

Beyond MVA: Why transformer size alone fails as a metric for Condition Monitoring ROI

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ABSTRACT

Transformer Online Condition Monitoring (OCM) is often prioritized for high-capacity units on the assumption that greater MVA ratings justify larger investments. However, practical field evidence shows that transformer capacity alone is not a reliable indicator of monitoring value.

Instead, factors such as redundancy configuration, replacement lead time, and process dependency are the primary determinants of risk exposure and financial return.

This paper explores two wind farm cases: a 150 MVA transformer with a cold spare and a 40 MVA transformer without any spare, to illustrate that system context, not size, defines the business case for OCM systems. It further explains how OCM helps in information-driven risk reduction.

KEYWORDS:

Online Condition Monitoring, transformers, Return on Investment, spare transformers, case study

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1. Introduction

Modern power system end users are integrating Online Condition Monitoring (OCM) to improve transformer asset management - reliability, lifecycle cost, and prevent catastrophic failures [1]. These OCM systems continuously measure critical transformer parameters such as oil temperature, dissolved gas, moisture, and bushing health, etc., providing early fault detection that enables proactive maintenance [2].

In practice, however, monitoring investments are frequently allocated based on transformer nameplate size (MVA/kV). Large transformers are perceived as "more critical" because they are expensive and central to grid operation. However, experience shows that this rule of thumb method can be misleading.

Yet, smaller transformers can be operationally irreplaceable, meaning particularly in renewable generation sites or isolated systems where failure leads to complete loss of output for weeks or months. In such cases, a smaller transformer's operational interruption can have disproportionately large economic and contractual consequences.

This article examines why MVA rating alone is not a sufficient measure of monitoring priority and presents a framework for OCM Return on Investment (ROI) based on functional criticality rather than equipment size.

2. Traditional bias toward large transformers

Historically, transformer monitoring strategies have followed asset-value logic:

- High-MVA transformers are expensive, so they must be monitored.
- Smaller transformers are cheaper, so they are treated as lower priority.

This perspective assumes economic loss is proportional to equipment value.

While intuitive, this approach neglects the system-level role of each transformer. In modern energy systems, especially in renewable generation and distributed assets, the economic consequence of failure depends less on equipment replacement cost and more on revenue interruption and operational interdependency.

3. Criticality: Influence of spare unit

Transformer criticality is determined by the combination of [3]:

- Consequence of failure: influenced by generation dependency, spare availability, replacement time, and commercial exposure.
- Probability of failure: derived from design characteristics, age, and operating conditions.

The product of these two components defines a criticality index, which guides the depth of OCM justified for a given transformer. In this analysis, the focus is on spare availability for two different wind farms.

Typically, three common configurations exist across end users in Asia Pacific as listed in Table 1.

3.1 Case A: Cold spare unit available

- 1x150 MVA, 132/33 kV transformer
- A spare unit exists but is cold (not a hot standby)
- Replacement and commissioning require 4 - 6 weeks

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Table 1. Definitions of spare units

Configuration	Description	Typical outage duration	Failure consequence severity
Hot standby spare	Fully commissioned spare unit in service-ready condition	Hours to 1 day	Low
Cold spare	Installed but de-energized or stored; requires installation/commissioning	2–6 weeks	Moderate
No spare	No replacement unit on site; procurement and delivery lead times 1–2 years	>1 year	High



- Estimated generation value: $90 -120 per MWh (yearly average variation since commissioning)

3.2 Case B: No spare unit available

- 2x40 MVA, 132/22 kV, each handling 50% of total output (but not parallel operation)
- No spare transformer; replacement lead time >2 years
- Outage during failure reduces capacity by 50% of total farm output

The ROI analysis aims to demonstrate that transformer redundancy significantly alters outage duration, failure consequence severity, and consequently, the financial justification for OCM. Both sites were recommended identical OCM architectures:

- Electronic Temperature Monitor (ETMs) for top-oil and winding temperatures,
- A multi-gas monitor for online dissolved gas analysis (DGA),
- An integrated transformer monitor including bushing analysis.

The total investment (CapEx + installation + support) varies per transformer, depending on OCM system configuration, shipping costs and communications infrastructure

Collected data are processed through intelligent algorithms in the integrated transformer monitor and displayed via a centralized platform, allowing asset managers to identify degradation trends and schedule interventions before failure occurs.

4. ROI framework and cost - benefit components

4.1 Cost components

The total investment (Capital Expenditure (CapEx) + installation + support) varies per transformer, depending on OCM system configuration, shipping costs and communications infrastructure. For this example, an investment of $150,000-$200,00 was estimated. Due to remote location of the wind farms, travel time, accommodation, and mobilisation of technicians increase investment costs.

4.2 Benefit streams

Annualized financial benefits are categorized as [3]:

- Failure-related savings: reduced repair or replacement costs due to early fault detection,
- Generation continuity: limited revenue loss from downtime,
- Maintenance optimization: reduced manual oil sampling and inspection costs.

For decades, transformer MVA rating has been used either implicitly or explicitly as a proxy for criticality

4.3 Analytical model

ROI is derived from discounted cash flow analysis:

$$NPV = \sum_{t=1}^{n} \frac{B_t - C_t}{(1+i)^t}$$

Where:

- NPV = Net Present Value
- B_t = annual benefit at year t
- C_t = annual cost at year t
- i = discount rate (used = 5%)
- t = time of the cash flow

4.4 Comparative results

The availability of a cold spare reduces outage duration from two years to one month, cutting the potential energy-not-supplied cost by nearly 90%. As a result (as listed in Table 2):

- The 150 MVA case with a cold spare unit shows a good ROI, reflecting a lower marginal benefit from monitoring since backup recovery time is manageable.
- The 40 MVA case with no spare shows an exceptionally high ROI (>200%) because monitoring directly mitigates the risk of prolonged outage with no standby unit.

5. Discussion points

5.1. Rethinking criticality: Why size became a misleading proxy

For decades, transformer MVA rating has been used either implicitly or explicitly as a proxy for criticality. This practice evolved naturally from a capital-cost perspective: large transformers are expensive, difficult to manufacture, and often central to transmission networks. From this viewpoint, it seemed logical to prioritize high-MVA units for advanced diagnostics and condition monitoring.

However, this logic conflates asset value with business risk. While MVA rating correlates with transformer replacement cost, it does not reliably correlate with the economic consequence of failure. For the March 2025 transformer failure at the North Hyde substation that caused the major Heathrow Airport power outage, the configuration was two (SGT1 and SGT3) 50 MVA transformers feeding the entire load in parallel and a third unit (SGT2) was on hot standby [4]. Even with this configuration, outage was not prevented and the airport was closed for almost a day with estimated loss of US$70-150 million [5]. Using forensic analysis, it was concluded that the catastrophic failure on one of SGT3's high voltage bushings which caused a fire was moisture ingress. Interestingly, an elevated moisture reading in one of bushings had been detected in oil samples taken in July 2018 but mitigations appropriate to its severity were not actioned!

In modern power systems, particularly those with high penetration of renewable generation or critical locations, the dominant cost of transformer failure is no longer the transformer itself, but the duration and impact of the outage that follows.

The case studies examined in this article clearly demonstrate this mismatch. A high-capacity transformer with a deployable spare may incur weeks of downtime, while a smaller transformer with no redundancy can immobilize a wind farm for years. In such cases, the smaller unit represents a far greater financial risk despite its lower MVA rating.

This observation challenges a deeply embedded heuristic in asset management and highlights the need for a more nuanced approach to monitoring investment decisions.

5.2. Redundancy as the dominant economic lever

Among all variables influencing the ROI of condition monitoring, redundancy configuration emerges as the most influential. Whether a transformer has a hot spare, cold spare, or no spare at all fundamentally changes the economic landscape.

A generic simulation using the same data points as in Table 1 is listed in Table 3.

Table 2. ROI results for 150 MVA vs 40 MVA OCM implementation

Metric	150 MVA	40 MVA
Spare availability	Cold (4–6 weeks delay)	None (2 years delay)
Annual loss-of-generation benefit	~$40,000	~$530,000
Annual failure-rate reduction benefit	~$4,500	~$4,700
Maintenance benefit	~$1,500	~$1,500
Total annual benefit	~$46,00	~$536,200
Internal Rate of Return (IRR)	27%	>200%
Payback period	3.7 years	<1 year
Net Present Value (NPV) (5%)	~$650,000	~$8,644,000

In systems with redundancy, the consequence of failure is bounded. Even if a fault occurs, generation or power transfer can often be restored within days or weeks. Under these conditions, the primary benefit of OCM lies in:

- Avoiding secondary damage,
- Optimizing maintenance scheduling,
- Extending asset life.

These benefits are real and valuable, but they tend to produce moderate ROI, typically in the range of 10–20%.

By contrast, in non-redundant systems, the same failure can result in prolonged loss of generation, contractual penalties, and reputational damage. Here, OCM functions as a risk mitigation instrument. Preventing a single catastrophic event can offset the entire monitoring investment many times over, leading to exceptionally high returns, such as the Heathrow Airport power outage!

Importantly, redundancy is a system-level attribute, it is largely independent of transformer size. This explains why MVA rating alone fails to predict monitoring value.

5.3. Replacement lead time and the new supply-chain reality

Replacement lead time has become an increasingly critical variable in transformer risk assessment. Global manufacturing constraints, custom design requirements, and logistical challenges have extended delivery times for new transformers well beyond historical norms [6].

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In this context, even transformers of modest rating can present severe business risk if replacement lead times are greater than 1 year. The generalized cases underpinning this paper illustrate how long procurement horizons amplify outage consequences far more than transformer size does.

OCM gains disproportionate value under long lead-time conditions because it increases the probability of life extension interventions. Detecting insulation degradation, thermal stress, or gas generation early allows operators to:

- Plan outages during low-price periods,
- Secure temporary mitigation measures, or
- Defer failure until a replacement strategy is in place.

Thus, monitoring ROI scales strongly with lead time again, independently of MVA rating.

5.4. Energy price volatility and revenue exposure

Another factor diminishing the relevance of MVA rating is energy price volatility. In merchant generation environments or under variable market pricing, the cost of lost energy can exceed equipment cost within weeks.

A smaller transformer feeding a high-value generation asset during peak pricing periods can generate greater financial exposure than a larger transformer operating in a regulated, meshed transmission network. In such cases, the true "size" of the transformer is measured not in MVA, but in revenue at risk per day of outage.

OCM directly addresses this exposure by reducing the likelihood of sudden, unplanned outages. As energy markets become more volatile, the economic

Redundancy is a system-level attribute, it is largely independent of transformer size

Table 3. ROI comparative results: Different spare configuration

Parameter	Hot standby spare	Cold spare	No spare
Average outage duration	< 1 day	4–6 weeks	1–2 years
Cost of lost generation (USD)	$5k–$30k	$200k–$500k	$1M–$5M+
Typical failure-related benefit	Moderate	High	Very High
Estimated annualized benefit	$20k–$50k	$40k–$80k	$400k–$600k
ROI (IRR)	10–20%	25–40%	150–250%
Payback period	5–8 years	3–4 years	<1 year

A smaller transformer feeding a high-value generation asset during peak pricing periods can generate greater financial exposure than a larger transformer operating in a regulated, meshed transmission network

justification for monitoring increasingly tracks market conditions rather than physical asset ratings.

5.5 Monitoring as risk transfer, not just diagnostics

One of the most important implications of this article is a conceptual shift in how OCM is perceived. Traditionally, monitoring is framed as a diagnostic or maintenance optimization tool. However, in non-redundant or long-lead-time systems, it functions more accurately as a risk transfer mechanism.

By investing in monitoring, asset owners are effectively transferring risk from: sudden catastrophic failure → managed degradation with decision-making time.

This reframing helps explain why monitoring ROI can exceed 200% in some cases. The investment is not justified by incremental maintenance savings, but by the avoidance of rare, high-impact events. From this perspective, the relevance of MVA rating becomes secondary. What matters is the magnitude of the risk being transferred!

5.6 Implications for asset management strategy

The findings presented here suggest that utilities and asset owners should reconsider how they prioritize digitalization investments. A uniform, size-based approach risks under-monitoring smaller but operationally critical transformers while over-investing in large assets with limited marginal benefit.

A more effective strategy is context-driven prioritization, incorporating:

- Redundancy and spare availability,
- Replacement lead time,
- Revenue or process dependency,
- Energy price exposure, and
- Failure detectability and appropriate corrective action in time.

Such an approach aligns OCM investment with enterprise risk management principles and supports more defensible capital allocation decisions.

As power systems become more decentralized and supply chains more constrained, the disconnect between asset size and asset importance will continue to widen. Smaller transformers will increasingly serve as single points of failure for entire generation blocks or industrial processes.

6. Why a spare transformer is not always an option?

While the availability of a spare transformer can significantly reduce outage duration and financial risk, maintaining spare units is neither universally practical nor economically justified. In many real-world applications, the assumption that a spare transformer can simply be procured, stored, and deployed is flawed. Several structural, economic, and technical constraints limit the feasibility of spares, particularly for generation and remote assets.

6.1 Capital cost and balance-sheet constraints

Power transformers represent a substantial capital investment. Even medium-rated units can cost several million dollars, tying up capital that may remain unused for decades. For many asset owners, especially independent power producers or renewable developers allocating funds for spare equipment competes directly with revenue-generating investments.

From a financial perspective, a spare transformer produces no return until a failure occurs. In contrast, online OCM delivers continuous operational value by reducing failure risk and optimizing



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maintenance. As a result, organizations often favour investments that generate measurable returns rather than capital locked in contingency assets.

6.2 Physical and logistical limitations

Storing a spare transformer is not trivial. Proper storage requires:

- Climate-controlled environments to prevent moisture ingress [7],
- Periodic oil testing and dielectric checks,
- Mechanical protection during long-term storage.

In remote wind farms, solar plants, or offshore installations, physical space and access constraints often make on-site storage impractical Even. when off-site storage is possible, transportation logistics such as heavy haulage permits, crane availability, and access roads can introduce delays comparable to new procurement.

A spare transformer may require refurbishment or upgrades before installation, eroding its perceived advantage over procuring a new unit

6.3 Aging spares and obsolescence risk

Spare transformers age even when idle. Insulation systems deteriorate over time due to moisture ingress, oxidation, and material aging. In addition, long storage periods can result in:

- Obsolete bushings or tap changers,
- Outdated protection interfaces,
- Non-compliance with evolving grid codes or standards.

Consequently, a spare transformer may require refurbishment or upgrades before installation, eroding its



While spare transformers can be effective in reducing downtime, they are not a universally viable solution

perceived advantage over procuring a new unit.

6.4 Long-term uncertainty in asset strategy

Asset portfolios evolve. Generation capacities change, substations are reconfigured, and grid codes are updated. A spare transformer purchased today may no longer align with future system requirements.

For renewable assets in particular, ownership structures and power purchase agreements may change within a few years. Committing to a spare transformer under such uncertainty introduces stranded-asset risk, making OCM a more flexible and adaptable risk mitigation strategy.

6.5 Supply chain constraints and global demand

Ironically, the same supply chain constraints that make spares attractive also make them difficult to obtain. Global demand for transformers has increased significantly due to grid expansion, renewable integration, and electrification initiatives.

Manufacturers prioritize confirmed project orders over speculative spares. Lead times for spare units can approach those of operational transformers, reducing the feasibility of spare strategies, especially for smaller asset owners with limited purchasing leverage.

Conclusion

Looking at only transformer MVA rating is an inadequate predictor of monitoring ROI. In this evolving landscape, OCM must be viewed not as a luxury reserved for the largest assets, but as a targeted tool deployed where the cost of silence is highest. The economic justification for OCM depends on outage duration, redundancy, and dependency and not only on size. When a spare transformer exists, monitoring offers moderate ROI. In the absence of a spare, it becomes a mission-critical investment with payback periods measured in months rather than years. Integrating spare-availability data into asset-criticality modelling enhances investment prioritization and ensures optimal allocation of OCM budgets.

While spare transformers can be effective in reducing downtime, they are not a universally viable solution. Financial constraints, logistical challenges, design specificity, and strategic uncertainty often limit their practicality. As a result, many asset owners must manage transformer risk without relying on spares.

When evaluated holistically, the decision is often not between "spare or OCM" but between capital-heavy risk mitigation and information-driven risk reduction. In these contexts, OCM becomes not just a supplement to spare strategies, but a primary mechanism for risk mitigation. By increasing fault visibility and decision-making time, OCM enables asset owners to manage uncertainty in systems where replacement is slow, expensive, or uncertain.

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