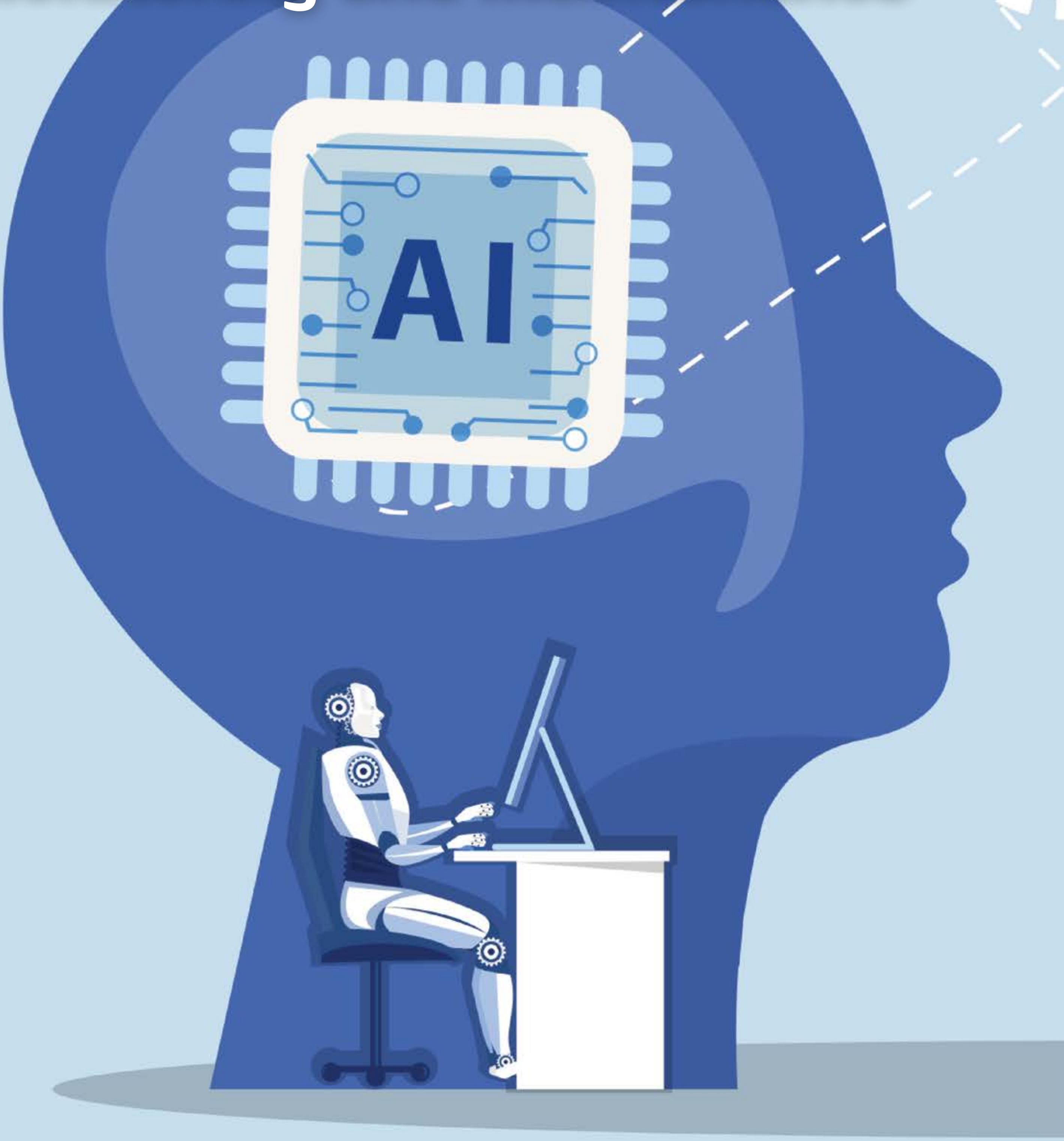
A comparative analysis of human expertise vs. digitalization in transformer monitoring and maintenance



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ABSTRACT

Power transformers are critical components in electrical grids, and their reliable operation is essential for the stability and sustainability of energy distribution. The debate between traditional, human expertise-based methods of transformer monitoring and maintenance (both offline and online) and modern, digitalized approaches continues to evolve as technology progresses [1], [2]. This paper explores the pros and cons of both approaches, particularly in terms of reliability, cost, and sustainability. By examining the trade-offs between human-led diagnostics and digitalization, we aim to determine which approach or combination provides the optimal balance for power transformer management. Additionally, we discuss how over-reliance on digitalization can erode human expertise over time, impacting both diagnostic accuracy and sustainability in the long term.

KEYWORDS:

transformer monitoring, transformer maintenance, power transformer management

Historically, transformer monitoring and maintenance have been conducted primarily through offline, human expertise-based methods

Introduction

The reliable operation of power transformers is fundamental to the sustainability of modern power grids. Historically, transformer monitoring and maintenance have been conducted primarily through offline, human expertise-based methods, relying on scheduled inspections and manual diagnostics. With the advent of digitalization, online monitoring systems powered by sensors, artificial intelligence (AI), and machine learning (ML) have emerged as alternatives, promising increased efficiency, cost savings, and improved sustainability [3]. However, each approach has its own set of advantages and limitations.

A key concern is the impact of over-digitalization on the development and preservation of human expertise. As digital systems become more prevalent, there is a risk that human operators will become too dependent on automated diagnostics, leading to a degradation of their problem-solving skills and judgment. This over-reliance on technology can have unintended consequences, including decreased credibility in the ability to handle novel issues and a reduction in overall sustainability as human expertise diminishes.

This paper will compare human expertise-based offline and online monitoring with digitalization, examining their impacts on reliability, cost, and sustainability. We will also assess the potential risks of too much digitalization in terms of its long-term effects on human expertise and its implications for sustainability.

Human expertise-based methods: Pros and cons

Offline monitoring and diagnostics

Pros:

1. Human judgment and adaptability: Offline methods rely heavily on the expertise of engineers who have years of experience working with transformers. These professionals are capable of recognizing subtle signs of degradation, accounting for unique contextual factors, and making informed decisions in complex situations. Human expertise is invaluable in identifying unusual failure modes or interpreting nuanced data that might be beyond the scope of current software algorithms.

2. Collaboration and knowledge sharing: Engineers frequently participate in conferences, meetings, and training sessions, where they share insights from real-world cases and discuss novel solutions. This exchange of knowledge ensures that human expertise evolves continuously and adapts to emerging challenges in transformer management. Such dynamic learning is difficult to replicate with static algorithms.

3. Cost of implementation: Offline monitoring requires relatively low upfront investment compared to the digitalization of transformers. Many power grids already have the necessary infrastructure and personnel in place for manual inspections, reducing the need for significant capital expenditure on new technologies.

4. Time delay between appearance of new phenomena in transformers technology that impact the operational mode, is minimized by human judgment, industrial discussions and immediate reactions, with the shortest time delay meaning more economical approach.

Cons:

1. Inconsistent reliability: Human-led diagnostics can vary in quality based on the individual's experience, training, and interpretation of data. Human error, such as overlooking early warning signs or misinterpreting symptoms, can reduce the overall reliability of the maintenance process. Additionally, the reactive nature of offline monitoring often means that issues are only detected after significant damage has occurred, leading to higher repair costs.

2. Increased downtime: Non-chemical offline methods often require transformers to be taken offline for scheduled maintenance, testing, and inspections. This leads to increased downtime, reducing grid efficiency and potentially affecting the reliability of the overall system. Oil tests possess the advantage of providing numerous measurements without disturbing power transformer operation.

3. Resource and environmental costs: Regular travel to remote locations for inspections increases the environmental footprint, as does the need for routine shutdowns and physical interventions. Moreover, the frequent use of consumables like insulation oils or testing equipment contributes to waste, which negatively impacts sustainability.

Online monitoring with human diagnostics

Pros:

1. Improved data availability: Online systems equipped with basic sensors allow for continuous monitoring of critical parameters such as temperature, voltage, and oil quality. This gives engineers access to real-time data that can enhance their decision-making capabilities. The integration of human expertise with online data allows for more informed decisions compared to purely offline methods.

2. Quicker response to emerging issues: By having access to live data, expert engineers can respond more quickly to potential problems before they escalate into major failures, increasing the reliability of the transformer.

Human expertise is invaluable in identifying unusual failure modes or interpreting nuanced data that might be beyond the scope of current software algorithms

Cons:

1. Frequent calibration and maintenance of sensors: Online systems require regular calibration and maintenance to ensure accurate readings. This adds to the operational complexity and can lead to increased downtime for the system, undermining the very reliability gains that online monitoring is meant to provide.

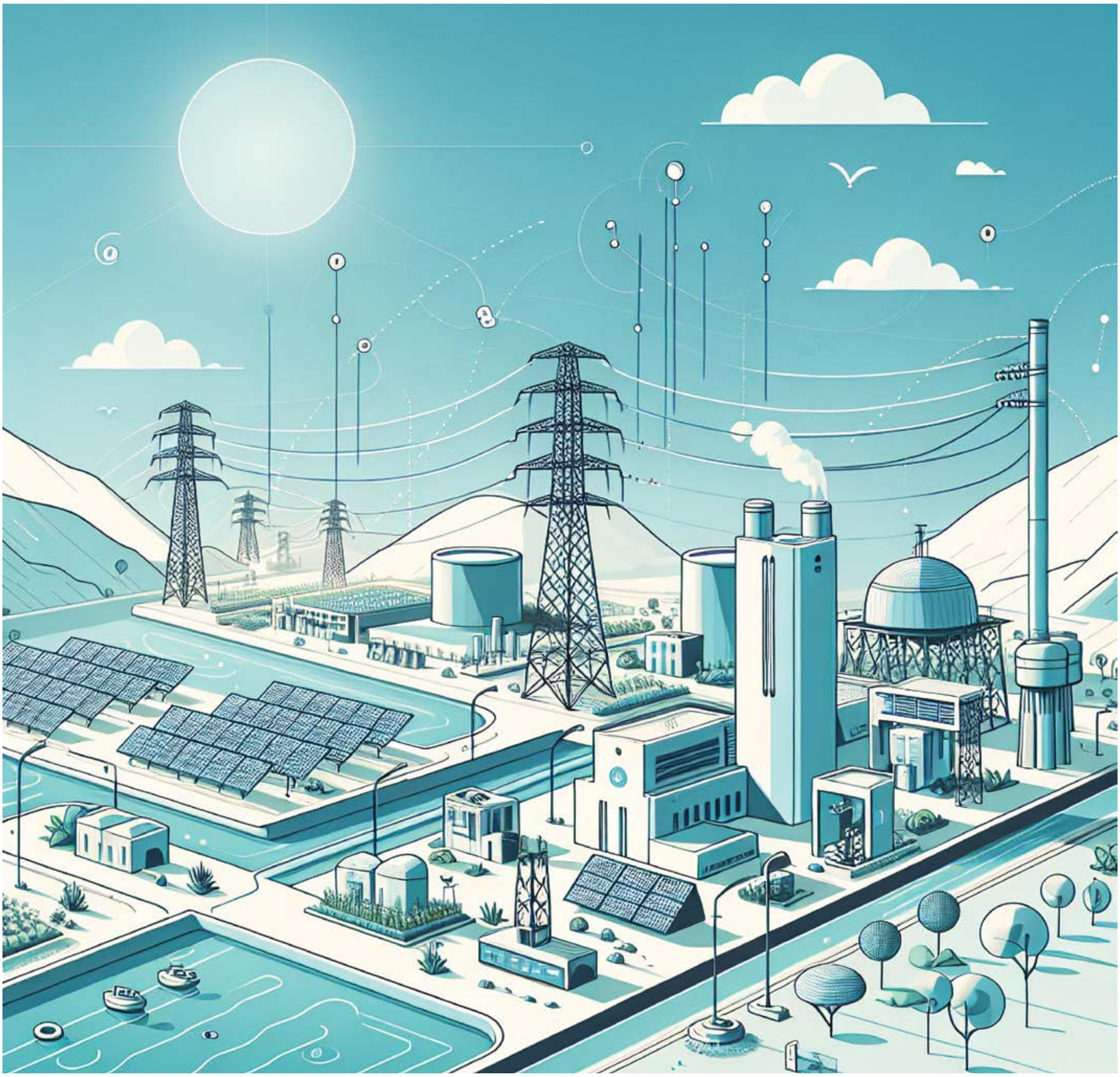
2. Increased costs: While online systems provide more data for human analysis, they also involve higher maintenance costs due to the need for sensor upkeep, calibration, and troubleshooting. These systems can become a financial burden if not managed efficiently

Online systems equipped with basic sensors allow for continuous monitoring of critical parameters such as temperature, voltage, and oil quality

Digitalization and software-based diagnostics: Pros and cons [4]

Pros:

1. Reliability through continuous monitoring: Digitalization enables continuous, real-time monitoring of power transformers through advanced sensor technology and machine learning algorithms. By collecting and analyzing vast amounts of operational data, software-based systems can detect early warning signs of failure and provide actionable insights to operators. This enhances the reliability of transformers by identifying issues before they become critical.



Digitalization enables continuous, real-time monitoring of power transformers through advanced sensor technology and machine learning algorithms

2. Cost savings in the long run: Though the initial investment in digitalization is higher, the long-term operational costs are lower. Digital systems reduce the need for manual inspections, decrease downtime by enabling condition-based maintenance, and prevent costly breakdowns by catching potential failures early. This predictive approach reduces unnecessary interventions and prolongs the lifespan of the transformer.

3. Enhanced sustainability: Digital systems promote sustainability by reducing the frequency of on-site inspections, minimizing the need for consumable testing materials, and lowering the environmental impact of travel. Moreover, condition-based maintenance reduces the waste of components, ensuring that parts are replaced only when necessary. By extending the operational life of transformers, digitalization also reduces the environmental costs associated with manufacturing and replacing equipment.

Cons:

1. Initial investment costs: The transition to digitalized monitoring systems requires significant upfront capital for the installation of sensors, data acquisition systems, and the integration of machine learning algorithms. This cost can be prohibitive for utilities with limited budgets, especially in the early stages of implementation.

2. Limited adaptability: Software-based systems, while efficient at analyzing patterns in data, are limited by the training data they have been exposed to. In novel or complex scenarios, digital systems

may struggle to recognize anomalies or adapt to new conditions. This can lead to false positives (triggering unnecessary maintenance) or false negatives (missing critical issues), reducing overall reliability.

3. Degradation of human expertise [5]: One of the long-term risks of over-reliance on digitalization is the potential erosion of human expertise. As more tasks are automated and software becomes responsible for routine diagnostics, engineers may become less involved in the day-to-day problem-solving process. This can lead to a decline in the practical knowledge and critical thinking skills needed to handle complex or novel situations. As human expertise fades, the industry becomes more reliant on software, increasing the risk of misdiagnosis when software encounters situations it hasn't been programmed for.

One of the long-term risks of over-reliance on digitalization is the potential erosion of human expertise

Impact on sustainability: The loss of human expertise affects sustainability in two ways:
- Reduced adaptability: In situations where digital systems fail to recognize new failure modes, humans with less hands-on experience may not be able to respond effectively, leading to increased breakdowns or inefficient maintenance decisions.
- Increased waste: As human expertise diminishes, reliance on conservative or automated maintenance schedules can lead to over-maintenance or premature equipment replacement, increasing material waste and resource consumption, which undermines sustainability.

4. Ongoing energy consumption: Digitalization requires a continuous supply of energy to power sensors, data processing units, and communication networks. While this energy consumption is typically low compared to the operational savings, it nonetheless contributes to the overall environmental footprint of the system. If digital systems are not optimized, the sustainability benefits can be offset by increased energy use.

As human expertise diminishes, reliance on conservative or automated maintenance schedules can lead to over-maintenance or premature equipment replacement

Human expertise vs. digitalization: A comparative analysis [6]

Reliability

- Human expertise: Human-led diagnostics, particularly in offline methods, are less consistent due to variability in expertise and the potential for human error. However, in cases of complex or novel failures, human adaptability and experience can outperform software, as engineers can apply judgment and nuanced decision-making that algorithms may lack.

- Digitalization: Software-based diagnostics are highly reliable in routine conditions, with continuous monitoring providing consistent data. However, in novel situations, digital systems may struggle to adapt, limiting their reliability when new or unforeseen issues arise. A hybrid approach, where humans intervene in complex cases, offers the most reliable solution. Over time, if human expertise declines due to over-reliance on digitalization, this could reduce overall reliability in the industry.

Cost

- Human expertise: Offline and human-led diagnostics are more expensive in the long run due to labor-intensive processes, regular shutdowns, and resource-heavy maintenance practices. Online systems with human oversight are slightly more cost-effective but still require significant personnel involvement.

- Digitalization: While the initial investment in digital monitoring systems is high, the long-term savings from reduced labor, fewer shutdowns, and optimized maintenance schedules make digitalization a more cost-effective solution in the long run. However, if human expertise degrades, the cost of dealing with unforeseen failures may rise.

Sustainability

- Human expertise: Offline diagnostics are less sustainable due to the environmental costs of frequent inspections, travel, and waste generation from consumable materials. The less efficient use of resources in routine maintenance also reduces overall sustainability.

- Digitalization: By reducing unnecessary maintenance, travel, and resource consumption, digitalization contributes significantly to sustainability. It reduces the environmental footprint of monitoring and maintenance while extending the operational life of transformers, promoting a more sustainable grid. However, over-reliance on digital systems may increase waste and reduce adaptability if human expertise continues to decline.

Cons:

Increased waste and lifecycle environmental impact

- **Short lifespan of digital components**: Digital devices and sensors typically have a shorter lifespan than the transformer itself. This means that

Human-led diagnostics, particularly in offline methods, are less consistent due to variability in expertise and the potential for human error

If software is trained only on specific datasets, it may fail to generalize beyond those cases, making it less effective in recognizing new patterns or unusual failure modes

the monitoring systems may need to be replaced more frequently than the transformer, contributing to **electronic waste**.

- **Sustainability impact**: The lifecycle environmental impact of online monitoring devices—from their production, installation, maintenance, and eventual disposal—can accumulate over time. This is especially true if these devices are replaced frequently, resulting in more waste, additional resource use, and a larger environmental footprint.

The inability of software to generalize from limited data

Real-world experience is hard to replicate: In many cases, real-world transformer issues are nuanced, involving a combination of environmental conditions, aging equipment, and varying load demands. Human experts can account for these subtleties because they have seen a wide range of scenarios and can apply judgment in ways that software can't. If software is trained only on specific datasets, it may fail to generalize beyond those cases, making it less effective in recognizing new patterns or unusual failure modes.

Impact on sustainability: If the software cannot generalize well, it may miss important issues or generate inaccurate diagnostics, leading to either overuse of materials (due to unnecessary repairs) or increased risk of transformer failure. Either scenario negatively impacts sustainability, as it leads to inefficient resource allocation and potential environmental consequences.

Conclusion

In the comparison between human expertise-based diagnostics (both offline and online) and digitalization, the digital approach offers significant advantages in terms of cost-efficiency and sustainability. However, human expertise remains invaluable, especially in complex or novel situations where adaptive decision-making is required. A hybrid approach that combines the best aspects of both human judgment and digital monitoring systems offers the most reliable, cost-effective, and sustainable solution for power transformer management.

One key concern is the potential for over-digitalization to erode human expertise over time. As engineers become more dependent on automated diagnostics, their ability to handle complex, real-world challenges may decline, leading to increased inefficiencies and a reduction in sustainability. To maintain balance, it is essential that human expertise continues to play a central role in transformer management, with digital tools serving as aids rather than replacements for critical human judgment.

As technology continues to advance, integrating human expertise with digitalization will be crucial for maintaining both reliability and sustainability in the long term.

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Marius Grisaru holds an MSc in Electro-Analytical Chemistry from the Israel Institute of Technology. He has almost 30 years of intense experience in almost all transformer oil test chains, from planning, sampling, and diagnosis to recommendations and treatments, mainly in Israel but also in other parts of the world. He is responsible for establishing test strategies and procedures and creating acceptance criteria for insulating liquids and materials based on current standardization and field experience. In addition, he trains and educates electrical staff on insulating matrix issues from a chemical point of view. He is an active member of relevant Working Groups of IEC, CIGRE, and a former member of ASTM. He is also the author and co-author of many papers, CIGRE brochures, and presentations at prestigious international conferences on insulation oil tests, focusing on DGA, analytical chemistry of insulating oil, and advantageous maintenance policy for oil and new transformers.