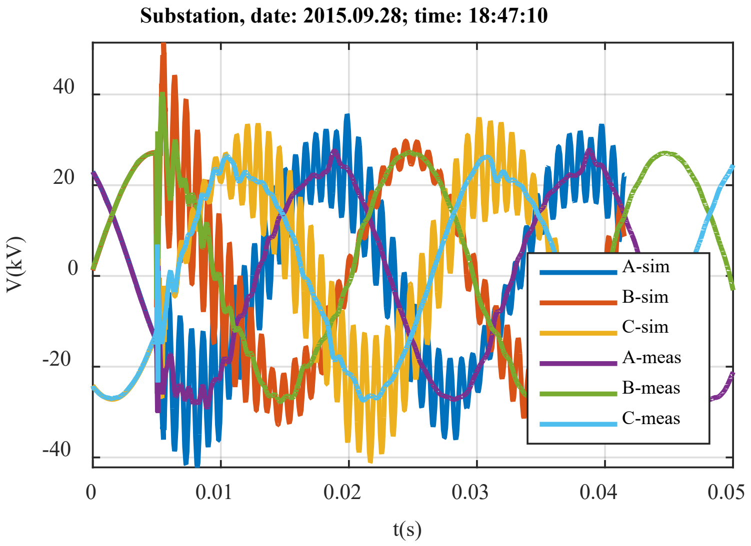


Figure 17 Voltage at T1 - radial A energizing

Figure 18 gives a closer look at the voltages. This figure reveals the VCB behavior. One could note that prestrikes in phases A and B is in a good agreement with the measurements. Only phase C shows a higher number of pre-strikes.

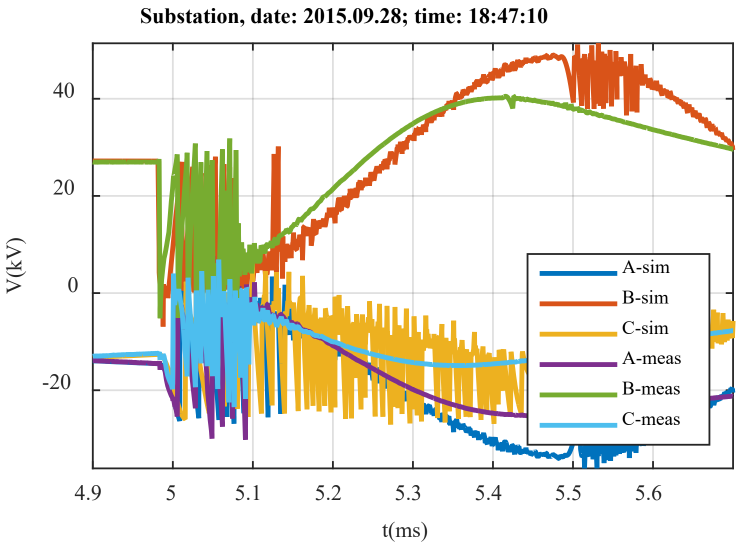


Figure 18 Voltage at T1 - radial A energizing – zoom

Figure 19 show currents in substation measured during radial A energizing. The peak currents have a good match. This confirms that the saturation model is good. The poor model damping can be noted in the current plots as well.

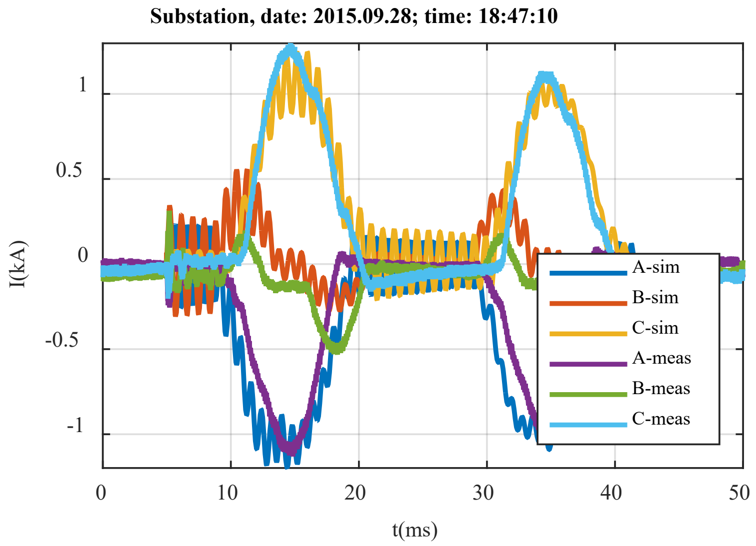


Figure 19 Current at T1 - radial A energizing

3.2.2 Radial B energizing

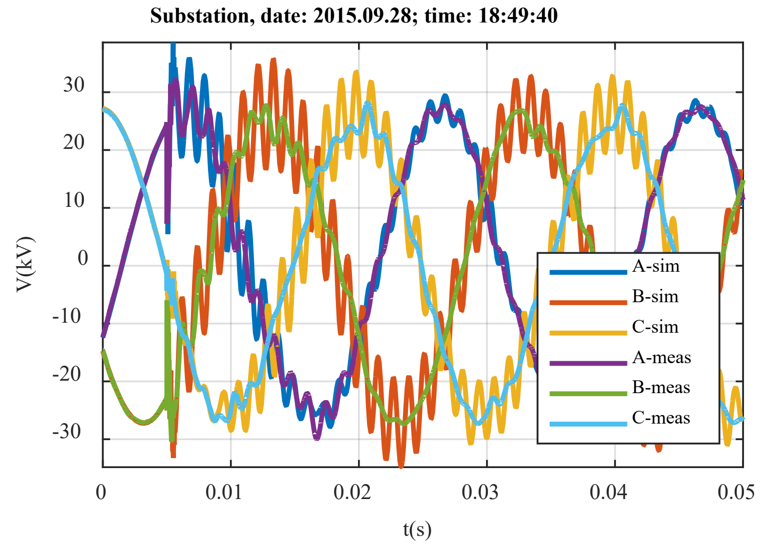


Figure 20 Voltage at T1 - radial B energizing

Radial B energizing is shown in Figure 20, Figure 21 and Figure 22. The voltage plot shown in Figure 20 shows rise of the magnitude of the oscillations in the measurements. The magnitude of the oscillations in the simulations is reducing and getting closer to the measurements.

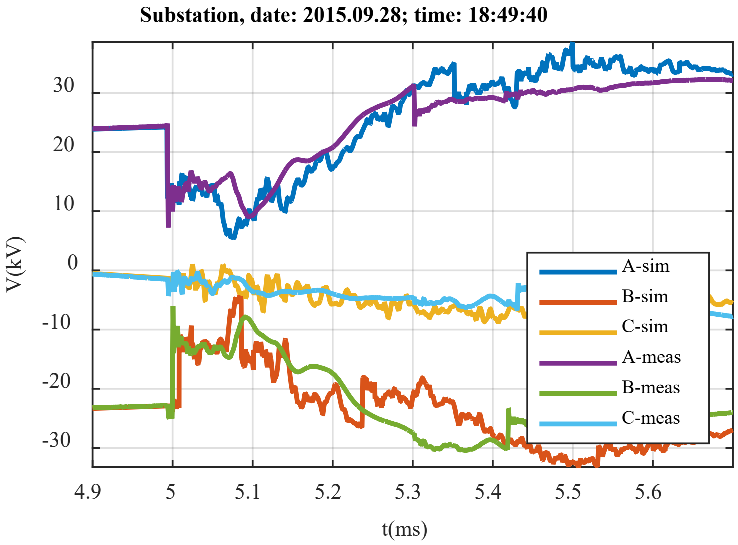


Figure 21 Voltage at T1 - radial B energizing – zoom

Figure 21 shows a good match in prestrikes caused by breaker at radial B. Number of prestrikes as well as the magnitude matches well.

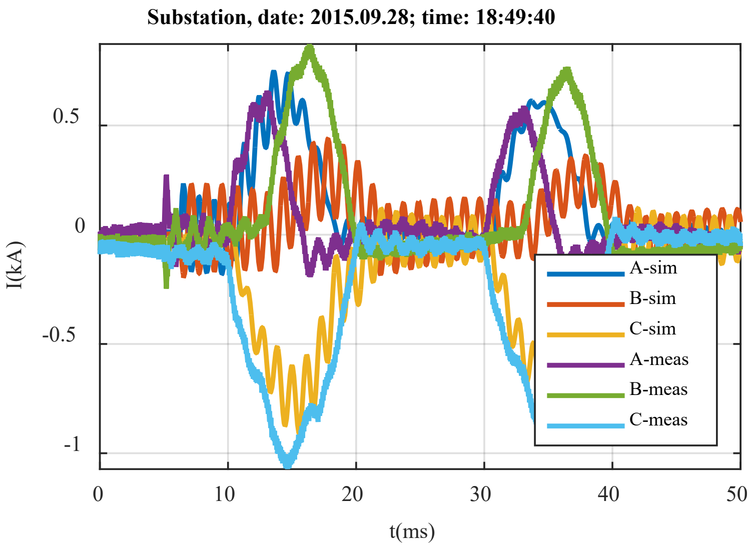


Figure 22 Current at T1 - radial B energizing

Figure 22 shows energizing currents at radial B. The magnitude of the energizing current is a bit higher than the simulated current. The discrepancy most likely comes from the remaining flux in the WT transformers. The damping in the simulations is much lower than damping in the measurements.

3.2.3 Radial C Energizing

Radial C energizing is presented in Figure 23, Figure 24 and Figure 25. Figure 23 shows voltage oscillations when the breaker connecting radial C is closed. It can be noted that the magnitude of the oscillations recorded in the simulations is getting closer to the measured values. However, the frequency of the low frequency oscillations that occur after the breaker operation matches quite well the measurements.

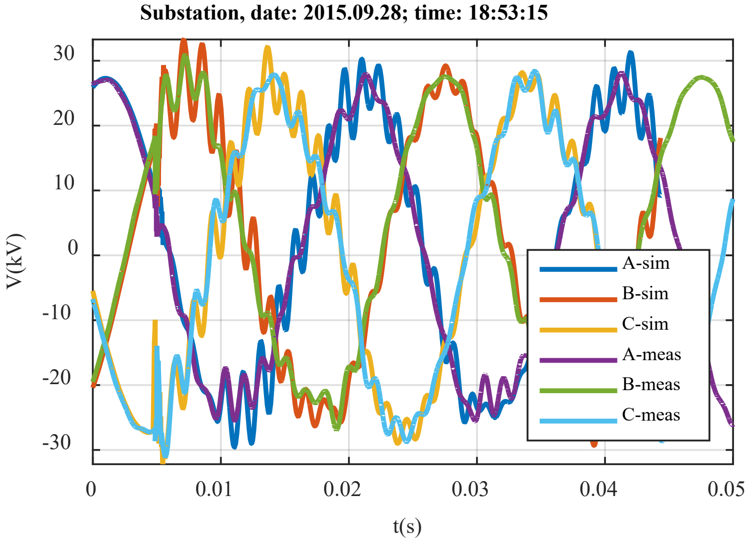


Figure 23 Voltage at T1 - radial C energizing

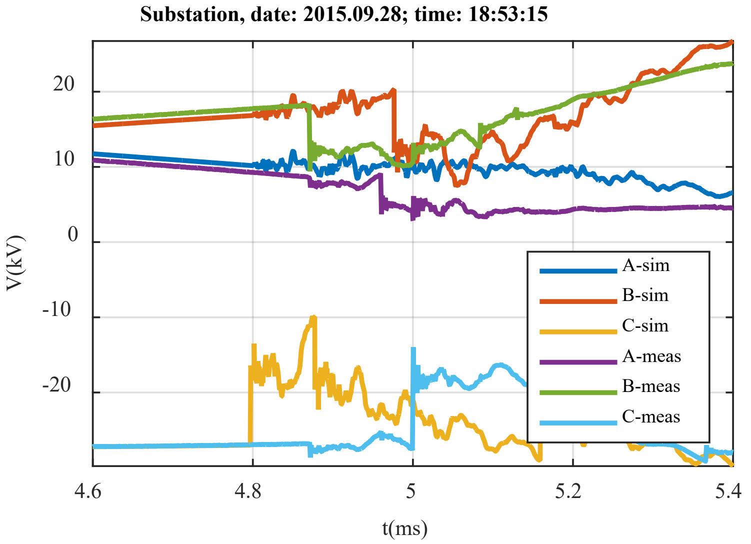


Figure 24 Voltage at T1 - radial C energizing – zoom

Figure 24 gives a close look on the high frequency oscillations on the breaker closing event. The number and the magnitude of the prestrikes are well matched.

Figure 25 presents the current energizing transients. The magnitude of the simulated currents are lower than in the measurements and the current oscillations are higher.

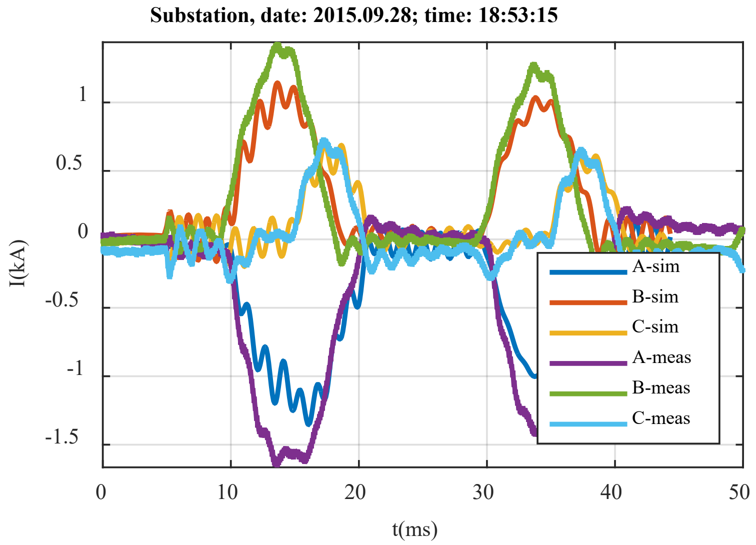


Figure 25 Current at T1 - radial C energizing

3.2.4 Radial D energizing

Radial D energizing is presented in Figure 26, Figure 27 and Figure 28. Figure 26 shows voltages after the closing of the radial D breaker. Simulations show really good match to measurements in magnitude of the oscillations and the frequency.

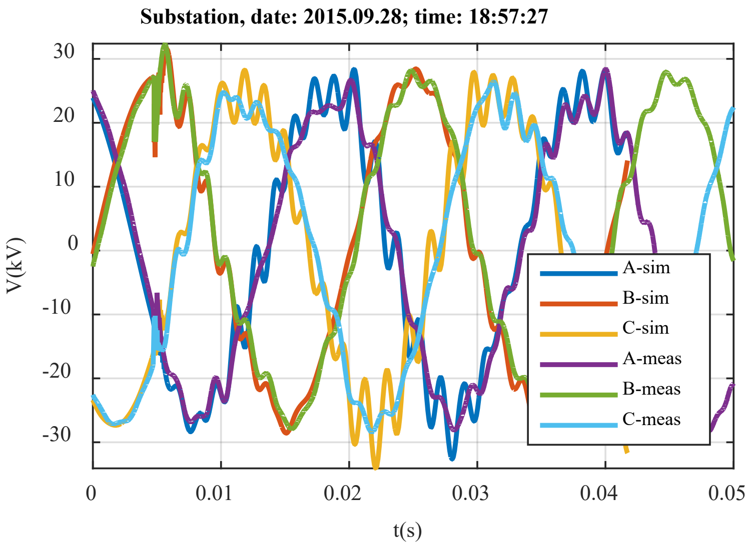


Figure 26 Voltage at T1 - radial D energizing

Figure 27 shows the high frequency voltage behavior capturing voltage pre-strikes. The magnitude and the number of the pre-strikes observed in the simulations matches well the measurements.

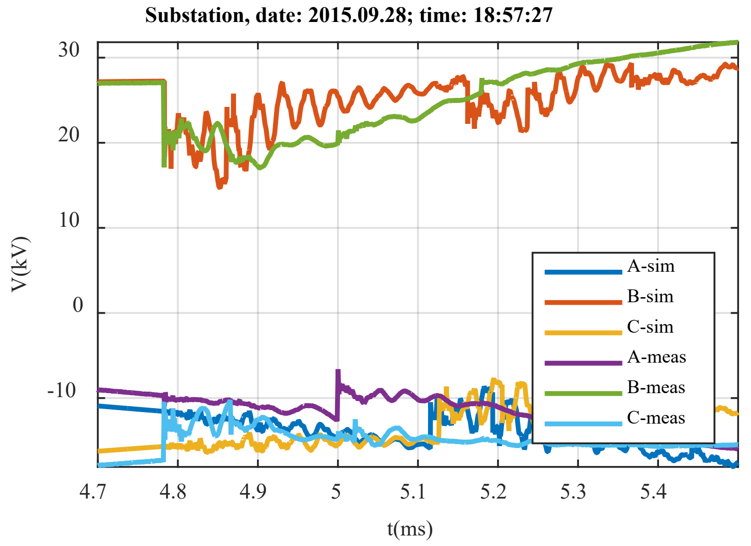


Figure 27 Voltage at T1 - radial D energizing – zoom

Figure 28 shows the current measurements recorded in the substation during radial D energizing. The magnitude of the measured current is higher than the simulated value and the current oscillations have a higher peak in the simulations

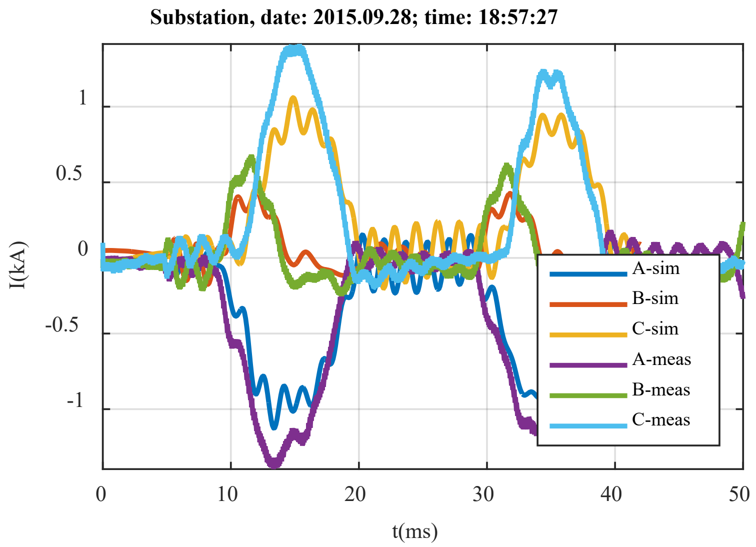


Figure 28 Current at T1 - radial D energizing

3.2.5 Verification of radial A energizing without WT transformers

Figure 29 show energizing of radial A without the WT transformers connected. This energizing transient represents only the radial A cable energizing. As observed in Radial A energizing, the model damps poorly such oscillations. That is even more evident in this case.

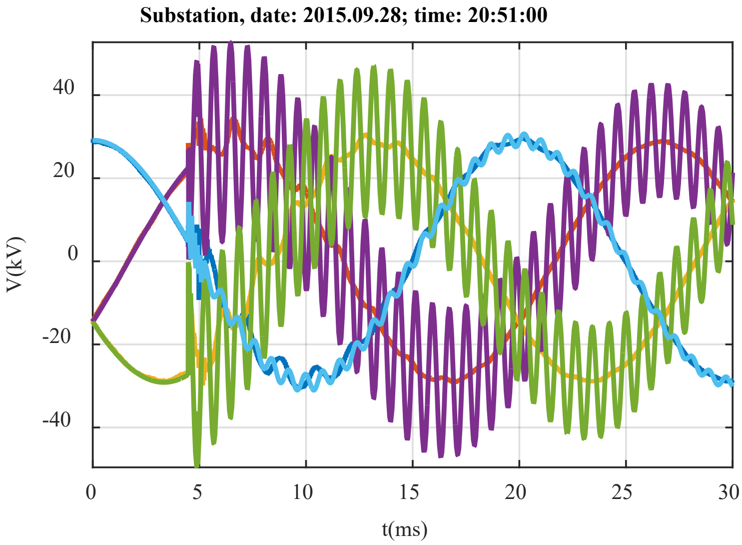


Figure 29 Voltage at T1 - radial A energizing without WTs connected

3.2.6 Energizing verification summary

The voltage waveforms show that the resonant frequency of the cables is modelled well. However, the damping in the system, especially for the cable resonant frequencies is quite bad. It can be noted that the matching is the worst for radial A, than it gets better for radial B and it is really good for radial D. The reason for that is that when radial B is energized, a part of the energy comes from radial A and a part comes from the grid. When radial D is energized, most of the energy comes from radials A,B and C and only a part from the grid. In that case, the quality of the 130kV grid model is not that relevant as it is in the radial A energizing. This points out that the discrepancy comes from a bad 130kV grid model that is quite simple in the WP model. In addition, the 130kV grid impedance at the moment of the measurements may be completely different from the one used in the simulations, which may have contributed to the discrepancy as well.

The peak energizing current matches quite well in the simulations. For some cases it is slightly higher than the measured value, while in some cases it is lower. Different levels of remanence WT transformer flux may have contributed to such a discrepancy.

3.3 ENERGIZING STUDIES

The previously presented radial energizing is used only for the model verification. The moment of the breaker closing in the measurements is not adjusted for the worst case scenario. However, additional simulations are performed with the worst case scenario in place where the breaker poles form the first pre-strike at the voltage peak of one of the phases. This is the worst case scenario since the highest voltages are obtained by doing this.

In addition, several different cases are studied. The first, the influence of different grounding models, the second, the influence of different grounding impedances used to ground the neutral of the grounding zig-zag transformer, and finally, the energizing of wind turbine transformers when a radial is energized.

In this report, only the cases that are most representative are going to be shown. Every simulation contains more than 120 signals that are studied analyzed for all the cases. The measured signals of the highest interest contain voltages and currents at the radials, at first and last turbine in every radial as well as voltages and currents at the low voltage side of the substation transformer.

3.3.1 Energizing for different grounding models

In the simulations, a simple grounding with 1Ohm resistance as well as the frequency dependent (FD) grounding model are used. The radial energizing is performed with the two grounding models.

All the figures that present simulated signals have a title that contains the simulation file name (SRL_WF_FOV8_Base0_RA, for example, where RA denotes radial A) and the signal name (V_C11_t, for example, where V_C11 denotes voltage at WT C11). All the voltage quantities presented in the report show the voltage against the respective shield voltage. That captures the voltage at the desired point against the nearest grounding point, as it would be measured in the real measurements.

Figure 30 shows the voltage at WT C01 during the radial C energizing. This the measurement that represents quite well the qualitative difference between the two grounding models.

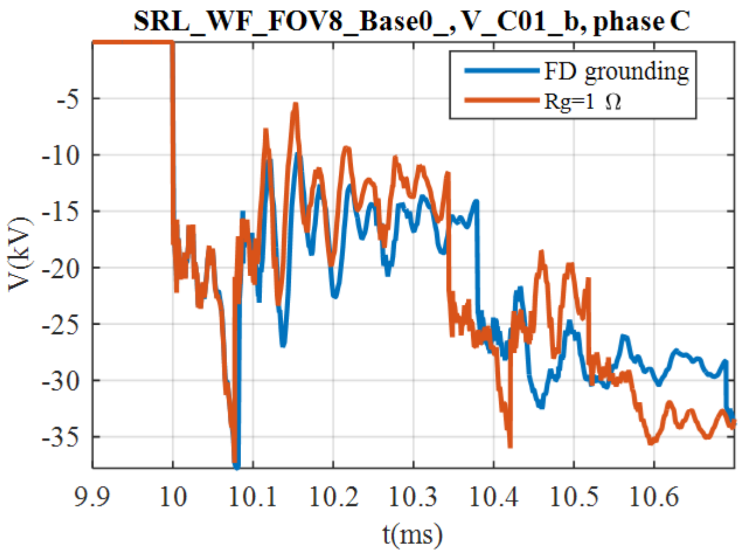


Figure 30 Voltage at C01 WT during radial C energizing – grounding model comparison

It can be noted that the difference is quite subtle and that the grounding model does not make a big impact when considering the chosen soil resistivity of 100Ohm/m. In general, the damping is a bit higher with the frequency dependent model but the magnitude and the rise times experienced in both cases at cable terminals are quite the same.

At a late stage of the project it was suggested that one should consider a much higher resistivity of the soil, but unfortunately, that was not possible to be completed within the given time frame. The soil resistivity we considered matches the measured grounding system resistance.

3.3.2 Grounding transformer impact on energizing transients

The study that considers different grounding at the grounding transformer is done to investigate the difference of different grounding systems. Generally, the grounding resistance is chosen so the short circuit current is limited to a certain value. In the Stor-rotliden WP, this resistance is 195.5 Ohms. We've considered two additional cases; the case with a direct grounding with a 0.1Ohm resistor and with the neutral completely disconnected.

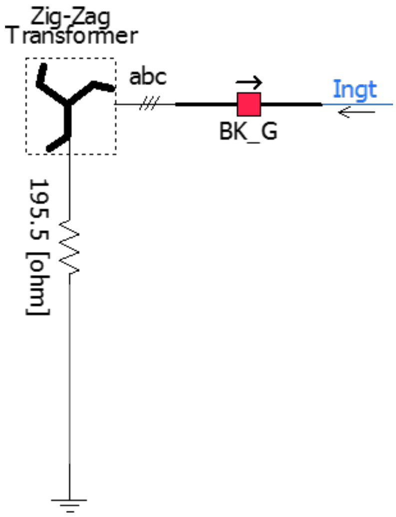


Figure 31 The grounding transformer

So, the three cases are as follows:

1. The neutral is grounded with a 195.5 Ohm resistor;
2. The grounding transformer is completely disconnected;
3. The neutral is grounded with a 0.1 resistor.

For the sake of comparison, the same signal is presented as for the case of the grounding model comparison, the voltage at C01 WT at radial C energizing. Figure 32 shows the C01 voltage for the three aforementioned cases. As it can be seen, the neutral grounding makes very little, to almost no impact at all. The reason for this is that the grounding of the cable system has a much stronger impact on non-symmetrical disturbances, such as radial energizing.

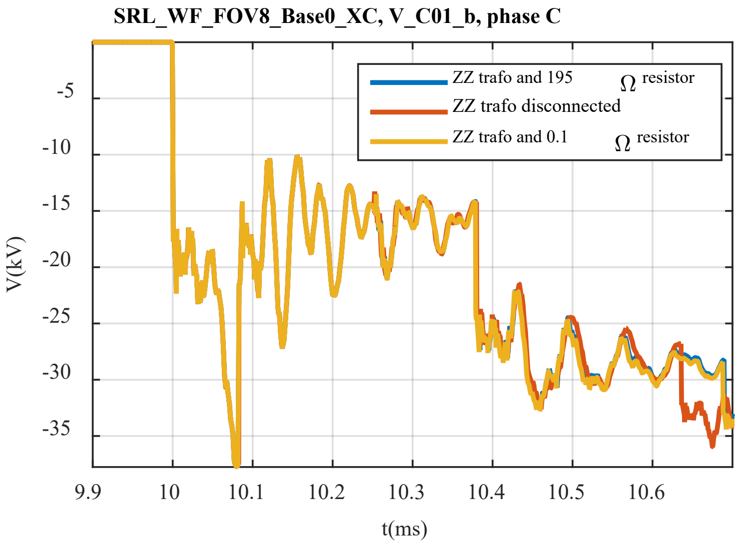


Figure 32 Voltage at C01 WT during radial C energizing – grounding transformer comparison

3.3.3 Impact of energizing on cable terminations

In order to estimate the impact on the cable terminations, the voltage signals to which the cable terminations are exposed are analyzed. This analysis considers detection of maximum voltage stress as well as time within it occurred. This time is actually the rise time of the voltage stress that appeared on the cable terminations. An example how this process works is shown in Figure 33.

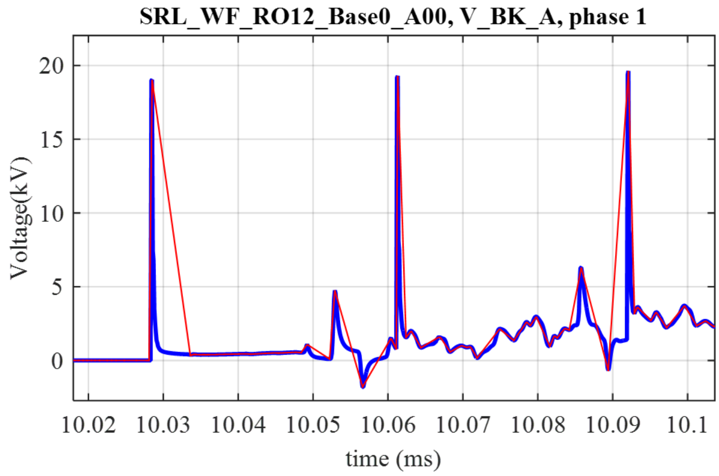


Figure 33 Voltage step/strike detection

The whole process can be described as the measurement of voltage differences between local minimums and maximums as well as the time required for the voltage change to travel between 10% and 90% of the value. In addition, these detected spikes needs to be put in a perspective on what the cable terminations should be able to withstand. According to the cable termination standards IEEE - 48-2009 [5], the cable termination in a 36kV grid should be able to withstand 200kV BIL. That is much higher than what the transformers need to withstand (170kV

BIL) [6], [7]. However, neither the transformer not the cable termination standards consider very fast transients that are much faster than the lightning pulse. Those are however considered in the large motor standards since the large motors have experienced insulation failures due to the very fast transients in quite a large extent due to use in inverter fed applications. That is why, the standards consider the voltage stress of 100ns and even shorter rise times [8],[9] and [10].

Figure 34 and Figure 35 show voltage strikes with respect to various transformer and large machine standards at the first (A01) and last (A11) WT in radial A.

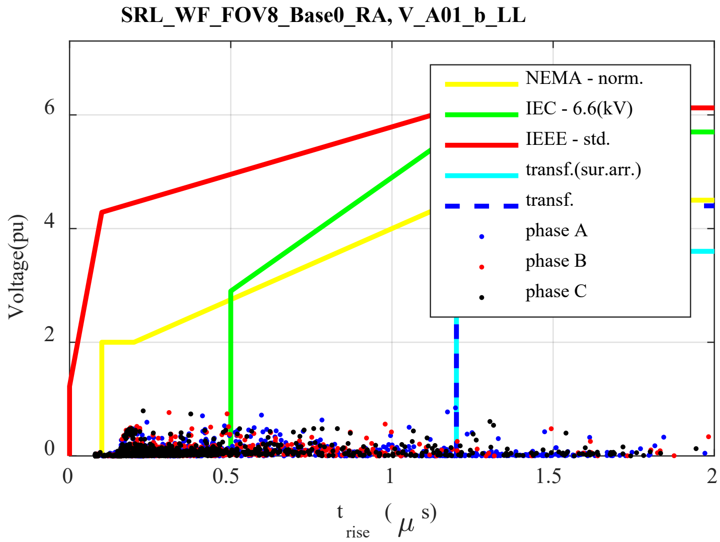


Figure 34 Voltage strikes due to radial A energizing at first WT

It can be observed that the first WT cable termination experiences a much higher magnitude of the voltage strikes with rise times close to 100ns. The magnitude is not high, but the rise time is much faster than allowed by the standards. It is even worse when we consider case of energizing of single WT's.

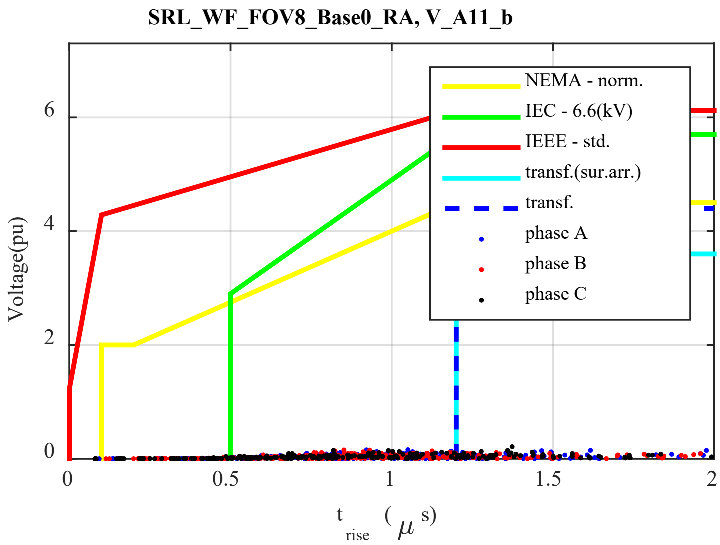


Figure 35 Voltage strikes due to radial A energizing at last WT

Figure 36 shows the voltage strikes at WT's A01 when the nearby VCB is closed to energize the WT transformer.

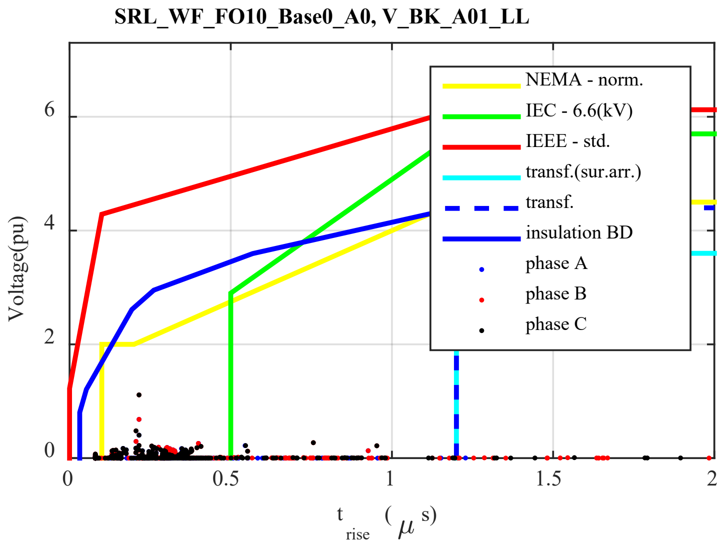


Figure 36 Voltage strikes due WT energizing of first WT in radial A

In this case, the recorded strikes have the same magnitude but a much shorter rise time. Such transients may have damage weak insulation.

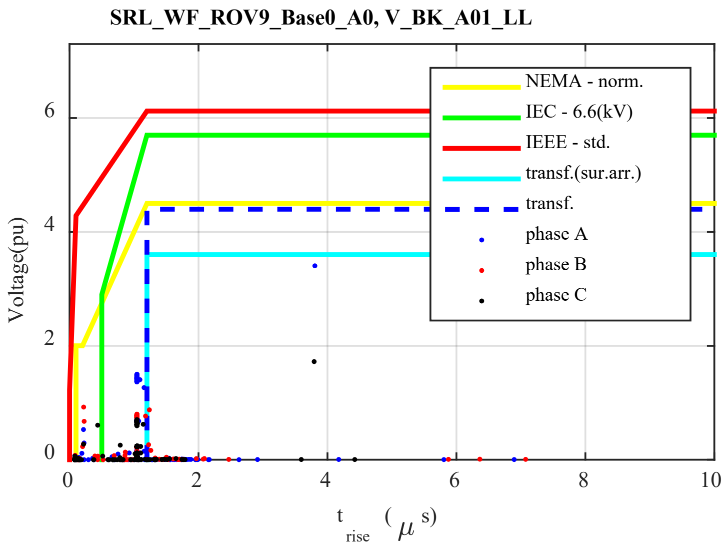


Figure 37 Voltage strikes due WT energizing of first WT in radial A – view at slower transinets

Figure 37 shows strikes of a high magnitude (3.5 pu) detected in the range of 4us rise time. This is recorded at the same event. Although the magnitude of the strikes is not above the standard values, they are very close.

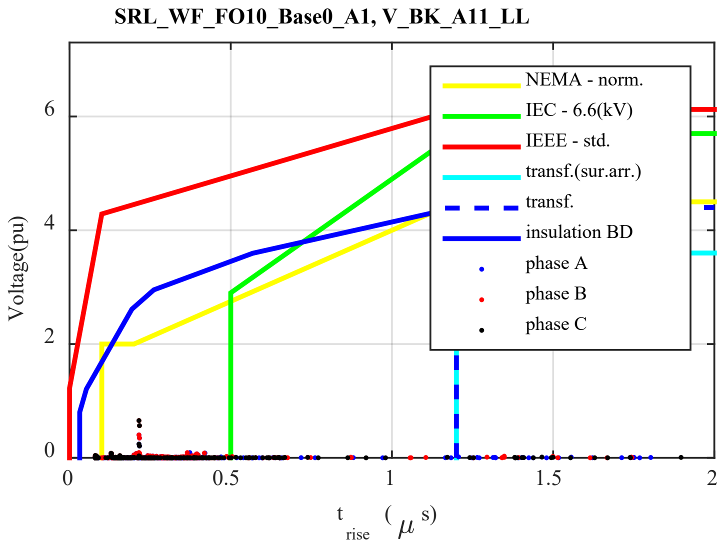


Figure 38 Voltage strikes due WT energizing of A11 WT in radial A

Figure 38 shows voltage strikes recorded at A11 when the breaker at A11 is closed. The results are very similar to the results of A01 energizing. Again, very fast transients of about 0.2us rise time and 1pu magnitude appear at the terminals. The equipment is not built to cope with such transients and they can damage insulation of the connected apparatus.

4 Discussion

The recorded voltage stress does not come even near the magnitude as defined in the standards for cable terminations. However, the observed voltages have a very short rise times that exceed substantially the 1.2us limit as defined by the lightning impulse tests. The geometric field cable terminations are designed well to cope with such a transients but the resistive cable terminations are not.

In addition, the worst case scenario is the WT energizing and not the radial energizing. WT energizing happens way more often than the radial energizing. Every act of maintenance requires that the circuit breaker disconnects the WT from the radial. Before the WT is put in operation, the circuit breaker needs to be closed. The closing of the circuit breaker is going to cause very fast transients that are potentially dangerous. Any breaker, not just vacuum circuit breaker would have the same impact.

The soil resistivity may have a much stronger impact if an extreme, but likely values were considered. This, however, remains as a future work.

Interruption of short circuit currents may lead to severe re-striking phenomena since it is known now that re-strikes appear due to current chopping of even short circuit currents [11]. This is also something to consider for the future work.

Finally, one needs to consider the surrounding grid in a higher detail than it was considered in this study. The model of the surrounding grid may discover resonances that may appear and contribute to cable termination failures as well.

5 Publications

[1] T. Abdulahovic "Very fast transients in land based wind farms", WESC June, 2017

[2] Abdulahovic, T. and Thiringer, T. Improvement of Admittance Measurements for Modelling of an Ungrounded Reactor/Transformer Winding, (International Journal of Modeling, Simulation and Scientific Computation - IJMSSC), 2016.

6 References

[1] T. Abdulahovic, T. Thiringer, M. Reza and H. Breder, "Vacuum Circuit-Breaker Parameter Calculation and Modelling for Power System Transient Studies," in *IEEE Transactions on Power Delivery*, vol. 32, no. 3, pp. 1165-1172, June 2017.

[2] B. Gustavsen and A. Semlyen, "Rational approximation of frequency domain responses by Vector Fitting", IEEE Trans. Power Delivery, vol. 14, no. 3, pp. 1052-1061, July 1999.

[3] B. Gustavsen, "Improving the pole relocating properties of vector fitting", IEEE Trans. Power Delivery, vol. 21, no. 3, pp. 1587-1592, July 2006.

[4] D. Deschrijver, M. Mrozowski, T. Dhaene, and D. De Zutter, "Macromodeling of Multiport Systems Using a Fast Implementation of the Vector Fitting Method", IEEE Microwave and Wireless Components Letters, vol. 18, no. 6, pp. 383-385, June 2008.

[5] IEEE 48-2009 - IEEE Standard for Test Procedures and Requirements for Alternating-Current Cable Terminations Used on Shielded Cables Having Laminated Insulation Rated 2.5 kV through 765 kV or Extruded Insulation Rated 2.5 kV through 500 kV.

[6] "IEEE standard test code for dry-type distribution and power transformers," IEEE, Std C57.12.91-2001, 2001

[7] "IEEE Standard Requirements for Liquid-Immersed Distribution Substation Transformers," IEEE Std C57.12.36-2007, pp.c1-29, March, 2008

[8] "IEEE Guide for Testing Turn Insulation of Form-Wound Stator Coils for Alternating-Current Electric Machines," IEEE Std 522-2004 (Revision of IEEE Std 522-1992), 2004

[9] National Electrical Motor Association Standards,NEMA Standard MG1.20-2006.

[10] "Rotating Electric Machines, Part 15: Impulse voltage withstand levels of rotating a.c. machines with form-wound coils," IEC 34-15, 1995.

[11] E. P. A. van Lanen, M. Popov, L. van der Sluis and R. P. P. Smeets, "Vacuum circuit breaker current-zero phenomena," in *IEEE Transactions on Plasma Science*, vol. 33, no. 5, pp. 1589-1593, Oct. 2005.

ANALYSIS OF VACUUM BREAKER GENERATED TRANSIENTS IN A 36KV WIND FARM CABLE GRID

Vindkraftägare och nätägare lyfter ofta fram problem med genomslag, det vill saga kortslutning i apparater och i parker med 36 kV kabelnät. Det leder till produktionsbortfall och ökade kostnader. Hittills har det varit oklart vad som orsakar problemen och därför har det saknats lämpliga lösningar.

Genom praktiska mätningar har nu kunskapen om orsaken till problemenn ökat. Arbetet har skett i samarbete med Vattenfall genom mätningar på vindkraftanläggningen Stor-Rotliden. Speciellt har utformningen av jordningssystemet och dess konsekvenser undersökts.

Resultaten är av stort intresse för vindkraftägare och projektet är ett bra exempel på hur forskningsresultat kommer till användning i industrin när ett praktiskt problem analyseras av forskare på en teknisk högskola.

.

Energiforsk is the Swedish Energy Research Centre – an industrially owned body dedicated to meeting the common energy challenges faced by industries, authorities and society. Our vision is to be hub of Swedish energy research and our mission is to make the world of energy smarter! Vindforsk is operated in cooperation with the Swedish Energy Agency.