Power Transformer Life Management; Relevance to Nigerian Power Industry

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ABSTRACT

Non-expansion of Nigerian grid network resulted in Increasing loading of the existing power equipment. Attempt to reduce life cycle costs resulted in decrease maintenance expenditures and postponement of investments. These resulted in higher failure rates and increasing risk of major failures. Frequent failure of power equipment at the transmission substations and distribution stations in Nigeria has prompted the need to establish a system that can give advance information on the state of power equipment in service. The ineffective monitoring system has also resulted to high cost of equipment maintenance. One way of achieving reduced maintenance cost is the use of real time condition monitoring technique. This paper discussed factors responsible for power equipment deterioration and failure, and the concepts of condition-based monitoring system. Typical scenario of online transformer monitoring is reviewed. A real time life management system which is under development for the monitoring of the health of power transformers at the substations and distribution stations is discussed. The objective of the ongoing project is to secure the quality of the generated electrical energy with minimized cost of expenditures for services (life management). This system will enable asset managers monitor their equipment in the field. This will save cost of asset maintenance and ensure a better service delivery to electricity end-users.

Keywords: [power transformer, substation, insulation life management, power asset management]

1. BACKGROUND

Power Holdings Company of Nigeria (PHCN), a public sector utility charge by law for the generation, transmission, distribution, and marketing of electricity to the public in Nigeria. Over the years, Nigerian government has struggled with improvement in electricity supply with little success. The stalled expansion of Nigeria electricity capacity has crippled industrial development of the country. Overuse of the stagnant electricity network has led to overloading of the power facilities. This has resulted in frequent failures in power transmission substations and distribution stations. The power infrastructures in Nigeria are in such a fragile state that nine full and five partial system collapse were recorded in the power sector between January and June 2012 [1]. Example of reported cases include; the transformer explosion in Benin that killed three in April 2010 [2], fire at 45-MVA Egbu sub-station in Imo state around September 2011 [3], explosion followed by a fire outbreak at the Benin Transmission Station in March 2012 [4], transformer explosion at the Katampe Sub-station in Abuja in April 2012 [5], transformer explosion near Krystal Lounge relaxation spot

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located at Wuse II, Abuja in June 2012 which some media reported as bomb blast [6], etc. There are other numerous failures that are hardly reported. For costly items such as power transformers, the cost of replacing them before the end of life time of the equipment increases the cost of running electrical transmission and distribution network. The cost of frequent power failure currently experienced in Nigeria has serious economic loss. The Commonwealth Business Council, CBC, announced in 2011 that Nigeria was losing $100 billion yearly due to lost output and high costs for local businesses [7]. Small and medium scale industries are folding up, Manufacturing companies are folding up, some international industries relocating their production site to neighboring countries with stable power supply, thus, increasing unemployment level in the country [8]. Nigerians have been reported to be among the top ten sources of Foreign Direct Equity Investment in Ghana according to a survey published in 2009 by the Bank of Ghana [9].

From the Road Map for Power Sector Reform, the Federal Government of Nigeria intend to achieve a 30% increase in the “true deliverable” transformation capacity of the country’s 330kV network, increase the capability of the distribution network by circa 20%, and reduce aggregate distribution losses (technical and non-technical) by at least 5% in April 2011 [10]. As at December 2012, this has not been achieved as fourteen systems breakdown was recorded in power sector between January and June 2012 [1]. Part of the effort that can improve electricity transmission and distribution is proper management of power assets. Without proper facility management, the generated power may end up as waste and not getting to the end user.

Most of the power sub-stations are over 40 years old and power transformers in the sub-stations have useful life of about 40 years. This put the transformers on serious ageing problem [11]. Lack of expansion and Improper planning of electric power distribution network often put the distribution transformers on overload. They therefore require adequate care to extend their useful life time, while maintaining system reliability. Just as people go for medical checkup to know the state of their health as a precaution against unexpected breakdown, inadequate attention on the health of power transformers often result in sudden breakdown of the power equipment. It may be emphasized that since the electric power transformer is a vital component of electrical transmission and distribution network, reliability of the insulation system in a transformer is a key element for a reliable operation of the transformer. Failure of the insulation system will affect the operation of the entire network. Some failures may result from manufacturers’ fault, but failures that occur due to accelerated ageing of the equipment can be limited or avoided by preventive maintenance. Asset management therefore plays an important role in the effective transmission and distribution of the generated power to the end user. Acquisitions of necessary information will enable asset managers ascertain the accurate condition of power equipment, including aged and new power transformers.

This paper discusses the factors responsible for power insulation deterioration and failure, and the concepts of reliability-based monitoring system. Typical scenario of online transformer monitoring will be reviewed. It will also introduce a real time life management system which is under development for the monitoring of insulation life of power transformers at the substations and distribution stations in Nigeria. The ongoing project is aimed at securing the quality of the generated electrical energy with minimized cost of service expenditures. The current challenges in Nigerian power industry have made it necessary to migrate the power system from the traditional corrective maintenance strategy to reliability-based monitoring technique. This type of preventive maintenance is planned and performed before the component fails with the aim of reducing the probability of future network failure. This will save asset management cost and could prolong the life of effective use of power transformers.

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2. POWER TRANSFORMER INSULATION DETERIORATION

Energy loss takes place in transformers while in operation. Two types of losses occurred in a transformer and two parts are responsible for most of the energy loss. No load losses occur at the magnetic core due to variation of alternating flux (hysteresis losses), the core's eddy-current loss, and dielectric losses. The load losses take place at the windings. The primary and secondary windings in most transformers are either copper, aluminium, or one of them may be aluminium and the other copper. Application of load current on the windings leads to interactions between the moving current carrying particles and the atomic ions that make up the conductor. This interaction leads to ohmic heating $\left(Q \propto I^2 R\right)$ [12]. These energy losses are converted to heat losses at the respective parts. Defects can lead to abnormal state such as; general overheating leading to abnormal rise of the oil temperature due to cooling deficiency, poor distribution of oil flow and core overheating. Local overheating associated with the main magnetic flux and local overheating associated with a stray flux can occur due to defect. Shorted winding strands also cause malfunction in transformers. Other factors that can lead to fault are local heating in places of poor joints, breakdown of oil due to severe contamination, formation of film coating leading to reduction in contact surface, local heating due to excessive eddy current etc. These will result in overheating, sparking and arcing, insulation deterioration, generation of gases, carbon and other degradation products [13].

Insulation deterioration in power transformers is the main factor that affects the transformer's life. Power transformers can be classified in terms of the insulation conditions. When a transformer is classified normal, it implies that there is no evidence of degradation in the system, and remedial action is not required. A transformer classified as aged and normal is not completely defect free, but is in an acceptable condition. A defective transformer is not far from failure and remedial action required to keep it in service. A failed transformer requires a repair before it can be return to service [13, 14].

Many failures occur due to ageing phenomenon in insulation system, bushings and on-load tap changers (OLTCs). Cellulose papers and pressboard fully impregnated with insulating oil constitute the electrical insulation system in electric power transformers. Paper and pressboards in a transformer constitute 40-60% of the total mass of the insulation structure [15]. The oil-paper insulation is subjected to thermal, electrical, electromagnetic and electrodynamics stresses when transformer is in operation. When the insulation system is overstressed by high temperature or electric discharges, the oil and cellulose molecules undergo ageing as a result of thermo-oxidative and hydrolytic degradation, and new molecules formed. Such reaction generates variety of by-products and gases that dissolve in the surrounding fluid [16]. The fluid is a part of the transformer and played a vital role in evaluating the condition of the system. The fluid is an information carrier as all the impurities in the oil are the properties of the entire dielectric system. The life time of transformer can be shortened by agents of degradation such as water, oxygen, oil degradation products, fibres, particles, etc. Moisture can be introduced into insulation system as a result of degradation of oil and paper insulation at elevated temperature. The heat may results from overheating of the HV windings due to poor cooling of the excessive of circulating current [17]. Ingress of water from the atmosphere can also increase the moisture content in transformer insulation. This is mostly due to flow of wet air or free water due to poor sealing under action of a pressure gradient. The presence of bubbles in oil may cause critical discharge (PD) [13].

Ageing of paper insulation involves chemical reactions that include pyrolysis, oxidation and hydrolysis. The decomposition of the cellulose insulation at elevated temperature is known as pyrolysis, its decomposition when reacted with oxygen is oxidation, while its decomposition when reacted with water is known as hydrolysis The presence of water is the

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most important factor in ageing of cellulose. These mechanisms acts simultaneously and are accelerated at elevated temperatures. One of the degradation products of oil-paper composite material as it ages is water. These increase the water content in the system over time. This makes hydrolysis the dominant ageing mechanism at elevated temperature. The available water in the system may attack the oxygen that bridged the monomers to form two hydroxyl ions attached to each monomer. This causes scission of the inter-monomer bonds and eventual degradation of the material. The number-average degree of polymerisation (DP) is the ratio between the number of monomers and the number of chains of all lengths [16]. Degradation led to decrease in the DP and the mechanical strength of the paper and hence a reduction in its tensile strength.

One other agent of deterioration of transformer insulation is particle contamination. Particles in transformers result from wear and tears of bearings, cellulose fibres, aluminium, copper, steel, carbon, etc. The conductive particles such as wet fibre, metals, carbon are the most dangerous of the particles. Some of the decay products are adsorbed by solid insulation. These adsorbed products may affect new oil when the system is retrofillled [15]. The adsorbed products such as copper sulphide can lead to accelerated ageing of the solid insulation [18].

The withstand strength of transformer will naturally decrease over time as a result of normal ageing. But defects such as excessive moisture in cellulose, oil contamination due to ageing, insulation surface contamination resulting from adsorption of conducting ageing products such as copper sulphide, partial discharge, creeping discharge which may lead to failure at normal operating condition of transformers, accelerated insulation ageing resulting from overheating, accelerated deterioration of components such as bushings and on-load tap changers (OLTCs), etc, could lead to accelerated degradation of the system [13]. Sources of failure can be in two modes; reversible (defects) and irreversible mode (fault). The distinction between the two processes is not clearly defined, but the presence of defect or fault in transformers can be detected through system monitoring and diagnosis [19].

Figure 1 shows a schematic diagram of simple ageing model for asset simulation [19]. The model describes an asset with reliable, degenerated and unpredictable state. Different calculations for situation such as strategic maintenance, renewal decisions and failure rates are made for each state. The principle behind the simulation is that an asset will pass through each state and spend a certain amount of time in each of the state during its life time. Activities such as maintenance and refurbishment will impede the rate at which an asset transforms from one state to the next. An asset will exhibit different performance level at each state. At the end of the life time of the asset, it moves out of the system by being replaced.

Most of the defects that may cause system failures in electric power network are of reversible mode and could have been corrected in the field if appropriate monitoring system capable of detecting such defects is put in place. Approximately 80% of transformer failures occur within the age range of 10 to 38 years due to wear-out problem. These failures could be predicted and prevented with the help of effective monitoring and diagnostic system [20]. Early detection of problems, at the incipient stage, will help reduce the risk and costs of unexpected failure, drives conditions-based maintenance, reduce cost of maintenance and repair, and extend life of transformers.

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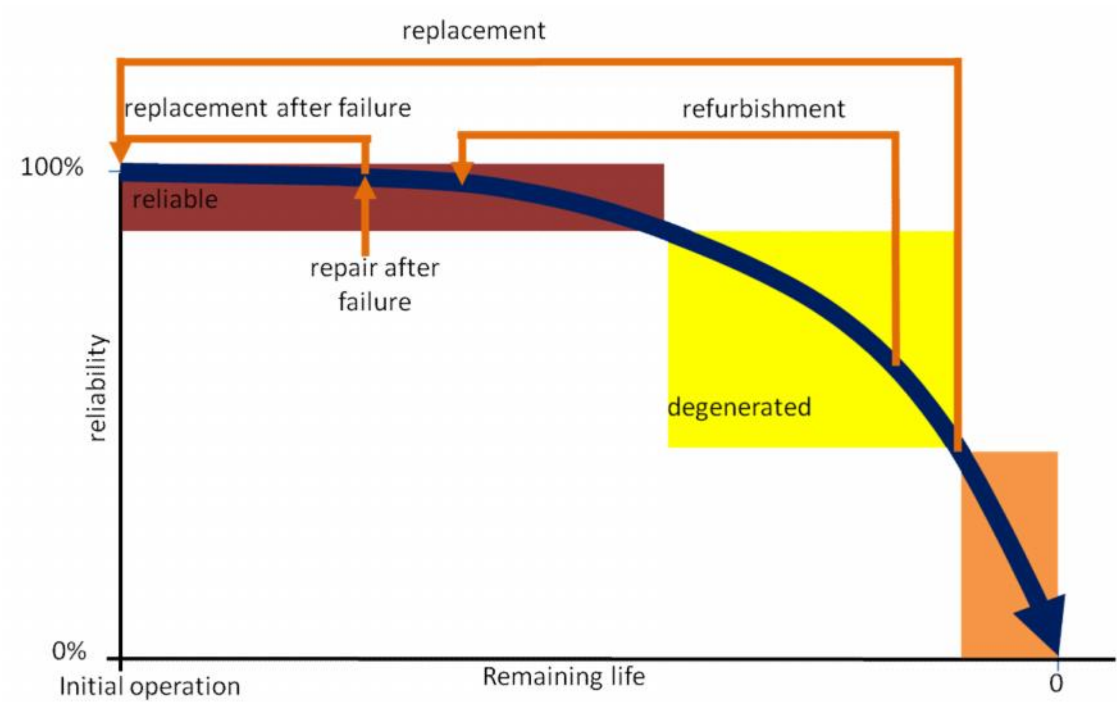

Figure 1: Simple ageing model for asset assessment

3. LIFE MANAGEMENT OF POWER TRANSFORMERS

Faults and defects processes in equipment are usually very complex. So, series of related data are gathered to establish the life model of transformer. Growing pressure over Nigerian government's handling of efficient electricity supply and customer satisfaction is placing asset engineering in a background role in electricity transmission and distribution. Preventive maintenance strategy is deployed in the management of power transformer to prevent failures and significant damage or even destruction of power equipment. Time-based maintenance (TBM) is the easiest preventive maintenance strategy. This maintenance plan is performed at fixed time intervals. The time intervals are chosen based on equipment manufacturers' specification or based on expert experience. However, Situation may arise where serious fault can build up before the schedule time for maintenance. This could result in costly damage or irreversible time bomb situation with degree of asset condition degeneration that could result in explosion of power stations [1]. In recent years, interest has shifted towards real time monitoring of transformer where the condition of the system can be simultaneously assessed while in service. This maintenance plan as shown in figure 2 is triggered by the estimated condition reaching certain thresholds and can lead to higher network reliability with moderate maintenance cost.

In Nigerian power sector, the current practice in the management of power transformer is the corrective maintenance strategy where the equipment is operated till it breaks down before it is decided whether the equipment should be repaired or replaced. This put the electricity end users in blackout pending when the equipment is restored. This strategy appears to have the lowest cost of maintenance, but the damage caused by the failure may result to higher cost compared to a more appropriate maintenance system is adopted [19]. The modern practice in electric power industry is fitting of monitoring and diagnostic systems in power equipment

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while in operation. These systems are used for surveillance of the service conditions of the power equipment. The parameters monitored by this system include: Gas and humidity content of the oil, oil temperature and oil level, temperature of the ambient air and of the cooling medium, service voltage and current, overload, partial discharge (PD) as far as measurable, tap changer position, torque movement of the OLTC motor drive etc. [15, 21-23].

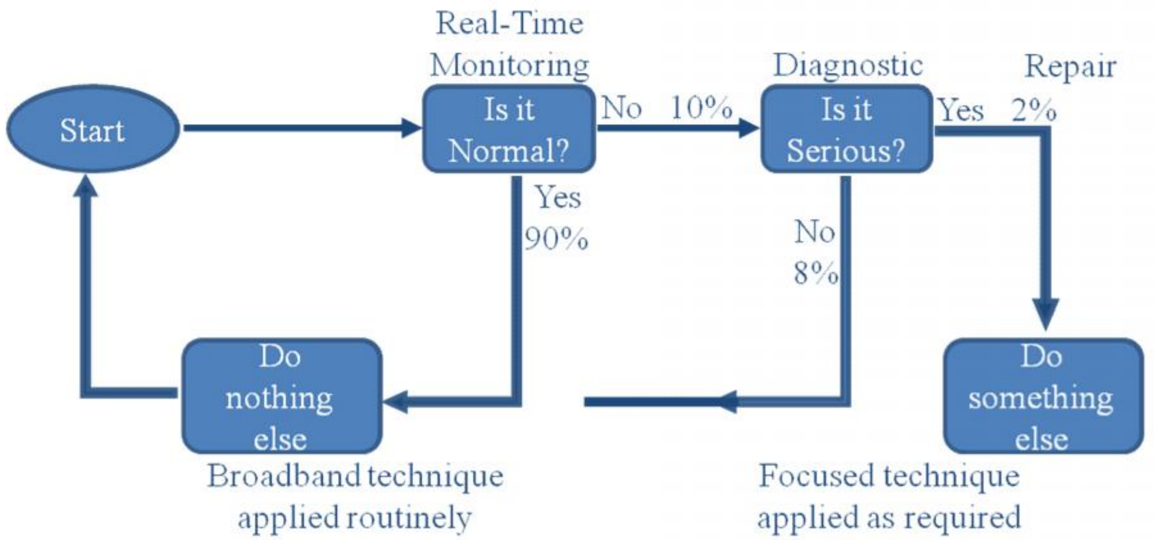

Figure 2: Block diagram of Real Time Monitoring and Diagnostics System

The life time of transformer is dependent on the load on the system, environmental conditions of the system, ageing and maintenance of the system. Performance and ageing model can be establish using factors such as accelerated stress, degradation agents, and simulated ageing products. A system that can monitor the state of transformer components while in operation can extend the life time of power transformer. Therefore, life management of power transformers should include establishing a maintenance standard for power transformer.

The most important test to determine the condition of a transformer is the dissolve gas analysis (DGA). It can serve as a monitoring system to detect incipient problem as the oil carries the discharged gases resulting from degradation reactions. A data base knowledge has been developed in an attempt to identify the type of fault and severity from the ratio of individual gasses [13]. Deteriorating solid insulation, insulating liquid, partial discharge (PD), and arcing can be identified. This test can be performed on-line and off-line. Cellulose degradation produces chemical compounds and gases that dissolve in oil. These chemicals include furans which are dissolved in the oil. The level of deterioration of cellulose Insulation paper can be assessed on-line to determine the state of the material [19]. This involves determination of the level of furans in the oil. If the on-line monitoring triggered a defect alarm, several other investigation tests are performed to determine the type of problem and the severity. Detection of abnormality may result in off-line test to determine the extent of the system deterioration. Partial discharge (PD), winding resistance, magnetizing currents, frequency response analysis (FRA), and polarization spectrum (recovery voltage) measurements are example of off-line tests often performed for transformers diagnosis. Degree of depolymerisation (DP) of cellulose insulation is one of the most dependable off-line tests to determine the extent of paper deterioration and remaining life time of solid

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insulation. As the paper ages the linked glucose rings begin to break, leading to a decrease in the degree of depolymerisation. Typical new cellulose insulation has a DP of 1200 - 400. As it decreases to 200, the solid insulation has approached end of life time and power equipment with such insulation need to be replaced [24, 25].

The obtained measurement results from the multitude of different methods are integrated with IT systems, data base and expert knowledge on equipment deterioration to execute the asset management task. The testing-monitoring-diagnostic management system in figure 3 is realize using the modern IT tools for prophylactic diagnostic of insulation conditions of transformers under surveillance [22].

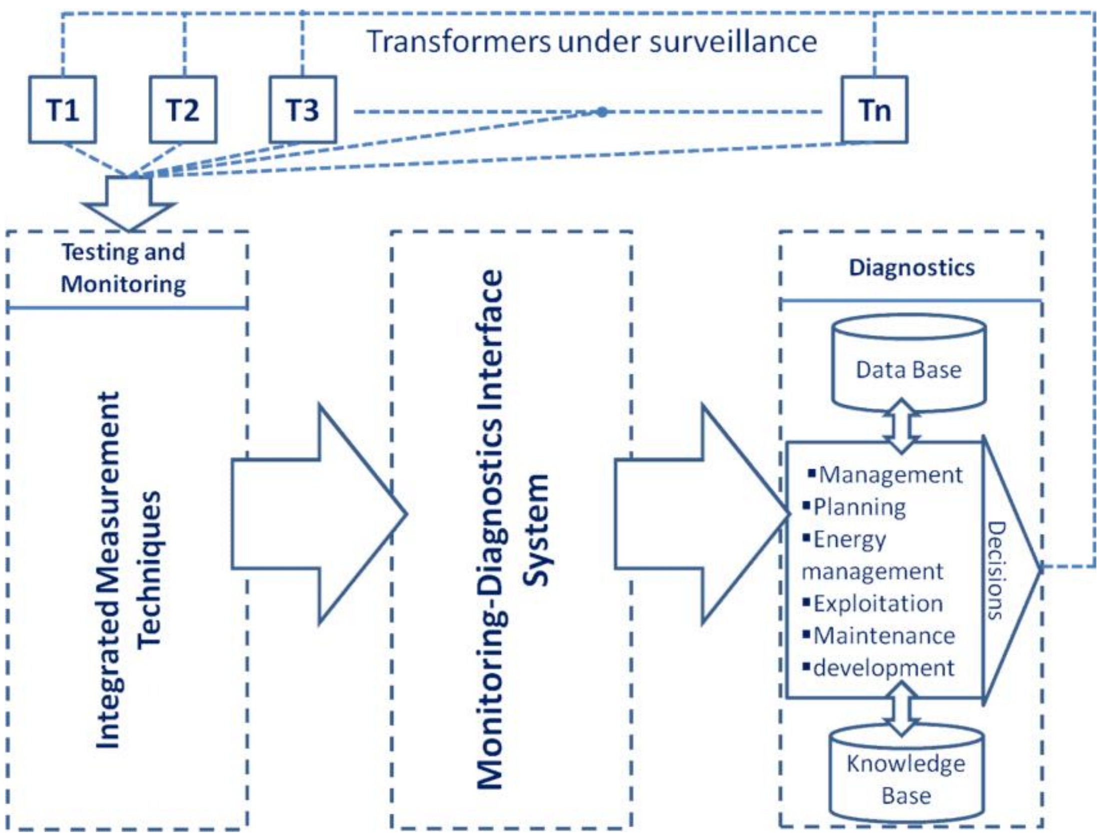

Figure 3: Testing-monitoring-diagnostic management system

4. THE RELEVANCE OF TRANSFORMER LIFE MANAGEMENT IN NIGERIA

Oil-filled power transformers are very important components of electrical transmission and distribution network. Their bushings, tap changer, and insulation system are critical to the operation of the power equipment. Their reliability and uninterrupted operation is a key factor in profitable generation, transmission and distribution of electricity. In the past years, on-line condition monitoring of power transformer has being adopted for asset management in many countries around the world to increase electricity availability and optimize operating management. One of the reported success stories is a report from a group in Germany [26].

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Critical damage of a 350 MVA grid coupling transformer was avoided by detection of a partial flashover of layers of a bushing indicated by a change in the bushing capacitance. Collateral damage was avoided by detection of an oil leak on a 850 MVA generator transformer by means of monitoring the bushing oil pressure. Operating condition of a 75 MVA furnace transformer was made transparent by monitoring the condition of the transformer from beginning of a fault until collateral damage. The monitoring system provided advance information before system failure. Another report on the intensive monitoring of two 275/132kV 180MVA transformers at a substation in the UK using multi agent system technology shows an enhanced estimation of the transformers health. This system integrates various diagnostic and anomaly detection modules, with data from approximately 50 sensors captured every five minutes. The integrated system was combined with knowledge-based method to interpret the obtained data from the site [23].

Experience from on-line management system shows that defects building up in power transformers while in operation can be detected earlier with the deployment of an efficient on-line monitoring system. This reduces the potential of transformer endangerment in the field. On this note, High Voltage Engineering experts and Materials Scientists in Ahmadu Bello University, Zaria, Nigeria, in collaboration with renowned High Voltage experts in the UK has initiated a pioneering asset engineering project in Nigeria. This project is focusing on life management of power transformers in transmission substations and distribution stations. It seeks to address the transformer insulation failure that is often responsible for the frequent breakdown of electric power equipment. This will be achieved by developing a real-time condition monitoring system that will be based on integrated technique. Integration of different measuring methods can serve as sophisticated tools to take decisions on the operation of the transformers. The designed monitoring system as illustrated in figure 4 will be deployed on an approved substation transformers. Real-time information will be obtained from the installed sensors in the power equipment under surveillance. The analysis and interpretation of the acquired information will be performed using a developed artificial intelligence system (AIS). The AIS will combine expert system and artificial neural network to detect known types of faults based on expert knowledge, assesses the transformer condition, locates the position of the fault, and recommend the required maintenance necessary to put the equipment in order. The monitoring system will further be deployed to other substations and the obtained information will be transported from the substations through the utilities network to monitoring centres. Asset managers and field engineers will have the opportunity to connect to the data base to obtain information and effectively assess the technical condition of their field equipment for the purpose of production planning, investments, repairs and other activities. This work will enable the overall migration of Nigerian power asset management system from the so-called “corrective maintenance strategy” which is costly to Condition-Based Maintenance (CBM) and Reliability-Centered Maintenance (RCM). This will ensure that decisions on power assets are taken based on account of the actual condition of the equipment and the level of reliability required to fulfil its function, rather than decision driven by an average timeframe defined by observations and past experience.

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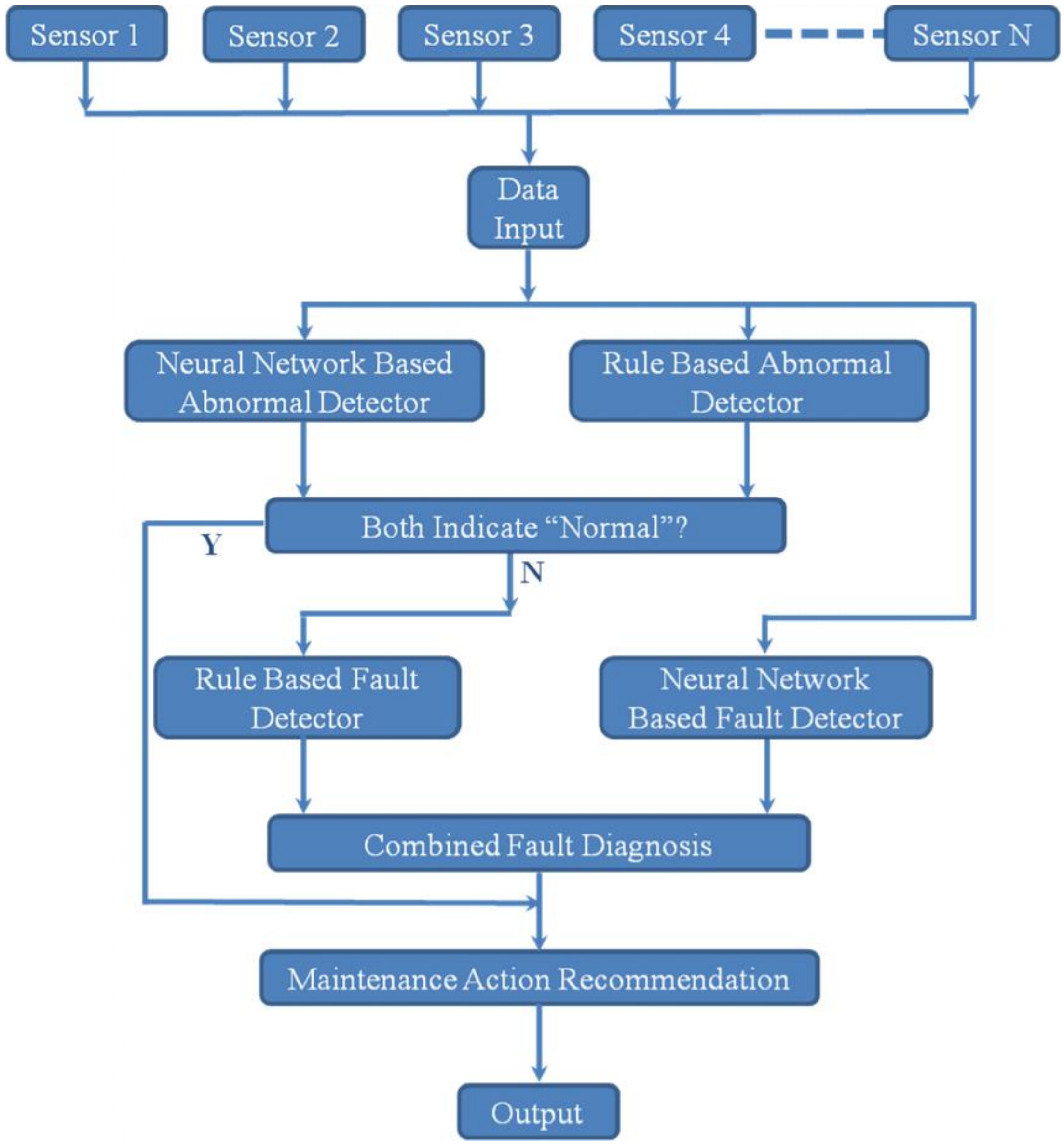

Figure 4: Schematic Diagram of Transformer Life Management System

5. SUMMARY AND CONCLUSION

A review of modern chemical, physical and electrical diagnostic techniques for the assessment of transformer useful life have being attempted in this paper. Dissolve gas analysis (DGA) is the most often used technique for the assessment of incipient faults. While transformer oil carry information that can be used to evaluate the condition of transformer, Furan and degree of polymerization (DP) measurement are widely used for monitoring cellulose mechanical strength. Solid insulation serve as mechanical support in transformer, loss of mechanical support can lead to breakdown of power transformer.

The state of electric power facilities in Nigeria calls for a more effective asset management system that will reduce the cost of asset management and meet the need of electricity end

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users. A reliability-centered maintenance strategy is being developed for Nigerian power industry with the capability of inquiring about incipient defects in transformers and provides advanced notice of such fault for necessary remedial action. It is anticipated that the project will produce first documentation on the performance and reduction of failure rate of power transformers in Nigeria. Proper management of power equipment will ensure effective utilization of the generated electricity in Nigeria. The project also seeks to create a database on component damages and outages in the country. The transformer knowledge database will not only allow the determination of component reliability indices, but in particular the analysis of the influences of component age and maintenance history. This will serve as an effective guide for transformer operators, field engineers and asset managers across the country. The obtained information about the health condition of a transformer will enable field engineers and asset managers take decisions on the disposition of transformers without additional consultation, testing, and analysis. The database from the forensic analysis of components of failed transformers will help in the development of typical failure and ageing model. This library will capture and share the obtained transformer failure information. It will be a multi-year project and the information obtained on yearly basis will be used to update the developed library. The obtained forensic results will be made available in a searchable format that will enable the beneficiaries to focus on the forensic results that is directly related to the particular situations of a transformer. This will improve decision making on replacement or refurbishment of transformers

The development of a centralize Artificial Intelligent System for monitoring substations will enable asset managers and field engineers receive regular information on the status of field equipments in operation. The obtained information about the health condition of a transformer will enable decisions on the disposition of transformers without additional consultation, testing, and analysis. Up-to-date information on the state of power equipment will limit unexpected interruption of power supply, reduce equipment failure rate, reduce cost of maintenance and repair of power equipment, reduce cost of collateral damage and will improve service delivery to electricity end-users.

COMPETING INTERESTS

There is no competing interest.

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