> **The COVID-19 pandemic has shown all of us that the reliability of our critical electrical infrastructure is the foundation for a safer society**

ABSTRACT

Electrical utilities all around the world face important challenges in asset management of rapidly ageing networks [1]. Ageing power transformer fleets represent a particularly significant issue for network reliability. The COVID-19 pandemic reminded us again that having reliable condition assessment metrics and prioritisation models for lifecycle decisions are more important than ever.

In the next era of machine learning, digital twins and predictive models using big data analysis, we will all be striving for the best methodologies of automated asset management decision making based on predicted time to failure and proposed maintenance action options with estimated costs. But could knowledge sharing between utilities based on common terminology and best practices get us there faster?

KEYWORDS

benchmarking, knowledge sharing, predictive maintenance, prioritisation of maintenance

The power of sharing knowledge

The future of prioritisation of maintenance activities and the importance of benchmarking

1. Introduction

The COVID-19 pandemic has shown all of us that the reliability of our critical electrical infrastructure is the foundation for a safer society. Utilities faced new challenges such as limiting or cancelling planned outages, disruptions in the supply chain, need for personal protective equipment for maintenance crews, adapting to changes in electricity consumption patterns, delays in mainte-

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nance activities, loss of personnel due to self-isolation measures. These new challenges have forced electrical utilities to adjust their prioritisation methodologies of critical equipment lifecycle management decisions.

Prioritisation of maintenance activities is the most challenging task in asset management. Best prioritisation decisions are made based on reliable asset health indices, data analysis, failure mechanism prediction models, budget, required outage duration, and human resources considerations.

Every electrical utility is unique in its own way of defining condition assessment and prioritisation of maintenance activities. Different approaches are used by utilities when it comes to deciding between risk-based or time-based maintenance using the health index of its transformer fleet. [2]

An effective maintenance program requires reliable model algorithms that consider multi-level failure mechanisms and interpretations of condition-assessment actions. Health or assessment indices are the foundation of an efficient transformer lifecycle management prioritisation model.

Investment in performance reporting and predictive modelling is one of the key elements that will ultimately provide electrical network operators with an important decision-making tool. Truly successful decision making relies on a balance between deliberate and instinctive thinking. The goal for all of us is to be able to make quick judgements based on reliable predictive models in order to prioritise proactive maintenance actions.

2. Anticipating the future

Rapidly ageing transformer fleets require more complex lifecycle management metrics. Due to the unprecedented industrial growth in the 60s and 70s, power networks in North America were forced to expand significantly in the following 20 years. Now, a significant majority of all power transformers in operation in North America are in the second half of their life expectancies. The good news is we have accumulated the empirical data on older designs over the years. This will let us identify genetic or design-related problems and predict possible failure mechanisms.

Identifying the genetic issues by pinpointing the root causes is the first step of anticipating the failure patterns. Only then can a predictive maintenance program be successful. The preventive maintenance is time-based maintenance or a periodic transformer check-up (Fig. 1). Preventive and predictive maintenance should coexist for reliable lifecycle management of a transformer fleet. The condition assessment provided from preventive maintenance activities will trigger a predictive maintenance protocol.

Sharing the inspection and failure pattern study data between electrical network operators would provide all end users with the ultimate modelling tool for predictive maintenance. With such benchmarking, a utility would be able to anticipate a failure mechanism without any prior experience or condition assessment action on an asset and to adjust its maintenance strategies accordingly.

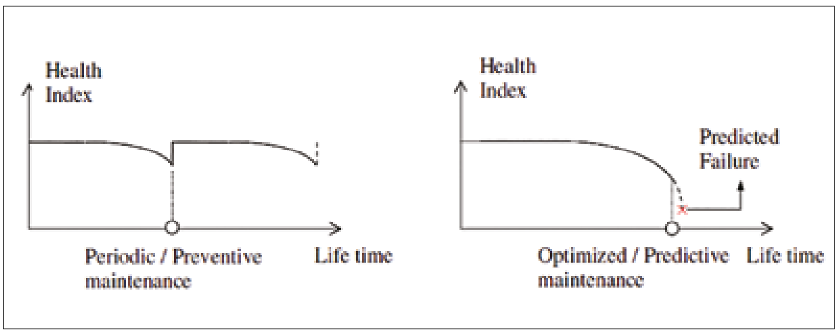

Figure 1. Preventive vs predictive maintenance

A detailed inventory of the power transformer fleet is the foundation for developing reliable maintenance strategies and estimating the failure risk factors

3. Get to know your transformer fleet

Most of the electrical utilities have diversified transformer fleets that include different types of transformers from 20 kVA grounding transformers up to several hundred kV autotransformers: some units with multiple tap changers and some units having up to 10 bushings. How can we model the increased failure risk factor when multiple bushings on a transformer exceed the recommended limit of the power factor? How can we prioritise maintenance actions based on common denominators?

A detailed inventory of the power transformer fleet is the foundation for developing reliable maintenance strategies and estimating the failure risk factors. All critical components should be inventoried and assigned to one or multiple families. Having a complete inventory of all critical components and accessories will help identify genetic problems and target individual assets for further surveillance or risk-based maintenance.

An on-load tap changer, for example, can be assigned to a family based on its manufacturer, model type, a range of manufacturing year, and estimated yearly number of operations.

Identifying and predicting critical component degradation patterns is what we will expect in the future. An artificial intelligence capability that will provide us with predictions of possible problems, the maintenance options, the estimated cost, and the time duration for each option is the ultimate goal, and it all starts with getting to know your transformer fleet.

Best practices require each transformer in the fleet to have a profile page, a datasheet with a list of all the critical components and accessories. Each data sheet should have a 'family ID' with individual critical component "sub-families". The profile of an individual asset would include data on each component's life expectancy, calculated periodic maintenance frequency, and statistical data on most common problems associated with specific critical component sub-families. Instinctive thinking and a probabilistic approach to identifying genetic problems create the basis for successful decision making.

4. Condition assessment

Periodic condition assessment inspections of power transformers are essential to ensure continued, reliable operation of an electrical network. Identifying a reliable condition assessment methodology to detect potential issues before catastrophic failure is crucial. However, determining the right frequency of condition assessment testing (CAT) and the nature of the tests is a difficult task.

For power transformers, the frequency of CAT may differ among similarly rated transformers, as an optimised frequency of CAT for a transformer depends on many parameters, such as:

- Manufacturer's recommendations
- Health or assessment index of the asset
- A common failure pattern of a critical component
- The criticality of the asset
- Transformer load cycles.

If the stakeholders work together to share knowledge and create common databases for failure mechanisms observed in their networks, condition assessment activities can be optimised, leading to better failure predictions. Knowledge sharing among end users can also help to compensate for unfamiliarity with a specific type of critical component, technology, or supplier. It is also important to remember the online monitoring accessories that may be installed on transformers as data from these devices should be included in the periodic condition assessment frequency calculation.

Periodic inspections and testing require power transformers to be offline for long periods of time and in some cases include unnecessary condition assessment activities depending on the complexity of the transformer. In some cases, complex failure mechanisms cannot be detected with conventional testing.

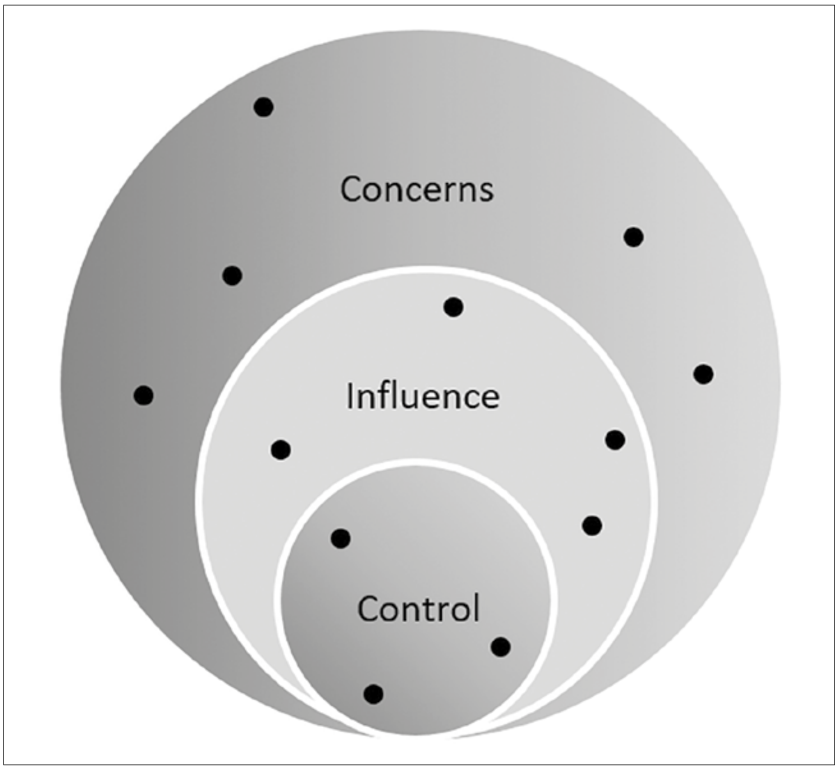

Figure 2. Circle of concerns

Optimising the condition assessment activities and creating custom testing sheets may be the foundation needed for reliable transformer fleet condition assessment.

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5. Predictive maintenance

Predictive or targeted maintenance is the most effective maintenance strategy. In this case, we know the problem, the failure mechanism, the solution, the maintenance action, and the time required for the proposed solution.

Let us try to see the targeted maintenance approach in terms of Covey's circles of concerns and influence [3]. This technique is used for teams to better understand how to prioritise proactive and reactive actions. The difference is that the proactive people would focus their efforts on their circle of influence, on the actions they can influence or control, such as where they live or their attitude. Reactive people focus their efforts on the circle of concern, general problems that they have little or no control over, such as the weather events, the economy, etc.

In our case, the circle of concern encompasses a wide range of reasons that would cause the unavailability of a transformer. The bigger inner circle, the circle of influence, encompasses those concerns that we can do something about, and we have some control over: choosing our suppliers, specifying higher than required short circuit withstand level, optimising the condition assessment frequencies. The smaller inner circle is the circle of control, containing targeted maintenance strategies. In this circle, we have identified and prioritised specific maintenance activities suggested by the predictive failure pattern models.

Electrical network operators should exchange important information on possible health, safety, and environmental problems related to power transformers. A common database of known failure root causes could be used for recall and safety notices. Electrical utilities can then take proper predictive maintenance actions within the circle of influence on similar or identical assets.

6. Refurbishment

Life extension of a transformer can be considered as an option if the active part is in fairly good shape and if the refurbishment is cost-effective compared to the cost of replacement and the downtime of the transformer.

Aged power transformer fleets would have many candidates for life-extension decisions. Specific prioritisation indicators can be developed in order to choose the ones that represent the lowest risk for the investment. A refurbishment decision tree can be developed with basic criteria: age, condition of the asset, and its maintenance history. It is also crucially important to properly determine the risk factors such as the condition of the paper insulation, the presence of an irreversible failure mechanism, PCB contamination, etc. For each combination of risk factors, a decision tree should be drawn.

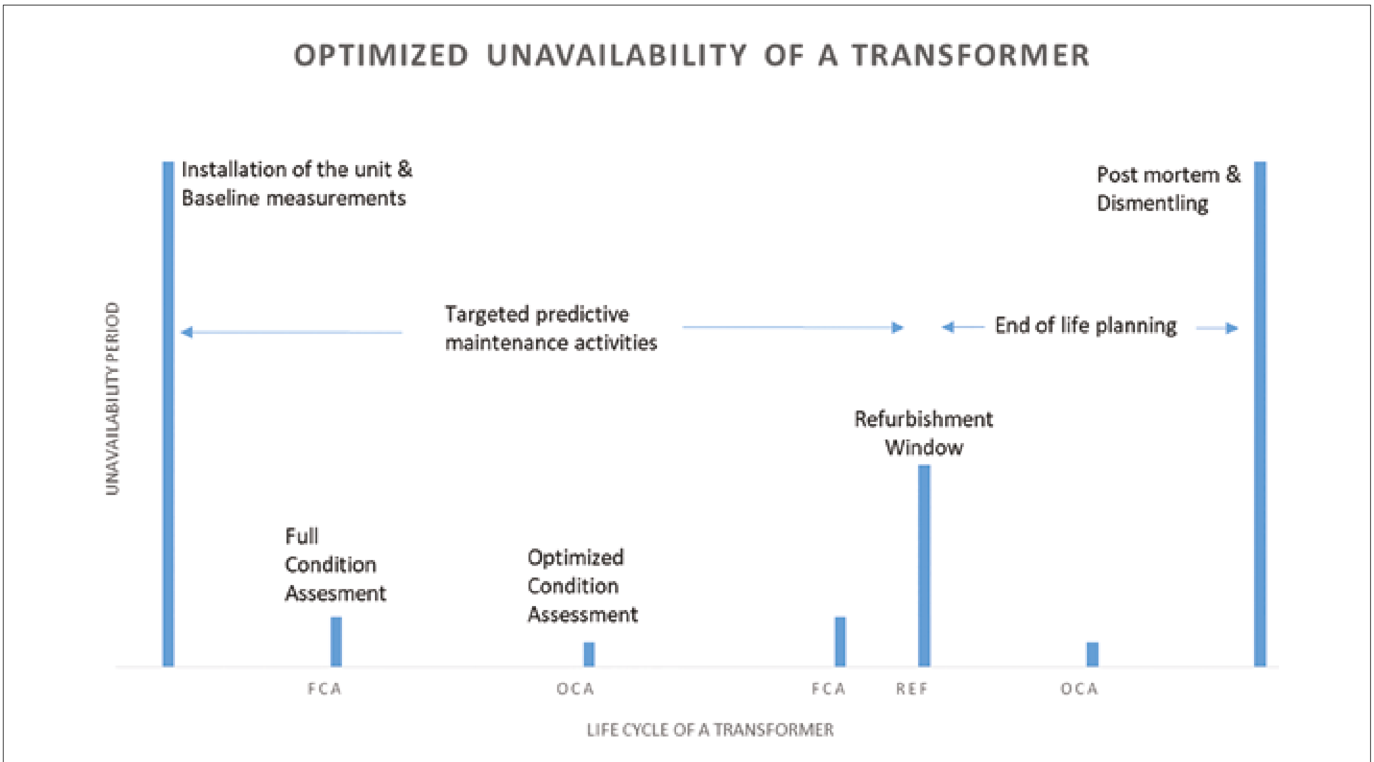

Figure 3. The optimum time for refurbishment

Electrical network operators should exchange relevant information data in order to take the proper predictive maintenance actions

In the 1970s, a cardiologist named Lee Goldman used a model created by mathematicians, who were developing statistical methodologies, to determine whether someone was suffering from a heart attack [4]. Goldman was interested in determining the best predictors of a heart attack. His work resulted in a decision tree – an algorithm that recommended a treatment option for each risk factor determined by the predictions based on every symptom that a patient was experiencing.

A patient who would have a high-risk factor would be sent directly to the cardiac care unit. Some would be asked to return to the hospital for periodic follow-ups. This decision tree was very helpful for the hospitals to prioritise patients by assigning them a certain risk factor. The risk in refurbishment can be defined as the degree of uncertainty of success and potential financial loss due to not achieving a certain number of years of service after the refurbishment. The equivalent of Goldman approach for power transformer fleets would be as follows:

- Very low risk = no symptoms of degradation of the active part; all condition assessment results within acceptable limits
- Low risk = only subjected to normal loading; normal insulation ageing; sister units have shown no degradation or failures; old condition assessment data
- Moderate risk = unknown reason for high concentration of hydrocarbons
- High risk = irreversible failure mechanism in the active part; high partial discharge activity.

7. Common goal

Each electric utility has different views on the design and lifecycle management of power transformers based on the company's profile and employee's experiences. The terminology of maintenance activities may differ but the actual work at all electrical utilities is very similar. With a common goal, electrical utilities would be able to exchange knowledge with other utilities with similar fleet profiles on best practices, predictive maintenance strategies, end-of-life estimations, reliability indices, and investment risk factor calculations.

Benchmarking large electrical networks based on common definitions and standardised prioritisation practices would be very beneficial for all stakeholders. Mergers and acquisitions between electrical networks would have a solid technical baseline. Organisations like North American Electric Reliability Corporation (NERC) would be able to establish more efficient interconnection reliability score metrics.

Maybe the best argument for utilities to work together is the serious brain drain that is occurring in the power transformer industry. Since 2010, a significant number of skilled electrical equipment specialists have retired from the industry. Utilities should have an effective strategy against the loss of experience and competency in specific technical fields. The electrical utilities should ensure a homogenous technical knowledge on critical substation equipment within the industry before the power of instinctive thinking walks out the door.

Today, most utilities tend to rely on technical societies such as IEEE, IEC, CIGRÉ to provide the information on evolving equipment issues. Even then it is up to the utility asset management engineers to stay current with the latest standards, publications and trends in order to identify the issues that may be relevant to their particular utility. Utility engineers should work together to avoid reinventing the wheel. There is already a substantial amount of data available waiting to be shared without the need for corporate oversight.

If developing reliable prioritisation indices and predictive degradation models for our transformer fleets is the ultimate goal, benchmarking across organisations based on common terminology, common condition assessment practices, and an efficient structure of knowledge sharing will get us there faster.

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Author

Ismail Güner received the B.E. degree in electrical engineering from École Polytechnique de Montréal, Canada. He worked as a power transformer electrical design engineer at ABB. He currently holds the position of transformer asset management engineer at Hydro-Québec. He is an active member of IEEE transformers committee working groups.