Transformer Optimisation:
Extending Asset Performance and Life

Maximising Transformer ROI Requires
a Paradigm Shift in Asset Management

Transformer Optimisation
CORE
Capex | Opex | Risk Exposure

insulect
VERSATILITY VIA COLLABORATION

CORE: A Fleet-Wide Whole of Life Approach to Transformer Optimisation

Transformers are one of the most critical assets within an electricity network. Effective management of these assets – from initial specification, to online monitoring, maintenance and eventual replacement – is an increasingly complex task with costly implications. To optimise the management of transformers first requires a transformation in the approach to these assets.

Adoption of a fleet-wide approach “whole of life” approach enables a broader evaluation of the transformer environment. It addresses the interrelated planning, operational and risk factors that impact transformer performance and life. And in doing so, it paves the way for better decision making, greater asset security and lower total cost of ownership.

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Introduction

Transformers are an essential part of today's power grid. By enabling efficient transformation of AC power to higher and lower voltages, transformers have shaped our power systems into what they are today – indispensable networks that underpin so many aspects of our lives.

Fundamentals of transformer design have remained much the same over the past hundred years. The specification, design and manufacturing of power and distribution transformers are based on proven, internationally established engineering standards (such as IEEE, IEC, and their local equivalent in AS/NZS).

By comparison, the broader environment in which transformers operate is fast changing and rapidly becoming more complex, resulting in less-predictability in the demand placed on these assets. This change is visible in network load profiles, reverse energy flows and seasonal demand, with commercial pressures from the market, regulator and political sphere adding further complications. And the speed with which new technologies emerge creates yet another layer of complexity around technology evaluation, adoption and integration.

While this change is happening, in many western countries – Australia and New Zealand included – transformer fleets are ageing and failures are on the rise. The result is an environment where control over planning, operational and risk factors is reduced, leading to increasing uncertainty and costs – in short, a need to do more with less and without clear knowledge of what the future holds.

> A whole of life approach to asset specification, design, manufacture, monitoring, maintenance and end of life decisions

Consequently, in recent years utilities and other asset owners have been revisiting the way they manage their transformer fleets. Now more than ever before, a complete paradigm shift in transformer fleet management could deliver considerable gains for individual networks and interconnected networks alike.

This paper examines the broader operating environment for transformers; asset design and emerging technologies; the changing grid; and how transformer optimisation – a whole of life approach to specification, design, manufacture, monitoring, maintenance and end of life decisions – can support a more efficient network and lead to a more sustainable fleet management model.

For ease of reference we have dubbed this concept "CORE" – transformer optimisation that incorporates the broader **Capex**, **Opex**, and **Risk Exposure** factors which impact total cost of ownership.

The Macro Environment: Whole of Life Considerations

There are many dynamics at work that impact upon the management of a transformer fleet. These are not limited to the micro environment – factors that directly affect transformers such as load, temperature, asset and component condition, etc. Rather they also include macro environment forces that are indirectly connected to the everyday life of a transformer, but which have a much greater ability to impact the level of control over fleet management.

The effects of these macro influences are more difficult to encapsulate, however it is at this macro level that real opportunity exists to affect significant change. By identifying the most substantial costs and risks at their source, and addressing them directly – at the specification and design stage – change can be affected that will lead to greater control, predictability and flexibility in transformer management, and ultimately greater return on investment. These macro factors can be summed up into three interrelated categories:

Capital Expenditure (Capex):

Network planning considerations such as load patterns, energy flows, seasonal changes, fleet expansion, asset design and technology selection, service continuity, contingency plans.

Operational Expenditure (Opex):

Asset availability, reliability, real-time function, preventative and corrective maintenance, outages, upgrades, refurbishment and regulatory conformance.

Risk Exposure:

Commercial impact of failures, unplanned outages, employee / community safety, insurance coverage, exposure to litigation, environmental impact, company reputation.

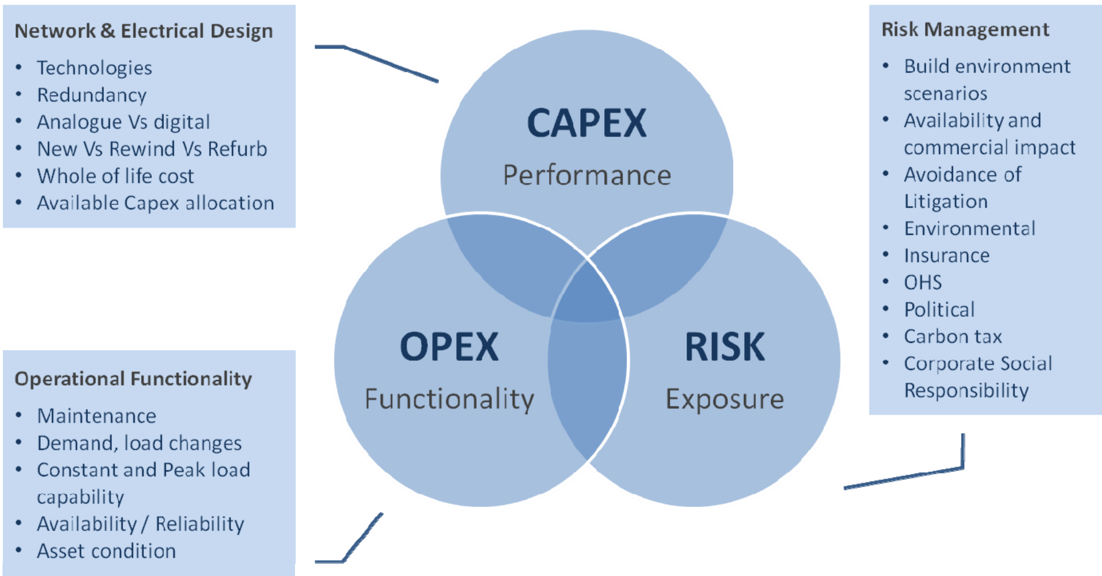

Figure 1 - **Dynamic Relationships**: Macro influences that indirectly impact the management of a transformer fleet.

Macro Priorities

The above figure highlights some of the topics relevant to each category, though they are by no means exhaustive, nor do they delve into the detail that exists within individual topics. The order of priority and weight given to each macro factor will vary according to the asset owner and their network configurations; however the fundamentals remain the same – the need to address the affect of these broader forces at the specification and design stage, engage industry and transformer OEMs more closely, leverage available technology, and introduce more flexibility into the specification process.

As an example, the number one priority for a **Transmission Utility** (TNSP) might be availability, due to considerable commercial and political implications if there should be a major outage. If they are running their assets on average at 35% rated load and have built in redundancy, then more performance is not an issue. Yet these are expensive, large power transformers, so maximising return on investment and asset life is critical. Similarly, maintenance costs may be a substantial burden on diminishing Opex funds, resulting in a need to review options to reduce expenditure. The transformers are located in secure locations without public access. Thus, while fire hazard and environmental concerns exist, public safety is not a high risk in these areas.

By contrast, a Distribution Utility (DNSP) operates a much more extensive network, with a broader mix of transformer sizes, skewed toward the distribution end. These are dispersed throughout towns, inside buildings and in environmentally sensitive areas. And a larger share of these assets is running much harder, sometimes under overload conditions and without redundancy. Whilst availability is still important, performance and capacity become more urgent, as does the need to provide measures to safeguard the public and environment. Maintenance requirements also are greatly varied, with a network of more heavily loaded assets spread out over an extensive area.

A Power Plant – or a Generation Company with several sites – may have similar requirements to a TNSP, albeit on a smaller scale. An Industrial Owner such as a Mining company or Smelter differ considerably again, with critical commercial needs, demanding loads, environmental concerns and a public image to maintain.

In each of these situations, ageing assets, service life and rising failures are likely to be a growing concern. In Australia, the average age of T&D assets is estimated at 30 - 35 years[1]. In New Zealand, Transpower's average power transformer age is around 40 years[2]. Similarly, all asset owners have a common interest in limiting insurance and legal burdens, as well as conforming to regulatory requirements.

Through a clearer understanding of the macro landscape and its impact upon a transformer fleet, an asset owner can apply this information to determine what options are available, what action needs to be taken, where industry engagement is needed, what changes can be made to the specification and/or design approach, so as to secure their network for the future and deliver the best possible return.

Transformer Specification and Design

Transformer design is based on proven engineering standards that govern the appropriate use of insulating materials and temperature control methods to balance performance levels and material life expectations. Standards such as AS/NZS (IEC) 60076, IEEE C57.12.00-2010 and IEEE C57.154-2012 provide the fundamental guidelines on how material selection and designs interrelate, and ultimately how they are best selected to control temperature, moisture and the impact these have on the degradation of the insulation system over the life of a transformer.

Where design principles have remained much the same, transformer design tools and manufacturing techniques have developed substantially over the last century. Computer aided design, advanced machinery and factory automation have enabled OEMs to produce transformers to tighter tolerances and reduce material and labour overheads.

Some transformer design tools are structured around traditional insulation materials only. Newer material technologies (relatively speaking) that are found in international standards – such as aramid paper and ester fluids – are not yet universally incorporated into these design tools. Thus, the resulting gains that could be achieved with these newer materials beyond those traditionally expected are underutilised.

Incorporating all material options into design tools introduces more flexibility and innovation into the design process, allowing the transformer designer to balance and optimise performance gains against achieving specific design goals, such as transformer impedance, whilst minimising losses.

Specification Flexibility

A better understanding of these materials and the potential impact each can have will open up numerous options for asset owners. This can be gained through closer engagement of the technology providers and transformer manufacturers, openly discussing the available options and determining where changes can benefit.

In turn, this approach supports an opening up of specification limitations. Where currently a single specification may be used for all transformers of a given size, flexibility can be introduced to these specifications in terms of the materials and design type, so as to better suit different requirements across a given network. Instead of being bound to a one-size-fits-all model, a network owner can utilise a more open specification that allows a range of options that are best suited to the diversity of needs across a given network – whether related to temperature, weather, load, environment, remoteness, etc.

This approach must still be a balance however, taking into consideration the need for spare transformers with common power, voltage and impedance ratings.

The Insulation System

A transformer is a closed system. Once constructed, there is no method for readily inspecting what is happening inside the tank. The internal components cannot be visualised, serviced or repaired easily.

From a design point of view, the insulation system is the weakest link and is thus the primary constraint to advancing transformer design. It represents the part of the transformer that is most susceptible to ageing, which leads to a reduction in its mechanical and dielectric strength and unsurprisingly is one of the principal causes of failure in transformers[3].

There are two parts to an oil-filled transformer's insulation system. Firstly the solid insulation, which is most often cellulose-based paper and board. It provides structural support to the windings, as well as electrical insulation. Second is the oil, or dielectric fluid. This is generally mineral-based oil, though silicone and ester based fluids are also used. The oil extends the insulating capability and life of the cellulose, and together they provide a stronger system.

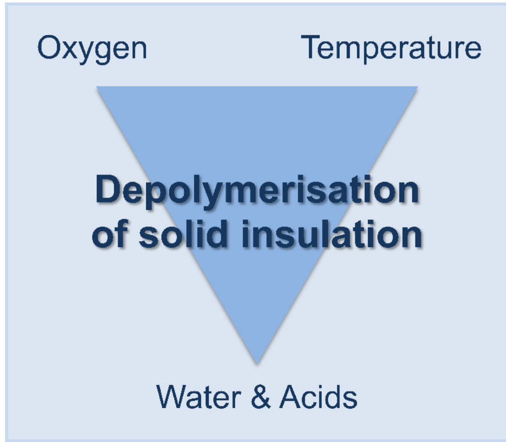

Figure 2 – Insulation Longevity & Transformer Life: Depolymerisation under the effect of temperature is accelerated in the presence of moisture, oxygen and acids.

It is widely accepted that the main impact upon insulation longevity and depolymerisation of cellulose paper is temperature (thermal ageing). This affect is accelerated in the presence of moisture, oxygen and acids.

Temperature

A closer look at the impact temperature has on a transformer yields deeper implications than just direct loss of life.

- Load is limited by the hot spot temperature, based on the design and the type of insulation system utilised.
- Hot spot temperature is similarly influenced not just by fluctuations in load, but by ambient temperature, cooling system design and fluid cooling effectiveness.
- Accurate temperature measurement is seriously impaired by the standard tools commonly used on transformers.
- Overloading beyond rated design results in non-linear increases in temperature and accelerated ageing.
- Accelerated ageing affects both tensile and dielectric strength of the insulation.
- An increase of 20°C equals approximately 90% reduction in asset life.
- Network planning and asset replacement forecasts are greatly affected by undetected, premature ageing.

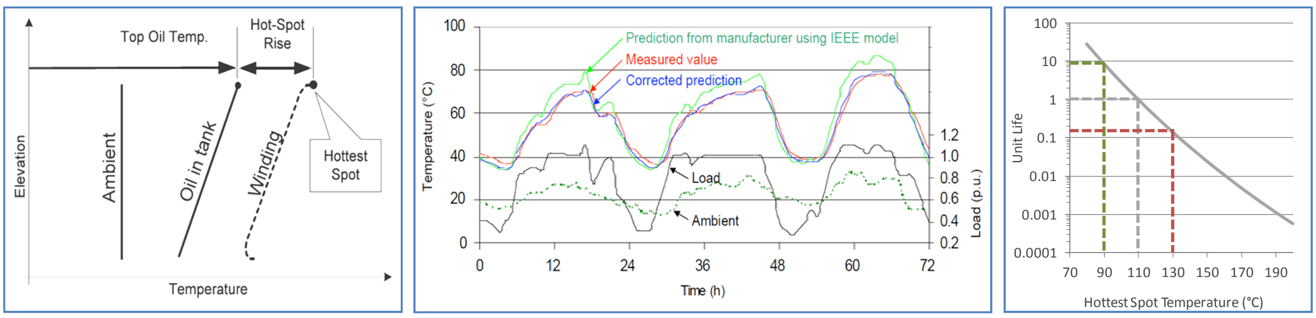

Figure 3 – Temperature: The effect on performance, life and design. The hottest spot as a limiting factor (left)[4]; accuracy of temperature measurements under normal and overload conditions (centre)[5]; IEEE loading guide and the effect of temperature on asset life (right)[6].

Moisture

Similarly, moisture has a serious role in premature ageing of insulation and the performance of the dielectric fluid:

- Moisture further reduces dielectric and tensile strength of the insulation
- It increases the risk of bubbling in the insulation
- It increases the risk of partial discharge
- An increase of moisture from 2% to 3% can decrease asset life by 10 years.

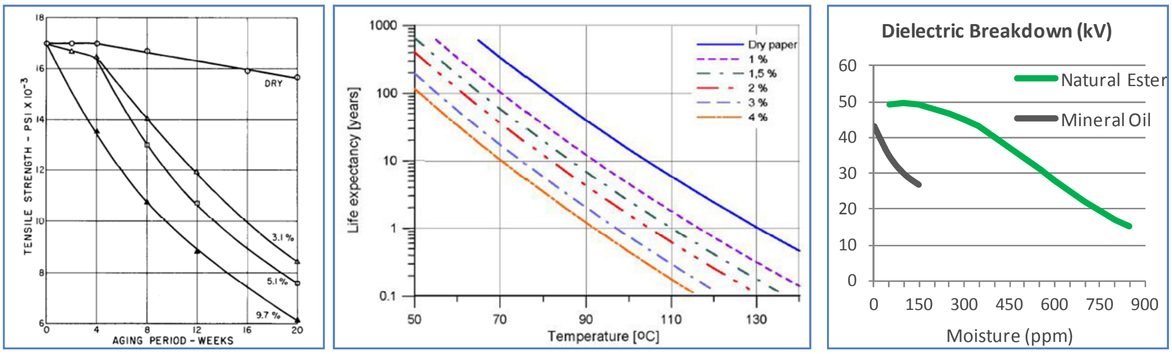

Figure 4 – Moisture & Transformers: A second major determinant of ageing. Reduction of tensile strength with increased moisture (left)[7]; transformer life expectancy and moisture (centre)[8]; and dielectric strength of transformer fluid with increased moisture (right)[9].

Bushings and Tap Changers

Beyond the insulation system, the next most critical components on a transformer in terms of both electrical stresses and failure rates are the bushings and on-load tap changers (OLTC).

There are several types of bushings technologies, the most common of which utilise insulating paper and/or dielectric fluid, not dissimilar to that used in the main tank insulation system. They too are therefore subject to insulation deterioration due to electrical stresses, temperature, moisture and impurities. If deterioration is left unchecked, explosive failure can occur.

Similarly, many OLTCs are partially immersed (the diverter switch) in their own insulating oil supply. The oil becomes heavily contaminated during arc quenching. This contamination ultimately effects maintenance intervals, lowers dielectric strength of the fluid and shortens mechanical life of the OLTC, especially in more demanding switching applications.

Visibility and Control

For a transformer owner to be able to effectively address these issues and gain control over their assets, it is critical that they first are able to visualise what is happening inside the transformer.

1. What operating conditions is it being subjected to?
2. What are the resulting internal changes to the insulation system and key components?
3. What impact does this have on performance, life and maintenance?

There are numerous hardware and software solutions – from the most basic with limited accuracy and function, to highly sophisticated devices that provide monitoring, trending and control capabilities. They offer either a direct protection function – such as rapid pressure relief – or enable the monitoring of one or more conditions, such as temperature, oil level and flow, moisture, pressure, partial discharge and gas levels.

Some devices need to be built into the transformer at the time of manufacture (cannot be retrofit); others while theoretically able to be retrofit post-manufacture, often still are limited for example by the number of mounting points available (e.g. drain valves, taps). Therefore such considerations need to be taken into account at the specification stage.

Given the closed-system characteristics of a transformer, it is these monitoring devices that provide the only way to see inside – enabling visibility of the operating condition and identification of potential problems. Logically, the extent to which such products are utilised determines just how much data can be retrieved, what can be done with the data (online monitoring, trending, early warning, alarm, trip, prevention) and what decisions can be made based on such data.

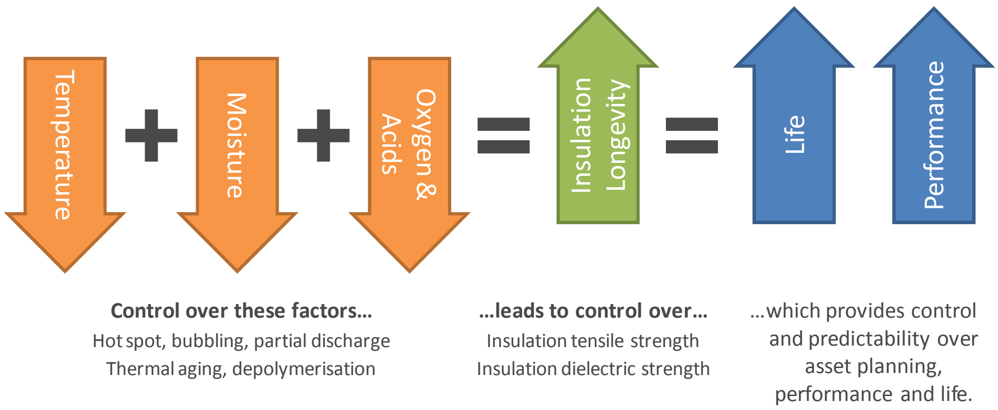

Figure 5 – Transformer Ageing: Improving predictability and control over asset life.

With increasing pressures on Capex, Opex and asset ROI, there is a clear need for asset owners and network planners to understand the cost benefit of available monitoring tools – in terms of performance, life and risk factors – and to be well informed on developing technologies.

If the required level of visibility and control can be planned for at the specification and design stage according to the needs of a given network, then asset owners will be able to effectively plan, monitor and make informed decisions for individual assets and a transformer fleet as a whole, by utilising trended information for the life of the asset.

Technology and Product Development

The continuum of product development for transformers is much like any industry. However, what stands out for transformers at this time is the way the financial model – or economics – of asset management can be fundamentally altered from what has been done in the past, significantly lowering operational and maintenance costs and maximising return on investment.

There have been a number of "game changing" technologies for transformers, which have opened the doors to completely new design methods with respect to these most critical areas reviewed in the previous section – the insulation system, key components, and protection/monitoring products. Evaluation of the added benefits offered in these new technologies leads to an ability to address macro environment issues, which in turn supports the further optimisation of assets from a performance and/or life perspective.

Advances

Many companies are engaged in research and development of new solutions aimed at improving some aspect of a transformer. In the digital age this is happening ever faster, with shorter time to market, shorter product life cycles and a converging of technologies. The electrical energy sector is furthering the innovation drive through smart grid initiatives and a desire to increase efficiency and interconnectivity across power grids.

These product developments generally occur in silos – each company with their own niche area of expertise. Thus product suitability is often promoted and evaluated at a functional level, rather than engaging in a broader cross-functional assessment of overall suitability and advantages.

Adoption

Many utilities and other asset owners have not widely adopted the most significant game changing technologies available, such as natural ester fluid, hybrid winding insulation, online DGA and fibre temperature monitoring. This is likely due primarily to the (understandably) risk-averse engineering approach common to this sector. That said there is still much room for improvement in the technology evaluation processes – a need to go beyond "just watching a small pilot for a decade under uncontrolled and often non-repeatable conditions" to quote one utility.[10]

Whilst individual or partial product adoption is occurring, what is not yet common is a transformer design philosophy that involves a broader evaluation of multiple technology types to determine their combined value, the synergies possible, and the real gains that can be accomplished for the entire organisation – not just a single department.

Some examples of this limited technology adoption include:

- Fibre optics temperature sensors, though largely only installed for heat run tests;
- Natural ester dielectric fluids, most commonly for its environmental benefits alone;
- Dissolved gas analysis, commonly as an annual lab test, or an online device as an alarm only.

The upside is that there remain many opportunities to utilise untapped technologies to their full extent, adding valuable capability and capacity into networks and lowering whole of life costs substantially.

What is missing is a design philosophy that evaluates multiple technologies to determine: their combined value, the synergies, and real gains that can be accomplished.

Optimising Transformers: Possibilities

Understanding the whole of life potential of each new technology is the first step toward optimisation of a transformer fleet and development of a more sustainable fleet management model. Below are some of the technologies which currently stand to have the greatest impact on transformer design and fleet management in the coming years[11 12].

Transformer Fluid: Natural Esters

Natural ester fluids represent possibly the greatest innovation for transformer design in several decades. This one product opens up numerous possibilities for performance, life, safety, environment and improved ROI. Some of the key characteristics of natural esters – supported by international standards – include higher operating temperatures, high fire and flash points (double that of mineral oil), "ultimate" biodegradability, and moisture affinity.

Whilst not all natural ester fluids are the same, some fluid manufacturers have proven the following benefits of a natural ester over mineral oil[13], based on field testing and technical validation of more than 500,000 transformers in service:

- Enables smaller transformer tank sizes and fewer materials – 3% lower construction costs, 15% less fluid
- Extends the life of transformers – the insulation lasts 5-8 times longer
- Increased performance with higher temperature insulation system, up to 20% more safe overload capacity
- Reduced insurance premiums, elimination of costly fire mitigation and deluge systems, improved fire prevention
- Environmentally safe, non-toxic and biodegradable, simpler and cheaper spill remediation and reduced risk

Insulation: Higher Temp Materials and Hybrid Windings

Beyond standard cellulose Kraft paper utilised in most Australian and New Zealand transformers, there are two recognised material alternatives in Thermally Upgraded Kraft paper (TUK) and Aramid paper (e.g. Nomex® or Metastar®). Both have higher thermal classes thus enabling higher operating temperatures and other additional benefits listed below.

Furthermore, new standards such as IEEE C57-154 and IEC 60076-14:2013 outline the usage of high temperature and hybrid insulation systems – where more than one material grade is used in the transformer winding to balance the need for higher temperature tolerances with the added cost of higher grade materials.

- Smaller transformer footprint (up to 50%) and reduced weight (up to 25%) for the equivalent kVA rating[14]
- Greatly reduce insulation thermal ageing
- Higher hot spot / temperature rise limits
- Run higher loads, higher safe short term overload per IEEE, IEC standards

Key Components: Maintenance and Reliability

Bushings

Modern bushing technologies such as Resin Impregnated Synthetics and Combined Composites eliminate the two elements in a bushing that are most subject to degradation due to temperature and moisture: the paper and oil. The result is a pressure free, fire resistant and explosion proof bushing with superior thermal, electrical and mechanical properties[15].

Fewer materials and more simple in construction, these bushings provide added benefits such as shorter manufacture lead-time, low or no partial discharge, no oil leaks (from the bushing), more compact and lightweight, and are impervious to moisture. This in turn means less maintenance, increased safety, greatly increased reliability and asset security.

On Load Tap Changers

Vacuum technology in on load tap changers (OLTCs) is another area that offers asset owners a chance to extend asset life, reduce transformer size (with more compact components), increase equipment and personnel safety, whilst reducing maintenance requirements (3 to 5 times fewer inspections, no maintenance time limits) [16].

Where in conventional OLTCs electrical arcing from the diverter generally occurs in insulating fluid (separate from the main transformer tank fluid), this now takes place in a vacuum interrupter, thus preventing wear of contact surfaces as well as sludging and contamination of the diverter housing oil supply[17].

Dehydrating Breathers

Transformer breathers are an underrated device where the maintenance costs (regular gel replacement, disposal and labour) are often significantly underestimated and hence overlooked – when in fact they require millions of dollars to maintain[18], across a transformer fleet.

The main alternative that has been available for many years is the Self Dehydrating Breather. It automates the drying process by regenerating its store of silica gel, reducing maintenance costs by up to 95%. It also improves moisture security and eliminates complex multi-breather arrangements on larger power transformers. There are several vendors employing different regeneration methods, with most designed much more rugged than standard breathers, lasting decades, possibly for the life of the transformer.

Generally to implement such a change in a utility in a cost-effective manner requires some adaption to fleet maintenance program / processes. When done in this way and rolled out across a fleet, the return on investment can be readily justified for power transformers circa 10 MVA and above.

Monitoring and Control

Temperature and Cooling

With temperature being a key determinant in the life of a transformer, direct hot spot temperature monitoring using fibre optic sensors is one of the most effective and reliable tools for introducing predictability and control over transformer life and optimising network planning.

As a result of transformer ageing and premature failure to hot spot temperature increase, the 2013 IEC and AS/NZS Power Transformer Standard (60076) recommends direct measurement of hot spot temperature rise through the installation of fibre optic sensors. In making this recommendation, the standard references the "radically increased possibilities to obtain proper thermal modelling of power transformers, especially at step changes in the load current" made possible through fibre optic sensors. For three phase transformers, fibre is recommended for 20MVA and above.

Beyond increased accuracy in measuring, monitoring and trending of temperature information, fibre optics also:

- Verify correctness of hot spot calculation models
- Confirm "real" ratings of new transformers via heat-run test results (to ensure the rating respects the nameplate)
- Avoid hidden overloading of transformers due to inaccurate hot spot modelling
- Maximise loading without compromising life
- Safe short-term overloading: control exact transformer ageing
- Effective cooling management: greatly reduced time lag in activating cooling mechanisms

Dissolved Gases

Dissolved gas analysis (DGA) is not a new tool for transformer owners. Most rely on DGA via annual lab sampling and some employ online DGA devices on problem assets or larger power transformers. The value of DGA is accepted in periodic checks of transformer condition or post-mortem evaluation.

However, what has not yet occurred is the widespread use of online DGA monitoring across an entire fleet and the continual monitoring and trending of this data for the purpose of providing real time alerts to impending issues, accurate diagnostics and better decision making. This is where the true value lies for DGA – not in post mortem, but in prevention and management – helping to maximise asset availability and security, whilst minimising premature ageing and catastrophic failures.

DGA devices vary significantly in design (number of dissolved gases measured) and cost, and thus can be suited to a wide range of needs and budgets. Most instruments are designed for online measurement of the main tank, though there are some that can accurately measure dissolved gases in the tap changer, or provide a portable "first response" solution.

Moisture

For measuring moisture in oil, there are dedicated sensors available. Many DGA devices also incorporate moisture measurement (as well as inputs for additional external sensors such as load current, ambient or top oil temperature) that can be trended alongside DGA values in terms of relative humidity or ppm.

For online removal of moisture from transformer oil there are a handful of available systems that, while more complex and expensive, are capable of reducing moisture levels down to 5ppm and maintaining it there.

Partial Discharge and Bushing Monitoring

There are a number of systems available that continuously monitor the condition of transformer bushings – changes in capacitance and/or power factor (tan delta) – to assess the bushing dielectric efficiency and insulation integrity. Previously this was only achievable by taking the transformer offline, which limited testing to once every few years. These online systems now allow faults to be detected in their infancy, allowing rapid response to rectify the issue.

Partial Discharge (PD) is the localised dielectric breakdown of solid (paper) or fluid (transformer oil) insulation system. The result of PD is localised gradual erosion of the insulation system, eventually leading to critical failure of the winding insulation. Some Bushing Monitoring systems are also able to detect the presence of PD activity in the main tank, though there are also separate online and offline systems available that do this using more sophisticated and directional methods of detection. In some cases, multiple transformers can be monitored using a single device.

Synergies and Unrealised Gains

Achieving real gains in the optimisation of a transformer fleet requires a collective evaluation of available technologies. This enables the potential benefits of several disparate products to be compared and categorised according to areas of need or priority for a transformer fleet, such as temperature or moisture management, environmental control, or maintenance requirements (refer Figure 6 below). This approach has two benefits:

Synergies can be identified (vertically down the table) between products that address the same problem or need in the transformer fleet.

For example, a utility wanting to better manage and limit ageing due to temperature on heavily loaded assets could utilise a combination of: natural ester fluid for higher temperature operation and higher safe overload; plus fibre optics for online hot spot temperature monitoring and cooling control.

Benefits can be maximised (horizontally across the table) for a single product.

Whilst a single product may be justified financially on a single attribute (e.g. Composite Bushings for their increased safety, or Natural Ester Fluid for its environmental benefits), by evaluating and making use of wherever possible the full benefits of each product, an asset owner can maximise the return on this investment (e.g. for Composite Bushings, reducing the maintenance scheduling, offline testing and/or monitoring requirements for these components).

Figure 6 outlines some of the major benefits according to the categories addressed earlier in this document. This of course is by no means exhaustive and can be expanded on according to fleet, network, or company needs and priorities, to support better decision making in the transformer specification process (or similarly for a retrofit / rectification program).

Product	Temperature	Moisture	Environment	OHS	Maintenance
Natural ester fluid	Run hotter, no life loss, high temp stability	High saturation point, moisture affinity / stability	99% biodegradable 100% renewable Carbon neutral	Non toxic, non hazardous high fire/flash point	No fire suppression, longer stability
Hybrid insulation	Run hotter, reduced ageing	Lower moisture content, affinity	FSC certified supply		
Direct winding temperature transformer monitors	High accuracy, Improved control				Low maintenance, ext service intervals
Composite Bushings	High thermal endurance	No humidity absorption	Very low silicone use(manufacture)	Improved safety, explosion proof	Maintenance free, no leakages, no PD
Vacuum Load tap changers				Improved safety	Reduced maintenance Easy inspection
Self Dehydrating Breathers		Always online, self drying	No silica gel replacement		Maintenance free
Online DGA for tank ,OLTC	Online monitoring of gases produced	Online moisture measurement		Avoid the need for offline DGA samples	Reduced maintenance No calibration, gases
Partial discharge monitor	Monitor PD activity with increased load				Extend transformer life and maintenance

Figure 6 – **Technology Synergies**: Maximising gains through comparative evaluation of available technologies.

Online Integrated Condition Monitoring

With regard to transformer monitoring, there are some additional synergies that can be achieved just through the integration of different monitoring technologies. On both the hardware and software side of monitoring, different technologies are converging. This is enabling the use of a single hardware platform to collect all monitoring data; a single software platform to analyse, trend and predict across all transformer (and substation) monitoring requirements.

Such advances further support the condition-based maintenance approach, classifying assets according to health indicators, identifying those with the greatest needs or highest risks, providing early warning of developing problems and lowering maintenance costs across a network. Furthermore, by introducing monitoring from the initial installation of assets onto the grid, trending of multiple data points will deliver a significantly more accurate and valuable model of a transformer's life. This will support the development of better condition-based maintenance programs, as well as more accurate forecasting for asset replacement and network planning.

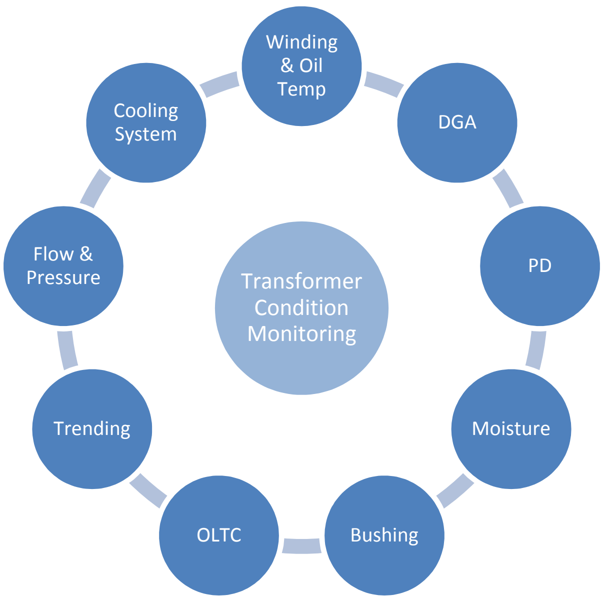

Figure 7 – **Online Monitoring**: Condition based fleet management; some commonly monitored components / systems

CORE: A Fleet-Wide Whole of Life Approach

What CORE Transformer Optimisation proposes is a seismic shift in innovation – not of product technology, design or standards – but rather in the approach to whole-of-life transformer management.

Justification for the CORE approach is relatively straight forward in that it is based largely on readily available information, backed up by internationally established engineering principles, and can deliver significant gains and cost reductions across a fleet. The challenge lies in the fundamental changes to transformer management that a company must implement, in order to achieve these gains. Indeed it involves bringing the existing areas of transformer management together –specification, design, procurement, fleet management, maintenance, refurbishment and end of life – and having them engage at both the micro and macro level, toward the common goal of fleet optimisation.

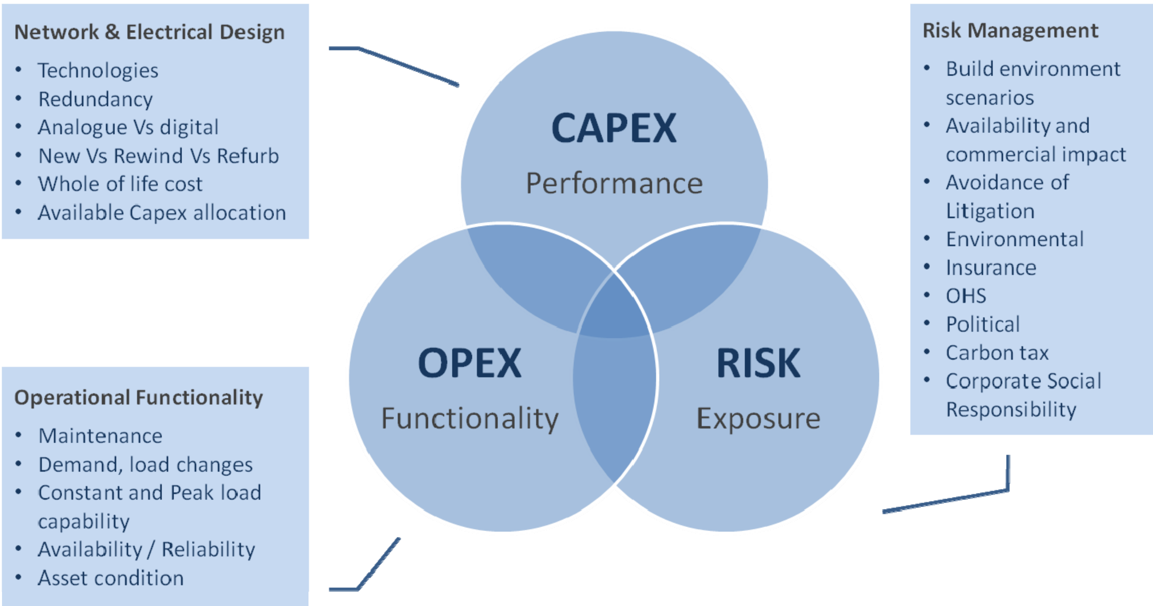

Figure 8 – CORE Optimisation: Understanding the impact of the macro environment

Outlined below are some of the major challenges that companies will likely face when embarking upon implementation of the CORE approach into their existing transformer / asset management departments and processes.

INTERNAL ENGAGEMENT – There is a critical need to involve a broader range of internal decision makers, from the transformer and substation (asset) side of the business, as well as those responsible for areas of indirect (macro) influence – especially for health and safety, environment, insurance, regulatory, property, etc. This needs to include senior managers in a position to visualise this bigger picture and the authority to initiate the needed change.

MACRO ENVIRONMENT – With the right people in place, a comprehensive assessment of the macro environment can be made – evaluating Capex, Opex and Risk factors – in terms of the impact each area has on the life, performance and effective management of the transformer fleet.

IDENTIFY THE CAUSES – Contrast the current problems, needs, opportunities and priorities of the transformer / asset teams (micro environment) with the above "macro environment" evaluation to determine the root cause of each, so as to be able to begin addressing these in the most effective way.

EXTERNAL ENGAGEMENT – Working with various sectors of the industry and supply chain (technology providers, manufacturers, government, regulators, and other networks) to understand available options for fleet optimisation, such as utilising new products, design changes, adapting processes, and/or working toward regulatory change.

EVALUATION – A collective evaluation of options. Balancing available resources with needs and priorities – performance versus life, new assets versus refurbishment, cost versus risk, etc – to determine suitability and viability of each solution, identify synergies and savings, and work toward minimisation of total cost of ownership. Some common considerations for fleet owners include:

- Asset costs
- Maintenance costs
- Property costs, land availability
- Capital works costs
- Fire safety, mitigation and deluge systems costs
- Insurance costs
- Environment, seasonal conditions
- Environmental costs
- Load profile, overload capacity
- Health and safety
- Risk factors and uncertainty
- Asset life and replacement timeframe
- New / Retrofit / Retrofill
- Short term life extension
- Brownfield Vs Greenfield
- Visibility and predictability

In the previous section, the table in Figure 6 provided an evaluation of various technology options by their potential benefits (controlling temperature, moisture, etc). This same comparison can be taken a step further to contrast technology options against the three CORE areas of Capex, Opex, Risk Exposure - or Performance, Life and Risk as in Figure 9 below. This further consolidation of priorities can help to improve decision making by focussing in on key fleet / company priorities.

Product	Performance	Life	Risk
Natural ester fluid	Operate at higher temps to increase load flexibility; smaller transformers	Operate at higher temps without loss of asset life or extend life at lower temps	High fire, flash point, biodegradable, renewable resource, non-toxic,...
Hybrid insulation	Operate at higher temps to increase load flexibility; smaller transformers	Operate at higher temps without loss of asset life	Risk mitigation through design
Direct winding temperature transformer monitors	Accuracy and control removes guess work on performance capability	Accuracy and control removes guess work on life expectation and network planning	Proactive management approach to performance life and asset availability
Composite Bushings	High availability - maintenance and inspection free		Increased safety. Avoid costly failures due to asset downtime
Vacuum Load tap changers	High availability due to maintenance free contacts	Extended service intervals	Avoid costly failures due to asset downtime
Self Dehydrating Breathers		Moisture, maintenance	Continuous moisture management
Online DGA for tank ,OLTC		Predict and prevent failures Defer replacement	Avoid costly failures due to asset downtime
Partial discharge monitor			Avoid costly failures due to asset downtime
Smart Grid ready	Operational visibility and control	Operational visibility and control	Operational visibility and control

Figure 9 – Technology Synergies Part II: Evaluating available products against top level company goals/indicators.

Designing Transformers using CORE

The final step in the evaluation process is to quantify the benefits of the various options under consideration – upfront capital investments, indirect costs, as well as foreseeable operational expenditure – according to fleet priorities. To illustrate this, below is a comparative evaluation of two theoretical fleets whose priorities lie at two extremes – Fleet A is focussed on maximising asset life, Fleet B on maximising asset performance.

For this example, the transformer size being evaluated is 132kV / 22kV, 50MVA. Figure 10 shows the standard transformer, along with two options that are being evaluated by the two fleets.

Option 1 introduces a natural ester fluid, fibre optic monitoring, self-dehydrating breather, composite synthetic bushings, 3 gas + moisture DGA monitor.

		Standard	Option 1	Option 2
Dielectric Fluid	– Mineral Oil	✓		
	– Natural Ester Fluid		✓	✓
Insulation	– Cellulose	✓		
	– Hybrid			✓
Monitoring	– OTI/WTI	✓	✓	✓
	– Fibre Temp Monitor		✓	
	– Integrated Monitor			✓
Moisture Control	– Breather	✓		
	– Self-Dehydrating		✓	✓
Bushings	– RIS		✓	✓
Tap Changer	– Vacuum			✓
Online DGA	– Single Gas	✓		
	– 3 gas		✓	
	– 8 gas			✓

Figure 10 – Designing with CORE: Two options

Option 2 includes the above, plus a hybrid insulation winding – taking advantage of the high temperature insulation system standards (IEEE C57-154 and IEC 60076-14:2013), vacuum tap changer, upgrades the DGA monitor to 8 gas + moisture, and adds integrated transformer monitoring and control.

Both these options utilise additional technologies within the bounds of existing engineering standards. The quantifiable benefits to each fleet are summarised in Figure 11.

Option 1 Advantages		Option 2 Advantages	
Fleet A: Life focus	Fleet B: Performance focus	Fleet A: Life focus	Fleet B: Performance focus
• Insulation life is extended by 5-8 times • Extended fluid life • Fibre temp monitoring safeguards against overload • DGA provides early identification of developing faults	• Higher rated capacity: 20°C higher hot spot temp • 20% more overload capacity • Fibre temp monitoring enables safe short term overload to maximise revenue	• Option 1 advantages plus • Insulation life is further extended with aramid winding insulation at the hottest spots • Fibre optic cooling control safeguards life with timely cooling activation • 8 Gas DGA provides detailed fault identification & trending	• Option 1 advantages plus • Higher rated capacity via insulation system thermal class increase • Higher safe overload • Fibre optic cooling control further supports maximum loading through timely cooling system activation
Advantages common to both Fleet A and B		Advantages common to both Fleet A and B	
• 3% lower transformer construction costs; 15% less fluid required • No deluge systems or fire walls required • Reduced clearance to buildings, assets • Lower insurance premiums • Reduced remediation cost in case of oil spill • Lower fire, environmental, health, safety risks • Moisture security • Reduced maintenance; extended maintenance cycles		• Option 1 advantages plus • Smaller transformer footprint (up to 50% possible) and reduced weight (up to 25% possible) for the equivalent kVA rating • Online trending of temperature, DGA and other data • Accurate data to support better decision making • Lower maintenance and service overheads through condition based monitoring and components with longer service intervals	

Figure 11 – Quantifying the Benefits: The direct Life and Performance benefits; as well as benefits that extend to both Fleet A and Fleet B

These advantages are then translated into increases or reductions in capital and operational expenditures, as applicable to each company's financial modelling methods. From this a final whole of life costing model is developed. The graph below summarises this by highlighting the major changes to total cost of ownership, along with the respective changes in the amount of life (for Fleet A) or performance (for Fleet B) that is achievable.

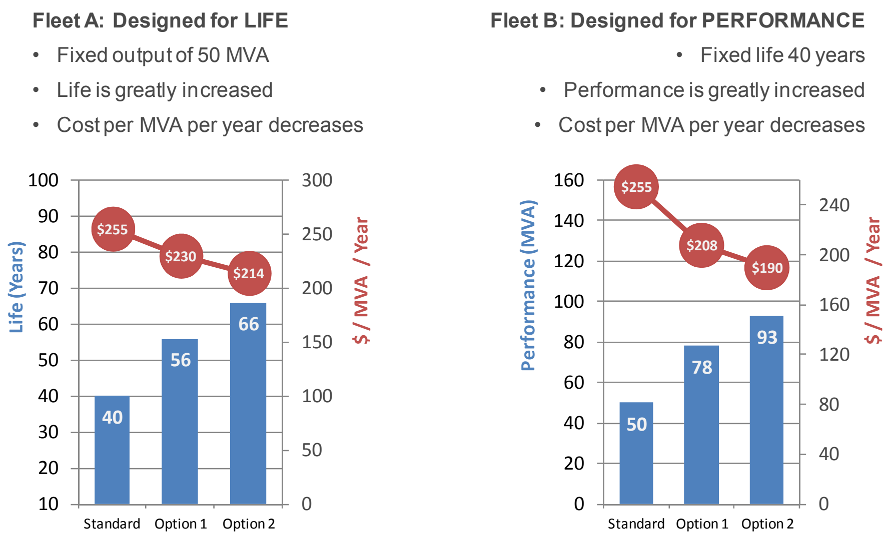

Figure 12 – Financial Summary: Evaluation of Capex, Opex and quantified risk for each transformer design

Though the initial capital cost of the transformer is increased, these graphs show how the predicted life and/or performance capability (rated load) of these transformers is also extended far beyond that previously possible – significantly reducing the cost per MVA per year.

Further, many other capital and operational costs as previously described are also reduced as a result of these changes in design to the transformer. These have not been included in the above calculations due to the unique approach and operating conditions of individual companies to these varied topics. However, when combined with the reduced asset capital costs and extended life/performance benefits, the reductions to the total cost of ownership for these assets is hard to ignore.

Conclusion

The management of a transformer fleet is a complicated undertaking, requiring a risk-averse engineering approach. Though the fundamentals of transformer design haven't changed in over a century, there are many internal and external factors with the potential to jeopardise the condition of the transformer and other substation assets, as well as affecting the operation of the grid.

The adoption of "newer" technologies aimed at further safeguarding transformers has been slow. The benefits of many of these technologies are far reaching and have been proven through standards adoption and independent analysis by the international engineering bodies. However, the quantifiable advantages and synergies are at times difficult for asset owners to determine.

CORE Transformer Optimisation solves these challenges by bringing together the direct factors that impact transformer management, along with the broader planning, operational and risk factors that indirectly affect transformer performance, life, and costs. This facilitates a complete assessment of the transformer environment and a comparative evaluation of available solutions.

The CORE approach introduces more flexibility into the management of a transformer fleet. It aids in maximising return on investment from individual technology adoptions, uncovers synergies between multiple technologies and visualises the benefits at the fleet level where they can have the greatest impact. Various scenarios can be considered and compared, such as asset replacement versus refurbishment, or the implications of Brownfield versus Greenfield sites.

The implementation of a CORE based approach requires the collaborative involvement of a broader range of people both inside and outside the organisation. It needs technical people, as well as senior decision makers from various departments within a company. Similarly the approach calls for engagement of industry players – regulatory, technology providers, consultants, and transformer OEMs.

The CORE approach aims to bring about a paradigm shift in the management of transformers, paving the way for better decision making, greater asset security, guiding investment to where it is most needed and lowering total cost of ownership. To affect this change will require significant effort from across the industry. Though so too will the outcomes benefit the entire industry, providing a more secure networks and encouraging smarter investment for a smart grid future.

About Insulect Australia

Insulect started out in 1993 providing solid insulation materials for transformers. More than twenty years later, transformers are still a big part of our focus. We now provide a much broader product and service offering from the insulation system, to major components, monitoring systems and high voltage testing devices.

Our goal for this paper was to introduce how whole-of-life transformer optimisation – incorporating specification, design, manufacture, monitoring, maintenance and end of life decisions – can support a more efficient network and lead to a more sustainable fleet management model. The intent is that this paper will promote the importance of this topic and generate further discussion throughout the industry.

Insulect is all about the optimisation of energy networks and the critical assets within.

Across the grid, from power generation through to consumption, our team collaborates with asset owners and key stakeholders to enable more efficient and reliable power systems through the implementation of modern technologies.

Insulect takes a broad view of key assets within the power system – not just from a product technology perspective, but from an integrated system perspective – the interconnected planning, operation, maintenance, compliance and risk factors that together impact the efficiency and effectiveness of an energy network.

This top-level approach allows us to uncover, innovate and solve significant challenges faced by various sectors throughout the industry: generation, transmission, distribution, industrial, equipment manufacturers, regulatory bodies and EPCs.

Our team is adding value through the optimisation of product selection and system design. We are enabling flexibility in asset performance, supporting condition-based maintenance methodologies and whole-of-life modelling, so as to facilitate better utilisation of resources and maximise return on investment.

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VERSATILITY VIA COLLABORATION