Buletin Teknik Elektro dan Informatika
(Bulletin of Electrical Engineering and Informatics)
Vol. 2, No. 2, June 2013, pp. 95~104
ISSN: 2089-3191

Recent Trends in Power Transformer Fault Diagnosis and Condition Assessment

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Abstract

Power transformers are interface between different voltage levels of essential importance. Because of the long manufacturing processes, transformers are one of the most critical and expensive equipment and so this is one of the reasons why condition monitoring becomes more popular. Monitoring systems as basis for diagnostics open the possibility for expanding the operating time, reducing the risk of expensive failures and allows several maintenance strategies. With different monitoring techniques, detailed informations about the transformer condition can be received and helps to minimize the probability of an unexpected outage. In this paper a methodology has been developed to use information derived from condition monitoring and diagnostics for rehabilitation purposes of transformers. The interpretation and understanding of the test data are obtained from the International Standards.

Keywords*: transformer, fault diagnosis, aging, dissolved gas analysis, condiion monitoring*

1. Introduction

Generally power transformers are one of the most important but also very expensive components in the electrical power supply system. An unexpected outage results in substantial costs mainly caused by the outage of the power station. Therefore a huge interest for monitoring and diagnosis systems to evaluate the condition of the transformer [2-15] is given. Different on-line and off-line monitoring systems are in use. The most common insulating system for transformer is the oil-board insulating system. The oil and the board are organic components and underlie aging, which depends mainly to the operating condition [11-15,17]. Deterioration processes relating to aging are accelerated by voltage and thermal stresses.

A defect in transformers can be caused by electrical, electromagnetic, dielectric, mechanical, thermal and/or chemical load (stress). The typical failure distribution of high voltage transformer shows that the highest risk for failure are the tap changer, windings and the core as well as the bushings. For a check of the transformer condition, different diagnostic methods are available and use chemical, mechanical, optical, thermal and electrical methods.

With these methods of technical diagnostics it is possible to record typical values, from which conclusions can be drawn about the future operational behavior of transformers. The conditions of transformers are the important inputs to the technical and economic models used to determine the most cost-effective alternative for operation, refurbishment or replacement.

2. Causes of Failure

The main components of power transformer are the windings, bushings, transformer oil, core, tank, cooling system, and tap changer. Failure analysis of large power transformers can be beneficial in determining which component is more important in evaluating the condition of transformers. Statistics [8] show that the most frequent causes followed by long outage damages are in tap changer, active component and in bushings. Table 1 shows percentage of failure in of power transformer.

Received November 20, 2012; Revised January 17, 2013; Accepted February 15, 2013

Table 1. Percentage of Failure of Power Transformer

Condition	Failures With OLTC	Failures Without OLTC
Tank	6%	17.4%
Tap Changer	40%	4.6%
Winding + Core	35%	33%
Auxiliaries	5%	11%
Bushing + Terminals	14%	33.3%

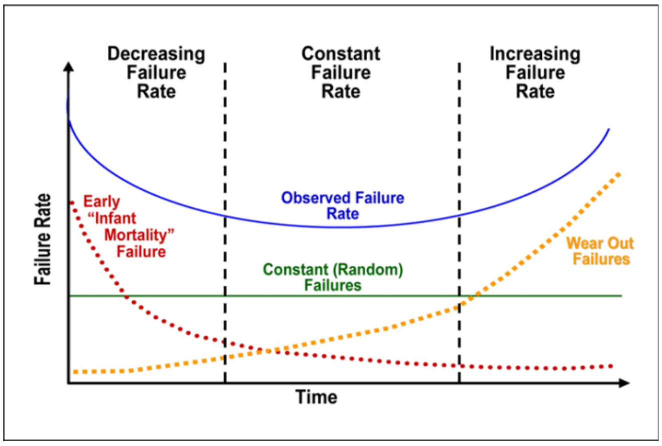

Figure 1. Power Transformers Failure Bath-tub Curve for [9]

On the bases of CIGRE report, the failure pattern of power transformers follows a "bath-tub" curve for 400 transformers, as shown in Figure 1 [9].

Table 2. Component-wise Failure of Transformers & Reactors-worldwide-Survey

Component	CIGRE Survey	IEEE survey-1986	EPRI 1991 Survey	Australia-New Zealand Survey 1985-95	Doble Client Survey-1996-98	ZTZ Services 2000-05-GSUs	ZTZ Services 2000-05-Transmission	PGCIL: AC Power Transformers	PGCIL : Shunt Reactors
Windings	27.6 %	41 %	21 %	30%	13.4%	11.2 %	17.3%	6 (23 %)	10 (44.45%)
Magnetic Circuit	5.2 %	10%			5.8 %	4.4%	9.5%	2 (7.69%)	
Bushings	32.8 %	13%	30 %	19%	9.6 %	13.3%	38%	12 (46.15 %)	6 (27.2%)
Tank & Di-electric fluid	17.2 %	3%	17.2 %	-		-		-	
Tap Changers (OLTC)	13.8 %		13.8 %	25 %	15.4 %	4.4 %	7.9%	4 (15.38 %)	
Other accessories	3.4 %	17%	12 %		6.9 %	-	-	2 (7.69 %)	6 (27.2 %)
Total		164	45 xer	498	52/22.4	45/21	63/20.5	26	22

The first part of the curve is failure due to infant mortality; the second part of the curve is the constant failure rate; and the last part of the curve is failure due to aging. The numbers of transformer failures in the second part is greater than the last part. The premature and unexpected failures in transformers can be caused due to the following stresses:

a) Electrical stresses
b) Electromagnetic stresses
c) Dielectric stresses
d) Thermal stresses & Chemical stresses

3. Condition and Monitoring of Power Transformer

Here, we have designed a FMEA process (failure mode and effect analysis) based on priority list which is helpful to establish a detailed asset management strategy for diagnostic testing and condition assessment. The importance of diagnostic methods can recognize which diagnostic parameters affect the transformer condition to a greater or lesser degree than other parameters. Figure 2 shows the importance of different diagnostic methods for the estimation of transformer conditions.

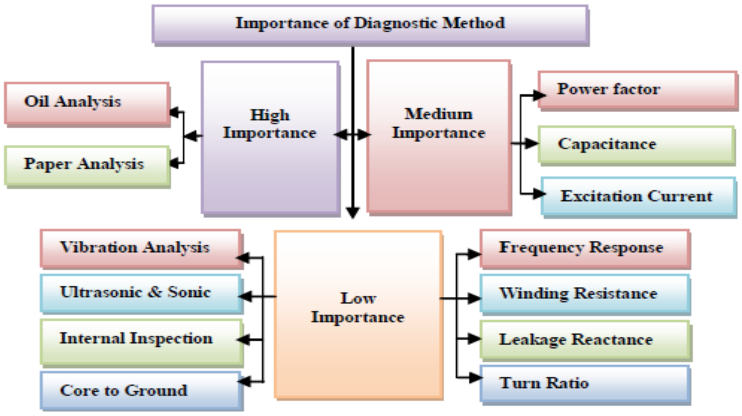

Figure 2. Importance Level Modal of Various Diagnostic Methods for the Evaluation of Transformer Conditions

Routine tests of transformer are carried out on all units on a periodic basis for protecting to detect incipient failure and indicate general condition. Type tests and Special tests are applied only as required for diagnosis and detailed assessment Statistics in [10].

4. Diagnostic Methods for Power Transformer

The most common insulating system for transformer is its oil-board insulating system. Basically the oil and the board are organic components and underlie aging, which depends mainly on the operating condition of transformer. Deterioration processes relating to aging are accelerated by voltage and thermal stress.

Diagnostic Methods for a transformer are broadly categorized into four parts:

a) Chemical Diagnostic Methods
b) Electrical Diagnostic methods
c) Optical/Thermal Diagnostic Methods and
d) Mechanical Diagnostics Methods

4.1. Power Transformer Diagnostic by Chemical Methods

Due to generation of high sensitivity sensors and techniques, chemical diagnostic methods are become more effectively. In the chemical methods oil analysis (i.e. Furan value, Moisture, Neutralization value) and Dissolved gas analyses (DGA) are carried out.

4.1.1. Online Dissolved Gas Analysis by Gas-Chromatograph

The production of organic gases such as methane, ethane, ethylene, propane, acetylene, and propylene as well inorganic gases such as hydrogen, carbon dioxide and carbon monoxide, in the insulating system of the operating transformers in alarming proportions in indicative of fault occurrence. These faults may lead to the breakdown of the equipment. Some of the faults that can be indicated by the production of particular gas are given bellow:

a) Acetylene in major concentration indicates arcing
b) Ethylene indicates over heating
c) Hydrogen with considerable proportion indicates partial discharge.

d) Methane with considerable proportion indicates partial discharge.
e) Carbon dioxide and carbon monoxide indicates the involvement of solid insulation in the fault.

Figure 3. Kelman Transport-X DGA Analyzer

Now it has been found that the quantitative analysis of the above mentioned gases is more reliable & far more sensitive that hazards fault detection devices, Such as bucholtz relay & differential relay. For quantitative gas analysis gas chromatography is one of the most sensitive commonly used techniques. Gas chromatography should be done online bases regularly while the transformer energized. The result of gas analysis provides an inside about incipient fault. Corrective action may be taken for preventive maintenance. This technology is however more useful in the case of power transformer but can be equally effective in the distribution transformer.

4.1.2. Furan Analyser

The Cellulose insulation has a structure of long chain of molecules. The cellulosic paper contains about 90% cellulose, 6-7% of hemicelluloses and 3-4% of lignin processed by the Kraft chemical process (Kraft in German is used for strong). Cellulose is a polymer of alpha-D-glucose units linked to one another in a special manner. It may be represented simply as [$C_5H_{10}O_5$], where n is the degree of polymerization (DP). The DP of paper can be determined using ASTM method D-4243. Generally, DP lie in the range of 1100-1600 for new paper but its value can drop by 10% after drying and oil impregnation [11]. The DP range of Kraft pulps varies from 110 to 1200, for mixed pulp fibbers it varies from 1400 to 1600 [12]. Middle aged and old aged paper have DP around 500 and <250 respectively. Correlation between Furan Concentration and DP are shown on Table 3. If the cellulose has DP around 200 or below [4], it is basically a power without significant mechanical strength and considered to be the end of useful life.

Table 3. Correlation between Furan Concentration and DP

Total furan level (ppb)	Range of DP	Recommended retest period (Months)
100	444-1200	12
101-250	333-443	6
251-1000	237-332	3
1001-2500	217-236	1
>2500	<217	Failure likely

Cellulose degrades slowly as the polymer chain breakdown during its service, releasing degradation products into the oil. The paper eventually degrades to such an extent that it loses all its mechanical strength which puts the electrical integrity of the equipment at risk. The damaged paper cannot provide adequate physical support for the windings and this may lead to premature failure. The rate of change of furan concentration can indicate the rate of aging of paper. The degraded paper insulation can be analyzed by the content of furanic derivatives present in the oil. Like DGA, 2-furaldehyde (FAL) is also an important diagnostic test. Other furanic derivatives are 5-hydroxymethyl-2-furaldehyde, 2-acetyl furan, 5-methly-2-furaldehyde, furfural alcohol, 2-furoic acids, which are produced in much smaller quantities when transformer paper degrades thermally. Furan concentration is sensitive to operating temperature, transformer loading, transformer design and concentration of moisture and oxygen in contact with the cellulose. Correlation of 2-furaldehyde with DP has been expressed by the following set of equations:

$$DP = \frac{1.51 - \log F}{0.0035}, Chendong[12] \tag{1}$$

$$DP = \frac{1.71 - \log F}{0.00288}, Scho\ln ik[13] \tag{2}$$

$$DP = \frac{800}{(0.186 * F) + 1}, Pohlavanpour[14] \tag{3}$$

$$DP = \frac{7100}{8.88 + F}, DePablo[15] \tag{4}$$

Where F is 2-furaldehyde concentration in the equation [1] is best used to estimate an average DP in transformer having Kraft paper insulation with free breathing conservator. For other insulation and preservation systems the equation can be used to estimate paper degradation from thermal events.

The main drawback of furan analysis is that when transformer oil is replaced or refurbished, the analysis of furans in the refused oil may not show any trace of degradation, although the cellulose may have degraded significantly.

4.1.3. Water in Oil Analyser

Another important oil analysis is the determination of water contents present in the insulating oil. Since the cellulose insulation used in power transformer is known for producing water when it degrades, so water in oil indicates extent of paper aging. A sample is taken from the transformer and the test is performed in the laboratory. Hence usually the Karl-Fischer titration is used which is standardized. The water content of oil can therefore be used for the determination of paper degradation. There is a correlation between the water content in oil and the water content in paper for the condition of equilibrium [15]. If the transformer is warm, the moisture migrates from the solid insulation into the fluid and as the transformer cools, the moisture returns to the solid insulation at a lower rate. These day on line water contents analyzers are also available for monitoring water contents in oil insulation.

Figure 4. Moisture in Oil – Test Sensor

4.2. Electrical Diagnostic Methods

4.2.1. Sweep Frequency Response Analyser (SFRA)

Frequency Response Analysis (FRA) testing makes a qualitative assessment of the mechanical condition of the transformer core and winding. The loss of mechanical integrity that may occurs due to large mechanical forces, fault current, winding shrinkage result in release of clamping pressure, transportation and relocation etc. A power transformer would experience large number of short circuits during its service life. Due to short circuits, there could be winding moment which changes its winding inductance and capacitance. Other mechanical faults occur is in the form of displace winding, hoop buckling, winding moment, deformation and damaged winding. These changes can be detected externally by low voltage impulse method or FRA method. It is therefore desirable to be able to check the mechanical condition of transformer periodically during their service life.

In the FRA technique, a low amplifier swept frequency signal is applied at the end of one winding and response is measured at the other end of the winding with one phase at a time. The method is based on the fact that every transformer winding has a unique signature of its transfer function which is sensitive to change in resistance, inductance and capacitance. Difference in signature of the responses may indicate damage to the transformer which can be investigated further using other techniques or by an internal examination. Several utilities have considered this test as benchmark for newly installed locations of Power transformer to ascertain mechanical integrity of the entire structure intactness before energizing at new location & prevent catastrophic failure [3].

4.2.2. Oil Testing by UV-VIS Spectroscopy

Apart from normal prevailing testing procedures with regards to ascertaining the electrical insulating quality of in use - insulating oil of the transformers i.e. Physical appearance, colour, density, electric strength, moisture content, gas content acidity, sludge inhibition content, flash point, power factor and insulation resistance that have been in practice by utility engineers for electric health assessment indicators, recently new techniques of UV-VIS Spectroscopy is also being suggested for knowing the degree of degradation of In–service oil filled transformers [4-7].

a) Spectroscopy is the study of the interaction between radiation and matter as a function of wavelength (λ) or frequency (v).
b) Spectrophotometer: A spectrophotometer is device that being which measure the intensity of the light as a function of the light source wavelength.
c) Spectrophotometers use a Monochromators containing a diffraction grating to produce the analytical spectrum
d) UV/VIS analyzer is used to the analysis of the relative content of dissolve decay in the insulation oil, according to ASTM standard.
e) UV Fluorescence is applicable for the sulphur analysis of insulation oil.

This is the linear relationship between absorbance and Concentration of an absorbing Species. The general Beer-Lambert law is usually written a: Lambert – Beer's Law.

$$A = a * b * c \tag{5}$$

Where:

a: Absorbance Constant
b: Sample Path length,
c: Sample Concentration,

Experimental measurements are usually made in terms of transmittance (T), which is defined as:

$$T = {}^{It}\!/_{Io} \tag{6}$$

Where *It* is the light intensity after it passes through the sample and *Io* is the initial light intensity. The relation between A and T is:

$$A = -\log T = -\log({}^{Io}\!/_{It}) \tag{7}$$

The basic concept behind all above methods is the idea that calls for either continuous or periodic monitoring of all key performance affecting parameters of the transformer. Any departure from its normal value indicates a fault condition which needs utmost attention to circumvent faults of all sorts & help prevent catastrophic failures. The brief details of above methods are enumerated below:

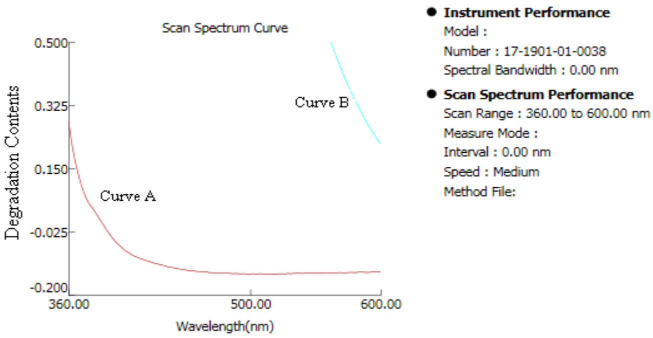

Figure 5. Dissolved Decay Content of Insulating Oil

4.2.3. Dielectric Dissipation Factor (DDF) or Tan Delta ($\tan\delta$)

Tan delta is an important property determining the insulating condition of power transformer. It can detect the insulation integrity in winding, bushing, arrester, tank and oil. When an AC voltage is applied to the insulation, the leakage current flows, which have two components, resistive and capacitive, as shown in Figure 6. The power factor $(\cos\theta)$ is dimensionless ratio of resistive current (Ir) to total current (It) flowing through the insulation. The dissipation factor or $\tan\delta$ is a dimensionless ration of the resistive current (Ir) to capacitive current (Ic) flowing through the insulation. Del (δ) is represented as loss angle.

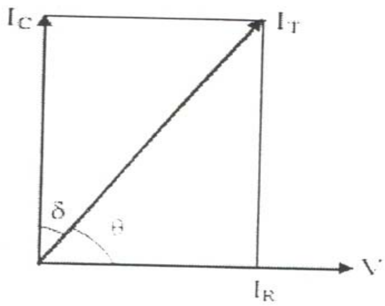

Figure 6. Tan Delta Representation

As per ASTM D 924 [16], tan delta or power factor is a measure of the dielectric loss in an electric insulating liquid when used in an alternating field. Tan delta may be useful as an indication of change in insulating quality resulting from contamination and deterioration. A low value of tan delta indicates low AC dielectric loss. The loss characteristics may be expressed in terms of decimal or in percentage. For decimal values up to 0.05, $\tan\delta$ or $\cos\theta$ values are equal to each other. The exact relationship between $\tan\delta$ and $\cos\theta$ is given by following equations:

$$Cos\theta = \frac{\tan\delta}{\sqrt{1+\tan^2\delta}}, or \ \tan\delta = \frac{\cos\theta}{\sqrt{1-(\cos\theta)^2}} \tag{8}$$

As per IS 335, tan delta at 90 centigrade is 0.002 (max) for fresh oil and according to IS-1866, it varies from 0.010 to 0.015 (max) at 90 centigrade depending upon the rating of power transformer.

4.2.4. Breakdown Voltage (BDV) Testing

According to the IEC 60156 specification, Breakdown voltage (BDV) measurements are achieved at room temperature. The BDV measurements are conducted on oil samples having no particles larger than 100 µm. So, the influence of the particles is considered as being negligible with respect to the class of particulate pollution we obtained for each sample [17]. The IEC 60156 method is not sufficiently sensitive to oil particle contamination [18] to be influenced by particles of this size present in the samples. The BDV results are characterized by means of the cumulative Gaussian probabilities approach, which is the most appropriate method.

4.2.5. Partial Discharge (PD) Measurement

Partial discharge is a localized discharged process i.e. insulation partially punctured. PD occurs in transformer in gas bubbles in the oil, cavity or voids in solid insulation material. Partial discharges have only a “short time effect” on the electrical firmness of electrical resources. The PD measurement is an important method to detect and locate a weak spot in the insulation system to assess the life expectancy of the insulating materials. The partial discharge activity is the most prominent indicator for insulation degradation.

The measurement according to the IEC 60270-S2-10 is a useful tool for laboratory measurement because it is a sensitive method, but on-site measurements can be affected by disturbances. .PD on insulation can be measured not only by electrical methods but by optical, acoustic and chemical methods also. Digital technique [19] is resent trend for PD measurement.

4.2.6. Thin Film Capacitor Sensor

The Polarization and Depolarization Current (PDC) Analysis is a non-destructive dielectric testing method for determining the conductivity and insulation humidity (moisture content) of insulation materials in a transformer. Thin film capacitor, popular to be used for on-line monitoring applications for humidity measurements. It is represented in Fig.8. With its electrodes and the liquid stream. The paper used in the sensor should be identical with the paper used as the transformer insulation. A measurement of the capacitance and the conductance in the sensor directly gives the humidity content of the paper, which further derive the humidity of the paper insulation from which the electrical and mechanical performance could be evaluated. A preliminary study revealed that most of the thin film sensors that perform well in air are not suitable in hot transformer oil due to poor response, instability and fluctuations [20].

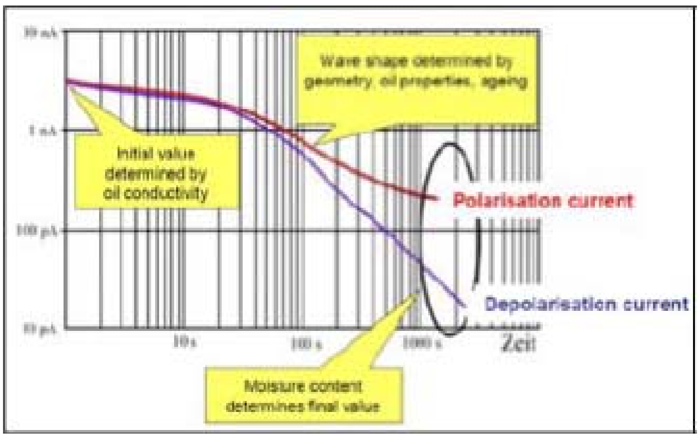

Figure 7. According [21] PDC Measurement of a Transformer Winding

Another method for investigate the slow polarization processes is the recovery voltage method (RVM).

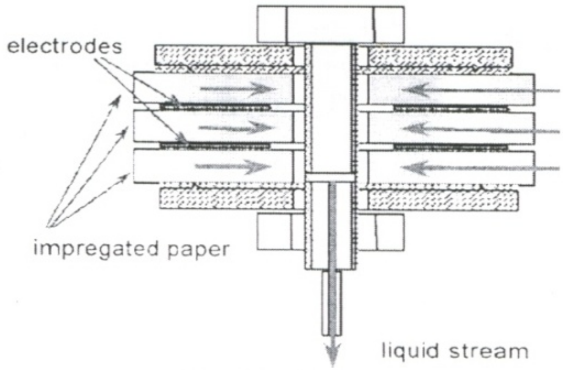

Figure 8. Humidity Sensor Using Thin Film Capacitor [20]

4.3. Optical and Thermal Diagnostic Methods

Both optical and thermal diagnostic methods are using the electromagnetic spectrum between 104Hz up to 1016Hz as information source. In this diagnostic methods Thermography, Temperature monitoring and routine inspection are carried out.

4.3.1. On Line Winding Temperature

Temperature of hot spot is measured by use of fiber optic technique embedded inside the H.V. winding. It has advantage lies in its direct measurement. The accuracy depends on the transducer used.

4.3.2. Thermography

Thermography is a technique to extend the human vision in to infrared region of electromagnetic spectrum. Normally infrared radiations are visible to human eyes for temperature bellow 800k. Thermography widens the total field of human vision and permit presentation of thermal range in real time of the object at temperature range of 250k to 2000k. The system consists of a scanner and display unit. The infrared radiation emitted by a source are received by scanner and transmitted through its optical system to detector. The detector cooled by thermoelectric couple (100K) converts the infrared radiation to video signal which is proceed and displayed as a line B/W picture on screen of the display unit.

4.4. Mechanical Diagnostic Methods

In the mechanical diagnostic methods acoustics test for vibration and dynamic test (for transformer oil pressure and oil stream) are carried out.

According to IEEE Standard C57.140-2006 [22], Vibration can result from loose core and coil segments, shield problems, loose parts, or bad bearings on oil cooling pumps or fans of transformers. If wedging has been displaced due to paper deterioration or through faults, vibration will increase markedly. It may also show if an internal inspection is necessary for transformers. Information gained from the vibration test supplements ultrasonic and sonic (acoustic) detection and DGA tests. The analysis can be made on line.

5. Conclusion

The asset management is a method for obtain the maximum of information by a minimum of expenditure from selected measuring and test methods as per corresponding acquisition of International Standards (i.e. ANSI/IEEE, IEC, ASTM and CIGRE). Standardization will make it easier to integrate data from sophisticated monitoring systems on transformers into asset management of transformers.

Presented transformer diagnostic model can improve the reliability and repeatability of the analysis of test data. It can also be used to extract information that is not available from the data directly. This systematic approach can not only help maintenance staff, but also managers to generate sound business cases for investments, to prioritize projects for operation and maintenance budgeting and to manage risks for the future and would definitely increase the life of transformer.

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