

Modeling and Simulation of Insulation Defects in High Voltage Transmission Lines: Case Study of Onitsha-New Haven 330kv Line

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This thesis is on the modeling and simulation of insulation defects in High Voltage Transmission Lines. The New Haven-Onitsha 330kV transmission line is the case study network. The exposed nature of overhead power lines makes overhead power transmission lines very vulnerable to various kinds of faults. Insulation-related faults contribute reasonably to the number of faults experienced in overhead transmission lines. These faults cause outages in the network and reduce the availability of the transmission lines. Poor transmission line availability means long and frequent outages which imply that industrial and domestic consumers will have to run standby generators for longer times to sustain production and power-dependent domestic activities. Considering that insulation-related faults constitute over 15% of all faults in transmission lines, one viable way of enhancing the availability of transmission lines is by minimizing insulation-related faults. This can be achieved by developing a system that can detect insulation defects in transmission lines. By eliminating these defects before they mature into faults, the transmission line would have been protected from outage thereby enhancing its availability. Having established in the literature that insulation defect in transmission lines is characterized by the presence of partial discharge current pulse; this work was then targeted at modeling and simulation an electrical system that can generate partial discharge and introduce it into the case study transmission line to make work on its detection and elimination fruitful. The three-capacitor-based partial discharge current pulse generator model was adopted for this research. A mathematical design was first done to compute the values of the series and parallel capacitors. The designed model was then implemented in Simulink/MATLAB. The developed model was then connected to a Simulink model of the case study network and then simulated to determine if the implemented model can introduce insulation defect (partial discharge into the test transmission line. Simulation results revealed that as soon as the control breaker opened once at 0.84 seconds, a partial discharge current pulse of amplitude, 5mA was introduced into the case study transmission line.

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ABSTRACT

Keywords: Transmission Lines, Simulation, Insulation Defects, Three-Capacitor-Based

Introduction

Transmission lines are designed and constructed for safety, stability and to withstand remote, long, vast and difficult terrains during the transportation of energy. Transmission lines are expected to be continuously available, thereby operating maximally, securely, reliably, and uninterrupted. However, the components of transmission lines are exposed to factors that disrupt the flow of electricity, including humidity, wind, rain, pollution, rust/corrosion, extreme temperature, atmospheric discharge, floods, landslides, uncontrolled vegetation growth in active areas, and human vandals, etc. (Himani and Ashish, 2014).

The above-listed factors are the leading causes of insulation breakdown and flashovers on the insulators in our transmission lines. Unfortunately, insulation-related faults contribute a reasonable percentage of faults in overhead transmission lines. One key way of improving the availability of overhead transmission lines is by reducing the number of outages relating to faults and their corrective maintenance. Insulation-related faults in power transmission lines can be minimized by detecting insulation defects in the power line insulators before they mature to flashover faults in the lines. Partial discharge is an indicator of defects in insulation. Partial discharges are known to result when cracks, voids, or pollution occur in insulators installed in overhead power transmission lines. If these discharges are detected and located, the defaulting insulators can either be fixed or changed before the partial discharge progresses to insulation breakdown, flashover, and faults in the line.

Partial discharge (PD) is defined as a localized electrical release of charges capable of partially bridging the insulation between conductors and the ground. PD is caused by local electrical pressure on the insulator or its surface. In a transmission line, PD is propagated as a low amplitude and high-frequency current pulse of short duration. Its amplitude ranges in mA while its frequency can come up to 10kHz to a few MHz. The duration of the pulse is in the range of 1 microsecond or less (Gunawardana, et al 2015). The above properties of PD added to corona noise interferences from the surroundings make it a bit difficult to detect the presence of PD in overhead transmission lines.

2. Literature Review

Partial Discharge as a Manifestation of Insulation Defect in Power Networks

As mentioned earlier, insulation quality plays a major role in the power network, and in fact, one of the daunting problems in high voltage power systems is insulation breakdown or its continuous degradation in the system. One of the outstanding issues that lead to a total collapse of the insulation is partial discharge (PD).

According to IEC 60270 (2000), a partial discharge is defined as “a localized electrical discharge that only partially bridges the insulation between conductors and which may or may not occur adjacent to a conductor” (Gianoglio, et al., 2021). In a wider sense, PDs are corollary of a local electrical stress concentration in the insulation or over the insulation. In general, PDs are characterized by short pulses with a duration not up to $1\mu s$. However, the severity of a deterioration spot producing partial discharge is not directly proportional to the discharge. It is proved that the extent of deterioration in a dielectric is a function of the energy squandered per unit volume of the dielectric rather than the energy dissipated in the discharge. It is therefore not feasible to evaluate the energy density from measurements obtained from the terminals of a high voltage component. This is one major inherent setback in using partial discharge measurement systems to forecast degradation rate or remaining life. Nevertheless, different types have unique characteristics and hence can be properly identified. Also, the degree of harmfulness and time to a breakdown of partial discharge is a function of the discharge type.

Causes of Partial Discharge

When, dielectric strength within a given location of the insulation of a power network device is locally exceeded, while the surrounding insulation is strong enough to resist total breakdown, the resultant effect is the occurrence of partial discharge. However, there are other causes of partial discharge which depend upon the type of partial discharge. It is probably safe to classify partial discharge into four different types with regard to the location of the discharge and its properties. These types are internal discharge, surface discharge or external discharge, corona, and electric treeing. Internal discharge occurs inside the insulation in a gas-filled cavity when the voltage stress in the

cavity exceeds the breakdown voltage. Surface discharge occurs at the interface between solid insulation and air. And it is caused by the creation of a strong electric field around irregular or sharp points at the end of each potential gradient; which ionizes the surrounding air and hence making it conductive. This brews some partial discharge in this region. Corona discharge occurs around sharp edges in the interface between metal and air. In a high voltage transmission line, corona discharge usually takes place at the metallic contacts at the cable ends. Electrical treeing occurs inside the insulation. As the name suggests, tree-like channels are formed inside the insulation. It is in many cases the final step towards an eventual breakdown of the insulation.

Effect of Partial Discharge on Power System Operation and Protection

Partial discharge has been identified as a symptom of a problem in a power network. However, by its very nature, it is harmful to the operation and protection of the network (Gianoglio, et al., 2021). Some of its effects are enumerated below:

- I. It causes deterioration of the insulation of the conductor by introducing puncture on the insulation.
- II. It causes corrosion in the aluminum conductor thereby forcing it to wear out.
- III. It poses a dangerous threat to personnel by allowing leakages in deadlines like insulator-supported lead in a transformer.
- IV. It disturbs the radio/TV signal in the nearby network thereby affecting the operations of communication equipment in the sub-stations.
- V. It produces light and noise, and sometimes a noisome smell.
- VI. Corona discharge comes with the formation of ozone which is highly toxic.

Partial Discharge Propagation in Transmission Line

Partial discharge pulse propagation in the cable distribution network sets limitations on partial discharge measurement systems. Partial discharge pulses diminish, disperse and reflect on propagating in the cable system. The propagation constant is a function of frequency that initiates distortion in partial discharge pulse shape.

The partial discharge pulse divides in half at the discharge location and begins to move bi-directionally in the cable. The discharge pulses that are induced in cables are broadband signals with frequency content in a range of 10 kHz – 1 GHz. A Cable acts as a low pass filter for the partial discharge signal and by implication only lower Frequencies (below 10 MHz) of the signal can be detected after some length (about 1km) of traveling in the cable (Ossi, 2011).

The propagation of partial discharge pulses has to be conceived and treated as a traveling wave problem due to the short duration of the pulses (10^{-9} – 10^{-6} s) and the long electrical length of the cable network (10^{-2} – 10^{-5} m). The implication of this is that the resistances, inductances, conductances, and capacitances have to be considered as distributed along the length of the cable (that is they cannot be lumped). How a power cable was constructed has a large influence on how partial discharge pulses propagate in it. There are usually at least two semiconducting layers. One on top of the conductor is called the conductor screen and the other on top of the insulation is called the insulation screen. These layers have a great impact on partial discharge pulse attenuation (Ossi, 2011).

As mentioned earlier, it is desirable to discover the origin of a partial discharge using its characteristics. Thus, Werle, et al. (2001) in a laboratory setting, applied different neural classifiers trained by sectional winding transfer functions (SWTFs) of transformer coils to determine the apparent charge and an adequate localization of the PD origin. The performance and the reproducibility of this method lead to a short outlook on planned investigations and the possibilities for integrating this technique in online condition monitoring systems. Likewise, Ossi (2012) sought to bring out the main principles of on-line partial discharge measurements and the current situation in the case of extruded medium voltage cables. In addition, aging and other phenomena leading to faults and partial discharges related to these phenomena in extruded medium voltage cables have been studied. Also, guidelines about how on-line partial discharge measurements could be used as part of condition monitoring of medium voltage cables have been created. The researcher mainly used a literature survey and the source material mainly consists of international publications. The researcher found that Cable joints and terminations seem to be the most fault-prone components

in the medium voltage cable network and in most cases partial discharges can be spotted before the breakdown. It is also noted that the quality of workmanship in the installation of cable accessories plays an important role while the reliability of these components is concerned. This work concludes that on-line partial discharge measurements are the most suitable for detecting problems in the cable joints, terminations, or metallic shields.

Imene et al. (2018) elaborated upon a previously developed software condition-monitoring model for improved EMI events classification based on time-frequency signal decomposition and entropy features. The researchers sought to develop a method to map multiple discharge source signals captured by EMI and labeled by experts, including PD, from the time domain to a feature space, which aids in the interpretation of subsequent fault information. Instead of using only one permutation entropy measure, a more robust measure, called Dispersion Entropy (DE), was added to the feature vector. Multi-Class Support Vector Machine (MCSVM) methods were utilized for the classification of the different discharge sources. Results show an improved classification accuracy compared to previously proposed methods.

Ahmed (2013) utilized an adaptive wavelet-based technique to handle large volumes of data and built a relationship between the monitored data and the equipment's electrical insulation level. The proposed technique can detect the early stages of Partial Discharge (PD) activities embedded in high noise and extract pulse shape PDs using a manageable data set that can be handled by Wireless Sensor Networks (WSNs). The proposed technique was investigated using laboratory and field data sets that were captured by non-intrusive high-frequency currents transformers and acoustic emission (AE) sensors to accommodate aging and operation stress and gave somewhat positive results in monitoring the early stages of PD activities.

Jiayang et al., (n.d) deployed a partial discharge (PD) measuring system to identify and measure PD in a high voltage (HV) cable joint under the impulse and superimposed voltages under laboratory conditions. The challenge is to enable the detection of PD during impulse conditions. The method of measurement was investigated by introducing an artificial defect in the cable joint in a controlled way to create conditions for partial discharges to occur. Next, the HV cable system was subjected to AC, impulse, and superimposed voltage. Two high-frequency current transformers (HFCT) installed at both ends of the cable joint were used to identify PD from the cable joint and to separate PD from disturbance. PD signals were separated from transient disturbances during data post-processing and employing pulse polarity analysis. The developed system enables the detection of so-called main and reverses discharges respectively occurring during the rise and tail time of the superimposed impulse. The measurement results obtained were promising for the presented PD measuring system for investigating the effects of voltage transients on an HV cable system in laboratory conditions

Hamed (2016) proposed a technique for the design, development, and testing of a comprehensive and automated classification system for single and multiple partial discharge (PD) source identifications based on the relationship between the variation of phase-resolved partial discharge (PRPD) patterns and the sources of PD. To present a comprehensive classification system, 10 well-known algorithms for the classification of PD sources were used. To evaluate the performance of the classification system, three laboratory test setups were designed and built to simulate various types of PD activities. To further enhance the proposed classification system, a novel algorithm to identify Multi-source PDs was developed and appended to the system. The overall results show that the classification system can identify the single and multi-source of partial discharges. More so, this identification system can assign a degree of membership" to each PRPD pattern, besides assigning a class label to it. This enables probabilistic interpretation of a new PRPD pattern that is being classified and results in safer decision-making based on the risk associated with different sources of PD.

Narong et al. (2009) presented the methods to mitigate PD on Partially insulated cable (PIC) in a distribution line system. The area located near a coast was selected as the pilot project because it tended to strong occurrence of PD which is mainly caused by salt contamination. The methods applied consist of using tie wires made from an insulation sheath of low voltage cable, the sheath of PIC itself; composite tie wire, and aluminum tie wire (reverse loop binding). Following the trial results, two methods were considered the most effective ways for PD solving; binding PIC by using the PIC's insulation sheath and the composite tie wire instead of aluminum tie wire (conventional binding).

Longfei (2014) proposed a new method to detect PD signals using a fiber Bragg grating (FBG) based PD sensor. By using a piezoelectric ceramic transducer (PZT), small PD signals can be converted to pressure signals and then converted to an optical wavelength signal with FBG. The optical signal is isolated from the electric field, and they observed that its attenuation and anti-jamming performance will be better than traditional methods. Two sensors, one with a resonant frequency of 42.7 kHz and the other at 300 kHz, were used to explore the performance of this testing system. There were issues with the sensitivity of the sensors of these devices that they used. The result they got deviated negatively from the accuracy of the conventional methods.

Tarek et al (2016) discussed different types of discharges and different factors that affect the nature of these discharges. In addition, an analysis of the PD modeling and frequency dependence of PD was elaborated and the effect of sometime constants on PD magnitude and the number of PDs per cycle was discussed. In addition, a developed model was established to study the effect of applying higher frequency on the behavior of PDs. The magnitude of the frequency of the applied voltage was studied as well as cavity size and location in the dielectric. The model can be used to study samples of different types of dielectrics and complete high voltage equipment can be investigated.

Gunawardana (2015) simulated partial discharge with a void inside an insulation medium. A detailed description of a simulation done with the MATLAB Simulink package, of the measurement of partial discharges was presented. Further, a calibrator for the measuring equipment was designed and integrated into the circuit. The linearity of the measuring system was confirmed using the calibrator. The model developed was validated using a cylindrical void inside an epoxy resin insulator. Results obtained show a close similarity with results obtained by other researchers. Antonella et al (n.d) present the first stage of a research activity that aims to develop a transmission-line matrix (TLM)-based simulation “workbench” useful to investigate PD events in a transmission line. The proposed approach allows the predicting of the electromagnetic disturbances generated by the PD event, and the analysis of external field coupling, such as from intentional electromagnetic interference or lightning, which can add to the field stresses. The paper focused on defining the right modeling method to simulate PD phenomena in a transmission line context. The best approach to integrate the PD model with the model of the transmission line, useful to describe the propagation of the conducted and radiated emissions produced by PD, was analyzed. A first workbench was proposed, and the first simulation results were described. The paper concludes with the topics of further research.

Ondřej et al. (2021) showed the PSA simulations and PD analyses performed at AC and partly at DC test conditions on typical PD test arrangements such as corona, surface, and internal discharges. It is shown that the simulations performed, compared, and validated with data obtained from measurements on different PD arrangements are a good match. This fact points to the possibility of PD source recognition in DC, especially the time-resolved pulse sequence analysis.

3. Methodology

Model in Simulink a System that will Introduce Partial Discharge (Insulation Defect) in the Test Network

The strategy in this research is to detect insulation defects in transmission lines to fix the detected defect before it progresses to flashover faults with its attendant forced outages and reduced transmission line availability. Since the partial discharge is a key indicator of the presence of insulation defect, we must design and model a system that will introduce the partial discharge to be detected and located in the line for fault avoidance and network availability enhancement.

The Three Capacitor-Based Model of Partial Discharge

The three capacitor-based models of the partial discharge introduction system described in Gunawardana et al (2015) are adopted for this study. Gunawardana et al (2015) considered an insulator defect in which a cylindrical void exists in an insulator in a transmission line. The resultant capacitance created by the presence of this void is modeled as two series capacitors connected in parallel with another capacitor. The two series capacitor represents the capacitance of the void and the capacitance of the good insulator in series with the void. On the other hand, the parallel capacitor is used to represent the capacitance of the remaining parts of the insulator under test. The three

capacitor connection for the development of partial discharge is shown in figure 1. From the figure, C_c and C_b are the series capacitor while C_a is the parallel capacitor.

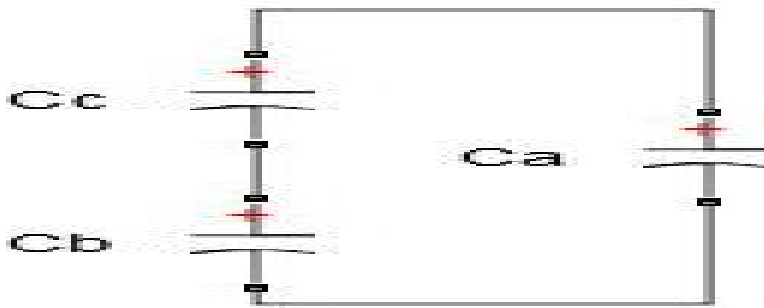


Figure 1: Three-Capacitor based connection for PD development
 Source: Gunawardana et al (2015)

Equivalent Circuit Model for Detection and Measurement of Developed Partial Discharge

Figure 2 shows an equivalent circuit model for the detection and measurement of developed partial discharge. The key components in the network include an AC voltage source, capacitors, a circuit breaker, and an impedance block (that is applied in the measurement of the magnitude of developed partial discharge). The maximum value of the 50Hz high voltage supply is 10kV. The inductor situated in the HV source functions as an open circuit for high-frequency PD pulses. The breaker simulates the breakdown of the air gap at the set time. The breaker is configured to close and open once during the simulation period. Hence, only one simulation period will be modeled for the purpose of simulation. On the introduction of a high voltage supply to the circuit model, the void gets charged and breakdown takes place bringing about the formation of partial discharge in the insulator.

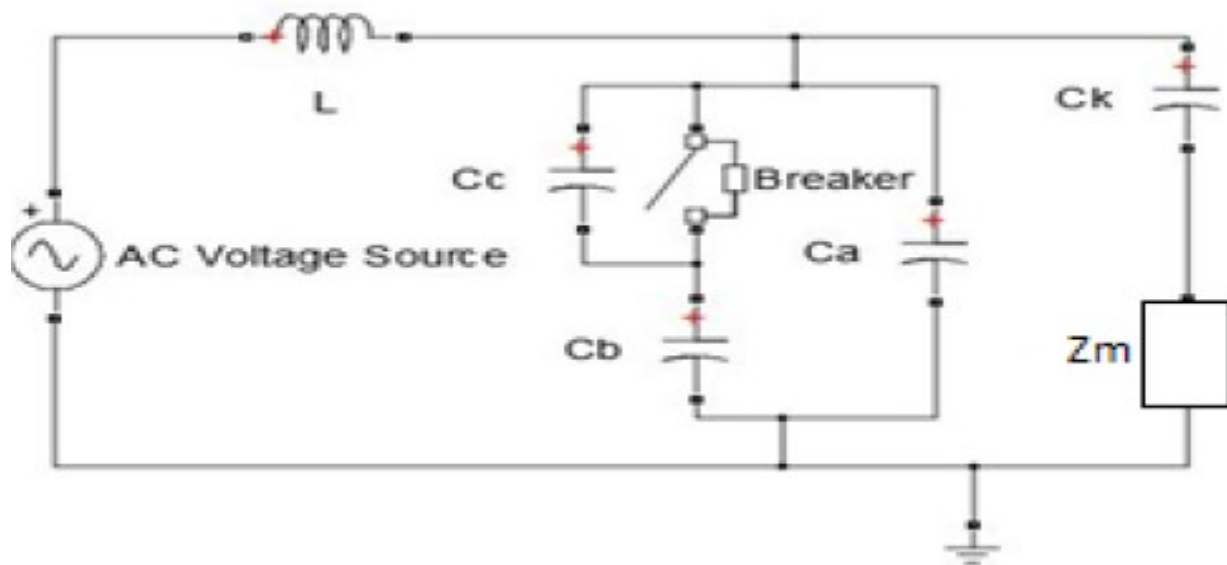


Figure 2: Partial Discharge Detection Circuit Model
 Source: Gunawardana et al., 2015

Design of the Partial Discharge Generation Circuit

Before the electrical model of the partial discharge, is implemented in Simulink/Matlab; the values of the circuit design in figure 2 need to be done. It is important to recall that the essence of implementing the electrical model of a partial discharge system is to help introduce partial discharge (insulation defect) in the transmission line. The design of the circuit in figure 2 involves mainly the determination of the value of the three capacitors used to model

the insulation defect that produces the partial discharge in question. The value of each of the capacitors of the insulator defect model can be determined using equations(1) to (3).

$$C_c = \frac{\epsilon_0 A_v}{d_v} (1)$$

$$C_b = \frac{\epsilon_0 \epsilon_r A}{d - d_v} (2)$$

$$C_a = \frac{\epsilon_0 \epsilon_r A}{d} (3)$$

Where:

C_c = Capacitance of the void

C_b = Capacitance of insulator in series with the void

C_a = Capacitance of insulator parallel with the void

ϵ_0 = Permittivity of free space

ϵ_r = Relative permittivity of the insulating material

d_v = Thickness of the void.

d = Thickness of the test material (insulator).

Taking ϵ_0 to have a value of 8.85×10^{-12} and ϵ_r to be 3.5 and using the void model proposed by Gunawardana et al., (2015) depicted in figure 2, the three capacitors can easily be computed to give the values of C_c , C_b and C_a as 0.278 μ F, 6.1952 μ F and 1.55 μ F respectively. With this, a convenient value for C_k can be chosen.

Implementation of the Partial Discharge Electrical Model in Simulink

Having obtained the values of the key components of the circuit to be implemented, the implementation of the circuit in figure 2 is then done. To achieve this, a new model space is first created in Simulink. From the Simscape library, all component blocks required (including capacitor, inductor, AC source, circuit breaker, LC branch, voltage, and current measurement units) are copied to the newly created model space. The components are then linked up to reflect the connections in figure 2. In the implemented model, Z_m is represented as an LC branch in parallel with an inductor. The values of inductors and capacitors used to implement Z_m were chosen to ensure that Z_m resonates at 50Hz. The Partial discharge generating model implemented in Simulink/Matlab is shown in figure 3. The implemented Simulink model of the partial discharge system is now ready to be connected to the test network for the introduction of partial discharge in the transmission line.

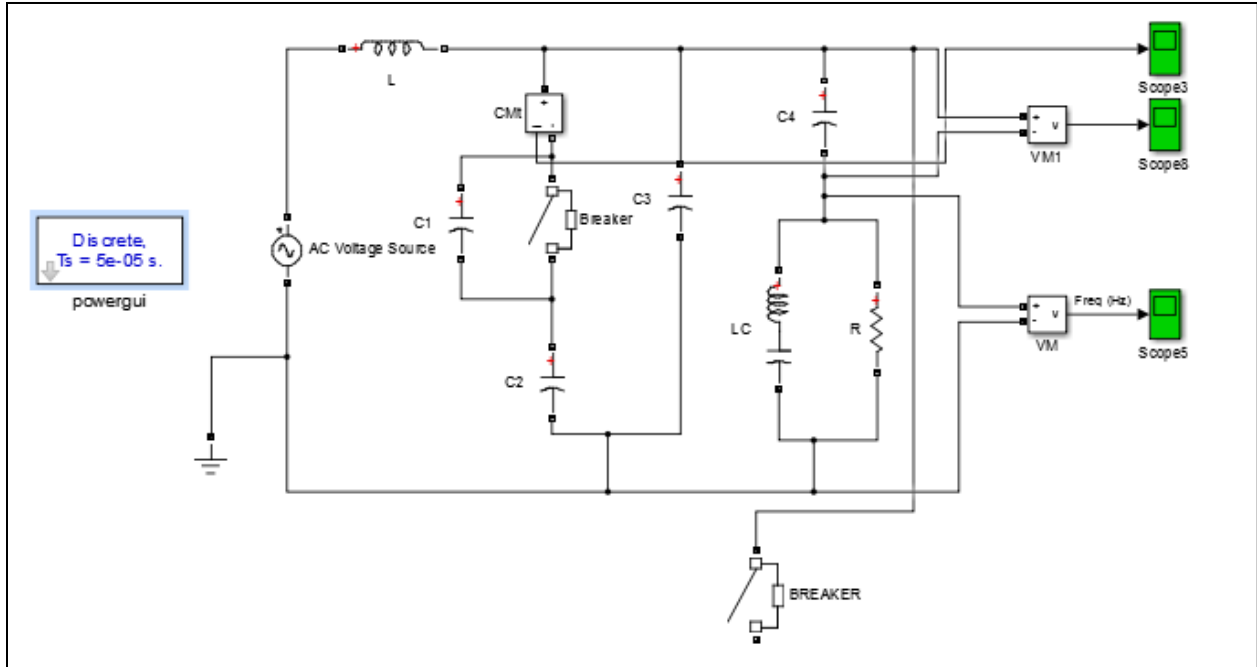


Figure 3: Simulink Model of the Partial Discharge Development Circuit

Connection of the Insulation Defect Generation Model to the ANN Controlled Insulation Defect Detection Scheme

With the adaptive PMU based insulation defect detection scheme in place, the next step is to connect the partial discharge (insulation defect) introduction model to the adaptive insulation defect detection scheme for simulation and performance evaluation.

The partial discharge (insulation defect) is introduced in the transmission line model by connecting current measurement unit sensing the partial discharge current pulse to the transmission line. The connection is done via a circuit breaker. The circuit breaker is configured to open and close once at the same time the partial discharge producing circuit allows partial discharge pulse to flow in the current measurement unit. On the introduction of the partial discharge current into the transmission line; the adaptive partial discharge (insulation defect) detection scheme is expected to detect the presence of the pulse current and show the distance from where the partial discharge is being produced with reference to the bus from where the detection is being made. Figure 4 presents the model of the insulation defect detection scheme and the insulation defect production model connected

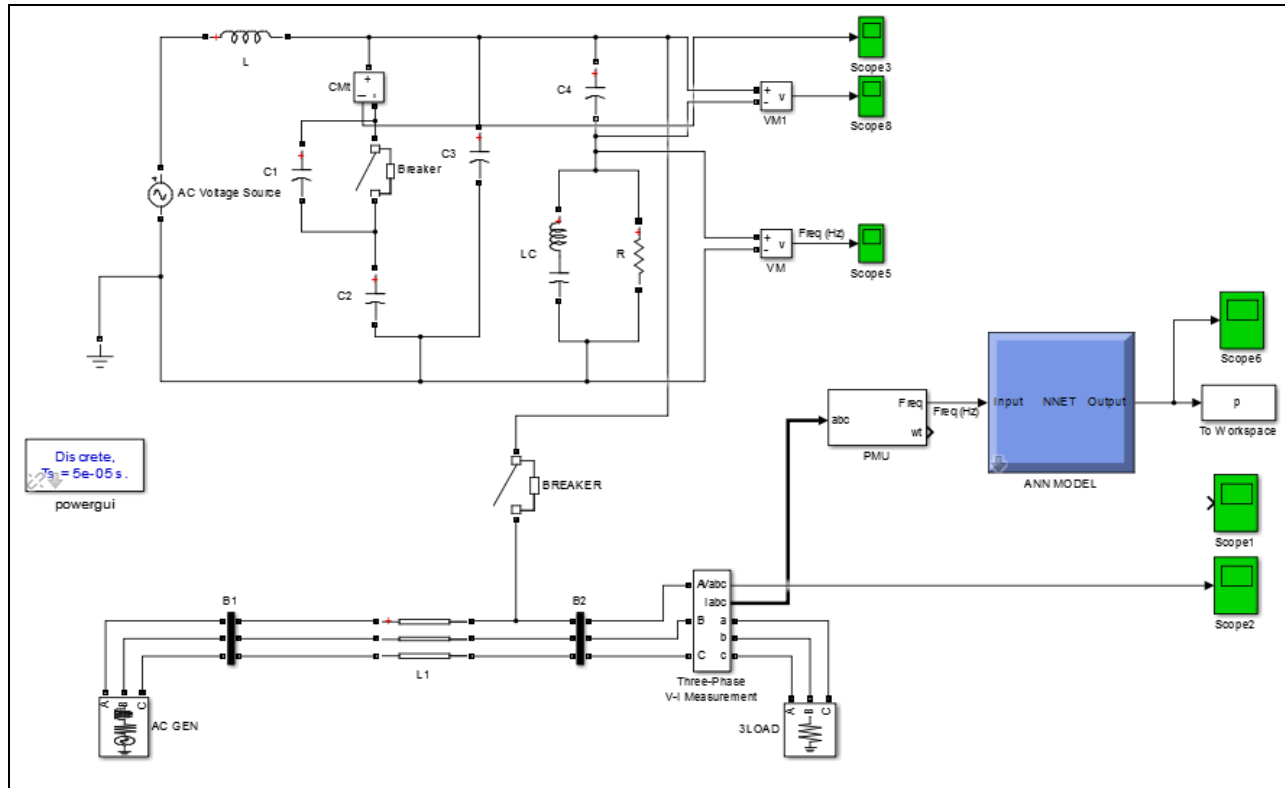


Figure 4: The insulation defect detection scheme and the insulation defect production model.

4. Results and Discussions on the Simulation of the Insulation Defect Generation Model

In this section, simulation results and discussions of the implemented insulation defect generation model will be presented to determine if it will effectively introduce insulation defects in the form of partial discharge into the test transmission lines.

Simulation Result of the Insulation Defect Generation Model

The role of the model in the research is to introduce insulation defects in form of partial discharge into the test network during simulation. Before connecting the model to the test network, the model was simulated to ensure that it generates a partial discharge current pulse (which confirms the presence of partial discharge) as expected. Figure 5 shows the waveform of the current signal obtained by simulating the model of figure 4 in which the breakers were operated at 0.84 seconds.

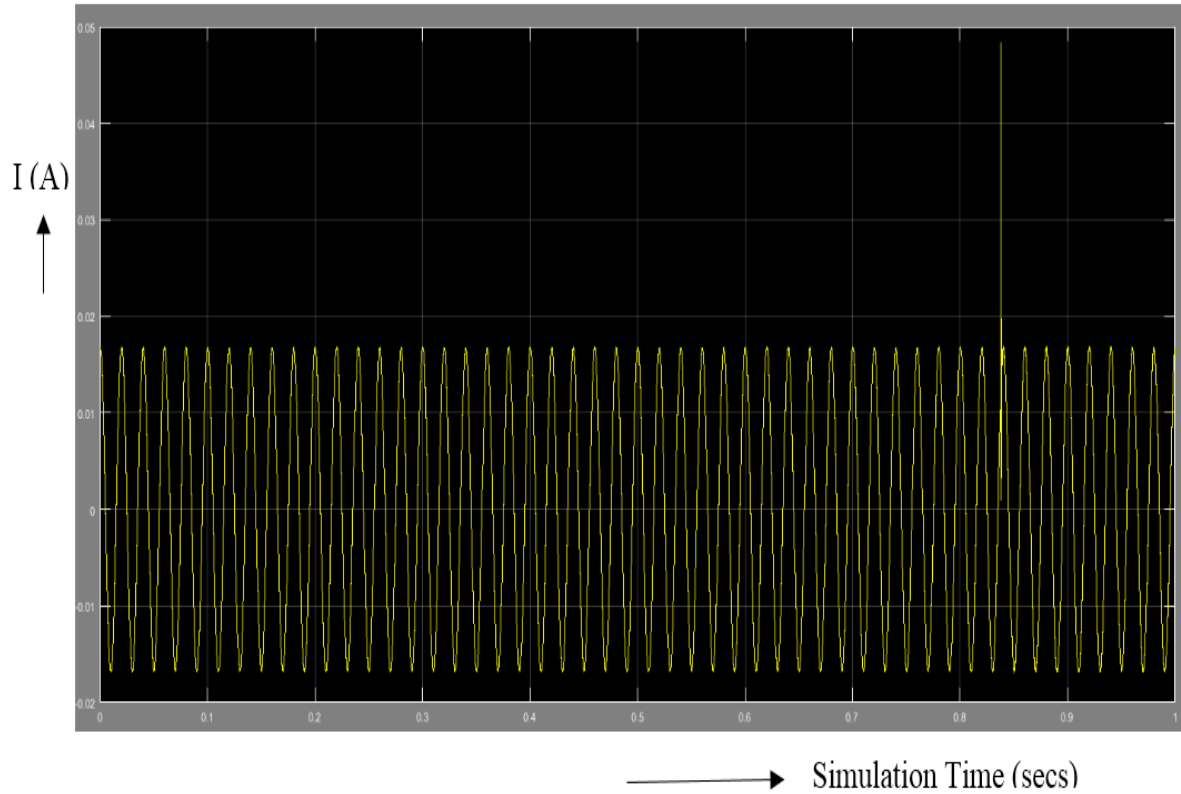


Figure 5: Current Signal Showing the Production of Partial Discharge Pulse Current During Simulation

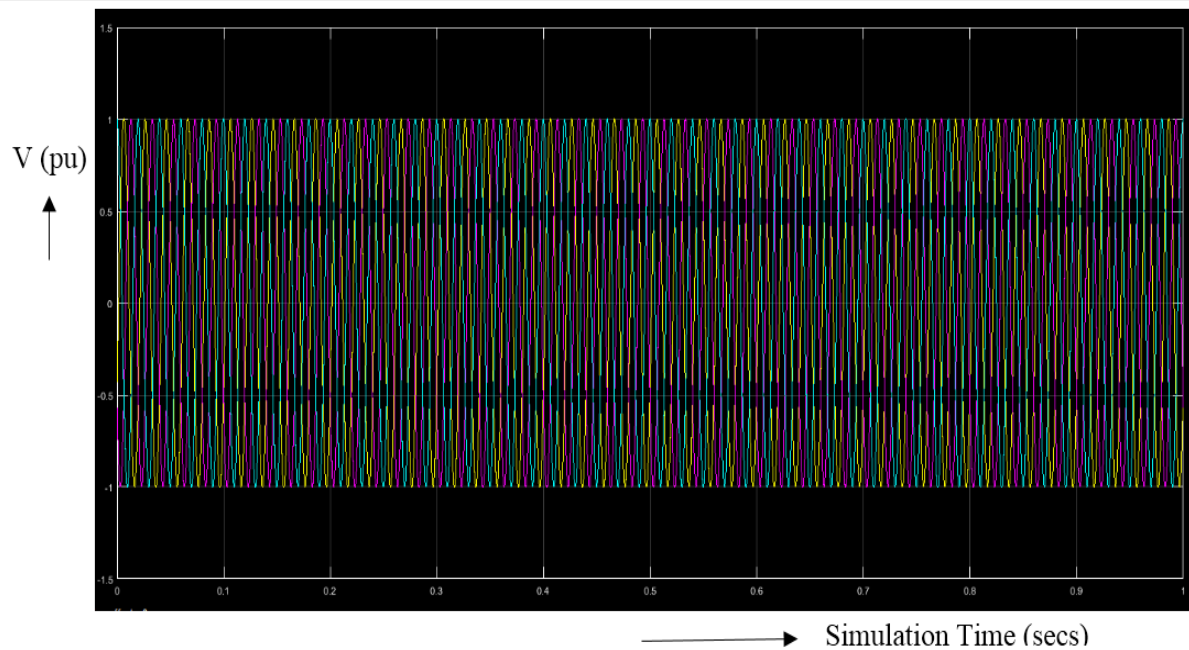


Figure 6: Voltage Magnitude Profile at Onitsha Bus before the Connection of Partial Discharge Producing Circuit

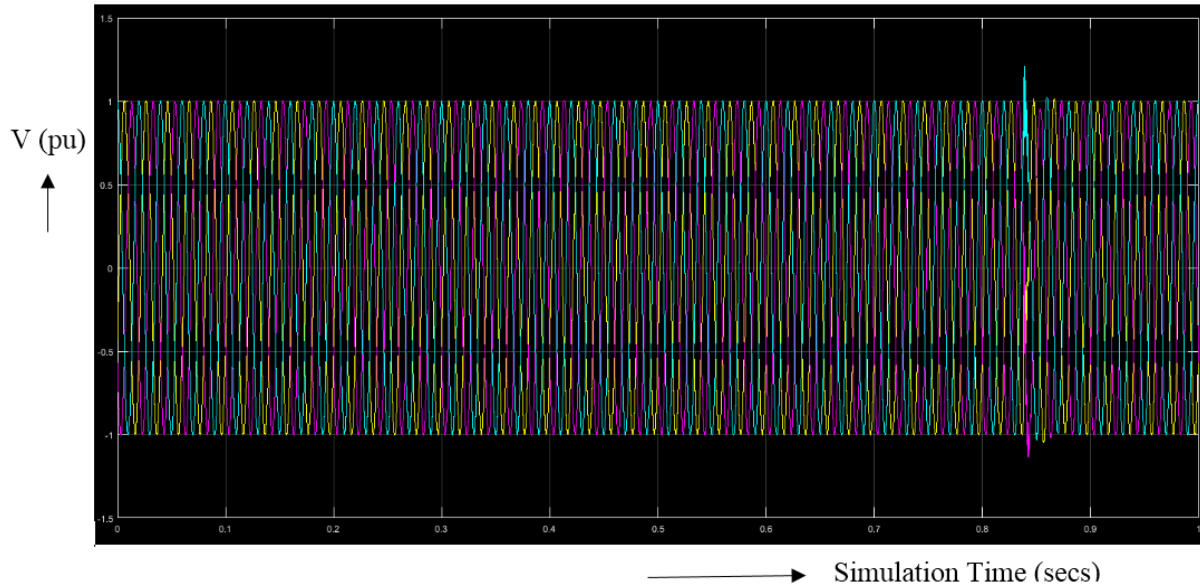


Figure 7: Voltage Magnitude Profile at Onitsha Bus after the Connection of Partial Discharge Producing Circuit and Allowing the Breaker to Operate at 0.84secs

Discussion of Simulation Result of the Insulation Defect Generation Model

Figure 5 presents the signal obtained when the Simulink model of the partial discharge producing circuit model was simulated. From the figure, it can be seen that the breaker opened once at 0.84 seconds. The partial discharge current pulse is of amplitude, 5mA as can be observed from figure 5. The amplitude of the nominal current from the circuit before the circuit breaker opened to produce partial discharge is 1.6mA.

Figures 6 and 7 respectively show the voltage magnitude profile at the Onitsha bus before and after the connection of the partial discharge producing circuit and allowing the breaker to operate at 0.84secs. In figure 6, the partial discharge pulse current representing the insulation defect was yet to be introduced. As a result, there is no form of distortion or transient high amplitude pulse noticed in the waveform of the voltage profile. On the other hand, in figure 7, it can be seen clearly that at 0.84 seconds, high amplitude, short pulse popped up in the waveform of the voltage profile of the Onitsha bus. Due to the transient nature of the pulse, it is difficult for the conventional protection scheme to pick up this pulse and this is so because the magnitude of disturbance it introduces into the system is still at a defect level and not up to a fault level. This necessitated the development of an adaptive scheme that can detect this defect on time so that it can be fixed before progressing to the fault level. This way, the time that would have been wasted in fixing the fault will be saved thereby improving the availability of the transmission line

5. Conclusion

It can be concluded that the three-capacitor model of partial discharge is effective in generating insulation defects in form of partial discharge current pulses in a transmission line. It can also be concluded that modeling and simulation of insulation defects (partial discharge) in transmission lines can facilitate the development of a better and improved protection scheme for high voltage transmission lines

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