# MONITORING AND DIAGNOSTICS OF POWER TRANSFORMER INSULATION

by

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*Liberalization of the energy market drives utilities to a more cost-effective power system. Power transformers are the most complex, important, and critical components of the transition and distribution power systems. Insulation system is the key component of life extension, better availability and higher reliability of a transformer. In order to achieve both decreasing operational cost and reliable service condition-based maintenance is needed. Monitoring and diagnostics methods and techniques, for insulation condition assessment of power transformers, are described. Date base and knowledge rules diagnostics management system, in internet oriented environment, is outlined.*

Key words: *transformer, insulation, monitoring, diagnostics, date base*

## Introduction

Significance of testing, monitoring, and diagnostics the condition of transformers insulating system is growing every year, together with the growth of production, transition, distribution, and consumption of electricity. Historically, since Nikola Tesla's concept of alternating current has definitely won the concept of direct current, the importance of transformers for power supply system has developed commensurably. It has been a century since Nikola Tesla introduced his patents of generators, transformers, and motors of alternating currents in the USA in 1888. Transformers and systems for their testing, monitoring, and diagnostics have developed together with the power supply systems. Figure 1 shows the development of methods for transformers testing and monitoring, from the first measurements which included defining the insulating resistance and oil dielectric breakdown voltage (fig. 1a) up to modern examinations which include dozens of measuring methods and procedures (fig. 1b).

Competitive electric energy market drives utilities to adapt to a lot of changing technical and economical requirements. Deregulation measures have created an increasingly competitive working environment which has to lead to a more cost effective power delivery system. Also, more high voltage installations and transformers have reached a service life of over 40 years, so the fraction of equipment in the terminative stage of operation increases. The "aging wave" of the electrical infrastructure due to installation of nu-

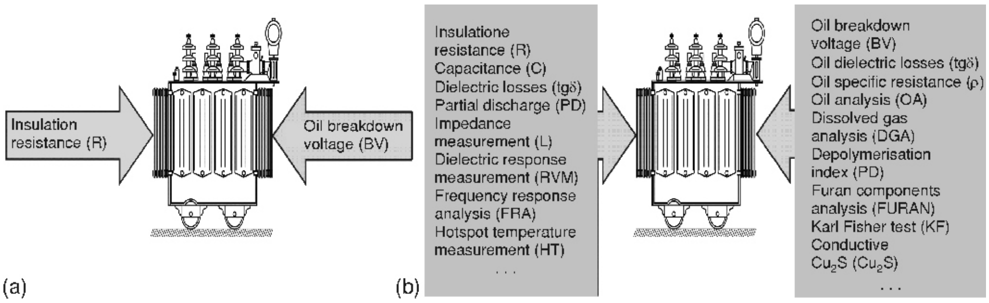


**Figure 1. Development of monitoring and diagnostics of transformer insulation**

merous high voltage substations in the 1960s and 1970s has its implication on the "unexpected" failure and nonaviability of the electrical system [1]. To meet these challenges, the electrical power company in the world is now making the transition from the conservative corrective and time based strategies toward condition based maintenance (CBM). This need for CBM has encouraged the development of adaptable and cost-effective diagnostics. Manufacturers, utilities, technical Universities, and Institutes have developed a wide range of diagnostics procedures to detect loss of life or functionally faulty or defective conditions [2].

Core, windings, insulation oil, bushing, and on-load tap changer are the main active parts of the transformer insulation chain. The degradation of insulation systems is accompanied by phenomenon of changing physical parameters or behavior of insulation components. Moreover, the degradation of insulation systems is a complex physical process. Many parameters act at the same time thus making the interpretation and diagnostics extremely difficult. Using the benefits of modern IT-technology like intranet, internet, data base, and knowledge rules the distribution of information about the condition of the transformers can easily be done by means of standardized web browser technology.

## Quality of transformer insulation

Winding solid (paper) insulation, insulation oil, bushing, and on-load tap changer systems are the main active parts of the transformer insulation chain, as shown on fig. 2. The aging and degradation of insulation systems are accompanied by phenomenon of changing physical parameters or the behavior of insulation system. The degradation of insulation system is a complex physical and chemical process where oil insulation processes influence on paper insulation and *vice versa*.

The aging process in the oil/cellulose insulation system under thermal stress and their measurable effects are due to chemical reactions in the dielectric. The temperature of the oil/paper dielectric is the critical aging parameter to cause enough change in the

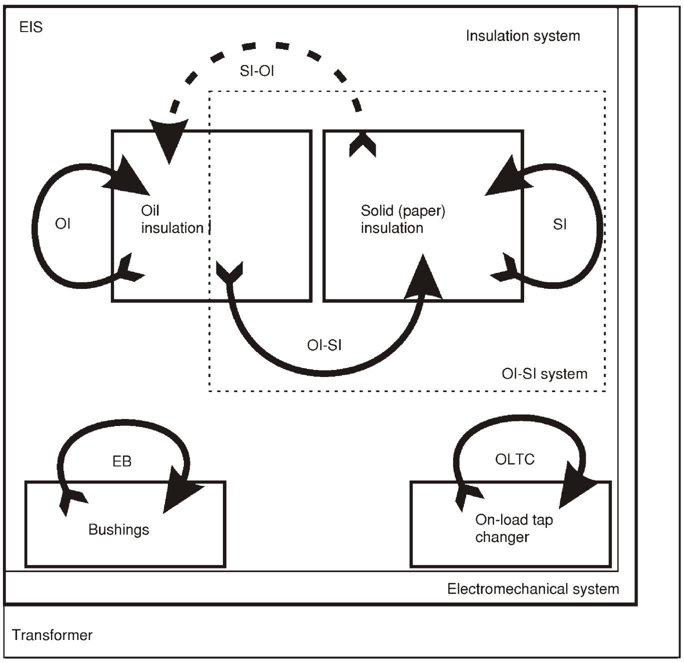


**Figure 2. Transformer insulation chain**

mechanical and electrical properties of the material. Apart from high temperatures, other important parameters affecting the aging of the solid and liquid insulation include the presence of water and oxygen in the system.

The monitoring and assessment of such components is vital to achieve better reliability of the system. By implementing correct operational and maintenance strategies the insulation aging/degradation process can be controlled and the asset life can be extended effectly. Asset's critical component monitoring (strict) is required for the technical assessment (normal to end of life) to ensure economical and safe operation. Also better asset management polices can be implemented.

### *General aspects of aging*

The insulation system of a transformer consists mostly of oil and paper which are subject to aging. Aging is defined as the irreversible changes of the properties of an electrical insulation system (EIS) due to action of one or more factors of influence [3]. Aging stresses may cause either intrinsic or extrinsic aging. In most EIS, extrinsic aging predominates because, in practice, they include imperfections and contaminants. A schematic representation of the basic process is shown in fig. 3.

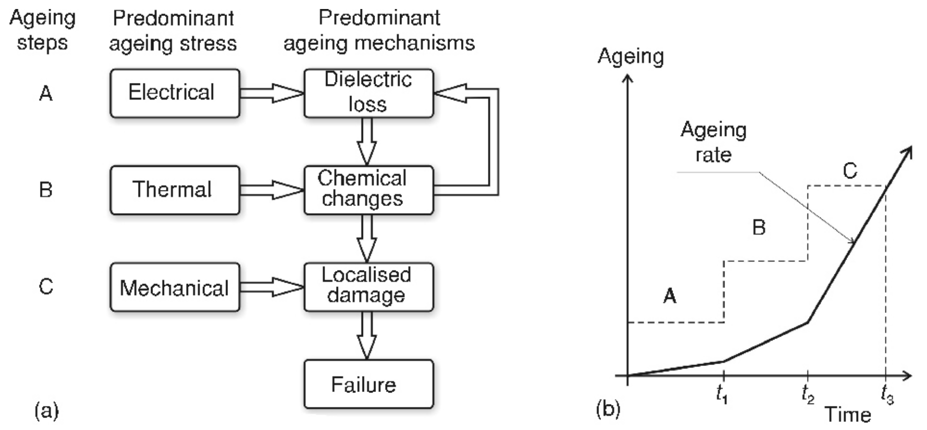


**Figure 3. Ageing mechanisms (a) and ageing rate (b)**

The type and level of contamination and/or the extend of imperfection in a EIS will significantly affect service performance. In general, the fever and less severe the contaminate and/or defects in EIS, the better the performance of the equipment.

The aging factors produce electrical, thermal, mechanical, or environmental aging mechanisms that eventually lead to failure. During aging applied stresses, which initially may not effect the EIS, can come aging factors that, as a result, modify the rate of the degradation. When aging is dominated by one aging factor, this is referred to as single-factor aging. Multifactor aging occurs when more then one aging factor substantially affects the performance of the EIS. Aging factors may act synergistically, that is, there may be direct interactions between the stresses. Interactions may be positive or negative. The aging of a practical EIS can be complex and failure is usually caused by a combination of aging mechanisms, even though there may be only one dominant aging factor [3] (see fig. 3).

### *Winding insulation*

Most winding insulation in power transformers consist of paper prepared from wood pulp and contains 90% cellulose which is a natural polymer of glucose with 1200 monomer units in its paper form. Paper on a new transformer would start with an average chain length or degree of polymerization (DP) of around 1000. Many experiments have showed that there is a linear decreasing relation between lifetime (aging range) and the logarithm of DP. The strength of paper is critically dependent upon DP, and at a value of DP = 150 and below, the strength of paper is inadequate to withstand any winding mechanical stress or movement. The aging rate is enhanced by increasing temperature, increasing moisture and presence of oxygen.

*Oil insulation*

The essential requirement for the oil is to maintain dielectric performance in the oil gaps and across solid surfaces, to age very slowly, and to have adequate thermal and viscosity properties to achieve factory heat run performance. A low quality oil, or one with a poor aging rate, is often associated with low transformer lives. The use of additives can allow a poorer oil achieve adequate initial properties for performance. Hence, if used, the additive content must be monitored and maintained, since the lost of property values can be very rapid.

## Measurement methods and techniques

Monitoring and diagnostic of power transformer insulation system condition is primarily directed to transformer life extension and reducing of operational costs and risks. Most diagnostic system, including laboratory measurements, off-line testing, periodical on-line, and continuous on-line monitoring, serve to detect changes in the insulation system in form of early warning system. Condition and defects that could be detect by appropriate measurement methods and techniques are: hotspots, degradation of the insulation, excess moisture in paper and oil insulation, partial discharges, localized faults, mechanical defects (partial rupture), and chemical or thermal ageing. Mainly, none of these defects can be detected by a singular measurement or monitoring procedure. Therefore we need to apply a multitude of different methods [4]. Furthermore we need quite frequently a sequence of samples and measurement to identify the velocity of change, the rate of progressiveness *etc*. [5].

From the large number of measurement and monitoring methods and techniques we select these that are currently in use in Nikola Tesla Institute, Belgrade [6]: 1 – insulation resistance/polarization index (*Ri/PI*), 2 – power loss factor (*PF*), 3 – partial discharge (*PD*), 4 – frequency response analysis (*FRA*), 5 – dielectric response measurement (*RVM*), 6 – high precision impedance measurement (*Lg*), 7 – low voltage no-load measurement (*Io*), 8 – DGA-analysis (DGA), 9 – Oil-analysis (OA), 10 – degree of polymerization (DP), 11 – furan components analysis (FURAN), 12 – Karl Fischer test (KF), 13 – conductive $Cu_2S$ ($Cu_2S$), 14 – hotspot temperature measurement (HT).

All these methods are explained in more details in tab. 1, with main defect detection, development status, application, and availability for continuous on-line monitoring. By combination of all mentioned measurements techniques main thermal and dielectric ageing defects (PD of low or high energy, abnormal aged oil, abnormal paper ageing, oil contamination, excessive water content, loose connections or sparking), magnetic core and winding circuit defects (abnormal circulating currents in the core, double grounding or short circuit, short between conductors, poor solder joints), tap changer defects (contact overheating, PD on surface and between lead structures, sparking or breakdown across support structures), and mechanical degradation (loosing of core and/or winding clamping, lead support failures, winding deformation, loss of DP of winding conductor, *etc.*) can be detected. Consequent maintenance, with both off-line and on-line testing and

**Table 1. Measurement methods and techniques**

| Methods | Main defect detection | Development status | Application | On-line monitoring |
|---|---|---|---|---|
| Ri/PI | Accumulation of polarizable material or contamination | Known | Utilities and laboratory | No |
| PF | Dielectric losses in the insulation system | Known, instrumentation development in progress | Utilities and laboratory | No, except of transformer bushings |
| PD | Deterioration of the insulation system | Known, research on noise suppression or data interpretation | Laboratories and utilities | Yes, research on the interpretation of the results |
| FRA | Loosening of winding or core clamping | Under research | Laboratories and utilities | No |
| RVM | Ageing and water content of the paper insulation | Under research, research on the correlation with HPLC | Laboratories and utilities | No |
| Lg | Winding deformation, loosening of winding clamping | Known | Laboratories and utilities | No |
| Io | Core defects | Known | Laboratories and utilities | No |
| DGA | Appearance of hot spots, PD and/or arcing | Known, widely used, research on linking of gases and causes | Laboratories and utilities | Yes, research on the interpretation of the results |
| OA | Oil contamination, PD and sparking, overheating | Known | Laboratories and utilities | No |
| DP | Ageing of the insulating paper | Known, research on correlations factors | Laboratories | No |
| FURAN | Ageing of paper insulation | Furan behavior in a transformer is under research | Laboratories and utilities | No |
| KF | Water content | Known | Laboratories | No |
| $Cu_2S$ | Conductive area deposition | Under research | Laboratories | No |
| HT | Overheating, life extension, load regulation | Known | Utilities | Yes |

monitoring, with diagnostics procedures like fingerprinting and trend analysis can be extremely successful to avoid catastrophic and costly outages, as well as making successful transformer life management.

## Diagnostic procedures

The aging of a practical EIS, as mentioned before, can be complex and failure is usually caused by a combination of aging mechanisms, even though there may be only one dominant aging factor. Mainly, none of these defects can be detected by a singular measurement or monitoring procedure. Therefore we need to apply a multitude of different methods together with diagnostics procedures like fingerprinting and trend analysis to identify the velocity of change, the rate of progressiveness *etc*. Data and knowledge base are the key elements of modern IT use in planning, exploitation, and managing the power supply system in technical and business sense. Using the benefits of modern IT-technology, the closed loop, up-to date and high effective testing-monitoring-diagnostics management system, presented in fig. 4, is realized.

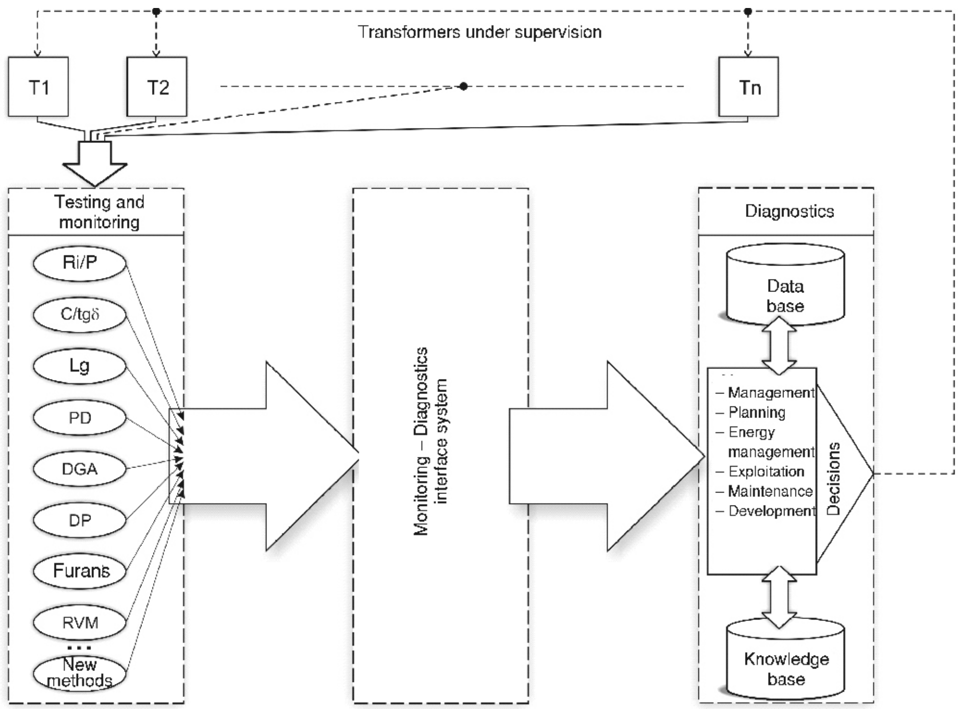


**Figure 4. Testing-monitoring-diagnostics management system**

To enable comparative decision making an information basis and data structure, which allows the assignment of attributes to measurement data, condition data, and operational conditions is needed.

In this project's phase testing-monitoring-diagnostics management system is primarily designed for prophylactic diagnostics of insulation conditions of transformers under supervision [7]. The Nikola Tesla Institute's clients have an opportunity to connect the data base to their information system. Thus, they can effectively assess the technical condition of their objects and machines for the purpose of production planning, investments, repairs, and other activities.

The basis major objects are transformer's data. Each transformer is uniquely marked and has its own code in the data chart. Structural parts of the base are data charts with measuring results for each transformer and they include factory measuring, start-up measuring as well as periodic and any extra measuring. Depending on the enquiry and report concepts, reports are generated from the chart data, which may vary from one case to another.

Server base carrier and web server, as can be seen in fig. 5, are the area in which the whole system works. MySQL server has been chosen for its ability of multiple clients' assessing through local network and internet. It also allows storing a lot of data, it is efficient and free of charge. Client's Access application enables data registration into the basis as well as change of existing data and report generation. This application is interface between laboratory users and the base (fig. 5), which is accomplished by local com-

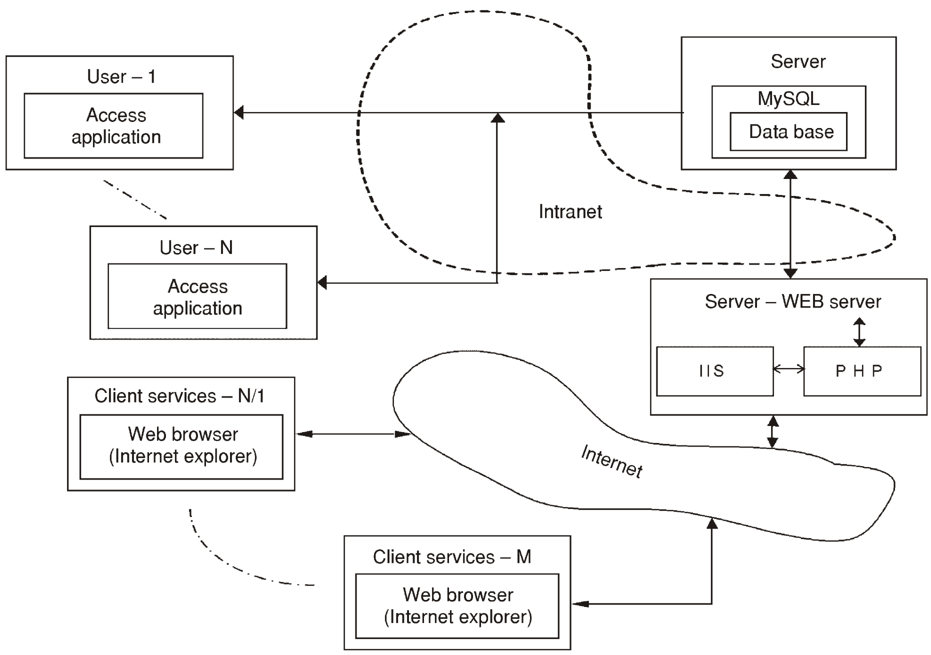


**Figure 5. Data-knowledge base and client services**

puter network through ODBC (open data base connectivity). This application sends standard SQL enquiries to the base through MySQL-ODBC driver so that the communication between Access application and MySQL is successfully performed. Users of Access application are analysts who do the measuring and have the access level that enables them to register the measuring results to the base.

Depending on the access level, client may get the required data about an object, measuring or diagnosis through internet WEB server. Chosen WEB server is IIS (Internet Information Service), and PHP (Personal Home Page), which is installed into Windows XP. Web browser (*e. g.*, Internet Explorer) sends an enquiry about certain base data to the WEB server address. The WEB server processes the enquiry and sends back the HTML text with required measuring data, objects and diagnosis from the base (fig. 5). Users who access the base through the internet have minimum level of authorization and access only to some data base information.

## Economic benefits of diagnostic

There is not a unique solution for economic benefits of diagnostic because a cost/benefit analysis requires hypothesis of many individual parameters and strongly depends on specific situation. However, there is a set of possibilities that can be counted, like: prevention of major failures and downtimes, avoidance of collateral damages, condition-based maintenance, transformer higher overload capacity, and lifetime extension [8].

### *Major failures and downtimes*

This part covers economic benefits from the avoidance of major failures and downtimes of the transformers itself. The total probability ($p_{tot}$) of detecting oncoming faults by an adequate testing, monitoring and diagnostic procedures can be calculated by multiplying failure rate ($f$), the failure risk of each part ($r_i$) of the transformer and detection rate of each part ($d_i$) of the transformer, so $p_{tot} = f \cdot \Sigma r_i d_i$.

To calculate the savings achieved by failure prevention ($S$), this probability ($p_{tot}$) must be multiplied by failure costs ($F_c$), so $S = p_{tot} \cdot F_c$, where $F_c$ is assumed to be a part of the price of a new transformer ($P_t$). All these parameters ($f$, $r_i$, $d_i$, $F_c$) must be estimated for the real system [8]. For the purpose of the paper the next estimations are made: $f = 2\%$/year, $\Sigma r_i d_i = 70\%$, $F_c = 0.5\ P_t$, so the savings achieved by failure prevention is 0.7% of the price of a new transformer per year.

### *Collateral damages*

The costs of a collateral damages of a transformer failure include:

- direct damages caused by transformer failure like additional destruction of equipment or injuries of people,
- indirect damages caused by loss of energy,
- loss of production capacity of a power station and/or system, and
- penalties due to not delivered electrical energy.

All these collateral damages strongly depend on the real specific technical and economic situation of the individual power transformer, utility, and the system.

### *Condition-based maintenance*

Additional cost savings can be achieved by changing the maintenance strategy from time-based to condition-based maintenance. The maintenance interval of an active part, bushings, cooling unit and on-load, tap changer can be extended and only necessary maintenance procedures will be done.

### *Higher overload capacity*

Load capacity of a transformer is mainly determined by a temperature of hot spot. To be able to operate a power transformer at a higher load than rated an overload calculation must be implemented in the monitoring system, with hot spot measurement as a priority. This kind of monitoring is necessary for strategically important transformers, like grid-coupling or generator step-up transformers, where financial profit comes from: transmitting extra load, prevention of a black-out and avoidance of unnecessary investment of the new transformers.

### *Lifetime extension*

The aging rate is enhanced by increasing temperature, increasing moisture and presence of oxygen, and is accelerated during the time, as can be seen on fig. 3. More high voltage installations and transformers have reached a service life of over 40 years, so the fraction of equipment in the terminative stage of operation increases. The “aging wave” of the electrical infrastructure due to installation of numerous high voltage substations in the 1960s and 1970s has its implication on the “unexpected” failure and nonaviability of the electrical system. By the exact knowledge of the condition and the failure risk the utilization period of a transformer can be extended. The knowledge of transformers lifetime is a valuable information for both minimizing the risk of sudden failure and to decide which transformer out of a whole population should be refurbished or scrapped. The saving of 10% of the value of the new transformer can be realized, by the two year delay of a new transformer investment, because of transformer lifetime extension, assuming an interest rate of 5% per year.

## Conclusions

Competitive electric energy market drives utilities to adapt to a lot of changing technical and economical requirements, so transformers and systems for their testing, monitoring, and diagnostics have developed together with the power supply systems, as shown on fig. 1. To meet these challenges, the electrical power company in the world is now making the transition from the conservative corrective and time based strategies toward condition based maintenance (CBM). This need for CBM has encouraged the development of adaptable and cost-effective diagnostics.

Core, windings, insulation oil, bushing, and on-load tap changer are the main active parts of the transformer insulation chain. The degradation of insulation system is a complex physical and chemical process. Many parameters act at the same time, as shown in fig. 2, thus making the interpretation extremely difficult. From the large number of measurement and monitoring methods and techniques we select these that are currently in use in Nikola Tesla Institute, Belgrade, as shown in tab.1.

Using the benefits of modern IT-technology the closed loop up-to date and high effective testing-monitoring-diagnostics management system, presented in fig. 4, is realized. The distribution of information about the condition of transformer insulation can easily be done by means of standardized web browser technology, as shown in fig. 5.

The cost-benefit analysis validate that, especially for aged transformers and transformers at strategic locations in the electric network, testing, monitoring, and diagnostics are necessary and valuable in purpose of the prevention of major failure and associated collateral damages, as well as higher overload capacity and extension of transformer lifetime.

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