TECHNOLOGY

Aligning the economic and technical end of transformer life using online condition monitoring

ABSTRACT

This paper presents a case study for a 30 MVA, 132/22 kV transformer in service for 35 years, which showed significant furans but stable DGA and other parameters. Online Condition Monitoring justified effective utilization of the transformer, i.e., load optimization to align technical and economic End-Of-Life within a planned replacement window in the next 5 years, achieving a 40-year economic End-Of-Life. This shift from time-based to condition-based operation supported informed decision-making while minimizing risk and maximizing return on investment, as presented in the paper.

KEYWORDS:

Technical End-of-Life, Economical End-of-Life, Condition Monitoring, Diagnostics, Asset Management

Aligning TEOL and EEOL is essential for optimal asset utilization, reducing capital expenditure, and ensuring system reliability

1. Introduction

Aligning the economic and technical End-Of-Life (EOL) of power transformers using condition monitoring is a strategic approach that ensures transformers are neither retired too early (losing economic value) nor too late (risking failure).

Technical End-of-Life (TEOL) is defined as the point at which a transformer can no longer perform reliably, due to degradation of insulation, which is determined by physical and electrical condition assessments [1]. Economic End-of-Life (EEOL) is the point in the life of the transformer where it is no longer cost-effective to keep the transformer in service, even if technically functional. This is driven by maintenance costs, efficiency losses, risk of failure, and replacement options [2].

Online Condition Monitoring (OCM) bridges the gap between technical degradation and financial justification, enabling end users to:

- **Avoid premature capital expenditure** - If the transformer is technically sound (no major degradation), condition monitoring data can justify extending operation unit TEOL is reached, beyond the traditional "age-based" EEOL.
- **Make data-driven, risk-aware asset lifecycle decisions** - If the transformer is nearing its traditional "age-based" EEOL, condition monitoring can help with the effective utilization of the transformer, i.e., load optimization to last unit TEOL.
- **Prevent unplanned outages and high failure costs** - Avoiding catastrophic failure by identifying the optimal intervention point—preserving both residual value and system reliability by feeding data into risk-based decision models. It may assess a shorter TEOL and feed that information in the decision model, whatever the EEOL it may have been assigned.

Aligning these two EOL definitions is essential for optimal asset utilization, reducing capital expenditure, and ensuring system reliability. OCM provides a bridge between these paradigms, enabling data-driven decisions to extend or replace transformers at the right time.

In this paper, we will present a case study of integrating condition monitoring into the asset management strategy for an aged transformer, which enhanced transformer utilization and aligned EEOL and TEOL. This study is for a 30 MVA, 132/22 kV transformer in service for 35 years, which showed significant furans but stable DGA and other parameters. OCM justified effective utilization of the transformer, i.e., load optimization to align TEOL and EEOL within a planned replacement window in the next 5 years. This shift from time-based to condition-based operation supported more informed decision making while minimizing risk and maximizing Return on Investments (ROI). ROI calculations for enhanced transformer utilization are presented in this paper.

Accurate estimation of a transformer's remaining useful life through OCM helps endusers to defer or accelerate procurement based on actual condition, not age

1.1 Importance in the present context

The traditional disconnect between transformer aging and procurement timing is no longer sustainable in today's constrained market. By integrating TEOL-EEOL alignment via OCM into procurement strategies, end users can:

- Mitigate supply chain risks.
- Avoid forced outages and high-cost emergency buys.
- Make smarter, phased, and cost-effective purchasing decisions.

Due to long lead times and raw material shortages, transformer replacements must be planned well in advance. Accurate estimation of a transformer's remaining useful life through OCM helps endusers to defer or accelerate procurement based on actual condition, not age. This helps in avoiding emergency replacements, which are expensive and logistically difficult. Budget forecasting can be smoothed, and sudden CAPEX shocks will be avoided.

Global supply chain disruptions (post-COVID and ongoing geopolitical tensions) have significantly increased delivery times for power transformers [3]. With procurement lead times now extending 18–36 months, there's a risk of reaching EOL before replacements are available. Emergency purchases often result in lower technical performance and/or higher costs.

Transformer procurement is now a multidimensional challenge requiring coordinated planning, technical clarity, supply chain risk management, and strategic investment. End users must move toward smarter procurement models that integrate condition data, which is critical for future resilience. Condition monitoring supports risk-based prioritization in procurement, for example, as listed in Table 1.

Apart from the above, insurers typically assess transformer insurability based on factors such as [4]:

- Age and maintenance history,
- Recorded fault events or tripping,
- Test and inspection records (e.g., DGA, insulation testing),
- Known design issues or past failures (e.g., OLTC type, bushing models),
- Compliance with safety and operational standards.

Transformers lacking documentation or monitoring are often viewed as high risk, especially if over 25 years old. Providing insurers with comprehensive reports including OCM data trends, transformer assessment index profiles, and TEOL estimated with risk scoring demonstrates a proactive asset management approach, often leading to lower premiums or extended coverage terms.

1.2 Role of online condition monitoring

OCM has become a cornerstone of modern asset management, offering real-time insights into transformer health. When integrated into procurement and replacement planning, it enables utilities to move from reactive to predictive and optimized decision-making regarding both TEOL and EEOL. It helps in avoiding: premature retirement and stranded value, over-extending deteriorated assets, rising OPEX, or unexpected failure.

1.2.1 Enhancing TEOL detection

OCM tools—such as Dissolved Gas Analysis (DGA), moisture sensors, and fibre optic temperature probes—provide actionable data on internal degradation mechanisms, enabling:

- Early identification of insulation aging (e.g., Degree of Polymerization (DP) trending),
- Detection of incipient faults before catastrophic failure,
- Assessment of thermal loading and cooling performance,
- Validation of dielectric integrity over time.

These insights help determine the actual TEOL rather than relying on age-based assumptions. Thermal ageing models (IEC/IEEE) help in estimating remaining insulation life [5].

1.2.2 Supporting EEOL decisions

OCM also plays a key role in assessing the economic viability of keeping a transformer in service:

- Quantifies performance decline or increased losses over time,
- Helps evaluate the cost-benefit of repair vs. replacement,
- Supports insurance and compliance justifications,
- Assists in identifying hidden costs, such as derating or deferred load growth.

OCM is the bridge between transformer health and procurement readiness. It enables data-driven alignment of technical degradation with economic rationale, transforming transformer procurement into a proactive, risk-informed process. In the next section, we discuss some of the criteria for TEOL and EEOL.

In terms of reducing premiums, insurers reward end users with:

- Lower premiums for monitored units,
- Reduced deductibles or broader coverage clauses,
- Continued coverage for transformers >30 years if health is proven,
- More favourable underwriting terms during renewal.

OCM has become a cornerstone of modern asset management, offering real-time insights into transformer health

Table 1. Risk-based prioritization in procurement

Transformer Assessment Index (TAI)	Procurement Priority
Poor	Immediate action (order or refurbish)
Moderate	Plan within 12–24 months
Good	Defer replacement, monitor periodically

2. End-of-Life definitions

Some of the TEOL criteria are listed in Table 2.

Table 2. Examples of transformer Technical End-of-Life (TEOL) scenarios

TEOL Scenario	Condition Description	Impact on Operation	TEOL Trigger
Insulation Aging (Low DP)	DP < 200 due to thermal aging	Loss of mechanical strength; winding collapse risk	Paper cannot be restored or rewound practically
Repeated Gas Generation (DGA)	High acetylene/ethylene levels	Internal arcing or hotspot risk	Sustained fault gases despite treatment
High Moisture in Insulation	Moisture >3% in paper	Dielectric failure, bubble formation	Dry-out ineffective; aging irreversible
Clamping Force of Windings	Loss of clamping force	Short circuit failure	Re-clamping is not feasible
OLTC or Bushing Failures	Arcing, PD activity, contact wear	Flashover, dielectric failure	Components beyond safe service life
Frequent Protection Trips	Internal short circuits, winding movement	Grid instability, reliability risk	Root cause cannot be economically fixed
Failed Dielectric Testing	Fails induced or impulse tests	Safety and compliance failure	Repair is not cost-effective or assured
Design Obsolescence	No spares or OEM support	Long downtime, maintenance impractical	Support no longer available; non-compliant

Based on the experience of previously retired transformers and experimental work, a DP of 200 or less means the TEOL of the paper insulation has been reached

Some of the EEOL criteria are listed in Table 3.

For this transformer under investigation, the key factors that led to the implementation of OCM for alignment of the two EOL's include:

- Paper Insulation Degradation (TEOL)
- Obsolete Design with No Manufacturer Support (TEOL)
- Capital Depreciation (EEOL)
- Insurance Cost Surge (EEOL)
- Reputation Risk (EEOL)

3. Transformer under investigation

The details of the transformer under investigation are as follows (Table 4):

3.1 Current degree of polymerization (DP)

DP is the main indication of paper health [6]. It has been proven, based on the experience of previously retired transformers and experimental work, that a DP of 200 or less means the TEOL of the paper insulation has been reached.

Typically, DPe_{nd} = 200 and DP_{start} = 1000.

A method of determining the DP value, without taking the transformer out of service, involves analysing the insulating oil for furanic compounds [7], which are produced during the ageing of the cellulose insulation. This method is referred to as the indirect method. Studies have been done that correlate the DP value with the furan content in the oil. Mathematical models showing this correlation have also been developed.

The studies have revealed, through laboratory tests, that 2-furfural, also referred to as the 2-furaldehyde (2-FAL) is the most stable byproduct of cellulose ageing as it is stable for years. It is therefore widely used as an indicator to predict the

Table 3. Examples of transformer Economic End-of-Life (EEOL) scenarios

EEOL Scenario	Condition Description	Impact on Business Case	EEOL Trigger
Capital Depreciation	Allocation of a transformer's initial purchase cost over its expected useful life	Net Book Value becomes a stranded cost or needs to be written down	Typically, 40 years for power transformers
Rising Maintenance Costs	Frequent repairs, oil processing, parts replacement	O&M costs exceed the value of continued operation	The maintenance budget is no longer justifiable
High Energy Losses (I^2R, Core Losses)	Inefficient design vs modern units	Increased electricity losses reduce profitability	Replacement pays back through loss savings
Decreased Reliability Leading to Penalties	Frequent outages, downtime fines	Regulatory penalties or customer dissatisfaction	Reliability risk outweighs continued use
Load Growth Exceeds Rating	Transformer regularly overloaded	Forced derating or risk of failure	Upgrade or replace with a higher-rated unit
Insurance Withdrawal or Cost Surge	Insurers view the transformer as high-risk	High premiums or denial of coverage	Financial risk is too high to retain the asset
Environmental Compliance Issues	Use of PCB oil, leak-prone design	Non-compliance with current environmental laws	Replacement required to meet standards
Opportunity Cost of Delayed Capex	Old asset prevents more efficient investment	Lost savings from the deferment of efficient tech	Better return from new equipment justifies replacement
End of OEM Support	Discontinued model; no parts or service	Downtime risk and cost are too high	The cost of operating an unsupported asset exceeds the benefit
Reputation Risk or Stakeholder Pressure	Aged assets seen as a risk to reliability image	Loss of stakeholder confidence or investor concern	Proactive replacement for risk mitigation
Supply Chain Synchronization	Part of fleet-wide upgrade plan	Streamlined procurement and maintenance	Economies of scale justify early replacement

Table 4. Transformer under investigation

Parameter	Values	Parameter	Values
Rated Power	20/30 MVA	Oil	Mineral
Voltage	132/23.33kV	Oil Preservation	Conservator
Impedance	18%	Cooling type	ONAN/ONAF
Vector	Ynd11	LTC type	OLTC
Manufacture Year	1990	Tapping	23 taps, 1.4% steps
Top Oil Rise (Max)	60K	Winding Rise (Max)	65K

paper DP value. There are different models, such as:

- Chengdong [8],
- De Pablo [9],
- Burton [10],
- Cheim [11].

The Cheim model, which uses a statistical analysis of all the different models to estimate the current DP value with a tolerance level, is a good indicator of the variation

The major setback with these models is in cases where the oil has been replaced or regenerated, which will vary the concentration of the furans. In such cases, when oil has been replaced or regenerated, the total picture in terms of 2-FAL concentration is distorted, and very inaccurate results are the only outcome. This distortion of 2-FAL is because the oil processing that is done to treat the oil for better insulation properties will discard or vary the furan concentration.

The advantage of the indirect method is that if it identifies a problem (very low DP value), a problem exists. Knowledge of the transformer design (paper type), dominating ageing factor, and oil history is required to reduce the degree of inaccuracy or to bring more understanding of the obtained results. The Cheim model, which uses a statistical analysis of all the different models to estimate the current DP value with a tolerance level, is a good indicator of the variation. Table 5 shows the comparison of the different models.

The studies have revealed, through laboratory tests, that 2-furfural, also referred to as the 2-furaldehyde (2-FAL) is the most stable byproduct of cellulose ageing as it is stable for years

Table 5. Ageing interpretation based on 2-FAL ppm values: All models vs Cheim

2-FAL (ppm)	Chendgong (Kraft)	DePablo (Kraft)	Pahlavanpour (Kraft)	Leibfried (Kraft)	Cheim (Kraft)	Ageing
0.01	1002.9	798.7	798.5	1133.3	956±177	Not an issue
0.1	717.1	790.6	785.4	800	746±54	Some ageing
0.5	517.4	756.9	731.9	567.01	574±57	Significant ageing
1	431.4	718.6	674.5	466.6	490±59	Significant ageing
2	345.4	652.5	583.1	366.3	406±61	Severe ageing
5	231.7	511.53	414.5	233.6	295±64	Severe ageing
7	189.9	447.1	347.52	184.9	255±65	End of life

If the hot spot temperature is maintained < 60°C and moisture is maintained < 2% in the paper, the TEOL exceeds the EEOL set at 40 years

Table 6. Parameters needed for Technical End of Life calculations

SI #	Parameter	Value	Status/Source
1	Voltage (kV)	132	Known, Nameplate.
2	Breathing type	To be estimated	Unknown, Not known.
3	Oil type	Mineral	Known, Nameplate.
4	Paper type	Kraft	Known, Nameplate.
5	DPstart	447	Known, Oil test report.
6	O2 (ppm)	~12,000 – 15,000	Known, Oil test report.
7	Water Content in Paper (%)	1.5-2%	Known, Oil test report & Calculated from Online DGA.
8	Hot Spot Temperature (°C)	59°C	Known, calculated from load, measured top oil (measured online), and transformer design data.

As per the latest oil test report (dated January 2025), the current estimated 2-FAL = 0.88 ppm, which translates to significant ageing of the transformer.

3.2 Estimating transformer Technical End of Life

To evaluate the remaining transformer TEOL [12], the following parameters are required, as listed in Table 6. The status/source of the information for this 20/30MVA transformer is listed as well.

Except for the transformer breathing type, the other parameters were known/calculated for this 20/30 MVA transformer. The type of breathing system in a transformer—sealed, conservator-sealed (with bladder & breather), gas-blanket, or air-breathing—plays a critical role in moisture ingress, oxidation, and overall aging rate, all of which directly influence the estimation of remaining life of the transformer. As the online DGA device does not measure O_2 and N_2, the previous laboratory results (Table 7) are used for interpretation.

The air saturation in oil ratio for O_2/N_2 = 0.5. Based on the O_2/N_2 clustering near the saturation ratio, it can be safely assumed that this is an air-breathing transformer.

The expected end of transformer paper life can be calculated using [13]:

$$\text{Expected life (years)} = \frac{\frac{1}{DP_{end}} - \frac{1}{DP_{start}}}{A \times 24 \times 365} \times \frac{E_a}{e^{R \times (T+273)}}$$

Where,

- DP = Degree of Polymerization,
- Ea is the activation energy required for the reaction in J/mol,
- T is the hotspot temperature of the paper in °C,
- R is the gas constant (8.314 J/mol/K) and
- A is the pre-exponential factor in h^{-1}.

Based on the latest oil test report, DP-start = 506 ± 58 (Cheim model) as listed in Table 8.

The TEOL is evaluated at:

- Maximum Hot Spot Temperature (HST) < 60°C
- E_a = 111 kJ/mol
- A (pre-exponential factor) based on O2 < 25,000 ppm and moisture < 2% in paper [13].

From Figure 1, even though this transformer has significantly aged, if the hot spot temperature is maintained < 60°C and moisture is maintained < 2% in the paper, the TEOL exceeds the EEOL set at 40 years.

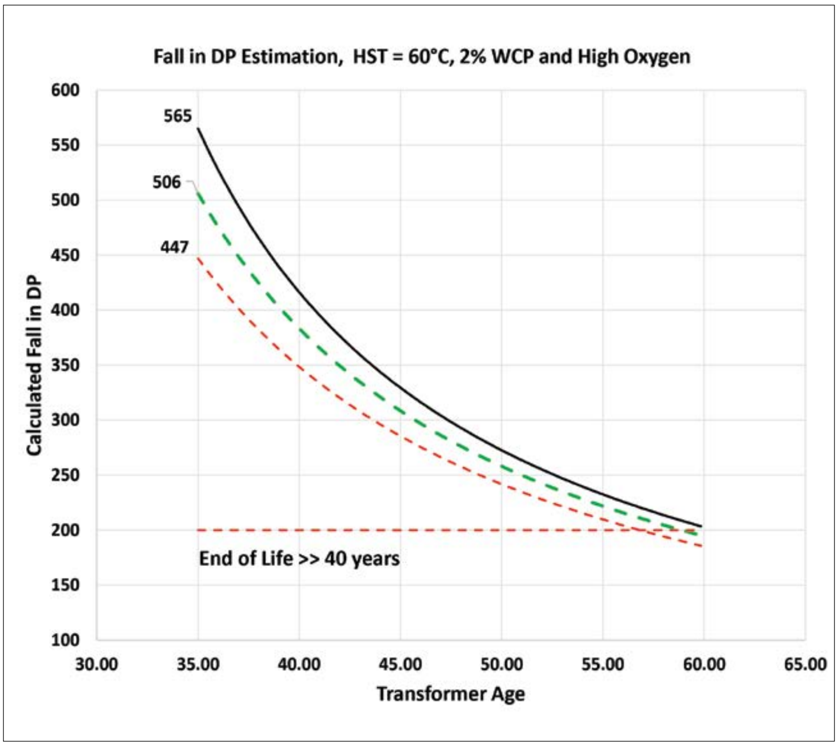

Figure 1. TEOL estimation: Fall in DP calculation

Table 7. Oxygen and nitrogen results

	Dec-24	Jul-23	Feb-23	Nov-22	Jan-22
O_2	12,329	14,268	15,068	16,379	15,371
N_2	37,455	39,189	40,819	41,827	39,533
O_2/N_2 ratio	0.329	0.364	0.369	0.391	0.388

Table 8. Estimated current DP as per Cheim model

Furan (ppm)	Max DP	Average DP	Min DP
0.88	565	506	447

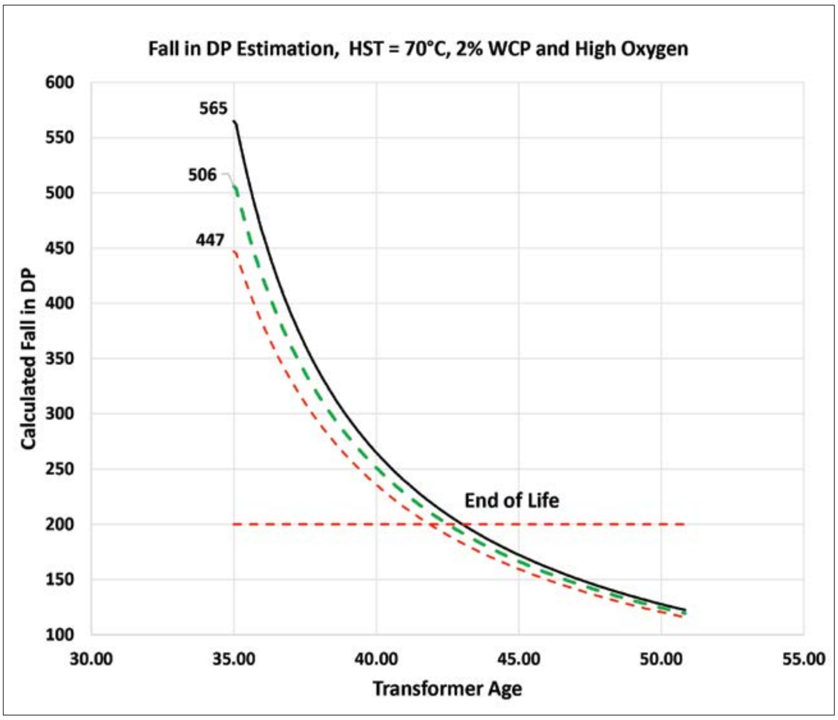

Figure 2. TEOL estimation: Fall in DP calculation at 25% extra load

3.3 Aligning TEOL and EEOL

By using OCM, the transformer is now operated at a hot spot of 70°C. Under such conditions, the TEOL ~40 years = expected EEOL (Figure 2), which optimises the loading of the transformer along with supporting risk-based procurement. OCM enabled optimized utilization of this 35-year-old transformer by tailoring loading strategies to real-time health data. The ROI benefit is discussed in the next section.

By carefully optimizing the load on this transformer nearing EOL, the end user was able to:

- Defer replacements by 5 years without increasing risk.
- Prioritize capital deployment toward truly at-risk assets.
- Improve ROI on legacy equipment due to extra loading capacity.

4. Cost-benefit analysis of aligning TEOL with EEOL

The profit margin on this extra energy delivered can be very significant for process plants without having the need to upgrade the transformer. The annualized benefit can be calculated considering the expected extra 20% load due to OCM implementation, as shown in Table 9.

With the above annual benefit, and the (assumed) cost of monitoring of $150,000 and a support cost of $5,000, the following can be calculated (Table 10).

Other benefits, like reduction in failure rate, loss of production benefit, reduction in insurance premiums, and capital deferment, can be quantified as well.

With the annual benefit of $473,000 from the transformer with the monitoring, and the assumed cost of the monitoring system of $150,000, the return on the investment is less than a year

Table 10. ROI on OCM implementation: Additional loading

Parameters	Outcome
IRR (Rate of Return)	307%
Payback period (years)	0.325
Discounted Payback period is less than	1 year

Table 9. Improved loading benefit (annually)

Increased Loading Benefit	Input	Without Monitoring	With Monitoring
Loading without monitoring at 13.5 (MW)	13.5	13.5	--
Extra loading with monitoring at 18.9 (MW)	18.9	--	18.9
Duration of extra loading (hours)	8760	8760	8760
Probability of extra loading occurrence (%)	100%	100%	100%
Value of delivered energy ($/MWh)	10	10	10
Transformer normal life (hours)	40 years	40 years	40 years
Replacement cost of transformer ($)	300,000	300,000	300,000
Aging factor at ~50% load	--	0.012	--
Aging factor at ~67% load	--	--	0.039
Gross value of extra energy delivered	--	$1,182,600	$1,655,640
Value of additional loss of transformer life	--	$0	$0
Benefit from monitoring			
Annual Benefit			$473,040

Aligning TEOL with EEOL enables optimal transformer replacement decisions—balancing physical asset health with financial efficiency

Conclusion

Condition assessment based on OCM provides a robust framework to quantify technical aging and economic viability of transformers. Aligning TEOL with EEOL enables optimal transformer replacement decisions—balancing physical asset health with financial efficiency. The integration of OCM empowers this alignment by providing real-time insights into degradation trends and operational risk, enabling data-driven economic decisions. Decisions can be based on real asset health rather than age, enabling budget smoothing and better resource allocation.

This approach empowers end users to extract maximum value from the ageing transformer while avoiding risk and financial inefficiency. This case study proves that a 35-year-old transformer's TEOL can be aligned with its EEOL while simultaneously extracting financial benefit. Planning for a replacement transformer can be done within the next 5 years under the present circumstances.

Additionally, investing in basic OCM can result in a significant reduction in insurance premiums for ageing transformers. This is the topic for the next paper.

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