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Investigation of Wind Farm Padmount Transformer Failure Through Transient Studies

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SUMMARY

Renewable energy resources, including wind power and solar power, are becoming popular sources of electricity generation because of certain features and advantages. Although wind power generation is a growing electricity source, it comes with some challenges regarding different aspects of integration of large-scale wind generation units into the electricity network.

Wind and solar transformers have their sets of challenges with considerably more complex requirements than standard distribution transformers. Voltage and load fluctuations are considerably higher in these transformers, which increases the stress on the transformers and makes them more susceptible to failures. This paper reviews some of the common causes of failures in padmount transformers in wind farm collector systems.

The failure mechanisms that are discussed in this paper are switching events from opening or closing circuit breakers that are a part of the collector systems which could lead to transients, pre-strikes, restrikes, or resonance/ferro-resonance, all of which are unwanted occurrences. These events lead to high frequency contents, either transient over voltages or transient recovery voltages, and cause stress on transformers and connected equipment.

Hatch Ltd was retained to investigate a wind farm in the United States, and to determine the cause of the failures that happened on multiple padmount transformers after feeder energization. The case study is further developed in PSCAD using the provided data. Various simulation cases were developed to investigate different phenomena that could contribute to the failures, including resonance/ferro-resonance, switching transients, ineffective grounding, circuit pre-strike, etc. The mitigation methods and their impacts were analysed and reported in this paper. The results show that these mitigation techniques can help reduce some of the observed transients and harmonic contents to prevent failure.

KEYWORDS

Transient Studies, Wind Farm, Padmount Transformer, Failure, Mitigation, Snubber, Switching

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I. Introduction

Renewable energy resources, such as wind and solar energy, are becoming popular sources for electricity generation because of certain features and advantages, including sustainability. The share of renewable resources in the electricity sector will increase from 24% in 2017 to almost 30% in 2023 [1]. Electricity generation by wind turbines is becoming a growing trend around the globe, but with it comes some challenges regarding different aspects of integration of large-scale wind generation units into the electricity network. Wind turbine generators often operate at low voltage levels (below 1000V) and they are often equipped with step-up transformers to increase the voltage level to medium levels (30-40 kV). Wind turbine transformers regularly face various electrical problems that can lead to their failure. Some of the possible causes include, but not limited to, ferro-resonances/resonances, switching surges, incorrect transformer specification, manufacturing defects, incorrect (lack) of earthing, unearthed core, open circuit current transformers, loose medium voltage (MV) connections and incorrect termination of MV cables.

II. Failure and Causes

Numerous wind farm padmount transformer and datacenter transformer failures have been reported in literature [2]-[6]. Wind turbine transformers have a specific design in comparison to conventional distribution transformers, as explained in [7]. Wind farm transformers have the same function as conventional transformers in that they step-up the voltage level from the generator. However, voltage and load fluctuations are considerably higher in wind turbine transformers, compared to solar farm or distribution transformers, thus, there is considerable stress on the transformers. These transformers can experience various conditions such as gassing, harmonics, transients, and switching surges; and mechanical problems such as vibrations and insulation failures.

The transformer failures that occur to the wind farm padmount transformers and datacenter transformers are reported to occur with other types of medium-voltage transformers as well. The failures include stress on insulation and insulation breakdown which are reported in [2],[4],[5],[8],[9],[10]; and damage to the switchgear which is predicted to occur in [8]. Additionally, the potential for power quality problems and protective relay mis-operations are discussed in [11],[12]. The following is a discussion of several of significant and common failure mechanisms.

Switching events are one of the main reasons for medium-voltage transformers to fail due to the fast transients they create. These switching events occur when the circuit breaker is either closed or opened. When a circuit breaker is closed, and the transformer is energized, the system can experience prestrikes. According to [11] and [12], during the closing operation, an arc occurs across the circuit breaker contacts just prior to them closing leading to a sudden high-amplitude inrush current and transient overvoltage (TOV). Similarly, when the circuit breaker is opened, restrikes can happen. An example of speculation of this phenomenon is reported in [8]. When the contacts are opened, there may be an arc across the contacts and this can happen many times, generating multiple re-ignitions. If the arc across the contacts is unstable and the arc collapses, the current flowing across the contacts will be interrupted before it goes through its zero point. This sudden change in the current is known as current chopping. As discussed in [13], a transient recovery voltage (TRV) results from the arc until current chopping occurs or current crosses the zero point. Both phenomena; prestrike and restrike, lead to high-frequency content and fast voltage transients in the system.

The failures, including insulation breakdown, are results of these transients. If the oscillations of the transients are at a natural frequency of the transformer, resonance occurs. This is an unwanted occurrence that is described as dangerous to transformers in [9], [18]. In [14], it is stated that resonance can cause excessive voltages to arise; thus, leading to dielectric failure and excessive stress on the equipment. As discussed in [2], the faster the rise time, the more damage that will occur to the insulation. The authors in [12] discuss that, even if surge arresters are in place, the high-amplitude voltages may exceed the capabilities of the protective equipment and expose the equipment to the dangerous frequencies and voltages. The authors in [18] also suggest that the surge arresters cannot protect the transformer, stating that the voltage rise is internal to the transformer windings only during this phenomenon.

Several factors contribute to the likelihood and the severity of the transients during switching events. These factors include the cable length between the circuit breaker and the transformer, the internal medium of the circuit breaker, and the loading on the transformer.

In terms of the length of the cable, short cable length between the circuit breaker and the transformer is a contributing factor in transformer failures upon switching. This has been discussed and explained in [8],[10],[15]. According to [19], the transferred resonance overvoltage (to the LV side) occurs when the cable quarterwave frequency and one of resonant frequencies of transformer match; and when the transformer input impedance is higher than cable surge impedance at resonant frequency. The authors of [15] indicate that the switching transients can be amplified by shorter cables. In a test scenario, transformers with short cables failed, whereas transformers with longer cables did not. It is concluded in [10] that, a longer cable, between the circuit breaker and the transformer, decreases the frequency and the voltage amplitude, whereas a short cable, or no cable, drives the voltage amplitude up and induces a restrike current. In [8], the short cable length is identified as the key contributing factor to the potential transformer failure at a large data centre. In addition, the internal medium of the circuit breaker at this station is vacuum circuit breakers which can also contribute to more transformer failures as opposed to SF6 breakers.

Vacuum circuit breakers (VCBs) are known to produce transients during switching events because of the short distance between the contacts, as discussed in [6],[9],[13],[16]. In comparison to air and SF6 gas, [13] has discussed how a vacuum medium has a higher dielectric strength and this is what shortens the distance between the contacts. The shorter distance is what leads to current chopping and the voltage transients in the system. The authors of [6] further explain and discuss this phenomenon. There are two scenarios when VCBs increase the likelihood of elevated voltages occurring; when a VCB opens and when it closes. If the transient recovery voltage, exceeds the VCB's dielectric strength, the current can restrike; thus, causing high-frequency oscillations. When the VCB closes, this may result in prestrike, with similar consequential damaging transients. The study conducted in [9] indicates that the influence of the circuit breaker contact material is additionally indicative of the result of the study. It also concludes that the presence of VCBs lead to multiple re-ignitions when an unloaded transformer is switched off.

The energization of unloaded transformers has been reported as one of the contributing factors to enhancing overvoltages and transients in [2],[8],[9],[14]. According to [8], this is the worst-case scenario for damaging resonance to occur. The authors of [14] further examine this stating that when the unloaded side of the transformer is the low-voltage side, that is where high overvoltages can occur due to transients. In [2], two models were run, energizing a transformer during no-load, and disconnecting a transformer during no-load. During the first test, transients, that had a high rate of rise occurred, leading to overvoltages, which were further amplified by short cables and VCBs. During the second test, if a restrike developed after the current interruption, overvoltages arose. VCBs feed into the likelihood of an arc occurring and lasting; thus, leading to multiple re-ignitions which exponentially increase the overvoltage until the re-ignitions cease.

Transformer and circuit characteristics additionally impact the behaviour of transformers under transients. The authors in [13] recognize that switching transients are closely related to circuit characteristics. In [6], the importance of the correct basic insulation level (BIL) and insulating liquid is discussed. A transformer's effective BIL is the highest right after it is manufactured. The BIL degrades over time by repeated transient activity, even if the magnitudes of the encountered voltage transients are below the BIL rating. The author also recognizes the characteristics of the transformer, including the differences in transformer design that may affect the frequency response, the differences in standard BIL ratings, the capacitance of the insulating liquid, or even the different habits/applications in facilities, as some of the factors that may contribute to the issues observed in some transformers.

III. Mitigation

These failures are avoidable with the use of several mitigation technologies and solutions. In [5],[6],[13],[16],[17], snubbers are installed and/or discussed. According to [17], snubbers are passive electrical devices that consist of a resistor and a capacitor in series. Snubbers are designed to protect medium-voltage transformers from transients specifically during circuit breaker switching. They work by reducing the high-frequency components of the transient so that they do not match the natural frequency of the transformer; thus, eliminating the risk of resonance. The report in [16] presents that, to design an RC snubber for a given system, the selected values of resistance and capacitance are best determined by a switching transient analysis study. This is done by simulating the circuit effects with and without the snubber. In [13], snubbers are used as an effective mitigation device. The authors in [5] explain that snubbers lower both the amplitude and the rate of rise of the transient overvoltages. As discussed in [6], the snubber can be placed directly next to the VCB and the transformer primary terminals to provide the necessary protection. The snubber acts as a filter to remove the high-frequency content. Additionally, [6] discusses some potential drawbacks of snubbers including the cost, the equipment footprint, the additional heating, and the new potential points of failure.

As addressed in [5],[6],[9],[16], surge arresters and surge capacitors provide protection by reducing the peak of the transient voltage. However, as discussed in [5],[16], a surge arrester only provides basic overvoltage protection since it only limits the peak voltage of the transient voltage waveform and it does not limit the rate of rise of the transient overvoltages, which is dissimilar to snubbers. Additionally, [9] acknowledges that surge arrestors fail to provide protection against the high-frequency components that lead to resonance. A surge capacitor in combination with a surge arrester further aids in limiting the transient overvoltage, but nevertheless, it is not full protection. Therefore, the authors of [8] have concluded that the maximum surge protection is provided by a combination of a snubber with a surge arrester. In this paper, the effectiveness of the application of snubbers with surge arresters has been verified via high-speed switching transient measurements on transformer windings. Additionally, the authors of [16] further explain the mitigation technique, that includes a combination of surge arresters and snubbers, concerning a ladle melt furnace application. The paper shows the successful protection against switching transients, and some practical aspects of the design and installation of the snubbers are presented.

As mentioned in Section II, [2],[8],[9] and [14] discuss that energization of unloaded transformers is a contributing factor to the overvoltages and transients. If it is possible to reconfigure heating loads within the Wind Turbine Generators (WTGs) so that they are energized upon transformer energization, it may be possible to reduce the negative effect of unloaded transformers.

It has been noted in [11] that controlled switching can help with the reduction of high inrush currents, dangerous switching overvoltages, and equipment failures. Controlled switching has been defined as controlling the point of conduction of each pole of the breaker with respect to the phase angle of the voltage. Additionally, in [12] it is concluded that controlling the phase angle of the voltage can reduce the inrush currents.

Several other mitigation techniques are available to prevent medium voltage transformers from failing due to transients. In [9], it is mentioned that "long-term high-frequency measurements of current and voltages" on the transformer can help identify the cause of insulation failure. It is reported in [13] that the transformer-winding design and series inductors are some of the methods to reduce switching transients. The authors of [14] recommend using a black-box method that can provide an accurate model of the cable-transformer resonance overvoltage. Different construction methods (i.e. stacked core) can lower the potential amount of internal overvoltage. Likewise, adding more insulation could help prevent failures. The study in [15] recommends the use of Sweep Frequency Response Analysis (SFRA) testing and transient simulation analysis for determining the internal resonance condition of the system. Lastly, [7] suggests harmonics studies to address overvoltage and power quality issues.

IV. Case Study

Hatch was retained by a client to assist in the investigation of the transformer failures at a wind farm in the US. Various padmount transformer failures were reported at different time frames after feeder energization. These failures occurred immediately after energization, within a few hours or within up to a few days after energization. Several feeder energizations and breaker openings occur during the commissioning process. The number of switching operations is further increased when transformer failures occur. It is believed that some transformers failed upon breaker closing, and others failed upon breaker opening, but were not discovered as failed until the feeder was re-energized.

Energization of the feeder involved switching-in the upstream circuit breaker with all padmount transformers connected with no-load conditions. Since wind turbine start-up happens with a delay after the transformer energization, at the time of energization of the feeder all wind turbines are isolated by the turbine main breaker at the base of the wind turbine. Traces of insulation breakdown both on LV and HV winding of the transformers were reported. Oil samples from damaged transformers were taken and dark colours were observed. Upon being engaged by the client, Hatch started developing the wind farm model in PSCAD including all details of the system from main power transformers to wind turbine units. The frequency-dependent line model in PSCAD was used to model the underground cables since it provides more accurate results compared to Bergeron and Pi section components, as it represents full frequency-dependence of the cables.

Various simulation cases were developed to investigate different phenomena that can contribute to these failures, including resonance, switching transients, inefficient grounding, circuit breaker pre-strike, etc. The PSCAD model was used to identify the resonance frequencies of the system by performing a harmonic scan. Depending on the number of feeders connected to the main transformer (from 1 to 8), a resonance frequency range of 600-1600 Hz was observed, as shown in Figure 1.

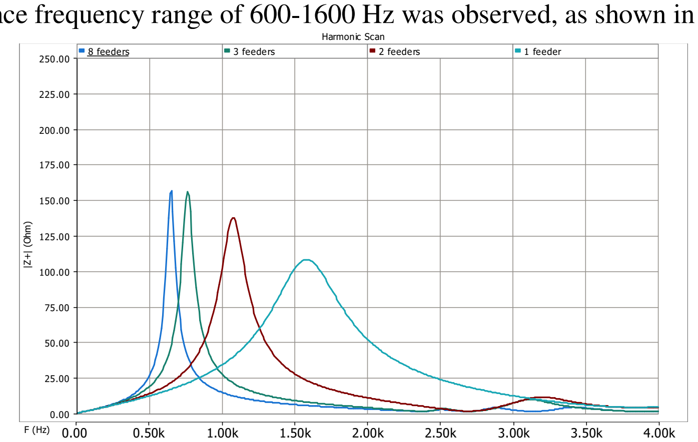

Figure 1 Frequency Scan of the Wind Farm Collector System

The results of Special SFRA on the padmount transformer units used in the wind farm also identified a resonance at 1000 Hz. This, in turn, increases the possibility of resonance issue being a contributing factor in transformer failures, especially because the wind farm itself has relatively shorter collector cables compared to other wind farms using the same padmount transformer design and specifications, and shorter cables between transformers and feeder circuit breaker are known to be one of the key contributing factors to such failures.

Various mitigation techniques discussed in the literature are investigated in this case to evaluate the impact of each case:

i. Energizing the transformers independently by use of a load break switch

It is common in a wind farm design to have an internal MV oil switch referred to as a Load Break Switch to allow isolation of the transformer while the operation of downstream wind turbines is continued. In this case, instead of energizing the whole feeder with all the padmount transformers connected, the transformers are energized in a sequence one by one after the feeder cables are energized, by using the load break switch. Following all arc flash and safety procedures is very important when transformers are being energized by a load break switch. Figure 2 shows the current and voltage waveform for energization of a transformer after the feeder has been energized before. The voltage transient is already dissipated in the feeder cables and the transformer does not see those transients upon closing of the load break switch.

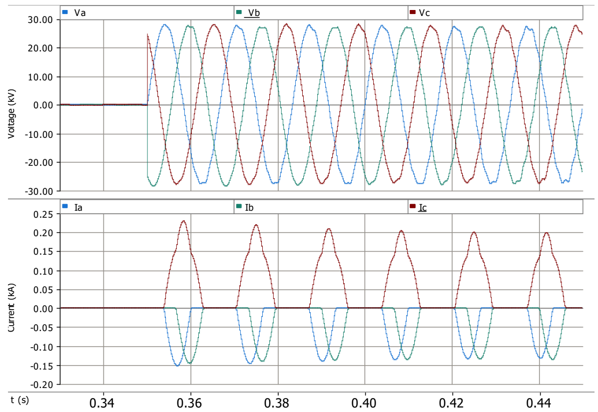

Figure 2 Voltage and Current Waveforms of an Energized Transformer

ii. Using R-C Snubber Circuits

Snubbers help to reduce the magnitude and frequency of a transformer transient terminal voltage. Resistance values are often within the ranges of 5-50 ohm and the capacitance value is within the range of 0.1 to 0.5 uF. The location of installation of the snubber circuit has been studied in this case. Once a snubber circuit is placed at each transformer terminal and in a second case only one snubber circuit is placed at the feeder circuit breaker terminals. Figure 3 shows the voltage waveform for the cases with no snubber circuits, one snubber at circuit breaker location and one snubber per each transformer. As it can be seen, the voltage transients are reduced significantly for the case with snubber circuits at each transformer location.

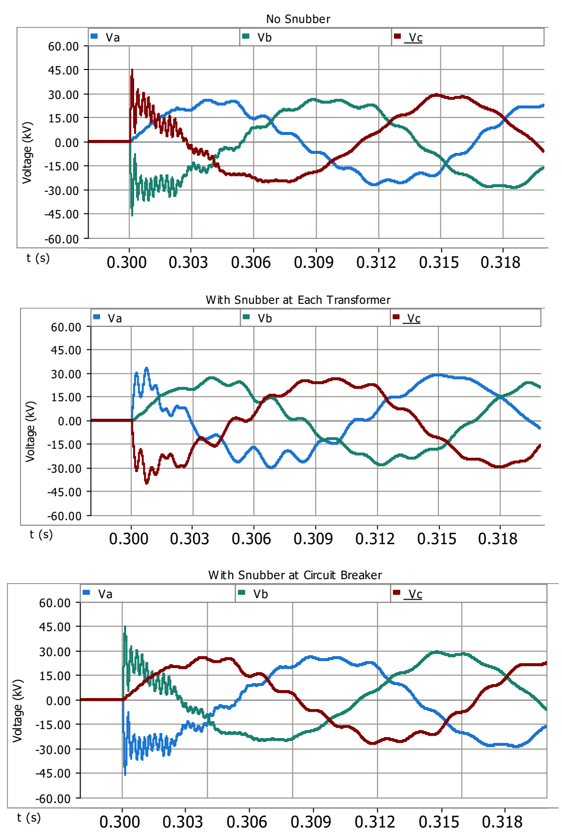

Figure 3 Impact of Installation of RC Snubber Circuits on Voltage Transients at Transformer Terminals

iii. Point-on-wave switching:

Depending on the point on the voltage waveform were the switching happens, the overvoltage and inrush current magnitudes can vary. The feeder switch-in time has changed from the beginning of a cycle up to a half cycle in 6 steps (1.38 milliseconds time steps). As it can be seen from Figure 4, the magnitude of inrush current changes significantly by varying the switching time. Respectively, the harmonic content of the transient voltage across transformer terminals decreases noticeably.

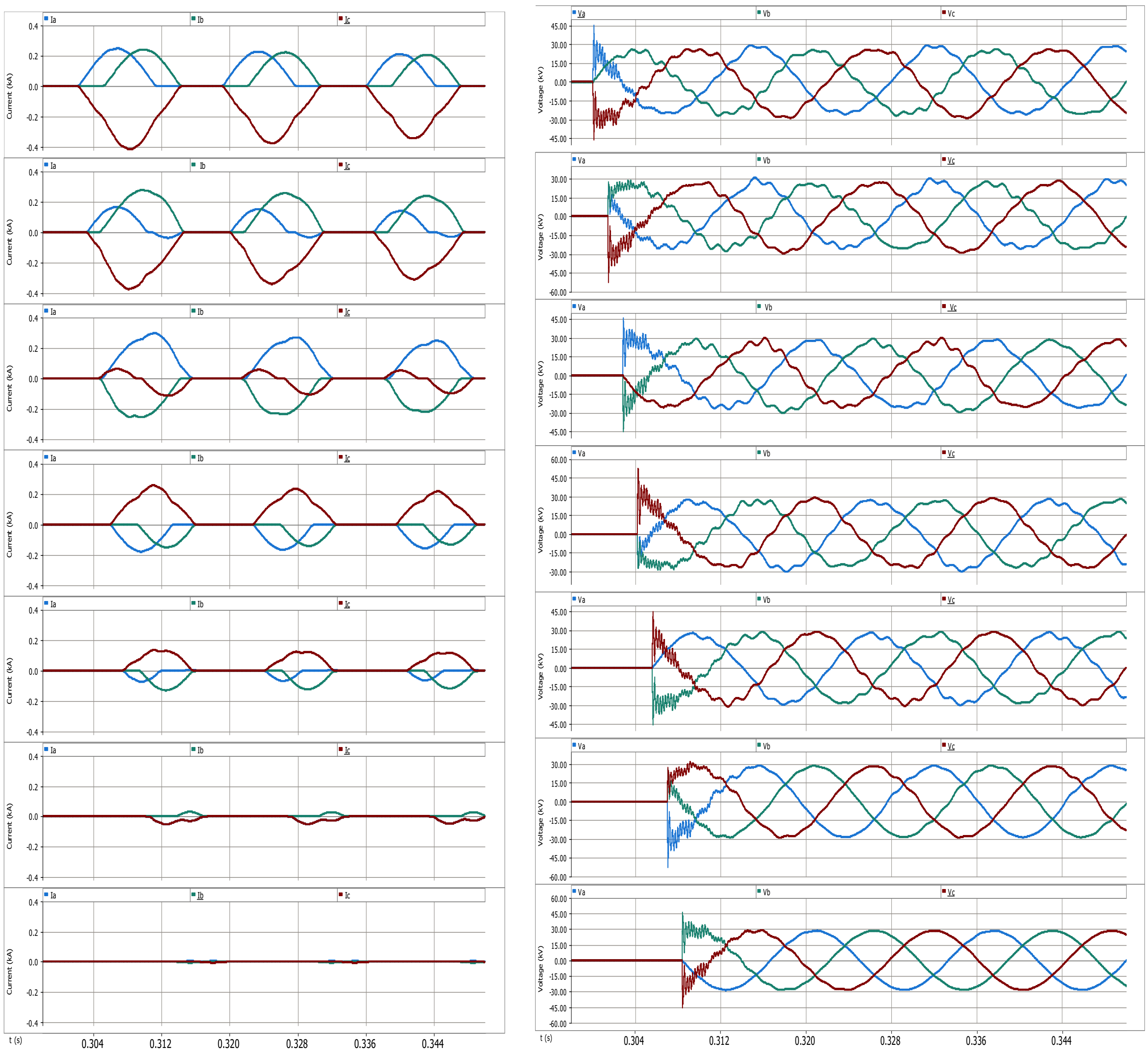

Figure 4 Transformer Inrush Current for Various Switching Points and Transient Voltage at Transformer Terminals for Various Switching Points

V. Conclusion

Transformer failure is a frequent issue for wind farms and other medium voltage systems. The failures include insulation breakdown, damage to the switchgear, power quality problems, and relay mis-operations. Several studies have indicated the causes include switching transients, which are amplified by short cables, vacuum circuit breakers, and no-load conditions, as well as the transformer and circuit characteristics. The likelihood of failure can be mitigated by installing surge arresters or surge capacitors in combination with snubbers, controlled switching, improvement or changes to the transformer and several system study methods. Hatch was retained to investigate transformer failures at a wind farm in Texas, US which were occurring after energization of the system at no-load conditions. It was observed that there was insulation breakdown, resonance, and short cables. The wind farm model was developed in PSCAD and several mitigation techniques were simulated including RC snubbers, point-of-wave switching, and energizing the transformer independently using a load break switch. The graphs in the report show that these mitigation techniques successfully lower the transients at the transformers to prevent failure.

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