High Frequency Transients in Large Offshore Wind Farms

Elforsk report 12:03

T. Abdulahović, T. Thiringer, M. Reza

May 2012

Vindforsk Energimyndigheten ELFORSK

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Foreword

Research on switching transient in a cable collection grid system was started already in Vindforsk II. The work has continued also during Vindforsk III. There has been two parallel projects carried out. One part has been carried out at Chalmers with Professor Torbjörn Thiringer as project leader. In this project Tarik Abdulahović has carried out his Phd-work with a thesis presented in December 2011. The other part has been carried out by ABB Corporate Research with Dr. Muhamad Reza as project leader. In the latter project extensive laboratory testing with measurements of transients in a purpose built test environment with a 20 kV cable system was carried out. For V-325 the Phd-thesis constitutes the main reporting of results. For V-326 there is a separate Elforsk report describing results. The present report summarizes the results from both projects. Vindforsk-III is funded by ABB, Arise windpower, AQ System, E.ON Elnät, E.ON Vind Sverige, EnergiNorge, Falkenberg Energi, Fortum, Fred. Olsen Renewables, Gothia Vind, Göteborg Energi, HS Kraft, Jämtkraft, Karlstads Energi, Luleå Energi, Mälarenergi, o2 Vindkompaniet, Rabbalshede Kraft, Skellefteå Kraft, Statkraft, Sena Renewable, Svenska kraftnät, Tekniska Verken i Linköping, Triventus, Wallenstam, Varberg Energi, Vattenfall Vindkraft, Vestas Northern Europe, Öresundskraft and the Swedish Energy Agency.

Comments on the work and the final report have been given by a reference group with the following members:

Anders Holm	Vattenfall
Lars Gertmar	ABB
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Stockholm, May 2012,

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Summary

General work and CIGRE standardization project

The Vindforsk projects V-325 analysis of high-frequency electrical transients in offshore wind parks and project V-326 High Frequency Transients in Large Wind Farm: Advanced Measurement and Characterization supported by the research program Vindforsk III are continuations of the project V-220 and the cable system transient study done in 2007-2008 with support of the research program Vindforsk II, project V-110. Within project V-110 a laboratory setup was built at ABB Corporate Research in order to study high frequency transients. This setup was utilized in project V-220 too. The project V-325 and V-326 are reported in two different reports [1], [2].

Although the laboratory and the test results were shared between the projects, the focus of research was a bit different. In project V-326, the focus was on getting different case scenarios by making changes in the laboratory setup. Test cases with additional feeders and wind-turbines were tested. Some new arrangements for mitigation devices were analyzed as well. Furthermore, work on characterization of the high-frequency transients was carried out and a contribution to the CIGRE working group on transformer standards was made.

In project V-325, the focus was on data characterization, and theoretical work on modeling and data analysis. A detailed modeling of some components used in the ABB's laboratory setup is conducted. Like in the V-326 project, a contribution to the CIGRE report on transformer standards is made.

For projects V-325 and V-326, the laboratory has been updated so that testing with higher voltage level ($20kV$) and with different type of transformers and different models of breakers could be performed. Furthermore, some additional protection schemes were tested.

The results from the new measurements confirm the appearance of the transient overvoltages in a cable system recorded in Vindforsk II project V-110 and V-220.

- The experiments verify the consistent occurrence of repetitive prestrikes and re-ignitions in a cable system. The occurrence is determined by the electrical circuit and the point-on-wave when the switching operation occurs.
- Surge arresters always limit the maximum voltage magnitude but voltage steps with a magnitude twice the protective level can occur while the voltage can swing within a band in magnitude below the surge arrester protection level from negative to positive polarity.
- Surge capacitors and the RC-protection show mitigation effects although not removing the repetitive overvoltage transients completely.

Furthermore, measurements of voltage distribution along the winding of a transformer during very fast transients is performed. This is done in order to analyze how very fast transients recorded in cable grids can influence the insulation of transformers. A background reason is that the present transformer standards don't account for very fast transients. Moreover, some switching scenarios have been tested in order to investigate if simple energizing transients can develop high overvoltages. It was found that the rise time of voltage transients

significantly influences the turn-to-turn voltages and that very fast transients don't have to have a very high magnitude in order to reach a critical level. The obtained critical voltage level is in accordance with existing standards for withstand voltage for induction motors. In addition, it was found that a simple energizing transient of a delta connected dry-type transformer can lead to a turn-to-turn voltage that is 2.5 times higher than the turn-to-turn voltage obtained during a lightning impulse test [1].

Generation and propagation of transients

High frequency transients are frequently produced in medium-voltage cable systems. During the switching of a breaker, regardless if the breaker is opening or closing, high frequency transients are generated. Different breaker techniques lead to different number of restrikes during opening, but the character of the transients remains the same. During the closing of the breaker, all breaker types generate very similar voltage strikes. The character of these voltage prestrikes is similar to the restrikes recorded at opening, although the number of prestrikes is much fewer than the number of restrikes in some cases. During breaker operations, it is not the breaker itself that determines the character of the transients. The breaker influences the quantity of the transients to a great extent, but the character of the transients is determined by the surge impedance of the energized system and the stray capacitance of the system that is being energized. If we take for example an offshore windfarm collection grid, it is the surge impedance of the cables and the surge capacitance of the transformers that characterizes the transients.

Cable parameters that determine the surge impedance of the cable, also determine another important property of the cables, the propagation speed of the electromagnetic waves. A slower propagation speed related to cables properties, contributes strongly to the development of the wave reflection phenomenon. This leads to generation of higher transient overvoltages due to switching. A wind installation which has a cable between the wind turbine's transformer and the breaker, represents a typical system where wave reflection phenomenon leads to higher surge voltages. However, a setup where the breaker is installed right next to the transformer has some disadvantages related to the generation of high frequency transients too. Although reflections are avoided in this case, the rise times of the transients are much shorter and very high internal turn-to-turn overvoltages in transformers can be generated [1]. This happens during closing breaker operations when a delta-wye connected transformer is energized from the delta connected windings.

Transformer winding impact

Transformers windings of these transformers are not designed with very fast transients in mind. The fastest transient that is considered in the design phase for these transformers are transients generated during lightning discharges. For that reason, standards to which these transformers comply, utilize lightning pulse tests as the worst case that may strike a transformer during it's lifetime. Large power transformers are tested more thoroughly, where a chopped voltage wave test is used as the fastest transient test. Furthermore, the beginning of the winding of a power transformer is designed with very-fast transients in mind, where a special wounding scheme is used in the beginning of the winding in order to reduce the turn-to-turn voltage stress caused by very fast transients.

Need for modification of standards and transient mitigation

Having identified the cases where the substantial turn-to-turn overvoltages are recorded, as well as the character of the transients that cause these turn-to-turn overvoltages, the aim of the work was to determine the magnitude of the voltage surges of different rise times at which the turn-to-turn voltages will remain under the critical level. The critical level is only defined for the lightning pulse, and it's definition for shorter pulses is estimated. It was found that the critical voltage level corresponds to a great extent to standards for large motors which account for the very fast transients. New standards for distribution dry-type transformers need to account for very fast transients since these transients are very common in windfarms. The voltage stress caused by these transients is beyond transformers design limit, and its hazardous influence on its insulation is substantial. Furthermore, a very efficient means of mitigation can slow down the rise time of the transients and their magnitude as well. In this project, various mitigation devices were tested, and its effect on transients is studied. It was shown that all tested means of transient protection reduced the magnitude and increased the rise time of the voltage strikes. When the protection is used, the turn-to-turn voltage is kept well under the critical level.

List of publications

The following publications have been made during this project.

- Abdulahovic Tarik, Thiringer Torbjörn, Modeling of the energizing of a wind park radial, Nordic Wind Power Conference, Roskilde, Denmark, 2007.
- Reza Muhamad, Breder Henrik, Sannino Ambra, Liljestrand Lars, Cable system laboratory for studying transient phenomenon in wind farms, EWEC, Marseille, March, 2009.
- Reza Muhamad, Breder Henrik, Liljestrand Lars, Sannino Ambra, Abdulahovic Tarik, Thiringer Torbjörn, An experimental investigation of switching transients in a wind collection grid scale model in a cable system laboratory, CIRED, 20^{th} International Conference on Electricity Distribution, Prague, June 8-11 2009.
- Reza Muhamad, Srivastava Kailash, Abdulahovic Tarik, Thiringer Torbjörn, Combining MV laboratory and simulation resources to investigate Fast Transient Phenomena in Wind Cable Systems, European Offshore Wind, Stockholm, 2009.
- Abdulahovic Tarik, Thiringer Torbjörn, Comparison of switching surges and basic lightning impulse surges at transformer in MV cable grids, Nordic Wind Power Conference, Bornholm, Danmark, 2009.
- Abdulahovic Tarik, Teleke Sercan, Thiringer Torbjörn, Svensson Jan, Simulation accuracy of the built-in PSCAD and an owner-defined synchronous machine model, Compel-the International Journal for Computation and Mathematics in Electrical and Electronic Engineering, 29 (3) pp. 840-855. 2010.
- Reza Muhamad, Srivastava Kailash, Roy Carlos, Wojciech Plasecki, Proposal to the simulation task force Cigre Working Group A2/C4.39 for studying transients on wind transformers, VI Workspot - International Workshop on Power Transformer, 25-28 April, 2010.
- Badrzadeh Babak, Hogdahl Martin, Singh Nand, Breder Henrik, Srivastava Kailash, Reza Muhamad, Transients in Wind Power Plants - Part II: Case Studies, Industry Applications Society Annual Meeting (IAS), October, 2011.

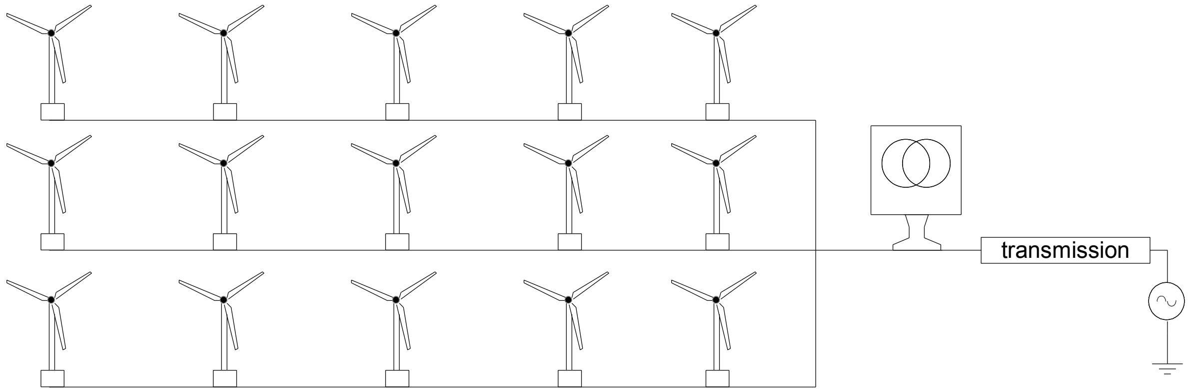
- Villar, F.S., Reza, M., Srivastava, K., da Silva, L.C.P., High frequency transients propagation and the multiple reflections effect in collection grids for offshore wind parks, Power and Energy Society General Meeting, July, 2011.

In addition, there are three journal articles and one conference article that are in preparation/submission stage. These articles are aimed to a better understanding and modelling of the vacuum circuit breaker, voltage distribution along transformers winding at very fast transients and comparison with current transformer standards, modelling of a reactor winding using vector fitting technique and analysis of the transient voltages for different common connection schemes at offshore wind farms.

Svensk sammanfattning

Kort bakgrund

Detta arbete berör hur man på ekonomiskt bästa sätt skall sätta samman komponenter till ett uppsamlingselsystem i en vindpark, se figur nedan.

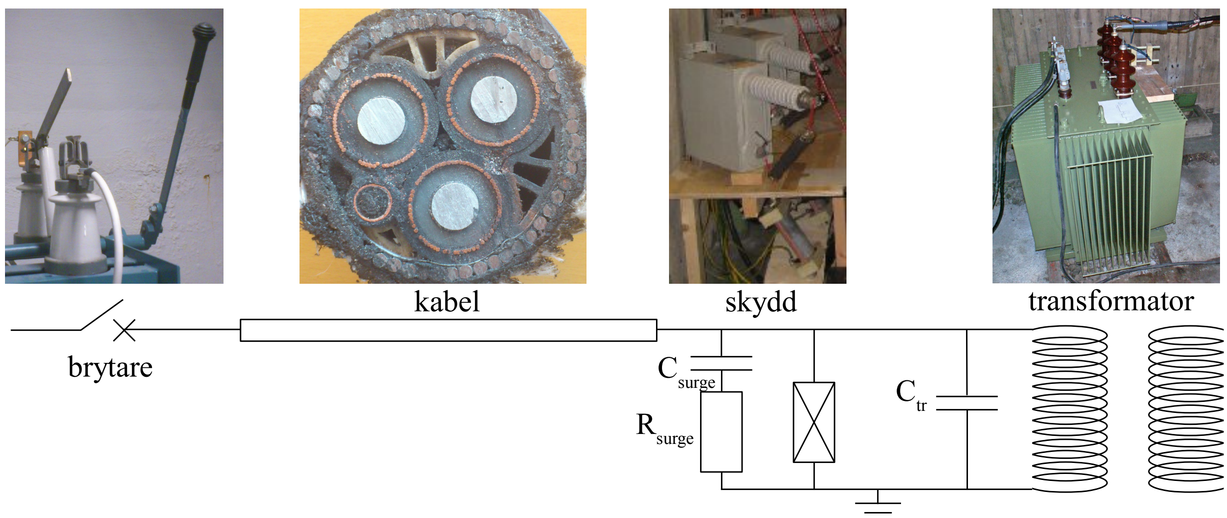


Figur 1: Vindpark.

I ett uppsamlingssystem för en vindpark så har vi komponenter som

- emitterar störningar,
- sänder störningar vidare,
- utsätts för störningar,
- skyddar komponenter för störningar.

enligt figuren nedan:



Figur 2: System.

Nu gäller det att sätta samman hur mycket

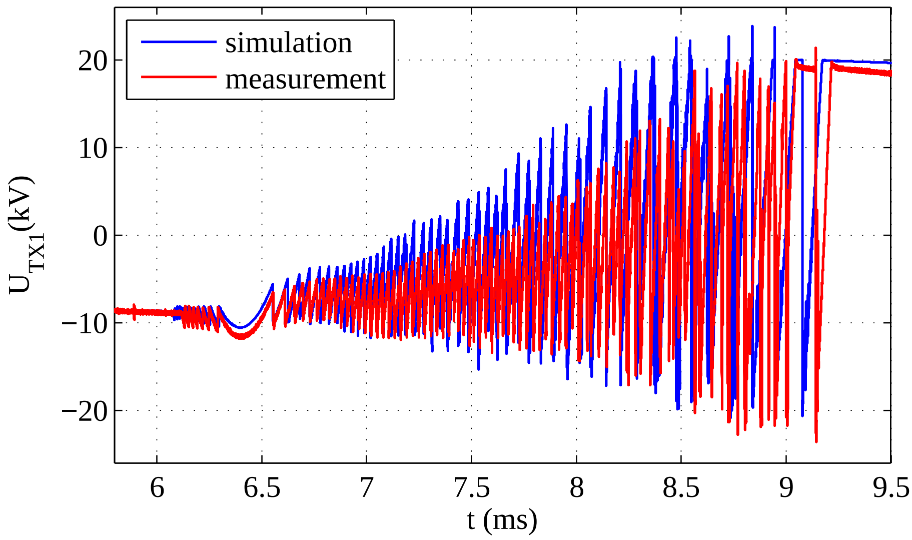
- störningar vi skall tillåta emitteras,
- hur mycket störningar som komponenter skall tåla samt,
- om vi skall installera skydd

för att få lägsta möjliga totalsystemkostnad. Nivåerna i ovan nämnda aspekter regleras utav standarder. Dessa standarder är dock i behov av uppdatering då nya komponenter har introducerats i vindparkerna, och haverier i transformatorer och generatorer har skett trots att dessa apparater har uppfyllt gällande standarder.

Av speciellt viktig natur är hur snabba spänningsstörningar med hög amplitud (spänningsnivå) skall hanteras.

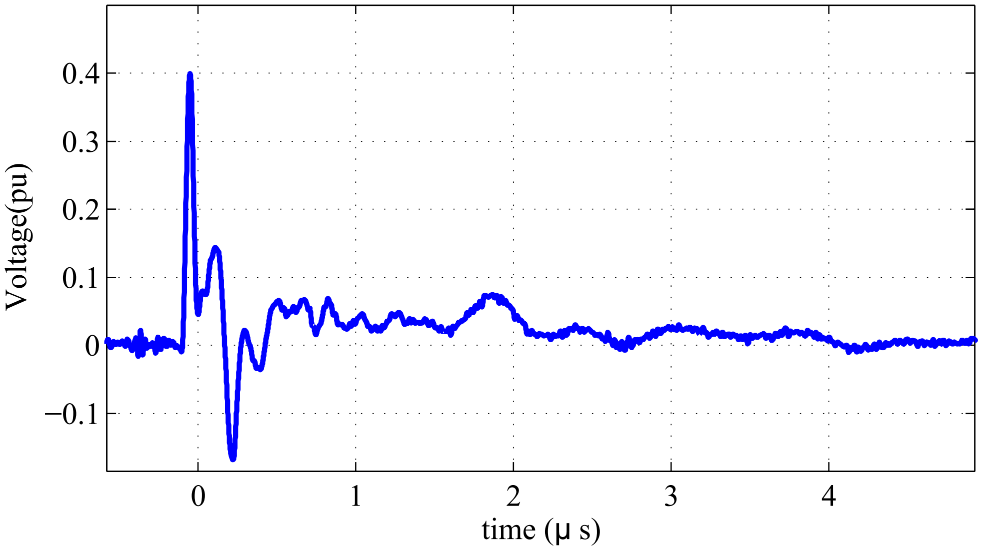
Bidrag från aktuellt arbete

I det aktuella arbetet har det studerats hur störningar genereras, framförallt från en ny miljövänlig och underhållsfri brytare, vakuumbrytaren. Ett bidrag från detta Vindforskprojekt är att ny modell av denna tagits fram och verifierats med mätningar. I bilden nedan visas en simulering (beräkning) och en mätning på hur spänningen över denna komponent ser ut vid brytning av ström. Noteras kan att mycket elaka spänningsstörningar är synliga och dessa skickas nu ut på nätet där de sedan kan skada ansluten utrustning med bristande immunitet.



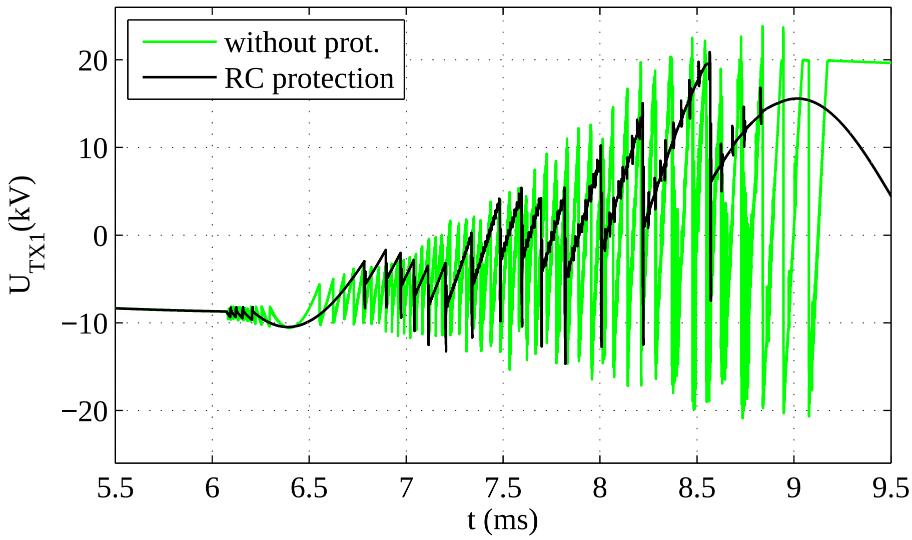
Figur 3: Spänningsstörningar.

När dessa störningar sedan flyter fram i systemets ledningar förändras de till karaktär. Även detta har behandlats i det aktuella arbetet. Dessa störningar anländer nu till "offret" som t. ex. kan vara en transformator. I transformatorn har vi ett stort antal varv, där spänningen normalt skall delas lika mellan varven. I figuren nedan visas ett resultat på en transformator med 1000 varv där spänningen trots detta inte är 0.1 % mellan de första två varven som det borde vara utan 40 % av fullt värde vid $1pu$ (100%) snabb (stigtid 50ns) spänningsstörning.



Figur 4: Spänningen mellan varven vid $1pu$ spänningsstörning.

Problemet är att standarden anger endast pulser med stigtid på $1.2\mu s$ vilket är en faktor 25 långsammare än vad som kan förekomma i en modern vindkraftsuppsamlingsradial. En $1pu$ (100%) åskpuls som är det som standarder idag anger ger bara 8.9 % spänningen mellan de första två varverna, vilket är en faktor 4.5 mindre en vid en snabb spänningsstörning. Slutligen i detta arbete har det även undersökts hur ett 'offer' skulle skyddas. En ventilavledare hjälper egentligen inte mot dessa nya snabba störningar pga. störningarnas korta stigtid. Däremot kan man i figuren nedan se hur en s.k. RC-snubber hjälper mycket bra, och ett bidrag från det aktuella arbetet är att det visats hur olika skydd hjälper.



Figur 5: Spänningen vid spänningsstörning med RC-snubber skydd.

Standardiseringsarbete

Som antydits ovan har det pga av den tekniska utvecklingen med bl.a. vakuumbrytare och havererade transformatorer blivit nödvändigt med en uppdatering av standarder, till vilket det aktuella forskningsprojekt bidragit (se exempel ovan med 50ns kontra 1200ns stigtid). Genom samarbetspartnern ABB, som deltar i detta standardiseringsarbete, har det varit möjligt att föra in resultatet från det pågående arbetet i det pågående standardiseringsarbetet inom Cigre arbetsgrupp A2/C4.39 rörande apparatimmunitet och apparatskydd. (med apparat i detta fallet menas en transformator)

Contents

Chapter 1

Introduction

1.1 Problem Overview

For many years, the lightning was considered to be the only phenomenon that could create high magnitude voltage pulses with very steep fronts with rise times in the order of micro seconds (μs). These wave pulses are reflected of junctions in the system producing high overvoltages. The high overvoltages produced by lightning are usually prevented from damaging insulation of the equipment by using surge arrester protection that is able to keep the voltage magnitude limited within the range that is not harmful to the protected equipment. This protection proved to be sufficient for the protection of the equipment, and the failures can be kept on an acceptable level.

Further research in this area was not needed until increased failures of the insulation of the equipment were detected again even on a low voltage level. These failures occurred more and more often with the development and improvements of electric power equipment, especially in motor drives. Two areas of the development are very important in this matter.

One of them is the development of semiconductors used in power electronic converters that feed motors. The appearance of the fast switching insulated gate bipolar transistors (IGBT's) led to pulses with very short rise times that were produced by IGBT's in pulse-width modulated (PWM) inverters. These inverters are often used with induction machines (IM) for variable speed drives. The rise time of the voltage pulses generated during IGBT switching could be as low as, or even below, 0.1 μs [3]. This is more than ten times quicker than the rise time of the lightning pulse. These fast switching IGBT's brought two major improvements to the inverters. Firstly, lower switching losses and secondly, reduction of the total harmonic distortion (THD) given a similar filter, due to the possibility of using a higher switching frequency.

Moreover, another important area is the development of the breakers used in the electric grid. Breakers used in grids can have a strong negative influence on insulation. The appearance of vacuum circuit breakers (VCB) brought switching devices with excellent interruption and dielectric recovery characteristics [4]. Vacuum circuit breakers have very low maintenance costs and good durability. They are the best breaker solution for medium voltage below 24 kV [5]. However, it was reported worldwide that many transformer insulation failures have occurred, possibly caused by switching operations of VCBs, although those transformers have previously passed all the standard tests and complied to all quality requirements [6]-[10]. However, another study showed that it is not only the vacuum breaker that can create surges potentially dangerous to the transformers, but also SF6 insulated breakers and disconnectors [11]. The breakdown in the SF6 medium can have a typical rise time between $2 - 20ns$, and in addition, SF6 interrupters can generate re-strikes and pre-strikes during the operation [11]. A 10 years long study which included an investigation of failures of thousands of transformers conducted by Hartford Steam Boiler shows that the high frequency transients are the major cause of transformer failures [12]. The transformer failures caused by the high frequency transients reached a level of 33.9% according to this study and it was said to be the most likely cause of a transformer insulation failure [12]. Although, the direct proof of the negative impact of the high frequency transients on the transformer insulation is not yet found [11], some studies give a description of the phenomenon that produces high overvoltages internaly in the transformer winding [6], potentially responsible for the transformer insulation failure during the high frequency transients. As some studies for induction motors showed, the appearance of repetitive strikes is dangerous for induction motors [13],[14] and it is very likely that the same phenomenon is dangerous for the transformers insulation. A major problem of the transformer insulation failures occurred in the wind parks(WP) Middelgrunden and Horns Rev where almost all transformers had to be replaced with new ones due to the insulation failures [15], [16]. It is suspected that the fast switching breakers caused the insulation failures in these WP's.

Some other studies showed that a lightning pulse can produce severe overvoltages [17]-[19]. However, a direct lightning strike on transformers high voltage side is not a very likely scenario in wind turbines.

Another study showed that a particular cable/transformer setup, where cables resonant frequency matches transformers resonant frequency, can produce overvoltages on the transformers secondary [20]. In this case, the secondary side voltages can get extremely high.

During studies of insulation failures of motors caused by switching phenomenon, it is found that the surges generated during switching of the air magnetic circuit breakers are very similar to the vacuum devices [21]-[23]. According to one of these studies, surges generated by air magnetic circuit breakers generated surges of $4.4pu$ in magnitude with a rise times of $0.2\mu s$ where the vacuum breaker generated surges with $4.6pu$ magnitude but with longer rise times of $0.6\mu s$ [21]. An important finding of this study, is that although the vacuum breaker generates more surges, the magnitude and the rise time of the surges generated by these two types of breakers are very similar [21].

Another factor that contributed to the failures caused by the fast switching operations of the IGBT's and VCB's is the use of the cables in medium voltage systems. The characteristic impedance of the cables is approximately ten times lower than the characteristic impedance of a transmission line. This results in a ten times shorter rise time of the transient overvoltage. The transient phenomenon is thus even more difficult to analyze since cables longer than approximately 50 m behave like transmission lines where the wave traveling phenomenon and the wave reflection phenomenon can be observed. This means that a proper high frequency transient analysis advanced cable model is required, which makes the transient phenomenon analysis fairly complicated. In order to perform calculations of the propagation of high frequency transients, an adequate modeling and an adequate software tool is accordingly needed.

Chapter 2

Background theory on surge propagation and reflection

The wave travelling phenomena on long transmission lines has been known for a long time. The waves that travel over the conductor at the speed of light belong to the group of transverse waves, and the behaviour of these waves is the same as the behaviour of other transverse waves that propagate in other media. The reflection of the waves we experience in everyday's life when we hear an echo or look on the reflection in the mirrors or on a water surface. The same phenomena occurs at the end of cables and transmission lines, and can produce very high overvoltages in a transmission line or at cable ends in some cases.

Let's take the light reflection for example. The light is actually an electromagnetic wave, and it's propagation speed and reflection as well, depend on electrical and magnetic properties of the material. The light has a frequency between $4.05 \cdot 10^{14} Hz$ $7.9 \cdot 10^{14} Hz$. Considering the speed of light $c = 300 \cdot 10^6 m/s$, the wavelength of the visible light varies between $\lambda = 380nm$ and $\lambda = 740nm$. The light has a very short wavelength, shorter than a micrometer. This means that the wave reflection occurs when the distance between the source and the reflection plane is in order of micro meters. Since our common perception is in the range of decimetres, meters, kilometres and so on, the light reflection is something very common in our world. If the light waves would have had the wave length in the order of meters and tens of meters, the light reflection would not appear if the distance between the source and the reflection plane is in the range of decimetres and meters.

The same can be said for the voltage waves that travel along a cable or a transmission line. An electric wave travels along a transmission line at speed of about $c = 300 \cdot 10^6 m/s$. In order to obtain a full wave reflection, the wave needs to reach it's peak at the sending end of the line latest at the moment when the wave reaches the receiving end. For a $1\mu s$ wave, in order to obtain full wave reflections, the minimum length of the line is $300m$. For a wave that travels along a cable at a speed of about $c = 200 \cdot 10^6 m/s$, for the same $1\mu s$ wave a $200m$ long cable is needed to observe reflections.

The surge characteristics is mainly determined by the characteristic or the surge impedance of the transmission line or cable,

$$Z_0 = \sqrt{\frac{L}{C}}. \tag{2.1}$$

Due to the differences in the geometry of the cables and the transmission lines, the capacitance and the inductance of the cable and the transmission line differ a lot. The value of the characteristic impedance for transmission lines is about Z_0=400 Ω. For the cables this value is about ten times smaller and has a value of about Z_0=40 Ω.

The differences in geometries lead to a difference in the wave velocities that the wave propagates with through the transmission line and through the cable.

$$v_0 = \frac{1}{\sqrt{LC}} \tag{2.2}$$

Another important characteristic of a cable is that the velocity of the wave that propagates through the cable is approximately one half to two thirds of the propagation velocity of the wave that propagates through the transmission line and varies from $v_0 = 1.5 \cdot 10^8\ m/s$ to $v_0 = 2 \cdot 10^8\ m/s$.

Surges that appear in cable systems are strongly influenced by these characteristics. If a system consisting of a cable and a transformer is studied, a good approximation of the system for the prediction of high frequency transients needs to have stray capacitances added to the the transformer. An example of such a system is presented in Fig. 2.1.

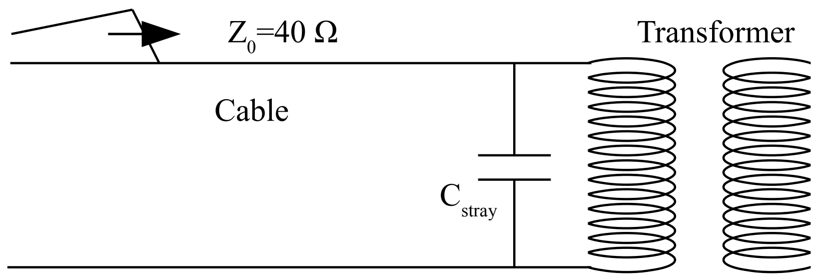


Figure 2.1: Simple system consisting of one cable and one transformer.

This system can be represented as a first order system neglecting the inductance of the transformer which is very large, meaning that its time constant is a couple of orders of magnitude slower than the time constant of the cable and the stray capacitance.

The time constant of the approximated first order system can be determined as

$$\tau = \sqrt{\frac{L}{C}} C_{stray} = Z_0 C_{stray}. \tag{2.3}$$

Taking into account the fact that the surge impedance of the cable Z_0 is ten times smaller than the surge impedance of an OH line, leads to the consequence that the time constant of the cable is also ten times faster. This means that the surge created in the system will have a ten times steeper front in a cable system.

Chapter 3

Transient voltage distribution along reactor winding

As it is presented in the introduction of this report, it was reported worldwide that many transformer insulation failures have occurred possibly by switching operations of vacuum circuit breakers (VCBs), although the transformers have previously passed all the standard tests and complied to all quality requirements [6]-[10]. Furthermore, a 10 years long study that included investigation of failures of thousands of transformers reported in 2005 by Hartford Steam Boiler earlier concludes that the high frequency transients are the main cause of transformer insulation failures [12].

In this chapter, the goal is to present the effect of different switching scenarios, different rise times of the surges and voltage derivatives on the internal voltage distribution and turn-to-turn voltages between two adjacent conductors. Furthermore, the aim is to determine the worst case scenarios and their possible negative impact on insulation lifetime. The results are compared with the turn-to-turn voltages obtained during the BIL test that are used as a reference.

3.1 Connection transients

In this section, only transients generated by closing operations of breakers are considered. Although the magnitudes of the voltages at the terminals of the transformer produced by the closing of the breaker are well within the limits and do not exceed the magnitude of the peak grid voltage, some transformer failures are reported during such transients [6]-[9].

The transformer energizing transients differ significantly depending on the connection of the high voltage side windings. In this section, only energizing of stray capacitances and leakage inductances is considered. Core energizing and inrush currents are not in the scope of this analysis since the observed time window is very short. For a wye connection, one end of the windings is connected to the common neutral point which is never excited by a voltage step. In the case of ungrounded transformers, the neutral may have a voltage, but it is never exposed directly to a voltage step. For a grounded transformer, the neutral point is always at zero voltage if the grounding is done properly, i.e. the grounding path is short thus minimizing grounding inductance L_g. During an energizing transient, the maximum terminal voltage to which a transformer winding is exposed, is the peak phase to ground voltage. This is presented in Fig. 3.1.

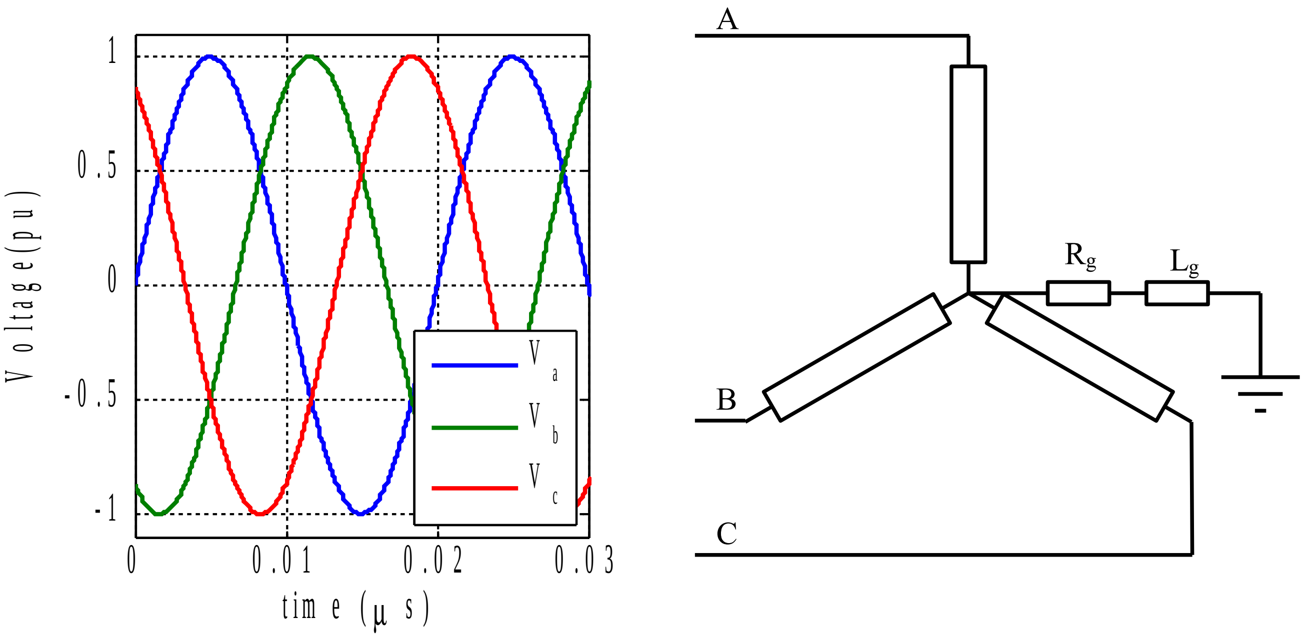


Figure 3.1: Star connected transformer.

In medium voltage cable grids, with voltage levels up to $30kV$, the high voltage transformer side is almost always delta connected. This is always the case in offshore wind farms, where the grounding is done either at the platform transformer or at an auxiliary transformer that is used to supply apparatus at the substation. For a delta connected transformer, a simple energizing transient can give a very complex response due to a wave traveling phenomenon. Consequently, it can produce much higher internal voltages in a transformer. In a delta connected winding, the end of one winding is connected to the beginning of the other winding. This means that a winding of a transformer can be excited from both sides. A winding of a delta connected transformer is excited by the line-to-line voltage. The maximum of the line-to-line voltage is achieved when one phase reaches $0.86pu$ and another $-0.86pu$ of its value. In this case scenario, the voltage by which the winding is excited exceeds $\sqrt{3}$ times the voltage to which a wye connected transformer winding is exposed. However, it can be shown how a transformer winding can be exposed even to a higher voltage. This scenario is possible when there is a certain delay between energizing at two ends of a winding. Let us closely observe such a scenario by looking to an energizing transient of an ungrounded winding. This transient can be seen in Fig. 3.2.

As can be observed in Fig. 3.2, the initial voltage distribution along the winding is determined by parallel stray capacitances of the winding. As the time progresses, the voltage along the winding rises as the voltage wave propagates through the winding. The voltage at the end of the winding oscillates with the highest magnitude at the resonance frequency of the winding. This resonant frequency depends directly on series stray capacitances, leakage inductance and the length of the winding. Ideally, the voltage magnitude at the end of the winding could reach $2pu$ magnitude due to wave reflections, while in reality it reaches about $1.8pu$. For this particular winding, this voltage level is reached after approximately $50\mu s$

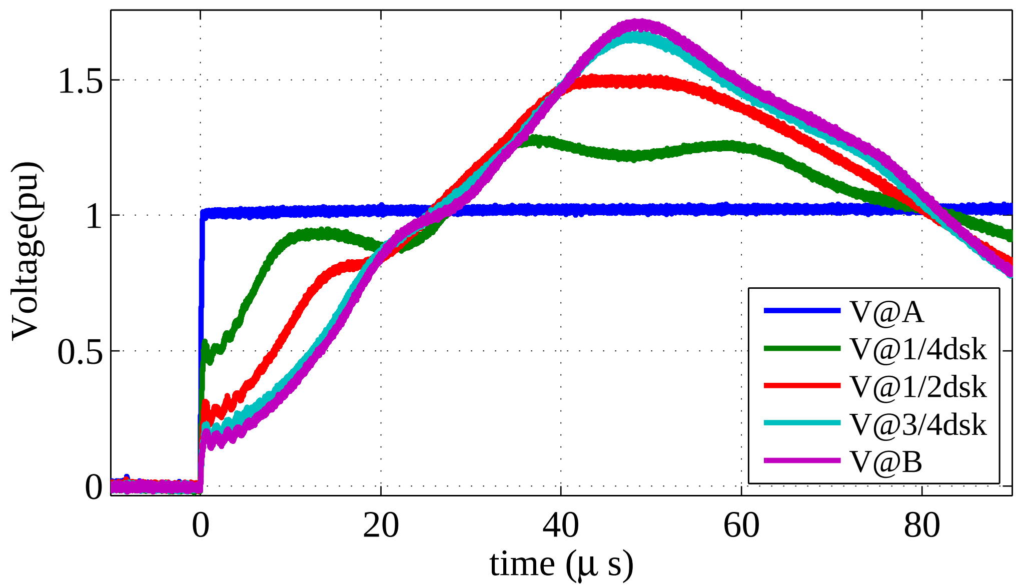


Figure 3.2: Energizing of a winding.

or $0.05ms$. Let us consider a very possible scenario in which the negative voltage step is applied at the end of the winding when the positive voltage reaches its maximum of $1.8pu$. If the magnitude of the negative voltage step is $1pu$, then the resulting voltage step is the difference between the positive and the negative step, which results in a $2.8pu$ voltage step. This is the worst case scenario. Such a case scenario is presented in Fig. 3.3.

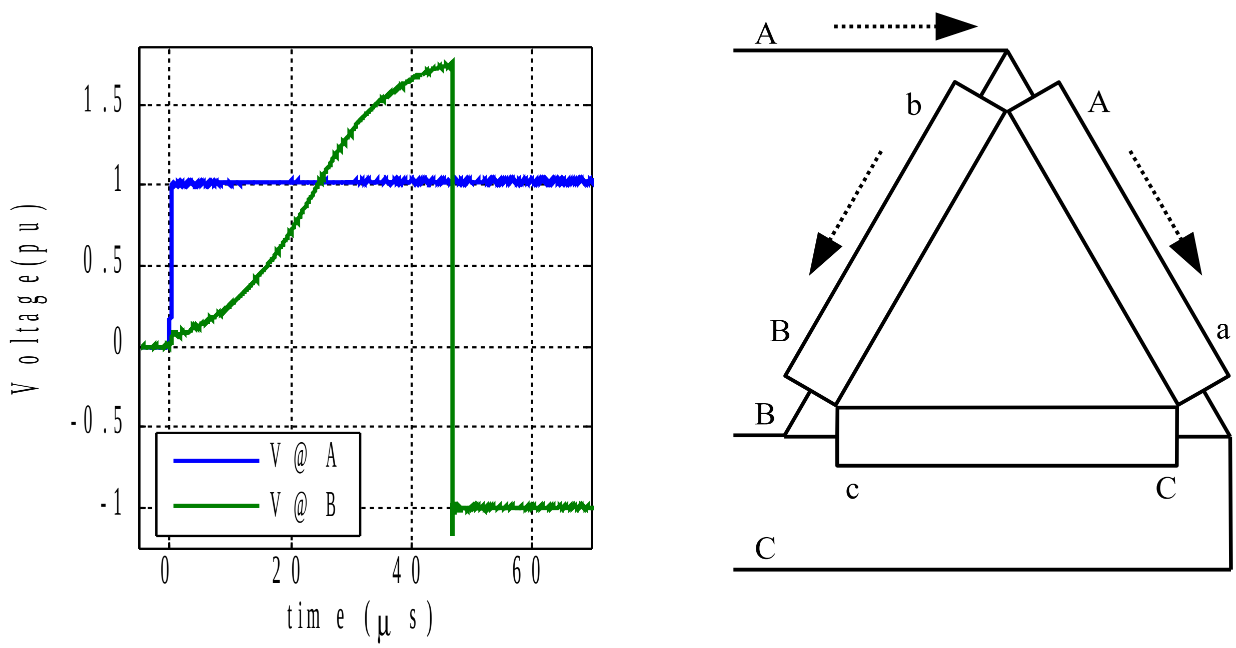


Figure 3.3: Delta connected transformer.

In Fig. 3.3 it can be seen that the voltage wave propagates along two windings connected to terminal A. At about $t = 45\mu s$, the wave will reach its maximum at terminals B and C. If any of these two terminals are excited by a negative voltage step at a time instant, the resulting voltage step will reach a magnitude of $2.8pu$.

3.1.1 Test reactor

In this test setup, a single phase $10kV$ reactor rated at $200kVA$ with two windings is used as a a test object. Ideally, a three phase delta connected transformer would be used, but this reactor is suitable to perform all the important switching tests one could perform on a three phase delta connected transformer. This reactor is built in such a way so the measurement points between the disks are easily accessible. The reactor is enclosed in an aluminium enclosure in order to give a more realistic distribution of the stray capacitances, while the front panel is made with holes in order to comfortably reach the measurement points. The reactor is presented in Fig. 3.4.

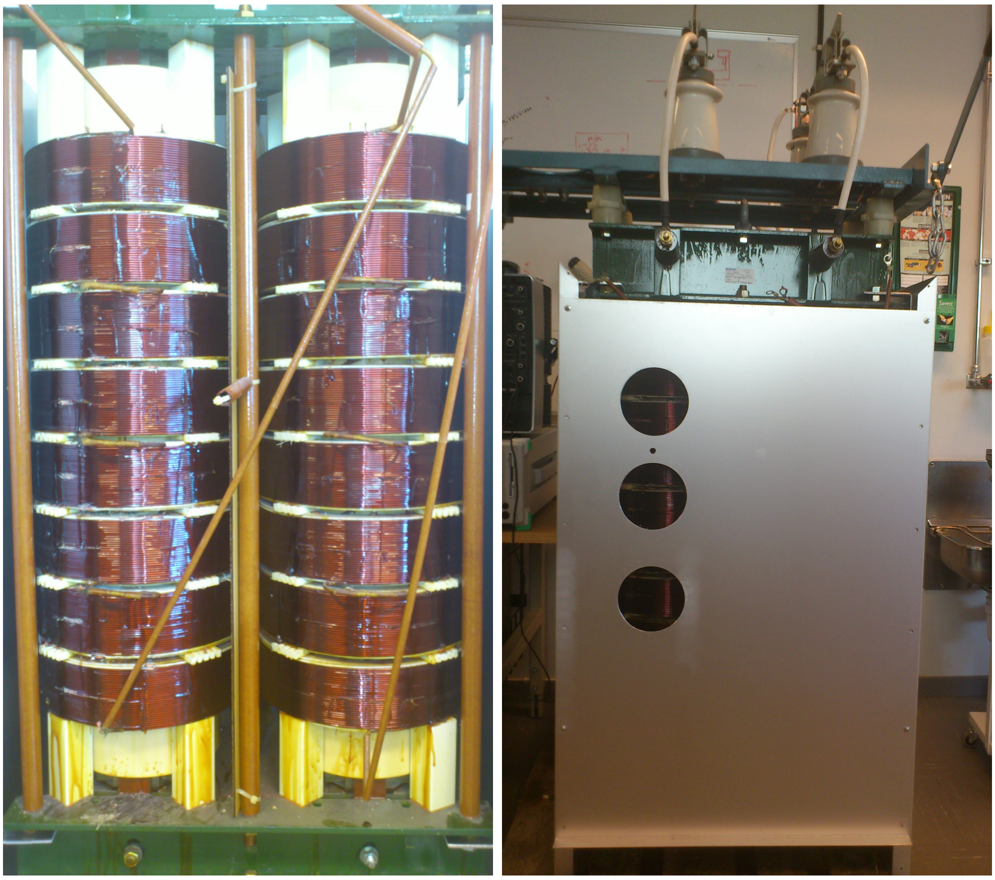


Figure 3.4: Reactor winding, enclosure with holes.

Each winding of the reactor consists of 8 disks. Each disk is wound in the same way, where the odd disks are wound starting from the outer layers while the even disks are wound starting from the inner layers. Each layer consists of 30 conductors, while each disk consists of 9 layers.

Since the focus of this work is not only to measure voltages at disks interconnections but inside the disks too, additional measurement points are made by pealing off the insulation from the top conductors. Measurement points for the first reactor are presented in Fig. 3.5.

It can be noted that the voltage step propagates following the maximum admittance path, which means the conductor. That means that the disk energizing is made by first energizing the outer layer from the top to bottom, then the next layer from the bottom to top, and so

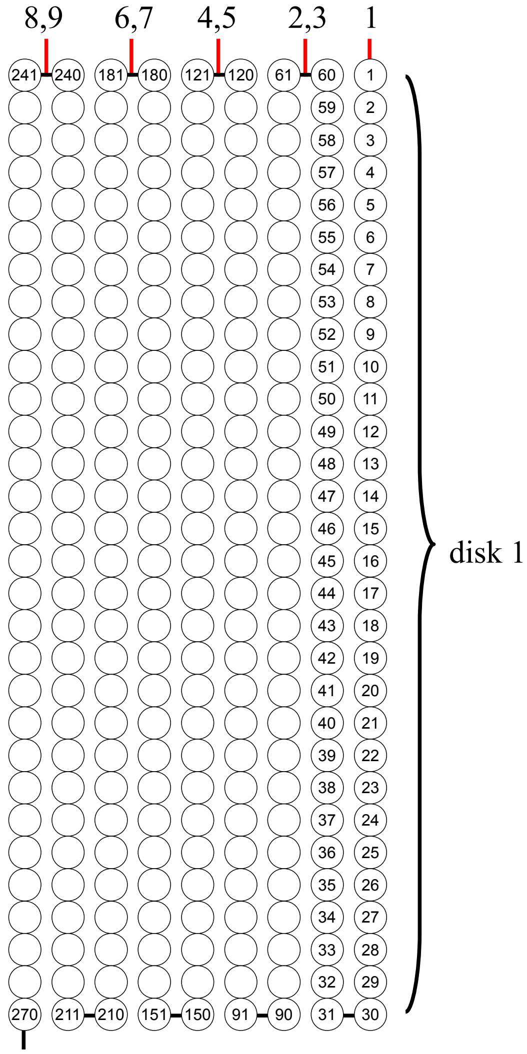


Figure 3.5: The 1^{st} disk winding scheme.

on. By this, the highest turn-to-turn voltage between two adjacent conductors is obtained at the beginning of the layers where the beginning of one layer meets the end of another layer, like conductors 1 and 60 for example. In that case, the initial voltage distribution at the top of the disk is determined by the distribution of the parallel stray capacitances between the top conductors. During the time in which the voltage step arrives from conductor 1 to conductor 60, a substantial turn-to-turn voltage is developed. Of course, this is not the case for the two adjacent conductors such as 60 and 61 where they are almost at identical potential, even during the very fast transients. Such a choice of the measurement points ensures that the highest turn-to-turn voltages are recorded.

3.2 Measurements and data analysis

The goal of this work is to study the voltage distribution along the winding during transients such as the lightning impulse or switching events. In our laboratory environment, these tests were performed using voltage generators that produce voltages of about $10V$. Using these voltage generators, both lightning impulses and switching events are generated. Since the high frequency transients above $10kHz$ are not affected by the core saturation [24] due to a high reluctance of the iron core during very fast transients [25], it is realistic to perform these tests with the scaled down equipment.

The results obtained in this work are compared to standard values of the basic lightning impulse voltage level (BIL). The standards for both dry-type and oil filled transformers define for each voltage level the BIL at which the transformer will not show any signs of insulation damages. These voltage impulse tests are considered as the strongest stress that can occur to the insulation of a transformer and therefore, if the transformer is able to withstand this voltage without any damages, its insulation should survive other high frequency transients. For this reason, the turn-to-turn voltage obtained during the lightning impulse shaped voltage stress are considered as the reference

The BIL defined by standards for dry-type and oil-impregnated transformers is given in Table 3.1.

Table 3.1: Nominal System Voltage and Basic Lightning Impulse Insulation Levels (BIL) for Dry-type Transformers [26]

	BIL (kV)	45	60	95	110	125	150	200
U_{nom}								
8.7		S	1	1				
15			S	1	1			
24				2	S	1	1	
34.5						2	S	1

In Table 3.1, "S" stands for the standard value, "1" is an optional higher level where the transformer is exposed to high overvoltages, and "2" is the case where surge arresters are used and found to provide appropriate surge protection.

This data is used for comparison with voltage stress during very fast transients. Since the voltage generators used in these tests produce low voltage impulses, the data is presented in per unit (pu). However, the BIL for each voltage level has a different value when expressed in pu making the direct comparison meaningless. The pu values are calculated as the ratio of the BIL and the peak phase voltage. For example, for the $8.7kV$ level, the basic lightning insulation level is $6.33pu$, while for the $34.5kV$ level the BIL value is $4.44pu$ with a surge arrester protection and $5.33pu$ as a standard BIL. As a reference, the $4.44pu$ BIL level is chosen since it has the lowest magnitude in pu. Another reason for taking this level as a reference is that the $34.5kV$ voltage level is used in large offshore wind farms where transformers are usually protected by surge arresters.

3.2.1 Turn-to-turn voltages in the 1^{st} disk

The focus of this study are the top disks of the winding. The reason for this is that the voltage derivative and the rise time of the voltage step applied to the terminal of the winding decreases significantly along the winding as the wave travels from one terminal to another. Since the speed of the wave propagation in the winding is constant, due to a lower voltage derivative and the rise time of the wave front, the voltage change, and therefore the turn-to-turn voltage, decreases along the winding.

Turn-to-turn voltages in the 1^{st} disk during the BIL test

The BIL test is taken as the reference. Since the standards define the lightning pulse as the strongest insulation stress, the turn-to-turn voltage magnitude obtained during the lightning impulse test is considered critical. The turn-to-turn voltages are measured at the top of the disk. This gives the possibility to measure it at the points where it reaches the maximum. As it was already shown in Fig. 3.5, these turns are 1, 61, 121, 181 and 241 respectively.

Initially, a low voltage $1.2/50\mu s$ impulse is used for the tests. The magnitude of the voltage is presented in pu, where as the reference a $4.44pu$ value is chosen which corresponds to the maximum BIL of a surge arrester protected dry-type transformer at a $34.5kV$ voltage level. The difference between this test and a real lightning impulse test is that the other end of the winding is not grounded. From the perspective of the voltage stress on the top disk, this does not make too much of a difference since the highest turn-to-turn voltage is recorded during the rise time of the lightning pulse, during which the voltage at the end disk is almost zero.

The plot with turn-to-turn voltages is presented in Fig. 3.6. It can be noticed that the highest turn-to-turn voltage is not developed at the first turns. Instead, the highest voltage of $0.38pu$ is obtained towards the end of the disk.

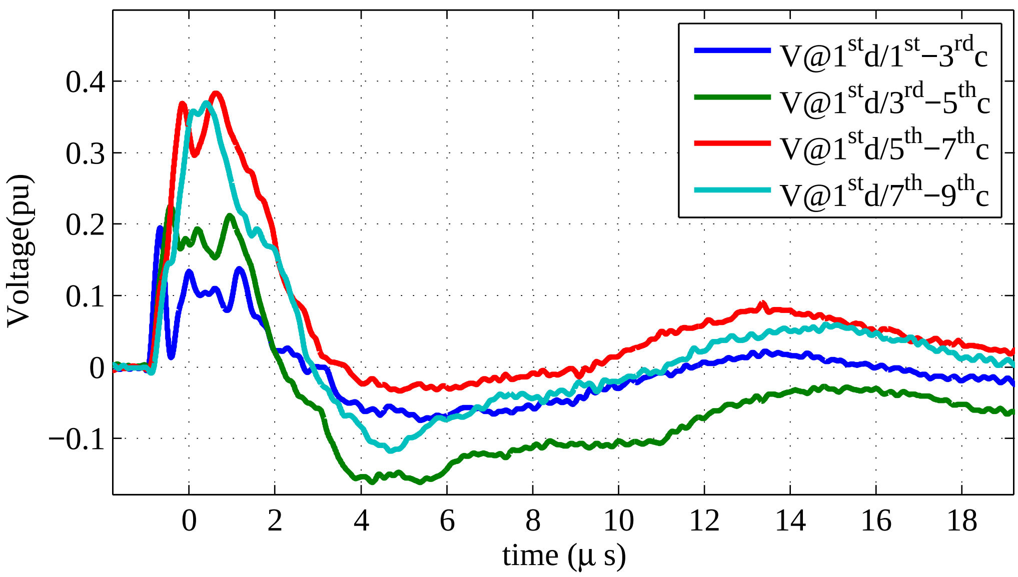


Figure 3.6: Turn-to-turn voltages at 1^{st} disk during BIL; d=disk, c=coil.

Turn-to-turn voltages in the 1^{st} disk during connection of a wye connected Transformer

In order to observe turn-to-turn voltages during the connection of a wye connected transformer, a single voltage step is applied to the reactor. The magnitude of the voltage step is set to $1pu$, which corresponds to the peak phase-to-ground voltage. This is the worst case scenario, which is selected to perform this study.

This test is performed with different rise times of the voltage step. This is done in order to study the turn-to-turn voltage for different types of insulation. It is known that different insulation types contribute to different stray capacitances of transformers, and therefore, the voltage step rise times [27], [28]. Because of that, the rise time is varied between the minimum of $35ns$ to approximately $500ns$.

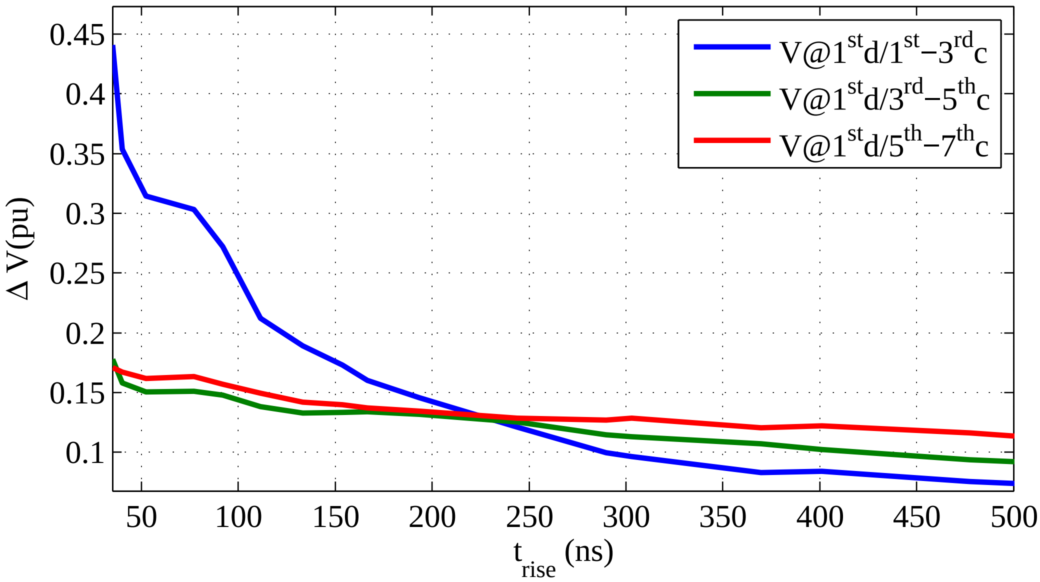


Figure 3.7: Turn-to-turn voltages at 1^{st} disk for different rise times t_{rise}.

The measurement results are shown in Fig. 3.7 that presents the turn-to-turn voltage as a function of the rise time. Due to a quick increase of the rise time of the voltage wave as it progresses through the disk, the highest turn-to-turn voltage is obtained for short rise times at the beginning of the disk.

Turn-to-turn voltages in the 1^{st} disk during connection of a delta connected transformer

In order to observe turn-to-turn voltages during the connection of a delta connected transformer, two voltage steps are applied simultaneously to the reactor winding terminals. This test is performed with different rise times of the negative voltage steps. With this method, it is possible to study and compare the turn-to-turn voltages for different types of insulation. As for the previous tests, a $35ns$ rise time is referred to as the minimum rise time, while a $500ns$ rise time t_{rise} is set as the maximum, because that is the maximum rise time determined by oil insulation.

Fig. 3.8 shows how the turn-to-turn voltage decreases with increasing rise time of the voltage step. The highest turn-to-turn voltage is obtained for short rise times of the conductors, where for this case of the energizing of a delta connected transformer, the turn-to-turn voltage exceeds 2.5 times the voltage recorded during the BIL test.

Measurements of the transient turn-to-turn voltages recorded at the first disk showed clearly that a simple connection of a delta connected dry-type transformer in a cable grid results in a voltage with a very high magnitude. As the measurements show, the highest stress is in the beginning of the winding. This finding can explain failures of transformers

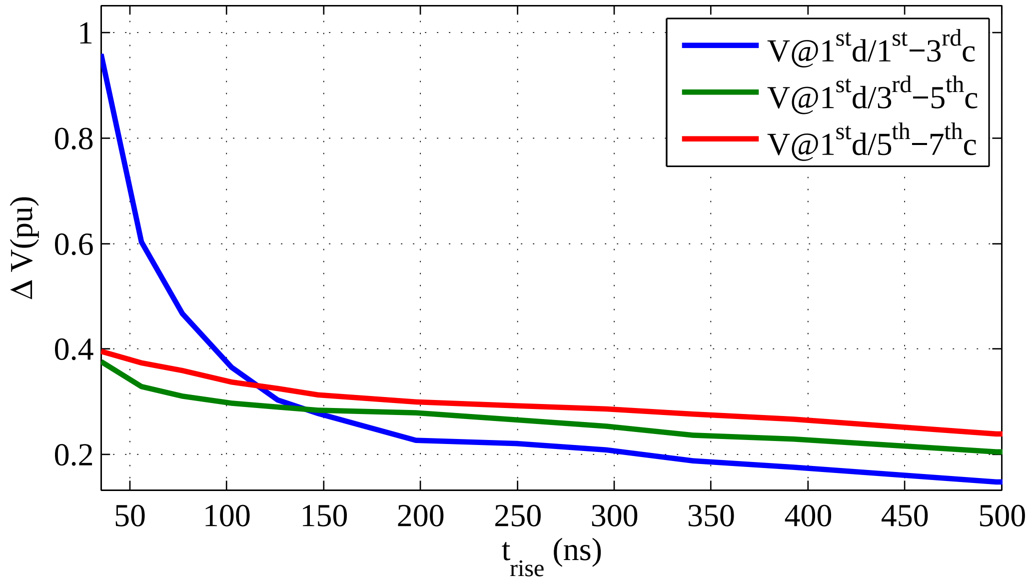


Figure 3.8: Turn-to-turn voltages at 1^{st} disk for different rise times t_{rise}.

reported in [8] and [9], where insulation failure and flashovers are noted at the beginning of the winding.

3.3 Comparison of critical voltage with existing standards

Plots shown in this section, show how the turn-to-turn voltages increase with the rise time of the voltage steps. The highest voltage stress considered as a reference is determined by the lightning pulse. In this case, a $4.4pu$ lightning pulse produced the maximum voltage of $0.38pu$ as shown in Fig. 3.6. Therefore, the voltage steps are considered critical if the magnitude of the generated turn-to-turn voltage exceeds $0.38pu$.

It is assumed that the insulation breakdown appears at the same voltage level for different rise times. This assumption is not entirely accurate, instead it is expected that breakdown voltages decreases with rise times due to a higher voltage derivative.

The results obtained in this work are compared to standard values of the basic lightning impulse voltage level (BIL). The standards for both dry-type and oil filled transformers define for each voltage level the BIL at which the transformer will not show any signs of insulation damages. These voltage impulse tests are considered as the strongest stress that can occur to the insulation of a transformer and therefore, if the transformer is able to withstand this voltage without any damages, its insulation will most probably survive other high frequency transients.

The BIL defined by standards for the IEEE Std C57.12.91-2001 and IEEE Std C57.12.36-2007 tests on dry-type and oil-impregnated transformers is given in Table 3.2.

Table 3.2: Nominal System Voltage and Basic Lightning Impulse Insulation Levels (BIL) for Dry-type and Oil-filled Transformers [26],[29].

	BIL (kV)	45	60	75	95	110	125	150	200
U_{nom}									
8.7 (DT)		S	1		1				
15 (DT)			S		1	1			
24 (DT)					2	S	1	1	
34.5 (DT)							2	S	1
8.7			S						
15				S					
24								S	
34.5									S

In Table 3.2 "S" is referred as the standard value, "1" as an optional higher level where the transformer is exposed to high overvoltages, "2" is the case where surge arresters are used and found to provide appropriate surge protection and DT is dry-type transformers.

Standards [26],[29] do not specify any additional test that may produce voltage waveforms with a very short rise time, such as the chopped-wave test used for power transformers at higher voltage levels. As it is shown in Chapter 3, distribution transformers can be exposed to transients with very short rise times. Consequently, these transients produce critical turn-to-turn voltages even when the magnitude of the voltage steps is reduced significantly. However, when it comes to standards for distribution transformers, nothing is defined yet.

NEMA, IEC and IEEE standards for motors consider maximum voltage withstand for transients with rise times shorter than $1.2\mu s$ [30]-[32]. The IEC standard for large motors includes surges with a rise time as short as $0.5\mu s$, NEMA standard accounts for surges with up to a $0.1\mu s$ rise time, while the IEEE standard includes even an ideal voltage step with zero rise time in it's voltage withstand envelope.

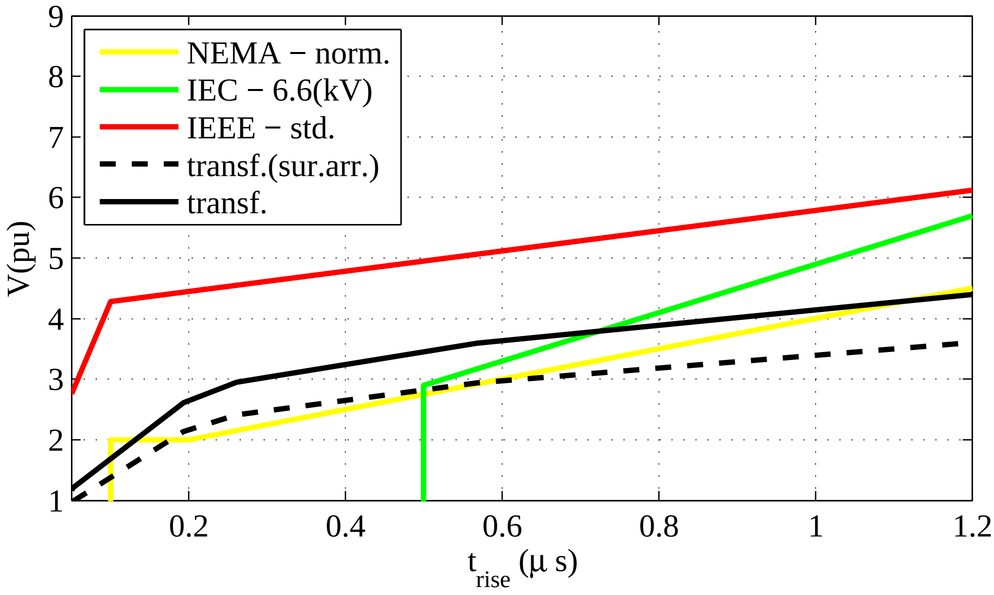


Figure 3.9: Standards for motors and transformers measured critical voltage.

Fig. 3.9 shows critical voltages for motors given by NEMA, IEC and IEEE standards, and measured critical voltages for transformers determined using the turn-to-turn voltage magnitude vs. rise time plots. The measured critical voltages are calculated in per unit with respect to the rms value of the line-to-line voltage both for a standard level and a decreased level when surge arresters are used. This corresponds to a BIL level of $150kV$ and $125kV$ for a $34.5kV$ dry-type transformer, or in per unit, $4.35pu$ and $3.6pu$. NEMA, IEC and IEEE standards for motors each give at least two critical voltage envelopes, and in Fig. 3.9, only the one with the lowest voltage level is presented. However, it can be noted that the trend of the measured critical voltage of the transformer shows a similar pattern compared to the mentioned motor standards, i.e. the magnitude of the measured critical voltage reduces proportionally to the standards.

The main reason that standards for motors include voltage surges of short rise times, is that the insulation of inverter-fed motors failed very quickly when the first inverter-fed motors were used with a long cable connecting motors and inverters. Transformers are not that often exposed to such high frequency transients. In fact, only during switching of transformers in cable systems there is a risk for such transients.

As shown before in this section, the lightning impulse does not produce the highest voltage stress on turn-to-turn insulation. It is very fast transients (VFT) with a very short rise time that produce the highest voltage stress. Therefore, it is needed to extend the standards for transformers in order to account for VFT. By doing that, transformers insulation will be designed accounting for the voltage stress caused by VFT too.

Chapter 4

Analysis of the high-frequency transient in the cable lab

A cable lab for the transient analysis studies is built in the facilities of ABB Corporate Research in Västerås, Sweden. The cable lab is built in order to replicate a feeder/turbine system found in the wind farms for the fast transient studies. The benefits of the lab measurements compared to the measurements in the field are many. The lab is built in a way so it enables reconfiguration of the test setup so it can replicate various wind turbine and feeder connection arrangements. Furthermore, various protection measures can be tested and compared in an environment that provides a good platform for the comparison of the protective devices.

4.1 Layout of the Three Phase Test Setup

The cable lab is a three phase setup where full scale tests are performed for the purpose of high frequency transient studies. The setup of the cable lab consists of $550m$ long $20kV$ XLPE three core cable with $240mm^2$ cross section of conductor, a $52m$ long $20kV$ XLPE single core cable with the same conductor cross section and two transformers, where the transformer TX1 represents the transformer placed in the wind turbine while the transformer TX2 represents the platform transformer. Two different transformers are used as transformer TX1, where one is an oil-insulated and the other one is a dry-type transformer. As a switching device, a vacuum circuit breaker is used. The full test setup is presented in Fig. 4.1

The setup is built so it may provide different connection arrangements found in real wind parks. Cables marked as SC1 and SC5 with $72m$ of length, represent the cable in the wind turbine which is placed between the wind turbine transformer (TX1) and the breaker (BRK). Cable SC5 is terminated at the other end, and in the test setup represents a disconnected wind turbine. This is very suitable for the analysis of the wave reflection and its impact on the high frequency transients. The SC2 cable is a cable which connects two turbines. The length of the cable is a bit too short compared to the cable between two wind turbines in a real wind park collection grid, but still, its length is sufficient for the high frequency transient analysis. Cables SC3 and SC4 represent two feeders of the WP collection grid with the length of $162m$. Feeder 2 or SC4 cable is terminated at the end, and represents a feeder with all wind

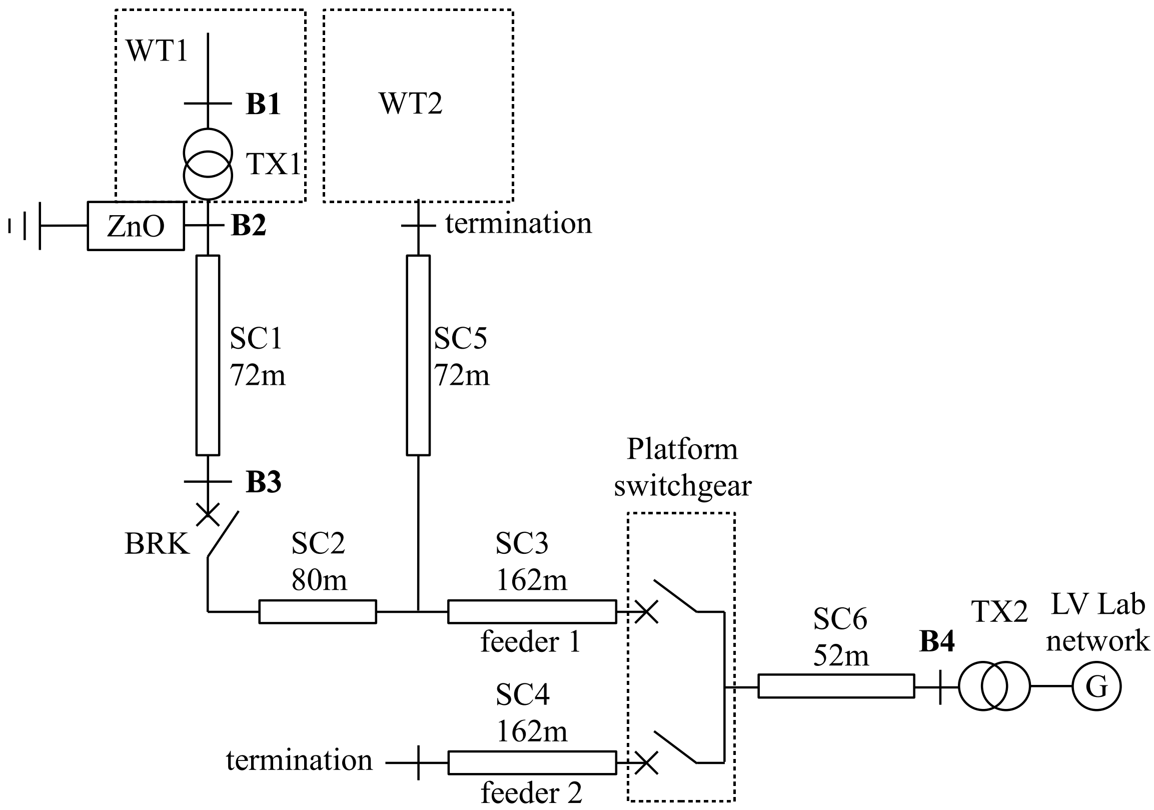


Figure 4.1: The cable lab setup layout.

turbines disconnected. The setup allows having this feeder both connected or disconnected. When connected, Feeder 2 adds additional capacitance to the system and reflection point at its end where it is terminated. The switchgear platform is connected to the platform using a single phase $52m$ long $20kV$ XLPE cable. On the platform, TX2 transformer is placed and it is connected to the grid from the low voltage (LV) lab network. Since both TX1 and TX2 transformers are connected in delta arrangement on the high voltage side, an artificial neutral point is provided using three $24kV$ rated voltage transformers connected with their primary windings connected in wye. During the inductive load test, an inductor with a $0.318mH$ inductance is placed at the bus **B1** for test with the oil-insulated transformer, while a $17mH$ inductor is used with the dry-type transformer.

In tests with the oil-insulated transformer, the transformer TX1 is protected with a surge arrester consisting of two ZnO blocks connected in series in order to prevent overvoltages of very high magnitude that can damage the transformer. Furthermore, in tests with the oil-insulated transformer, the low voltage level supplied from the lab network is set to give $12kV$ voltage level on the high voltage side of the transformer TX2. The voltage is set to $12kV$ since the voltage rating of the vacuum circuit breaker used in the testing with the oil-insulated transformer is also $12kV$.

The tests with dry-type transformer are performed at the rated voltage level of $20kV$. Due to an increased voltage level, three or four ZnO blocks are used for prevention of high overvoltages. Furthermore, a $20kV$ ring main unit (RMU) with a VCB as a switch is used instead of the $10kV$ VCB used in the tests with the oil-insulated transformer.

The rating of the equipment installed in the cable lab is as follows:

- $550m$ of $20kV$ XLPE three core cable with $240mm^2$ cross section of conductor;
- $52m$ of $20kV$ XLPE single core cable with the same conductor cross section;
- Transformer TX1(oil-insulated), $20.5/0.41kV/kV$, $1.25MVA$, Dyn11 $Z_k = 5.4\%$;
- Transformer TX1(dry-type), $20/0.69kV/kV$, $0.9MVA$, Dyn11 $Z_k = 6\%$;
- Transformer TX2, $20/0.69kV/kV$, $1MVA$, Dyn11 $Z_k = 5.1\%$;
- Breaker rated at $12kV$, $3.15kA$;
- ring main unit (RMU) rated at $20kV$, $200A$.

In the lab, several protection devices are tested. As mentioned before, during the tests, the transformer TX1 is always protected using the ZnO surge arrester in order to prevent damage to the transformers. For the transient studies, an RC protection and a surge capacitor protection with different connection arrangements is tested. During the tests, the following surge protection is used:

- Two, three or four blocks of ZnO connected in series with continuous operating voltage $COV = 14.3kV$, with characteristic points of $1mA@17.2kV$ and $10kA@28.5kV$;
- Surge capacitors with $83nF$ and $130nF$ capacitance;
- Resistors with 20Ω and 30Ω resistance.

During the tests, different protection schemes are tested. In some cases, different protection devices were placed at two buses at the same time in order to find the best solution.

4.2 Measurement Setup

In Fig. 4.2 the measurement setup is presented. Measurements are performed at the buses **B2** and **B3**, where **B2** is the bus where the high voltage side of the transformer TX1 is connected. The breaker is placed at the bus **B3** where cable SC1, which represents the wind turbine cable, is connected.

On the bus **B2**, only the voltage is measured. It is of the highest importance to measure this voltage with good accuracy since the voltage measured at this bus is the voltage that stresses the insulation of the transformer TX1. On the bus **B3** both currents and voltages are measured. Since this is a bus where a breaker is connected, the measured current represents the current through the breaker which is important to study the breaker phenomena. By measurement of voltages at these two buses it is possible to observe the wave traveling and reflection phenomenon which creates high frequency transient overvoltages.

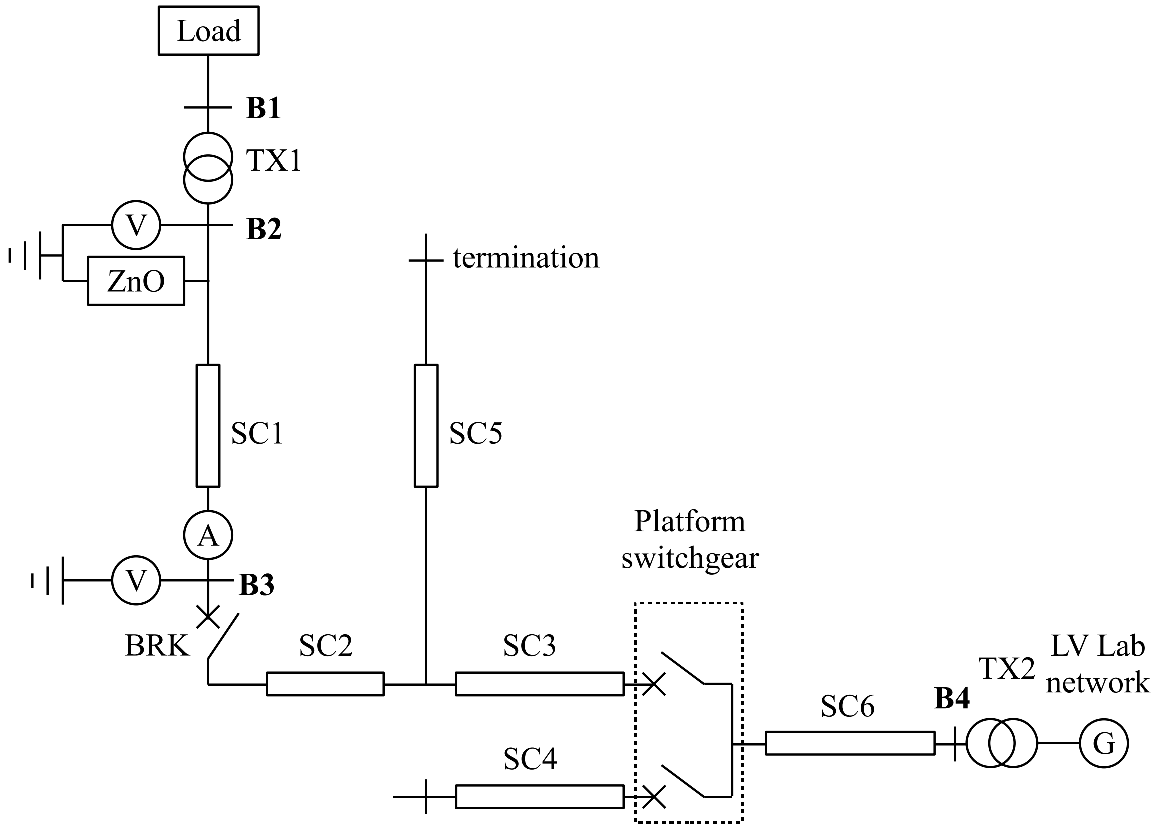


Figure 4.2: The cable lab measurement setup layout.

Since a high frequency phenomenon is measured, measurement equipment with high bandwidth is used. For measurement of the voltages at the bus **B2**, Northstar voltage dividers Type VD-100 are used. The accuracy of these voltage dividers is 1% in the frequency range between $10Hz - 1MHz$ while at frequency range between $1MHz - 20MHz$ it is 3%. The divider ratio is 10000 : 1. At the bus **B3** HILO Type HVT40RCR voltage dividers are used. The bandwidth of these dividers is $10MHz$ while the ratio is 2500 : 1. For the current measurement at the bus **B3**, a Pearson current monitor type D101 is installed. The bandwidth of this current probe is $4MHz$ with a maximum peak current of $50kA$.

The signals from the voltage dividers and current probes are lead by an optical link to two transient recorders type W+W TRA 800s. By using optical links it is ensured that the measured signal is not disturbed. Nine channels in total are recorded at a sampling rate of $25MS/s$ with a 12 bit resolution.

4.3 Measurement Results and Analysis

In this section, the results obtained during the measurements and the simulation results, are compared and analyzed. The purpose of the analysis is to verify the model developed for simulation of high frequency transients, to study generation and propagation of the high frequency transients, and to analyze the impact of different mitigation methods.

The parameter estimation of the components is based on the measurements for the base case. The base case is the case with only surge arresters connected to the system. The results obtained using the transient mitigation equipment are compared to the base case and the influence of the different mitigation devices is studied.

Since the voltage breakdown, the current chopping and the high frequency current interruption are stochastic phenomena and very much determine the results presented in the time-domain, the exact replication of the measurement results using simulations is not possible. This is especially the case for the opening of the breaker, where larger number of the stochastic strikes appears. Therefore, the verification of the simulation models is performed by verifying characteristics of the high frequency transient such as the magnitude and the rise time.

Furthermore, the obtained results are compared to standard values of the basic lightning impulse voltage level (BIL) extended using the critical voltage curve and withstand voltages for motor standards given in Section 3.3. The results obtained in this section for the oil-insulated transformer are measured at a non-standard voltage level which is set below the rated voltage of the transformers, cables and other equipment. This is performed in order to avoid damages on the equipment used for testing, since the simulations showed that transient overvoltages of very high magnitudes are expected during some tests.

The standards for both dry-type and oil filled transformers define for each voltage level the BIL at which the transformer will not show any signs of insulation damages. These voltage impulse tests are considered as the highest stress that can happen to insulation of a transformer and therefore, if the transformer is able to withstand this voltage without any problems, its insulation will most probably survive other high frequency transients. Since these standards are not defined for very fast transients, the maximum allowed voltage stress in the region of transients between $50ns$ and $1.2\mu s$ is defined by the critical voltage and the withstand voltages for the motor standards given in Section 3.3.

For the presentation of the voltage strikes in the scatter plots, the magnitudes of the voltage strikes are shown in per unit, where $1pu$ presents the nominal voltage of the transformer. This is done because, the maximum magnitudes of the voltage strikes obtained at any voltage level with properly calculated surge arresters is the same when presented in per unit. However, the BIL for each voltage level has a different value when expressed in pu making a comparison difficult. For example, for the $8.7kV$ level, the basic lightning insulation level is $5.2pu$ for dry-type transformers and $8.6pu$ for oil insulated transformers while for the $34.5kV$ level the BIL values are $3.6pu$ (with surge arrester used) and $4.35pu$ respectively. For this reason, the minimum value in per unit is used as the reference value for the dry-type and the oil insulated transformers. The comparison is done for both standards since the magnitude of the voltage strikes is the same for both dry-type and oil insulated transformers and the difference is only in the rise time of the surge. Furthermore, as the standards do not define critical voltages for surges with rise times shorter than 1.2 μs, characteristics measured in Section 3.3 is used to extend the area of critical voltages.

Inductive load case - oil insulated transformer

The case with a switching of an inductive load is chosen since it represents one of the worst case scenarios for generation of transient voltages. When the current reaches the chopping level, the voltage in that phase is very close to its maximum because of the 90° phase shift. If the breaker contacts are opened at that time instant, the transient voltage is superimposed to the power frequency voltage when it is at its maximum. This produces transient overvoltages with the highest magnitude.

It is important to stress that an interruption of an inductive current is an extreme case conducted to obtain the worst case scenario. However, it does not represent a normal operation in a wind park where it should not be normal practice to open the breakers and switches when the transformer is fully loaded. This case could still happen accidentally, due to malfunction or other reasons. Furthermore, even if such an accident happens, the risk of generation of multiple reignitions and the voltage escalation is quite low since this phenomenon can appear only if the contacts open during a very narrow time window when the current is below the current chopping level.

If a voltage escalation incident occurs in a setup where surge arresters are omitted for some reason, the transient voltage can easily breach BIL and damage the transformer. This case is not performed during the measurement for the sake of the tested transformer. Simulations show that in this case, a very high overvoltage is generated.

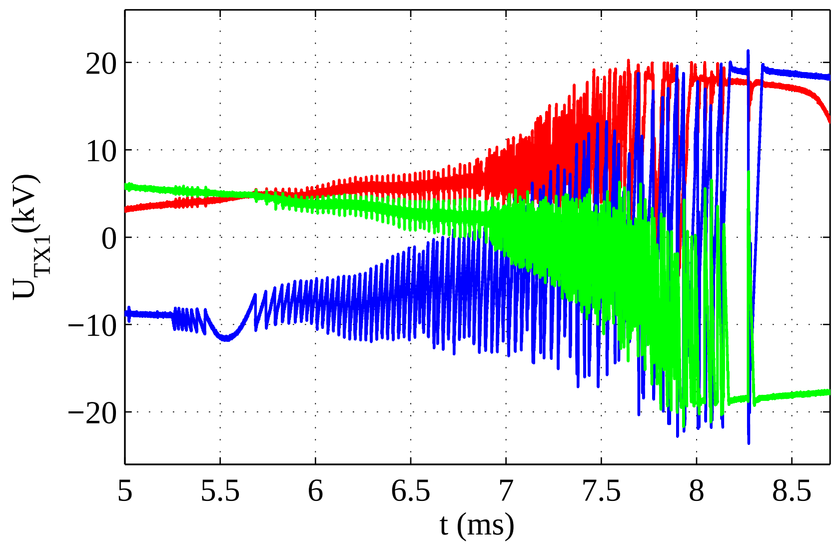


Figure 4.3: Transient voltage at TX1 during opening - inductive load - measurement.

Figure 4.3 shows voltage restrikes recorded during measurements. Due to presence of the surge arresters, the voltage is clamped at about $20kV$. Simulation of the same switching event shows very similar voltage transient.

The voltage strikes obtained by characterization of the line-to-line transient voltages are presented in Fig. 4.4. These strikes are obtained in the simulation of the inductive load case. This case present a critical case where the transients with the highest magnitude are developed. The simulation predicts the highest stress voltage stress with a 5% error, while the rise time prediction is within a 10% margin. The fastest voltage surges have a rise time of 0.5 μs. This group represents the voltage surges formed during the breakdown of the dielectric in the breaker.

Surges obtained during simulations and measurements are compared with the standard

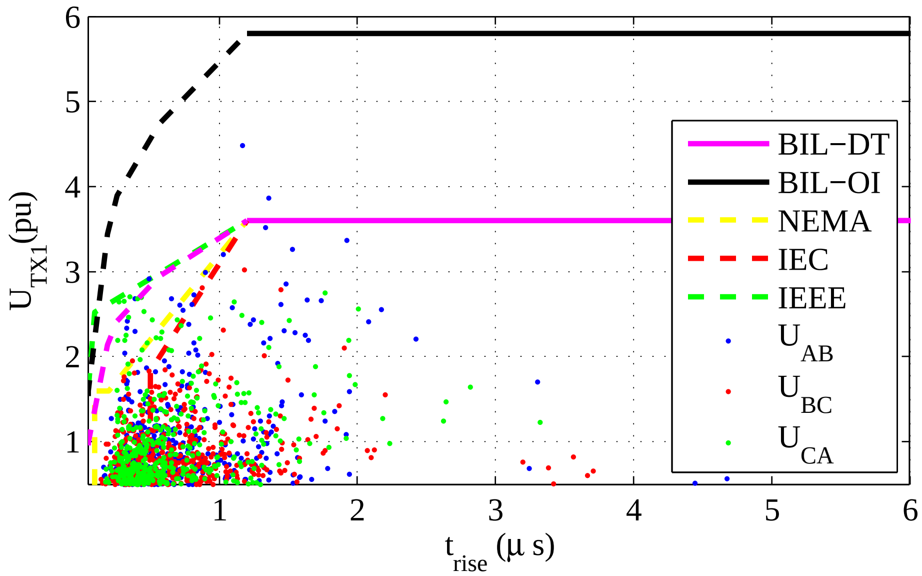


Figure 4.4: Strikes at TX1 during opening - inductive load - simulation.

BIL level for oil-insulated transformers (BIL-OI) and lower BIL level for dry-type transformers protected by surge arresters (BIL-DT). Furthermore, these BIL curves are extended into a region below 1.2 μs rise time using the proposed critical voltage envelope obtained in Section 3.3 and adjusted NEMA, IEC and IEEE critical voltages for large motors. The withstand voltage envelopes for large motors given by NEMA, IEC and IEEE standards are adjusted so the critical voltage with a 1.2 μs rise time corresponds to the BIL of dry-type transformers protected with surge arresters.

Surges recorded both in simulations and measurements show that the magnitude and the rise time of the surge exceeds the limits defined by the BIL. In Fig. 4.4 two strikes that exceed this limit are shown. One strike with a 4.5pu magnitude and a 1.15 μs rise time, and another one with a 3.9pu magnitude and a 1.35 μs rise time. This occurs even with a surge arrester installed at the terminals of the transformer, proving that the surge arrester protection can not provide sufficient protection without the use of additional protective devices. Moreover, the voltage strikes with a 0.5 μs rise time have a magnitude that is higher than the critical voltages defined by NEMA, IEC and IEEE standards, as well as the proposed critical voltages presented in Section 3.3. Similar overvoltages are shown in Fig. 4.6.

Inductive load case - dry-type transformer

The dry-type transformer tests are performed at a rated voltage of 20kV. Consequently, the number the ZnO blocks is increased to four, where the voltage is clamped at approximately 40kV. Four blocks are used in order to make it possible to make a direct comparison with the results obtained at a 12kV level using the oil-insulated transformer. Furthermore, this test is performed with both SC4 and SC5 connected.

A ring main unit (RMU) with a VCB is used in this setup. The rate of rise of dielectric strength (RRDS) of the VCB in the RMU is about four times quicker compared to the RRDS of the VCB used with the oil-insulated transformer.

Due to a lower current level in this setup, it was not possible to generate in the laboratory environment the worst case scenario like it is performed with the oil-insulated transformer. The peak current is about $3.6A$, which corresponds to the chopping current. This means that very low current is interrupted when the voltage is at it's peak. A low di/dt gives a lower voltage rise and fewer number of restrikes due to a slower transient recovery voltage (TRV). However, for the sake of better comparison, the inductive load test with the dry-type transformer is simulated both with a $17mH$ load and a $0.94mH$ in order to get the same current level through the breaker.

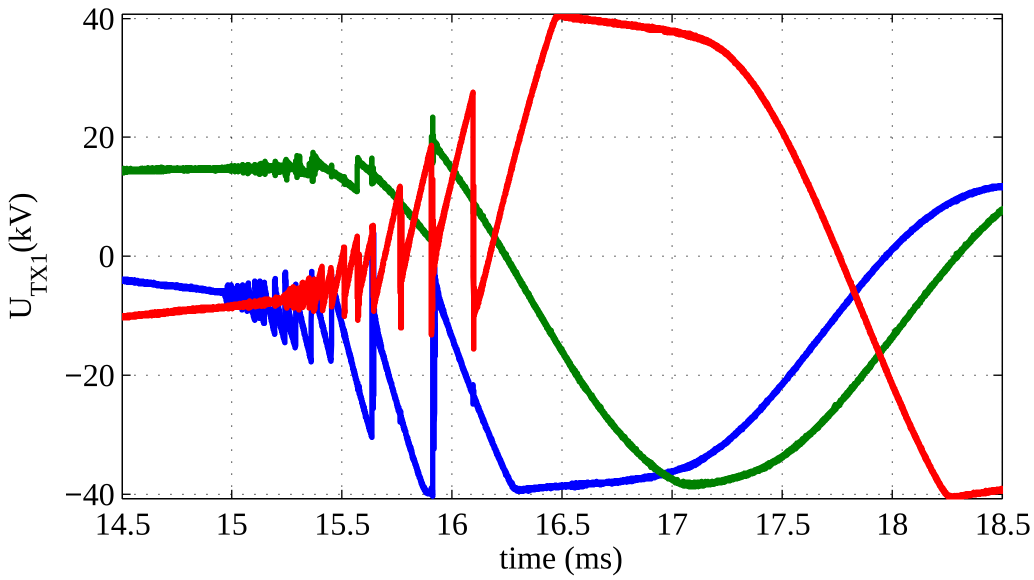


Figure 4.5: Transient voltage at TX1(dry-type) during opening - inductive load ($17mH$) - measurement.

Fig. 4.5 shows measurements of voltage restrikes at the dry-type transformer TX1. It can be noted that the voltage restrikes do not begin at the maximum voltage since the breaker interrupts the current as soon as the contacts start to separate.

In order to make a comparison with the oil-insulated transformer test, the simulation with the dry-type transformer is performed using the same current level as it was with the oil-insulated transformer. This represents the worst case scenario since the current is interrupted close to zero crossing.

Fig. 4.6 shows the voltage strikes during an interruption of the load current drawn by a $0.941mH$ inductor. This represents the worst case switching scenario, where the breaker opens when the load current reaches chopping level at maximum voltage. None of the strikes reach over the BIL when surge arresters are used. However, a large number of recorded strikes with a $100ns$ rise time have a very high magnitude. Many of these voltage strikes are placed above the critical voltage, and the most critical ones are the strikes with a $100ns$ rise time since their magnitude is about three times over the critical level. These strikes exceed the voltage withstand level defined by NEMA, IEC and IEEE standards substantially. This case shows why dry type transformers need additional means of protection that increase the rise time and reduce the magnitude of the voltage strikes such as surge capacitors and RC protection. It is worth mentioning that voltage strikes obtained at some dry-type transformers where a breaker is placed at the transformer reach rise times of about

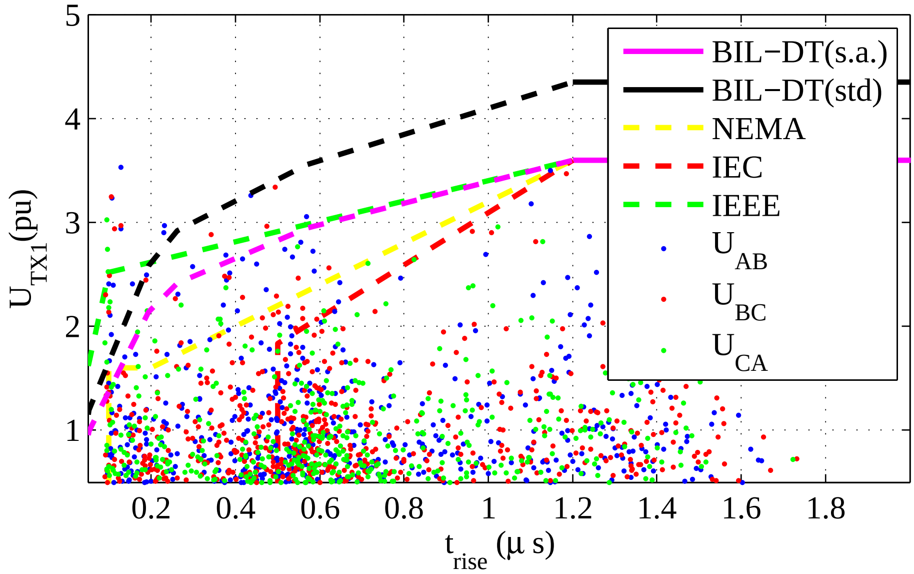


Figure 4.6: Strikes at TX1(dry-type) during opening - inductive load $0.947mH$ - simulation.

$50ns$ [28]. The turn-to-turn voltage stress in that case is even higher.

4.3.1 Surge Capacitor Protection

Surge capacitors have been commonly used as protection devices to mitigate transients. The combination of surge capacitors and surge arresters has been used to protect medium voltage induction motor windings from steep-fronted voltage surges [33]. The purpose of using the surge capacitor is to increase the rise time of the surge [34]. In this report, a surge capacitor protection with a $130nF$ capacitance is used. The surge capacitor is installed in front of the transformer TX1 shown in Fig. 4.2. The surge arrester is kept at the transformer terminals to limit the maximum overvoltage appearing on the transformer.

The purpose of having the surge capacitor is to slow down the surge front and the transient recovery voltage. The consequence of reducing the steepness of the voltage surge is that the rise time of the surge is brought into the limits defined by standards (1.2 μs).

This is achieved by increasing the time constant of the transformer by adding additional capacitance as shown in Fig. 4.7.

The time constant of the surge generated in the system shown in Fig. 4.7 is given by

$$\tau = Z_{cab} \left(C_{tr} + C_{surge} \right), \tag{4.1}$$

where C_{surge} is the capacitance of the surge capacitor.

In Fig. 4.8 the impact of the surge capacitor protection on the surge rise time is observed. The plot marked with $C83$ shows the surge when a $83nF$ capacitor is used, the plot marked with $C130$ shows the surge with a $130nF$ capacitor. The results obtained by the simulation agree with the analytical calculations presented with dotted lines. The oscillations of the

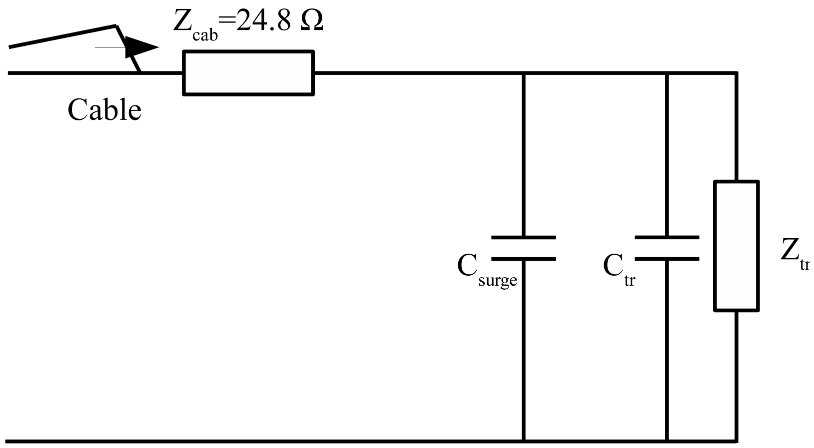


Figure 4.7: Surge capacitor protection - simplified circuit.

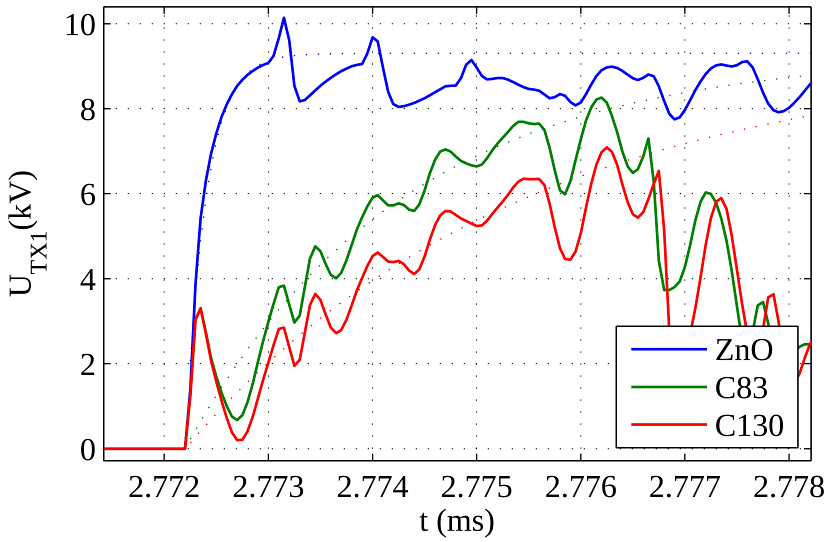


Figure 4.8: Voltage surge rise time without and with surge capacitor protection - simulation.

voltage that appear in the plot are caused by the stray inductance of the capacitor leads and can be minimized when shorter leads are used. The value of the lead stray inductance is calculated according to the length and the cross section area of the surge capacitor leads.

A stiffer voltage obtained by added capacitance in the system results in a significantly reduced magnitude of the voltage strikes during an opening of the breaker. This behavior is noted in Fig. 4.9.

As it can be noted from Fig. 4.9, the number of reignitions during the breaker opening operation is significantly reduced when the surge capacitors are used. Moreover, the magnitude of the voltage strikes is reduced by a factor of two.However, the additional capacitance causes voltage oscillations during the energizing transient.

The voltage strikes from the simulation obtained by the characterization of the transient voltages are presented in Fig. 4.10. Although the measurement show the presence of strikes with a rise time of almost 5 μs, in the simulations, the slowest strike has the rise time of

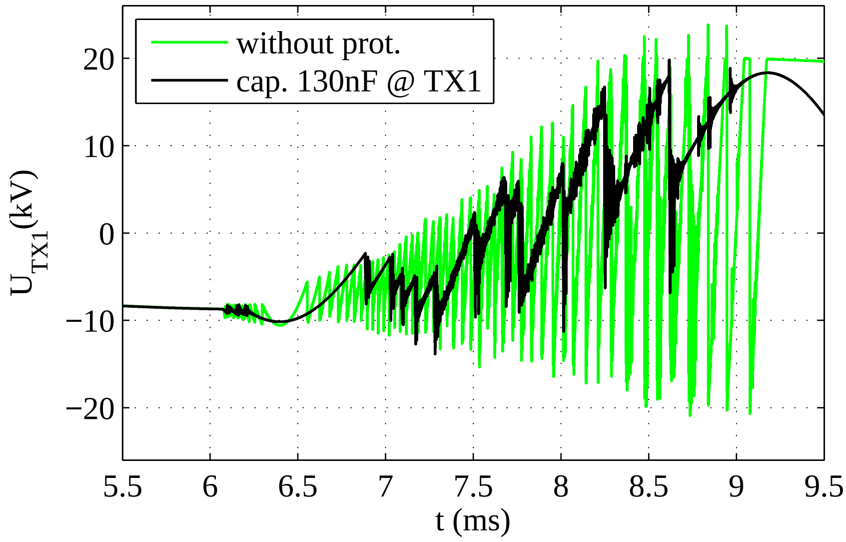


Figure 4.9: Impact of $130nF$ surge capacitor on transient voltage - simulation.

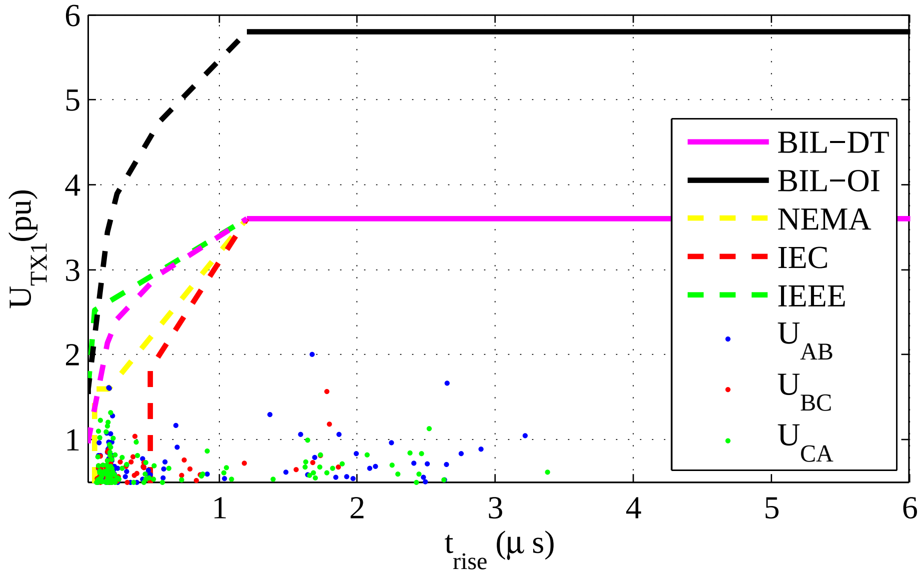


Figure 4.10: Strikes at TX1 during opening - surge capacitor 130nF - simulation.

4 μs. A good agreement is observed when the voltage strikes are compared. The error in the magnitude of the simulated voltage strikes is below 10%, while the comparison of the voltage surge rise times is within a 20% error. The surge magnitudes dropped significantly when compared to the base case and are kept below a $2pu$ limit.

4.3.2 RC protection

The RC protection is used for mitigation of the high frequency transients and protection of transformers and induction motors [35], [36]. It is very effective and proved to reduce the number of reignitions [35]. The principle of an RC protection is very simple. The wave reflections which give the highest magnitude of transient overvoltages occur in the systems where the surge impedance of the transformer Z_{tr} is much higher than the cable surge impedance Z_{cab}. In order to prevent such reflections, a resistor with a capacitor is connected in parallel to the protected transformer. This is presented in Fig. 4.11.

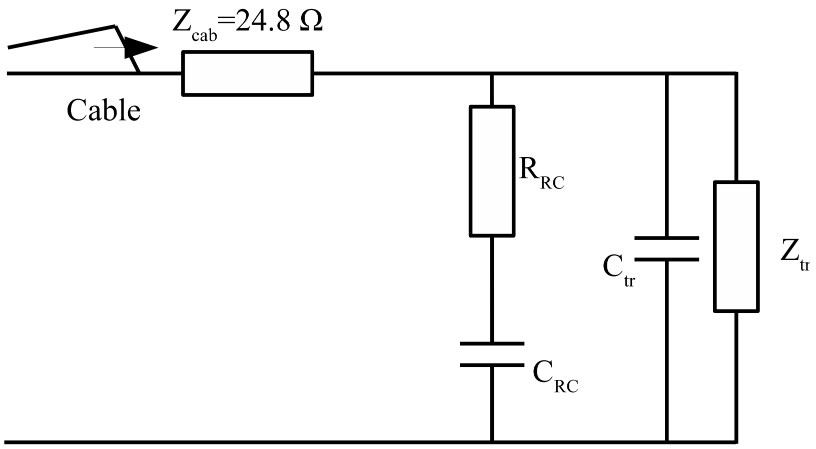


Figure 4.11: RC protection scheme.

The resistance of the resistor is chosen so it matches the surge impedance of the cable Z_{cab}. By doing this, the wave reflections are avoided since the reflection coefficient is zero

$$\alpha = \frac{R - Z_{cab}}{R + Z_{cab}} = 0. \tag{4.2}$$

By damping the high frequency current superimposed to the power frequency current, the current zero crossing and thus the reignition is avoided if the power frequency current is very high. This method is shown to be very effective during the induction motor starts [35].

However, the generation of the reignition depends on other factors such as the rate of rise of the breakers dielectric strength and the rate of rise of the transient recovery voltage. For this reason, the RC protection may not be sufficient to eliminate reignitions completely, but will definitely reduce the number of reignitions and the magnitude of the voltage strikes.

RC protection - oil-insulated transformer

The RC protection is placed at the transformer. It is made using a $R = 20\Omega$ resistor and the capacitor with a capacitance of $C = 130nF$. The surge impedance of the cable is calculated to be 24.8Ω, and used RC protection does not present a characteristic impedance termination. However, the resistance of the surge resistor is very close to this value and this is acceptable for an RC protection study.

A graph which shows the voltage strikes in a scatter plot is presented in Fig. 4.12. From a transient protection perspective, an RC protection is very good since it keeps the magnitude of the voltage surges within the BIL and below the critical voltage levels obtained in Section 3.3 and defined by standards for large motors.

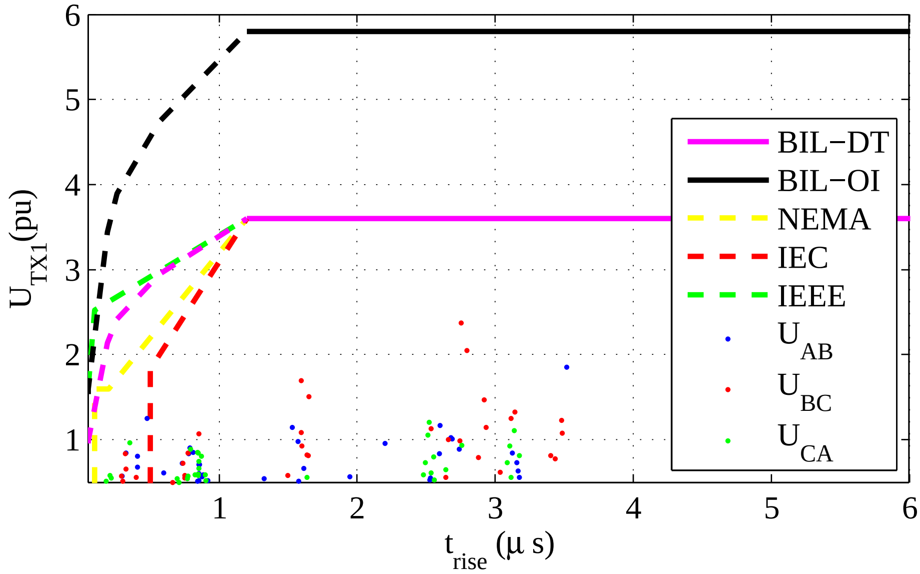


Figure 4.12: Voltage strikes $R20\Omega \& C130nF$ - simulation.

RC protection - dry-type transformer

The test with the RC protection is performed with the dry-type transformer. The RC protection is placed at the buses **B2** and **B4** as shown in Fig. 4.2. The RC protection at the bus **B2** consists of an $R = 20\Omega$ resistor and a $C = 83nF$ capacitor. At the bus **B4**, an $R = 20\Omega$ resistor and a $C = 83nF$ capacitor are used. Furthermore, in this test, three ZnO blocks are used as a surge arresters protection, clamping the voltage at about a $30kV$ level.

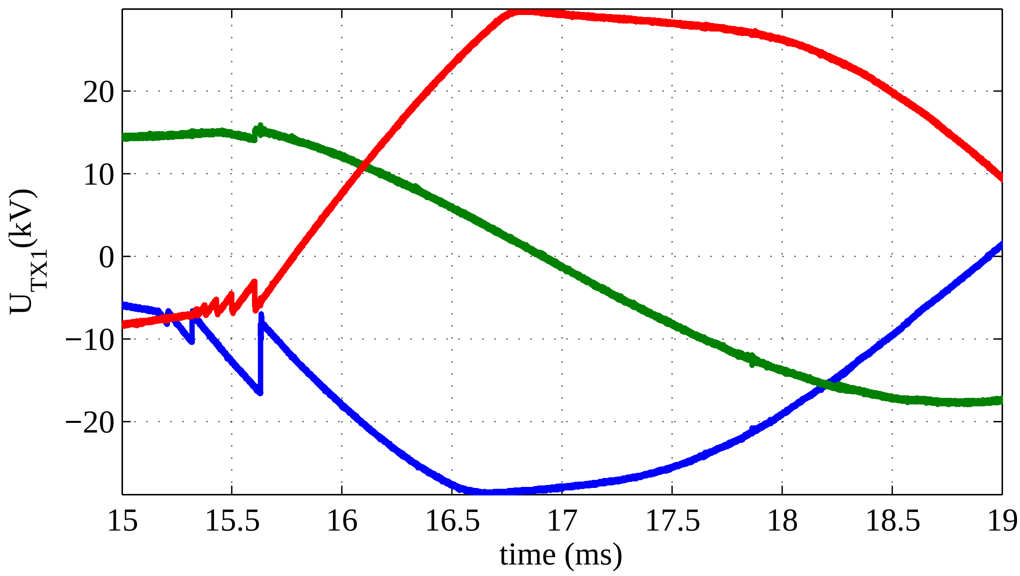


Figure 4.13: Transient voltage at TX1(dry-type) during opening - RC protection - measurement.

Fig. 4.13 shows the transient voltage recorded at dry-type transformer, TX1, when the RC protection is used. It is observed that restrikes have a very small magnitude. The rise time of the restrikes is still about $100ns$, but the magnitude is well below the critical level.

Chapter 5

Conclusions and Future Work

In this report, a summary of the results of the high frequency electromagnetic transient analysis from the Vindforsk projects V-325 and V-326 is presented. Measurements of high frequency transients are performed at Chalmers University of Technology and in the cable laboratory at ABB Corporate Research in Västerås, Sweden. The measurements are used for the parameter estimation of the models and for the simulation verification. Cases where surges of the magnitude and/or rise time above the basic lightning impulse voltage level appear are identified. Also, some transient protection schemes are studied and the performance of different transient mitigation devices is analyzed. Although the situation can be as most severe in cable networks where vacuum circuit breakers as well as dry insulated transforms are used, which has frequently been pointed out, the phenomena are similar also using other breaker and transformer technologies.

5.1 Conclusions

In this study, it is concluded that:

- A closing of a breaker can generate excessive turn-to-turn overvoltages. The most severe turn-to-turn overvoltages appear in the case of delta connected dry-type transformers. The maximum turn-to-turn voltage exceeds 2.5 times the voltage obtained during the lightning impulse test. The magnitude of this overvoltage does not depend on the type of a breaker and it is possible to obtain it with all types of commercially available breakers;
- The rise time of the transient has a strong impact on the magnitude of turn-to-turn voltages. During the breaker switching in cable systems where dry-type transformers or reactors are installed, severe turn-to-turn voltages can appear due to short rise times of the transients. Consequently, the critical voltage as a function of rise time is proposed. The proposed critical voltage is similar to those ones found in standards for the withstand voltages of large motors;
- During the simulations and the measurements, surges which exceed the BIL of dry-type transformers specified by IEEE standards, both in magnitude and rise time are recorded

even when surge arresters are used. Furthermore, the obtained voltage strikes exceed the proposed critical voltage level, as well as the standard voltage withstand levels for large motors. The highest overvoltages are recorded with dry-type transformers due to a low stray capacitance of dry-type transformers that contributes to a short rise time of the voltage surges;

- The RC protection used in the tests did not prevent the appearance of repetitive surges and voltage escalations due to a very high rate of rise of the transient recovery voltage which is much faster than the rate of rise of the dielectric strength (RRDS) of the breaker. This was the case even when a breaker with a very fast RRDS is used to interrupt current. Among the mitigation methods tested in this study, it is observed that a surge capacitor protection or an RC protection coupled with surge arresters decreases the voltage stress below the BIL and critical voltage level defined by motor standards and obtained in the measurements in this work.

5.2 Future Work

The cable modelling for high frequency transients can be improved using a cable model developed in FEM where the frequency dependent impedance and admittance matrices of the cable are obtained. The estimation of the electric and magnetic properties of the insulating materials used in the cable can be obtained by measurements in order to obtain better accuracy. In this work, only the magnitude of turn-to-turn voltages of a particular winding is used to calculate the envelope of the critical voltage. Furthermore, the voltage breakdown in the insulation material is not studied for different rise times of voltage surges. Therefore, it would be of great interest to perform similar research on different types of transformers with different design of transformer windings and different power ratings in order to find the envelope for critical voltages. Furthermore, this research needs to include a research about the influence of the rise time of voltage surges on the voltage breakdown of insulation materials.

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