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Research article

# Improving the Availability of the Onitsha-New Haven 330kv Transmission Line Availability Using Adaptive PMU-Based Insulation Defect Detector

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ABSTRACT

*This thesis is aimed at improving the availability of the New Haven-Onitsha 330kV transmission line by using an adaptive PMU based insulation defect detecting and location scheme. 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. The availability of the test transmission line was also evaluated over three years (2018 to 2020). Outage data obtained from TCN regional office Enugu was used for the evaluation. The performance of the proposed technique in enhancing line availability and reducing forced outage duration in the test transmission line was evaluated against the result of this characterization. Having established in the literature that insulation defect in transmission lines is characterized by the presence of partial discharge current pulse; a model of a three capacitor-based partial discharge current pulse generator was used to inject partial discharge current pulse into the test network in a controlled manner. A PMU based insulation defect detecting system was then modeled in Simulink to detect the insulation defect that will be introduced into the network. An ANN model that will make the PMU based insulation defect detection scheme intelligent was created, trained, and converted into a Simulink model. Developed models were then connected and simulated to determine the performance of the adaptive insulation defect detection system in detecting and locating insulation defects in the test transmission line. The impact of the use of an adaptive insulation defect detection system in preventing insulation-related faults and improving line availability (and reducing forced outage duration) was evaluated against the values obtained without the adaptive insulation defect detection system connected. Simulation results revealed that the proposed technique improved transmission line availability by 2.05% with respect to the network without the adaptive PMU based insulation defect detection scheme. It was concluded that an adaptive PMU based insulation defect detection scheme was effective in detecting and locating insulation defects in High Voltage transmission lines. It was also concluded that the adaptive detection scheme improved transmission line availability of the test network relative to the transmission line without the adaptive insulation defect detection scheme*

***Keywords:*** *Transmission Line, Outages, Pulse Generators, Insulation Defect Detector*

## Introduction

Electrical energy has remained one of the most useful and indispensable forms of energy; especially in this dispensation when so much of technologies are dependent on electricity for their operations (Adeyemi et al., 2016). Given this, it is pertinent that electricity not only becomes available continuously but also in a stable, reliable, and secured condition. Overhead Transmission Lines (OHTLs) is the Electric Power networks (called the grid) that are used around the world by power utility companies to transport Very High Voltage (VHV) and Extra High Voltage (EHV) bulk electrical energy from the generating stations to the areas where the energy will be distributed to the consumers (Gupta, 2013).

The exposed nature of overhead power lines makes overhead power transmission lines very vulnerable to various kinds of faults (Dharmender, 2014). 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. This results in increased production costs for industrial and commercial consumers and reduced standard of living for domestic consumers while increasing the pollution of the environment, noise plus other environmental hazards (Eberhard et al., 2011). High production cost and a lower standard of living results in poor economic and national development in the country.

To enhance the availability of overhead transmission lines, the number and frequency of transmission line faults and attendant long outages need to be substantially minimized. Considering that insulation-related faults form a reasonable percentage of transmission line faults, prevention of insulation-related faults will reduce the number and frequency of transmission line faults thereby reducing line outages and improving the network's availability. Insulation-related faults in power transmission lines can be minimized by detecting insulation defects in the power line insulators before they progress into flashover faults in the lines. Since Partial discharge is an indicator of defects in insulation, this research is targeted at using a PMU based adaptive detection technique to detect the presence of insulation defect to fix the detected defect and avoid its progression to flashover faults. The adaptive technique detects insulation defects in the line by detecting the presence and source and location of partial discharge in the transmission line.

The strategy in this study is to apply an adaptive technique precisely Artificial Neural Network-based phase measurement unit (PMU) to effectively detect the presence and source of PD in overhead transmission lines as a way of preventing insulation-related faults for an improved transmission line availability.

PMUs have been applied recently in power system protection schemes for improved detection of frequency and phase angle-related faults. The capacity of PMUs to detect frequency variations caused by the presence of high-frequency current pulses (caused by PDs) will be exploited in this research to effectively detect the presence and source of PD (caused by insulation defects in transmission lines) in overhead transmission lines.

### Faults in Power Systems

Electrical power systems have evolved into complicated networks comprising generators, switch gears, transformers, power receivers, transmission and distribution circuits. Thus, it is obvious that such a delicate network cannot be immune to faults. According to Gupta (2009), a fault in electrical equipment or apparatus is a defect in the electrical circuit due to which current is diverted from the intended path. A fault is an abnormal flow of current which may be open-circuit or short-circuit. A fault is also the unintentional and undesirable creation of a conducting path or a blockage of current (Yindeesap, 2015). Most of the faults in the power system lead to short circuit conditions. Regarding the transmission lines, a fault occurs when energized conductor or conductors come in contact with the ground (earth fault) or when two or more conductors come in contact (line-to-line fault). Gupta (2009) posits that the probability of fault occurrence in power lines is about one-half of the total faults occurring in a power system. This is owing to fact that the power lines are widely branched with the greater length being operated under variable weather conditions and are subject to the actions of atmospheric disturbances. Broadly, faults are classified as symmetrical and unsymmetrical faults (Alçin, 2009). Symmetrical faults are known as balanced faults while unsymmetrical faults are called unbalanced faults.

**Partial Discharge as a Manifestation of Insulation Defect in Power Networks**

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) (Golenishchev-Kutuzov et al., 2019).

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" (Reid, et al., 2011). In a wider sense, PDs are the consequence 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 inimical potency and time to the breakdown of partial discharge is a function of the discharge type.

**Three Capacitor Model of Partial Discharge**

For a more insightful understanding of PD and how electrical networks respond to the excitation of the pulse, it is pertinent to model the system. The model of PD of a cylindrical void inside an epoxy resin cube and the mechanism to measure the maximum discharge has been modeled using MATLAB Simulink.

The void parameters are the most essential factors for modeling partial discharge. The characteristics of PDs vacillate per the size of the void. Voids come in several types such as cubical, cylindrical, etc. Figure 1below shows the test object employed which is assumed to be composed of epoxy resin and for the sake of modeling is delineated by three capacitors. Two of these capacitors are in series connection and parallel to the third one. The series capacitances are the capacitance of the void and the capacitance of the healthy insulator in series with the void. The parallel capacitance to the aforementioned two is the capacitance of the remaining parts of the insulator. Figure1 illustrates also the dimensions of the test object used for the modeling.

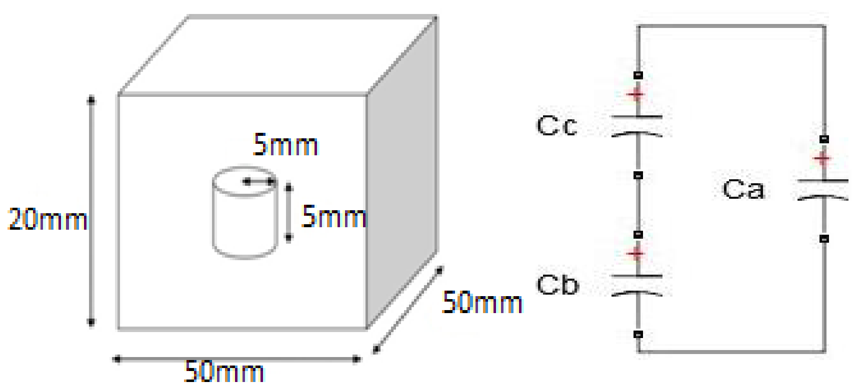


**Figure 1: Void Model of the Epoxy Resin Insulator**
***Source: Gunawardena et al, 2015***

**Capacitor Sensor for Measuring Partial Discharge**

The fundamental components needed for the measurement of PD are a coupling capacitor, a high voltage source, high voltage connections, measuring impedance, a test object, and software to evaluate the generated data.

**Phasor Measurement Unit Application in Power System**

The phasor measurement units (PMUs) can accurately report power system data at a rate up to 50/60 times per second. This has massively increased resolution and provided a colossal view of power system dynamics.PMU takes advantage of the global positioning system (GPS); it obtains current, voltage, and frequency readings and timestamps them by GPS. The control centers receive these measurements via a high-speed broadband network. The information is a highly comprehensive and synchronized feed of power system data that furnishes operators with real-time intelligence thereby assisting them to swiftly respond to system disturbance and act judiciously to avert a blackout or at least prevent a disturbance from escalating. (Akanksha, n.d). The deployment of PMU coverage in the power transmission line (which is somewhat delicate) has better equipped the network to respond appropriately to disturbances and equipment failures, thereby improving grid reliability, enhancing utilization of transmission assets, and importantly allowing integration of renewable generation.

## 2. Review of Related Literature

Obodoagwu (2019) analyzed line outage detection in Nigeria 330kV transmission lines using a phasor measurement unit (PMU). PSAT / MATLAB SIMULINK was used to execute power flow on the data obtained from the Transmission Company of Nigeria and the result obtained shows that PMU gives an accurate monitoring and total observability when introduced in the Nigeria Power system. Mekhamer et al. (2012) propose the application of PMU in the detection of single line outages in power systems. Support Vector Machine (SVM) protection scheme was used against overloading to prevent system collapse. It was shown that the effectiveness of the SVM improved when it utilizes output information from the PMU to determine the status of each line. Qi et al. (1996) proposed an ANN approach for distance protection of power systems by taking trained data from a simulation of a simple power system under load and fault conditions. The integration of ANN into relay operation improved the relay to detect nonlinear arc resistance, high impedance fault, and variable source impedance. In like manner, Khaparde et al. (1991) applied the ANN model in offline mode protective relaying operation of transmission lines. This results in adaptive distance protection of the transmission lines. Vaidya and Venikar (2012) proposed ANN-based protection of long transmission lines by considering the effects of fault resistance. ANN was employed as a pattern recognizer to improve relay performance.

## 3. Methodology

**Method Adopted**

The availability of the test transmission line is evaluated over three years (2018 to 2020). Outage data obtained from the Transmission Company of Nigeria (TCN)Enugu regional office was used for the evaluation. The performance of the proposed technique in enhancing line availability and reducing forced outage duration in the test transmission line was evaluated against the result of this characterization.

Having established in the literature that insulation defect in transmission lines is characterized by the presence of partial discharge current pulse; a three capacitor-based partial discharge current pulse generator that will inject partial discharge current pulse into the test network in a controlled manner was designed and implemented as proposed by (Nwani et al., 2022). The PMU based insulation defect detecting system was modeled in Simulink to detect the insulation defect that will be introduced in the network. To make the PMU based insulation defect detection scheme intelligent, an ANN controller was created, trained, and deployed as a Simulink model. The developed models were then connected and simulated to determine the performance of the adaptive insulation defect detection system in detecting and locating insulation defects in the test transmission line.

**Evaluation of Transmission Line Availability**

To determine the availability of the Onitsha - New Haven 330kV transmission line availability, outage data of the transmission line was collected over three years (2018 to 2020) from TCN, New Haven substation. The outage data is then used to compute the availability of the transmission line of the test network. A Transmission line availability evaluation technique was then adopted to compute the availability of the transmission line. The value obtained was used to evaluate the performance of the proposed technique.

The availability (A) and damage probability of transmission lines can be calculated as follows:

$$P_A(n_1) = P(A|n_1) = P_U(n)(3.1)$$

$$P_F(n_o) = P(F|n_0) = P_R(n)(3.2)$$

$$P_F(.) + P_A(.) = 1 \qquad (1)$$

Where:

"n" denotes the type of relays and the subscripts
"1" or "0" denote "tripping" or "no tripping of relays'', respectively.

The percentage availability is calculated for each transmission element as follows:

First, calculate the Availability index ($A_i$):

$$A_i = \frac{T_t - O_t}{T_t} (2)$$

Second, compute the Availability:

$$A_V = A_i \times W_f \qquad (3)$$

where:

$A_v$ = Availability
$A_i$ = Availability index
$T_t$ = Total time under consideration
$O_t$ = Outage hours due to unscheduled interruptions.
$W_f$ = Weighted factor
Percentage availability= $A_i \times W_f \times 100$(4)

Outage data obtained from TCN (between 2018, 2019, and 2020) are processed in section four and with the help of equations 3.4, 3.5, and 3.6, to obtain the availability of the test transmission line.

**Development of a Simulink Model of the Phase Measurement Unit (PMU) Based Insulation Detection and Location Scheme for the Test Network**
Phase measurement unit (PMU) is fast becoming popular in effective phase and frequency measurement in power systems. The PMU can accurately measure the synchronized voltage and current phasors and frequencies in power systems. This capacity has also made it a viable tool to detect and measure phase and frequency variations of signals in power networks. The ability of the PMU to detect frequency variations in power transmission lines in which current pulses of high frequency are present will be exploited in this research to detect and locate the partial discharge caused by insulation defects in the transmission line.

**Implementation of the PMU Based Insulation Defect Detection and Location Scheme**
The PMU based partial discharge detection and location scheme is made up of the PMU connected to the test transmission network. The test transmission network is first extracted from the grid network and then modeled in Simulink. Thereafter, the PMU block is sourced from the simscape library, configured, and connected to the developed model of the test network.

To achieve the above objective, the PSAT model of the 45 bus Nigeria 330kV transmission network was first developed. Having developed the 45-bus model of the Nigeria grid network, the Onitsha - New Haven 330kV line is then extracted from the 45-bus transmission grid network in Simulink MATLAB.

The required Simulink blocks are imported into a new Simulink model space from the Simscape library. These blocks include a transmission line, a three-phase voltage supply (that was used to model the inflow of power at the Onitsha bus), bus bars, RLC load (That represented the outflow of power at the New Haven bus), scopes, and 'to workspace', PMU (that detects the frequency variation in the line due to the presence of PD), etc. The imported blocks are then connected before configuring them to reflect the parameter obtained from characterization. The developed Simulink model of the 45 bus Nigeria grid network is presented in figure 2. The Simulink model of the PMU based partial discharge detection scheme is shown in figure 3

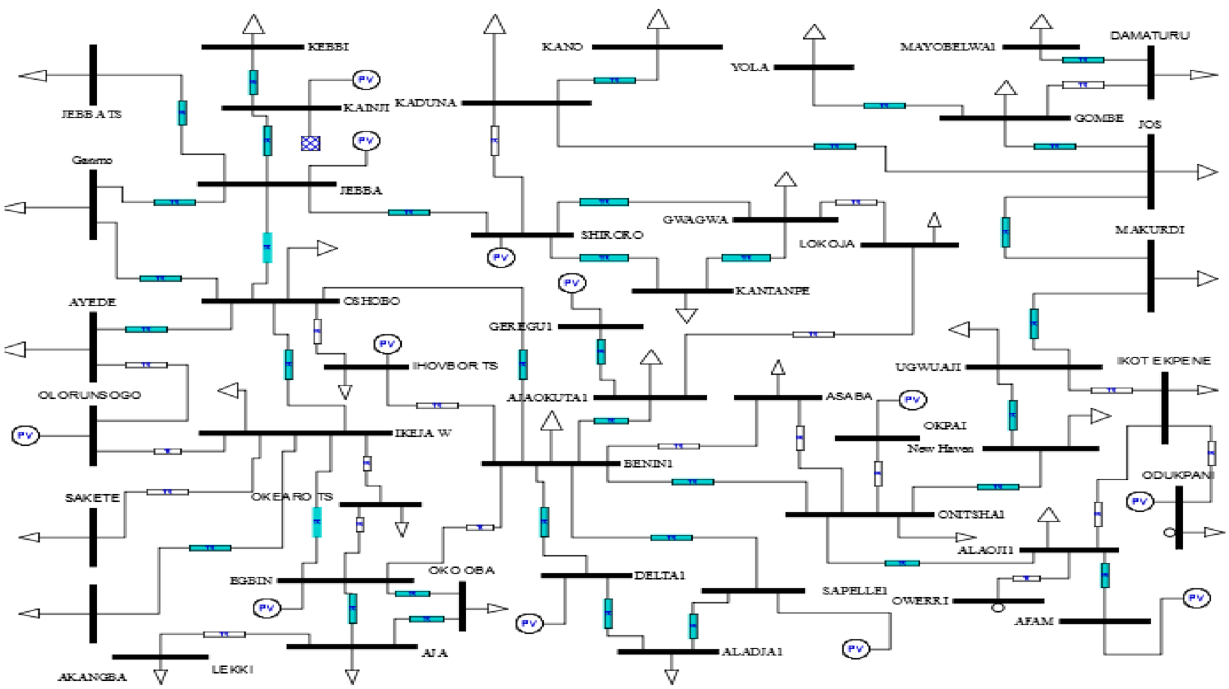


**Figure 2: Simulink Model of the Nigeria 45 Bus 330kv Grid Network**

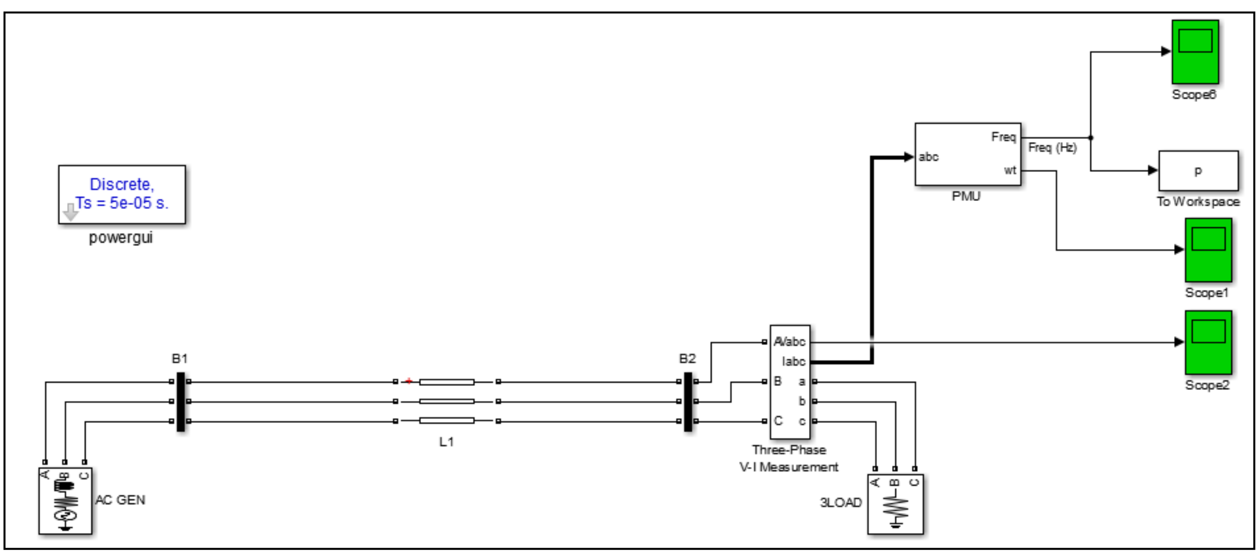


**Figure 3: Simulink Model of the New Haven - Onitsha PMU Based Partial Discharge Detection Scheme**

**ANN Development Strategy**

To optimize the performance of the PMU based partial discharge (insulation defect) detection scheme; there is a need to make its operation intelligent. This will increase the scheme's sensitivity and accuracy in detecting insulation defects even in the presence of noise. The neural network fitting application can map between a data set of numeric inputs and outputs with a very high degree of accuracy if properly trained with an adequate volume of data. So when given a set of input data characterizing the state or states of a system and the corresponding set of output data; the neural network fitting application will learn the input-output pattern such that when presented with another set of input data set for the same system, it can predict the output with a very high degree of accuracy. The degree of accuracy depends largely on the volume of training data and level of training. A higher volume of training data gives better accuracy.

**Generation of Training Data**

During simulations, frequency signal data obtained in the absence of insulation defect (partial discharge) were recorded. Also, the frequency signal data obtained when insulation defect (partial discharge) was introduced at 95km from the bus of interest was recorded. The frequency signal data were also obtained when the partial discharge was introduced at four other varying distances from (80km, 60km, 40km, 20km) the bus of interest and duly recorded. A distance of 0km is recorded for the case of no insulation defect introduced in the line. The recorded frequency values for all specified distances represent the input while the various distances of partial discharge introduction are specified as the target. The pattern of values obtained during simulation in the absence and the presence of partial discharge formed the input of the ANN while the corresponding distances from where the partial discharges were introduced formed the target of the ANN.

**ANN Creation and Training**

To create the above network, the data set for the input and target were first loaded through the Matlab workspace. The network was then trained with the data set. 15% of the data was used for testing 15% was used for validation while the remaining 70% was used for training.

The MSE progressively reduced to its best value of **4.6538** in **5** iterations. The architecture of the created ANN model is shown in figure 4; from which it can be seen that the developed ANN controller has 401 inputs, 10 hidden layers, and a single output.

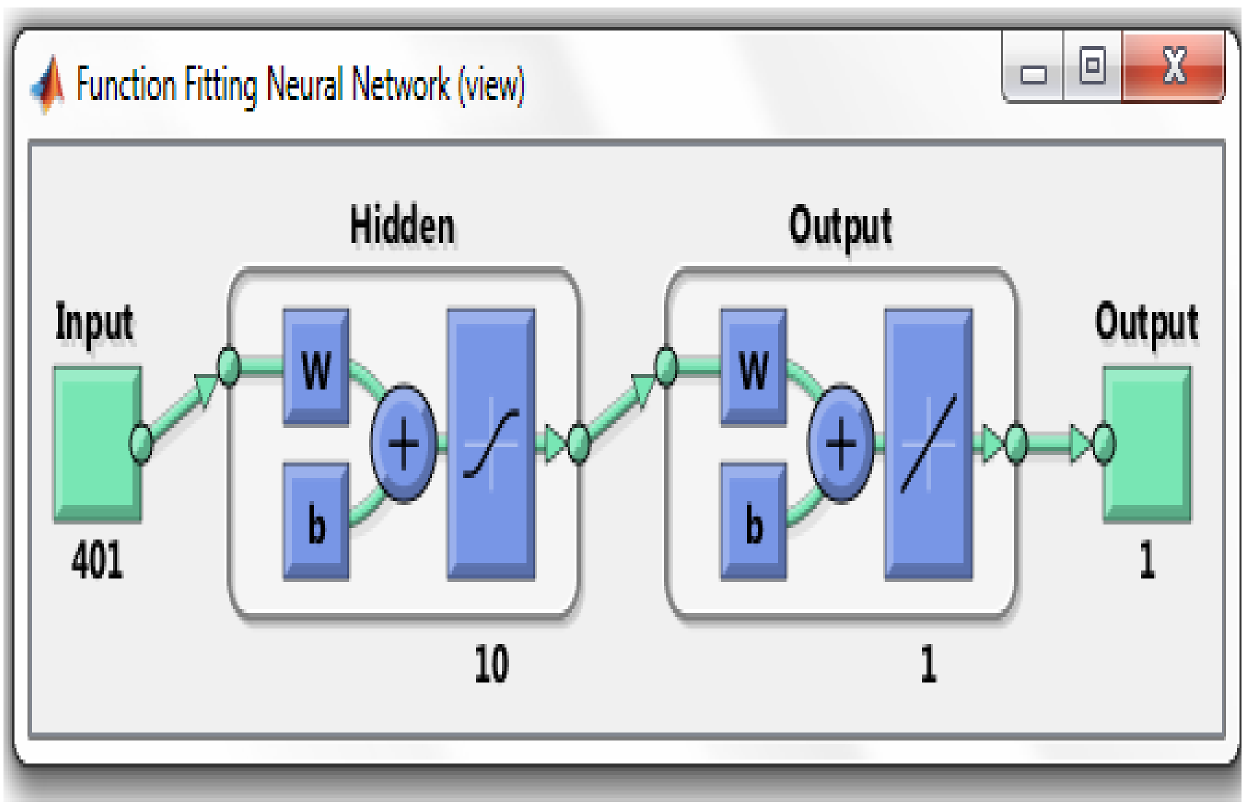


**Figure 4: Architecture of the Trained ANN Model**

The error in the overall mapping between the input and target in training, validation, and testing was less than 4%. This shows an accuracy of about 96%.

After the training, validation, and testing were concluded, the ANN Simulink model was then generated.

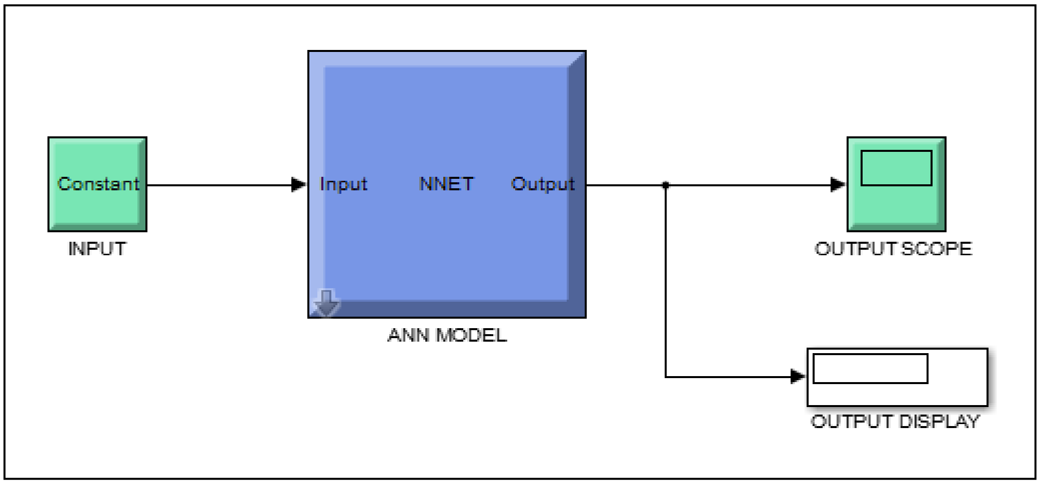


**Figure 5: Deployed Simulink Model of the ANN Model**

**Connecting All Developed Models and Simulating the Entire SYSTEM under Various Scenarios**
Three models were developed in this research work: the PMU based insulation fault detection and location scheme, the insulation defect generating system, and the ANN controller. The three models have to be strategically linked together for simulation and evaluation of the proposed technique.

**Connection of the ANN Controller to the PMU Based Insulation Defect Detector**
Having created and trained the ANN model that will make the PMU based insulation defect detection scheme adaptive, there is a need to connect the developed ANN model to the PMU based insulation defect detection scheme. The developed ANN model is connected to the output of the PMU in the insulation defect detection scheme. Based on its earlier training, the ANN model analyzes the frequency signals obtained from the PMU and then decides whether there is a presence of insulation defect (partial discharge) or not. If the insulation defect is present in the line, the ANN will also determine the distance of the source of partial discharge (insulation defect) from the bus of interest. The Simulink model of the developed ANN model connected to the insulation defect detection scheme is presented in figure 3.6

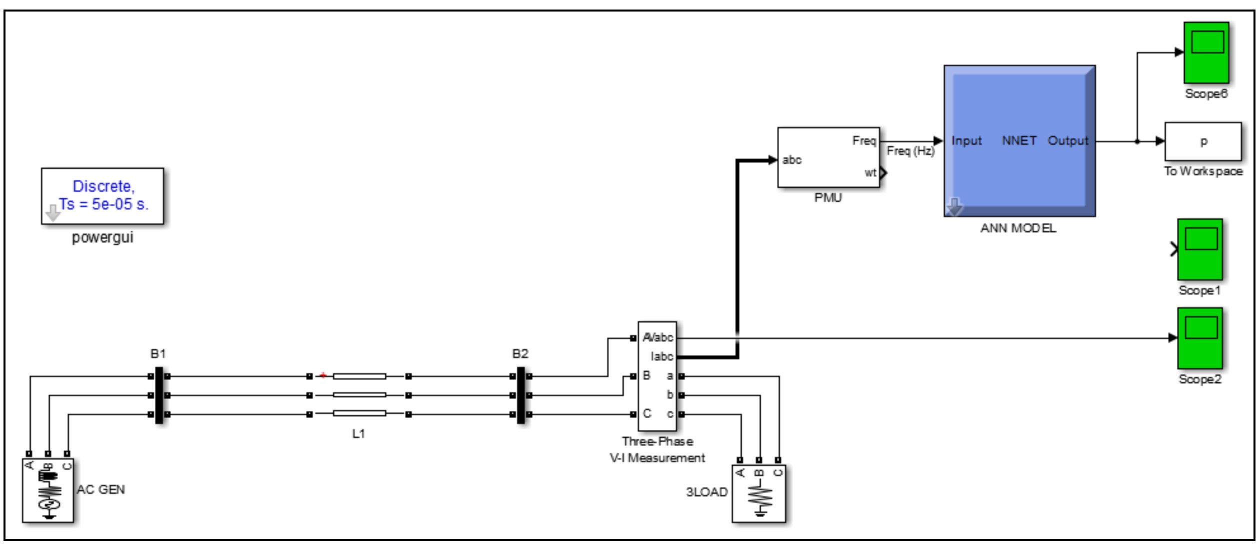


**Figure 6: Developed ANN Model Connected to the Insulation Defect Detection Scheme**

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

The partial discharge (insulation defect) generating system implemented in Nwani et al. (2022) was adopted for introducing partial discharge into the test network protection scheme. The Simulink model of the partial discharge generating circuit is shown in figure 7.

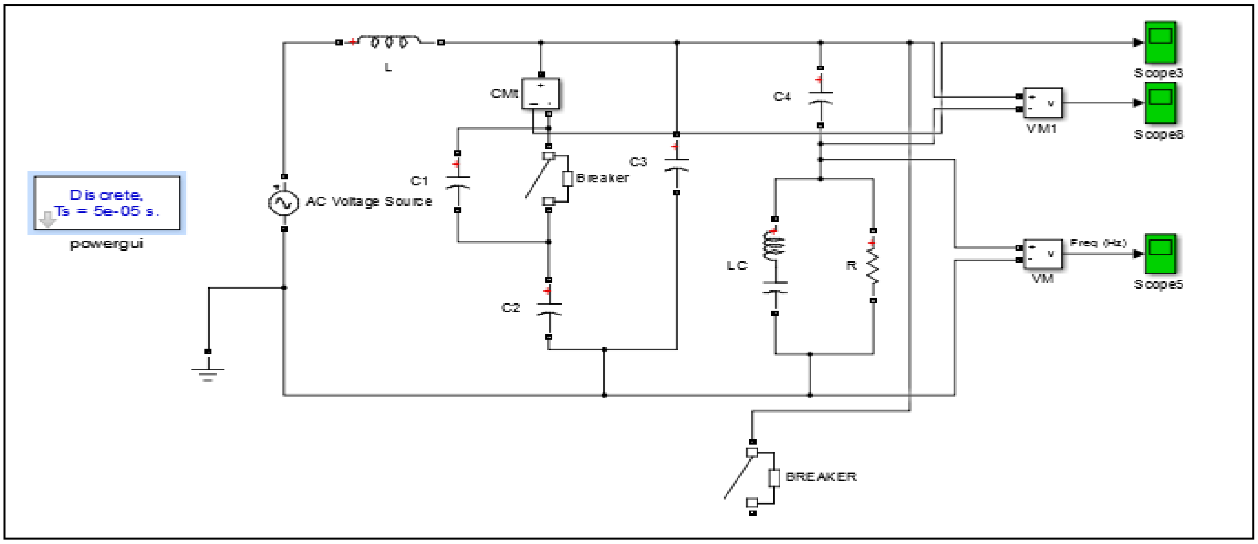


**Figure 7: Simulink Model of the Partial Discharge Development Circuit**
***Source: Nwani et al., 2022***

With the adaptive PMU based insulation defect detection scheme in place, the next step is to connect the partial discharge (insulation defect) introduction model (implemented in objective two) 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 the 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 8 presents the Simulink model of the insulation defect detection scheme and the insulation defect production model connected.

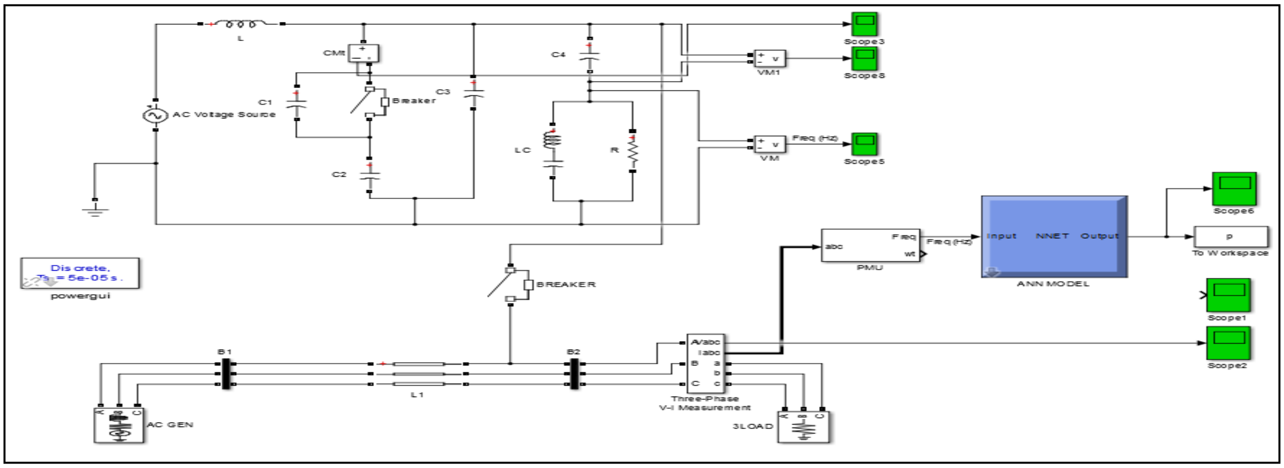


**Figure 8: The Insulation Defect Detection Scheme and the Insulation Defect Production Model**

## 4. Result and Analysis

**Results and Discussions of the Evaluation of the Availability of the Test Transmission Line**

To evaluate the performance of the proposed technique, the availability of the case study network was evaluated before connecting the proposed adaptive PMU based insulation defect detection and location scheme. With the help of the case study outage data obtained from TCN, Enugu, the availability of the network before connecting the developed models was computed using equations 2, 3, and 4. The result obtained was compared with the result of a similar calculation after the connection of the developed models to the network.

**Data Presentation for the Evaluation of the Transmission Line Availability of the Test Network Without the Application of the Proposed Technique**

From TCN Outage Data for Onitsha - New Haven 330kV Line in 2020, the following information can be deduced:

Total Outage duration =1134 Hours
Outage duration for Forced outages = 1085 Hours
Duration due to planned outage **=** 49 Hours
Outage duration due to insulation related faults = 258 Hours

Likewise, it can be deduced from TCN Outage Data for Onitsha - New Haven 330kV Line in 2019 that;

Total Outage duration =595 Hours
Duration due to planned outage **=** 24 Hours
Outage duration for Forced outages = 571 Hours
Outage duration due to insulation related faults = 165 Hours

Similarly, TCN Outage Data for New Haven-Onitsha 330kV Line in 2018;

Total Outage duration =362 Hours
Planned outage duration **=** 21 Hours
Outage duration for Forced outages = 341 Hours
Outage duration due to insulation related faults =89 Hours

**Computation of the Transmission Line Availability without the use of PMU Based Adaptive Insulation Defect Detection Scheme**

Total Planned Outage duration for the three years = 49 + 24 + 21 = 94 Hrs.

Total Outage duration for the three years **=** 1134 + 595 + 362 **=** 2091 Hrs.

$Q_f$ = 2091 – 94 **=** 1997 Hrs.

Total operational hour under consideration ($T_t$) = 3 x 365 x 24 **=** 26280 Hrs.

From equation (3.4)

$$A_i = \frac{T_t - O_t}{T_t}$$

$$A_i = \frac{26280 - 1997}{26280} = 0.9240$$

$$A_v = A_i \times W_f$$

Since other transmission line components outside the line are not considered;

$$W_f = 1$$

Therefore,

$$A_v = A_i = 0.9240$$

Percentage Availability without PMU based adaptive insulation defect detection scheme

$$= 0.9240 \times 100 = 92.4\%$$

**Result and Discussions of Simulation of the Entire Connected System**

The insulation defect generation system connected to the adaptive PMU based insulation defect detection and location scheme is simulated with partial discharge introduced at various distances from the reference bus. The result obtained will be used in the evaluation of the proposed technique.

**Results of Simulation of the Entire Connected System**

After connecting the developed models as shown in figure 4.7, the system is first simulated with the partial discharge current injected at various distances (95km, 80km, 60km, 40km, and 20km) from the Onitsha bus. In each case, the frequency response measured by the adaptive PMU based insulation defect detector is recorded. The partial discharge generator is then disconnected and the network simulated again. The frequency response obtained is also duly recorded. Simulation results obtained are presented in table 1 and figures 9 and 10

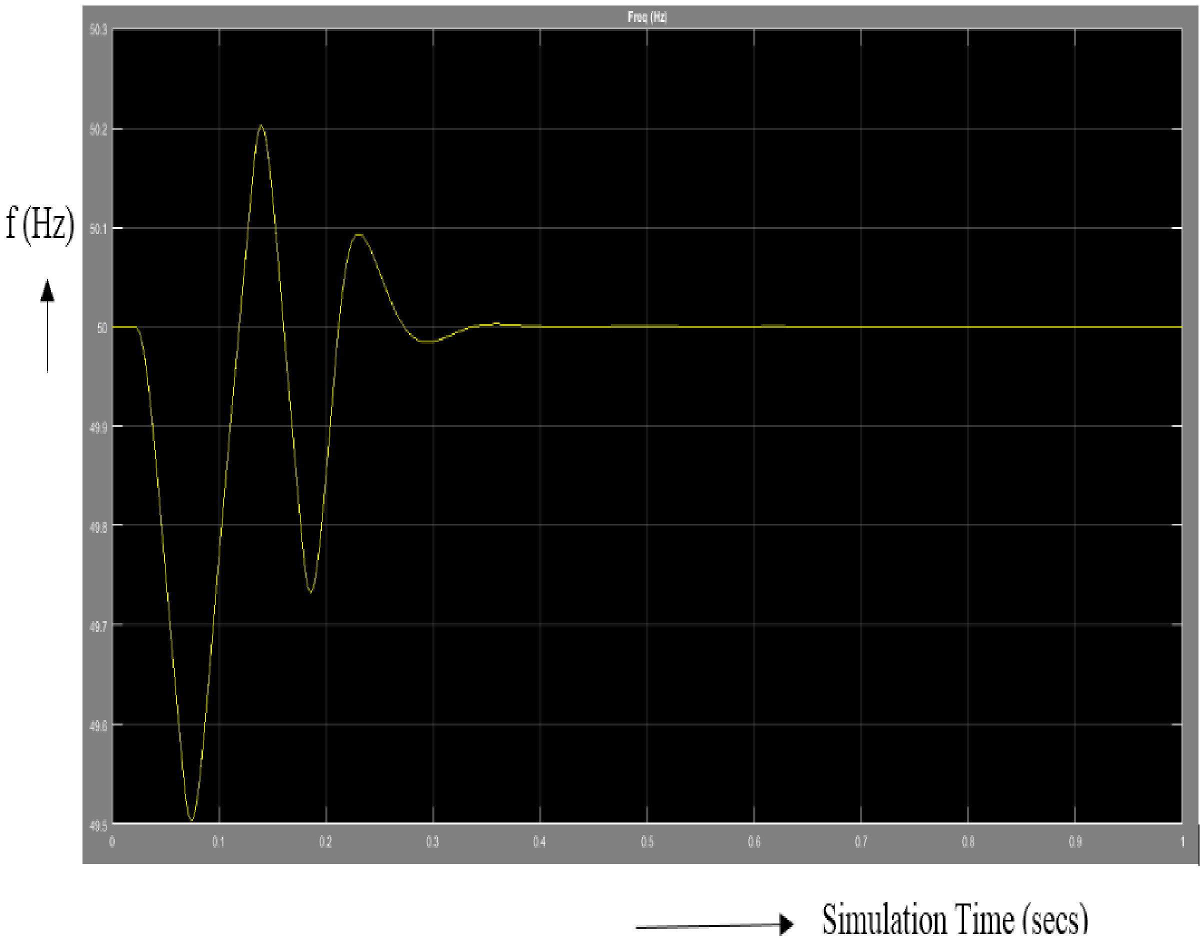


**Figure 9: Frequency Response at Onitsha Bus before Connecting the Test Network to Partial Discharge Producing Circuit**

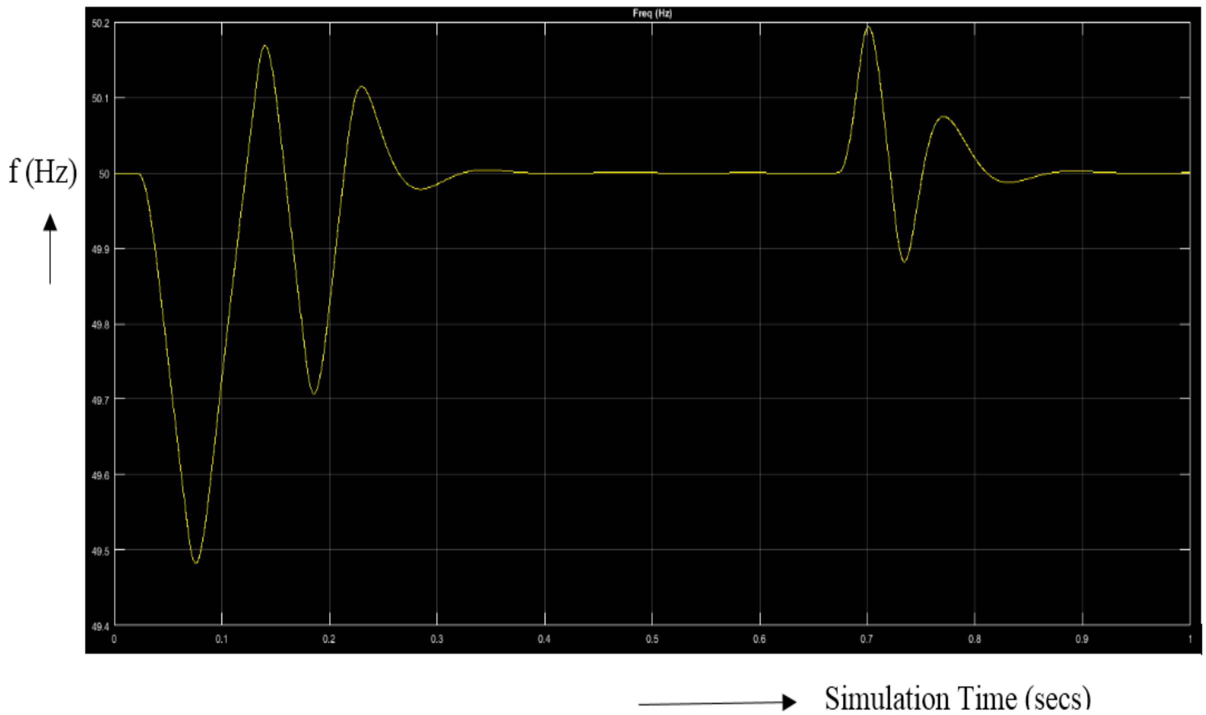


**Figure 10: Frequency Response at Onitsha Bus after Connecting the Test Network to Partial Discharge Producing Circuit and allowing the Breaker to Operate at 0.84secs to Introduce Pulse Current at 95km**

**Table 4.1: Simulation Results on Detection and Location of Insulation Defect**

| S/N | Detector Output (km) | Actual Distance (km) | Defect Status (Detector) | Defect Status (Actual) |
|---|---|---|---|---|
| **1** | 0.03 | 0 | 0 | 0 |
| **2** | 10.00 | 20 | 1 | 1 |
| **3** | 39.96 | 40 | 1 | 1 |
| **4** | 59.95 | 60 | 1 | 1 |
| **5** | 84.17 | 85 | 1 | 1 |
| **6** | 94.28 | 95 | 1 | 1 |

**Discussions on Result of Simulation of the Entire System**

It can be seen that the initial spike in between 0mins and 0.3minss is common to the frequency signals in figures 9 and 10. The spike is due to a transient power swing caused by the switching "on" of the generator at the Onitsha bus.

However, another spike is observed at 0.84 mins in the response of figure 10. This is obviously due to the introduced partial discharge current pulse (representing insulation defect) at 0.84 mins during simulation. With the help of "To workspace block" in Simulink library, the frequency responses at the Onitsha bus were recorded for partial discharge pulse current introduced at various distances (95km 80km, 60km, 40km, 20km, and 0km) from the reference bus (Onitsha). Results obtained from the responses due to the introduction of pulses at various distances are presented in table 1.

From the result of table 4.1, it can be seen that for the case of zero distance of pulse injection (which represents no partial discharge pulse current injected), the adaptive detection system correctly gave an output of zero. For the remaining six cases where partial discharge was actually introduced but at different distances from the reference bus, the ANN-based insulation defect detector gave correct outputs of one, indicating the presence of insulation defect (partial discharge). This means that the developed adaptive insulation defect detector can detect accurately all insulation defects in the transmission line.

On the other hand, the adaptive insulation system was able to predict correctly five out of six locations of sources of partial discharge current pulses. This amounts to 83.33% accuracy in partial discharge (insulation defect) source location.

The result of table 1 implies that with the use of the developed adaptive insulation defect detector, all insulation defects in a transmission line can effectively be detected and fixed before they progress to faults status. The implication of this is that forced outage duration relating to insulator faults would have been canceled out.

**Determination of the Availability of the Test Transmission Line after the Incorporation of Adaptive PMU Based Insulation Defect Detector**

In the light of the above, the proposed technique can be evaluated by re-computing the availability of the test network but with all insulation-related forced outage duration removed.

The computation is performed thus using the data obtained from TCN

Outage duration due to insulation related faults = 258 + 165 + 89= 512 Hours
Total Planned Outage duration for the three years = 49 + 24 + 21 = 94 Hrs.
Total Outage duration for the three years **=** 1134 + 595 + 362**=** 2091 Hrs.
$Q_f$ = 2091 – 94 - 512 **= 1**485 Hrs.
Total operational hour under consideration ($T_t$) = 3 x 365 x 24= 26280 Hrs.

From equation (2) we have:

$$A_i = \frac{T_t - O_t}{T_t}$$

$$A_i = \frac{26280 - 1485}{26280} = 0.94296$$

Since $$W_f = 1$$

$$A_i = A_v = 0.943$$

Percentage Availability with PMU based adaptive insulation defect detection scheme**.**

= 0.9240 * 100 = 94.3%

Improvement in Availability due to use of PMU, based adaptive insulation defect detection scheme is given as:

$$\frac{0.94296 - 0.9240}{0.9240} = 0.02052$$

$$\text{Percentage improvement} = 0.2052 \times 100 = 2.052\%$$

Similarly, the percentage reduction in forced outage duration due to use of adaptive insulation defect detection system is calculated thus:

$$\frac{1997 - 1499}{1997} \times 100 = 24.94\%$$

**Comparison of Results Obtained Proposed Technique Result with Characterizations Result**

Results of the evaluation of the proposed techniques are presented in table 2 and figure 11.

**Table 2: Comparison of Forced Outage Duration and Percentage Availability with and without Adaptive Insulation Defect Detector**

| Scenario | Percentage availability (%) |
|---|---|
| **Without an adaptive defect detector** | 92.24 |
| **With adaptive defect detector** | 94.3 |

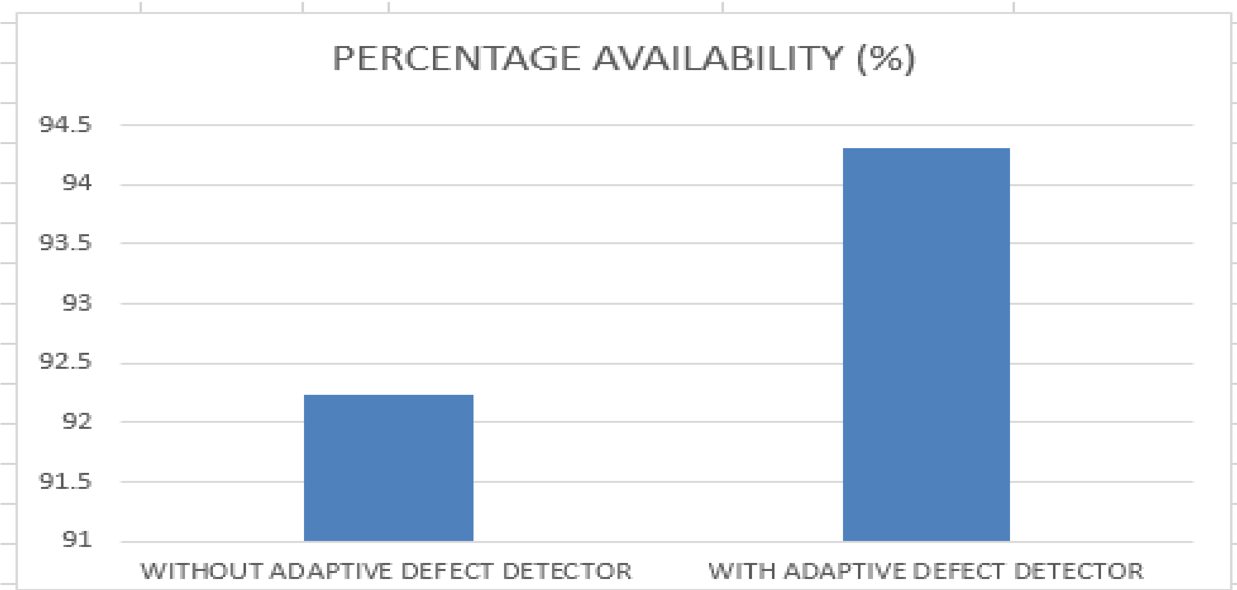


**Figure 11: Comparison of Percentage Availability with and without Adaptive Insulation Defect Detector**

From figure 11 it can be seen that with the incorporation of the adaptive insulation defect detection system, insulation-related faults were detected before they progressed to faults. Computations revealed the transmission line with the proposed adaptive insulation detection scheme achieved a 2.05% improvement in availability relative to the transmission line without an adaptive insulation defect detection scheme. It was also revealed that the transmission line with the proposed adaptive insulation detection scheme reduced forced outage duration by 24.9% relative to the transmission line without an adaptive insulation defect detection scheme.
The result will also enhance the maintenance of the insulation-related fault by the hotline method.

**5. Conclusion**

From the results and analysis presented, it can be concluded that an adaptive PMU based insulation defect detection scheme was effective in detecting and locating insulation defects in High Voltage transmission lines. It can also be concluded that the transmission line with an adaptive PMU based insulation defect detection scheme improved the transmission line availability by 2.05% with respect to the line without the adaptive insulation defect detection system.

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