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While periodic DGA is a powerful tool, it does not identify all dominant transformer failure modes. A comprehensive monitoring strategy that identifies slow and fast developing faults has been adopted.

Southern California Edison's business case for transformer online monitoring

1. Introduction

Online dissolved gas analyzers (DGA) and bushing monitors for power transformers have become increasingly popular. The decision to apply online monitoring is usually driven by the criticality of the transformer and the consequence of an unplanned outage, whether lost production at a generator or industrial site or customer minutes lost within a utility network.

Application of a comprehensive online DGA and bushing monitoring strategy across Sothern California Edison's (SCE's) fleet of EHV and HV transformers provides technical and operational benefits to all stakeholders. A detailed business case and financial model have been developed to show that SCE's online DGA, moisture, and bushing monitoring strategy is also economically prudent.

2. SCE's DGA strategy

EHV and HV power transformers are critical substation assets with a high cost and a long procurement time. Maximizing useful transformer life has always been one of the main targets for SCE's Asset Management. Adopting a "run for failure" transformer replacement strategy is not an acceptable solution due to the high mitigation cost in case of a catastrophic

ABSTRACT

The Southern California Edison Company (SCE) operates a fleet of 285 HV and EHV substation power transformers. Failure of one of these banks can have a significant financial and operational impact. Online dissolved gas analyzers (DGA) and bushing monitors for power transformers have become increasingly popular. The decision to apply online monitoring is usually driven by the criticality of the transformer and the consequence of an unplanned outage, whether lost production at a generator or industrial site or customer minutes lost within a utility network.

To reduce this risk, the strategic decision to equip the whole SCE fleet of EHV and HV transformers with online multi-gas, moisture, and bushing monitoring systems was made. This monitoring strategy is expected to result in:

- improved HV and EHV transformer reliability,
- reduced failure impacts,
- realization of complete transformer useful life, potentially several years beyond the nominal expected life,
- identification of units in urgent need of repair / replacement,
- early recognition of problems that the OEM's warranty should cover,
- substantial reduction in overall transformer operating risks,
- improved accuracy of transformers health assessments.

Application of a comprehensive online DGA, moisture, and bushing monitoring strategy across Sothern California Edison's (SCE's) fleet of EHV and HV transformers provides both technical and operational benefits to all stakeholders. A detailed business case and financial model have been developed to show that SCE's online DGA strategy is also economically prudent.

KEYWORDS:

ageing, asset management, condition assessment, dissolved gas analyzers (DGA), online monitoring

transformer failure. The ability to perform an accurate transformer health assessment is the key to maximizing useful transformer life, managing fleet replacements, and minimizing the probability of catastrophic failure.

Dissolved gas analysis (DGA) and moisture measurement are industry-recognized and among the most advanced tools for online transformer health assessment. DGA and moisture measurement can identify deterioration of paper insulation and assess transformer oil condition; more importantly, they can provide early warning for many transformer failure modes. For more than 30 years, oil samples have been manually drawn from all substation power transformers and sent to laboratories for DGA and oil analysis. Yearly, DGA has effectively identified and eliminated slow evolving failure modes; faster failure mechanisms are often not detected.

While online DGA monitoring is a powerful tool that identifies slow and fast developing faults, there are gaps; DGA does not detect all dominant transformer failure modes. The addition of online bushing monitors closes these gaps and is an essential component of SCE's transformer online monitoring strategy.

In 2006, SCE started a program to equip all EHV and HV power transformers with an online DGA, moisture, and bushing monitoring system. Online DGA, moisture, and bushings monitoring systems provide real-time DGA helping SCE asset engineers to act quickly and effectively at the first sign of a transformer health concern.

At SCE, online DGA, moisture, and bushings monitoring units do not have any alarms connected to the SCADA system. Different software has been used to analyze, notify, and store the results during this 30-year period. Today, several third-party software packages are readily available to support utility DGA programs. Currently, SCE uses "Transformer Oil Analyst" (TOA 4) by Delta X Research company.

Secure communication circuits connect each DGA, moisture, and bushing monitor to the TOA 4 program. Test records are assessed to identify incipient transformer failures and monitor misoperation. The TOA-4 program stores historical DGA test records from the main tank and LTC, analyzes each new DGA sample, integrates manual test data, compares results with SCE analysis norms, creates reports, and assigns a Gassing Status using a 1 to 4 scale. The TOA 4 program sends a High Gassing Status notification email to predefined user groups. The responsible transformer "Subject Matter Expert" (SME) reviews the DGA results and requests desired actions from the accountable substation operation or maintenance organization when this occurs. Similarly, the TOA-4 program is also used to analyze and store test data from the bushing monitors.

3. The need for a business case

Maintenance engineers and substation operators quickly understand the benefits delivered by Transformer Online Monitoring. Implementing a comprehensive online monitoring program across a fleet of 285 EHV and HV transformers require a significant capital investment that must be prudent and provide demonstrated value to all stakeholders.

To be successful, the SCE Transformer Online Monitoring Business Case needed to be:

- **Understandable.** The benefits of transformer online monitoring need-

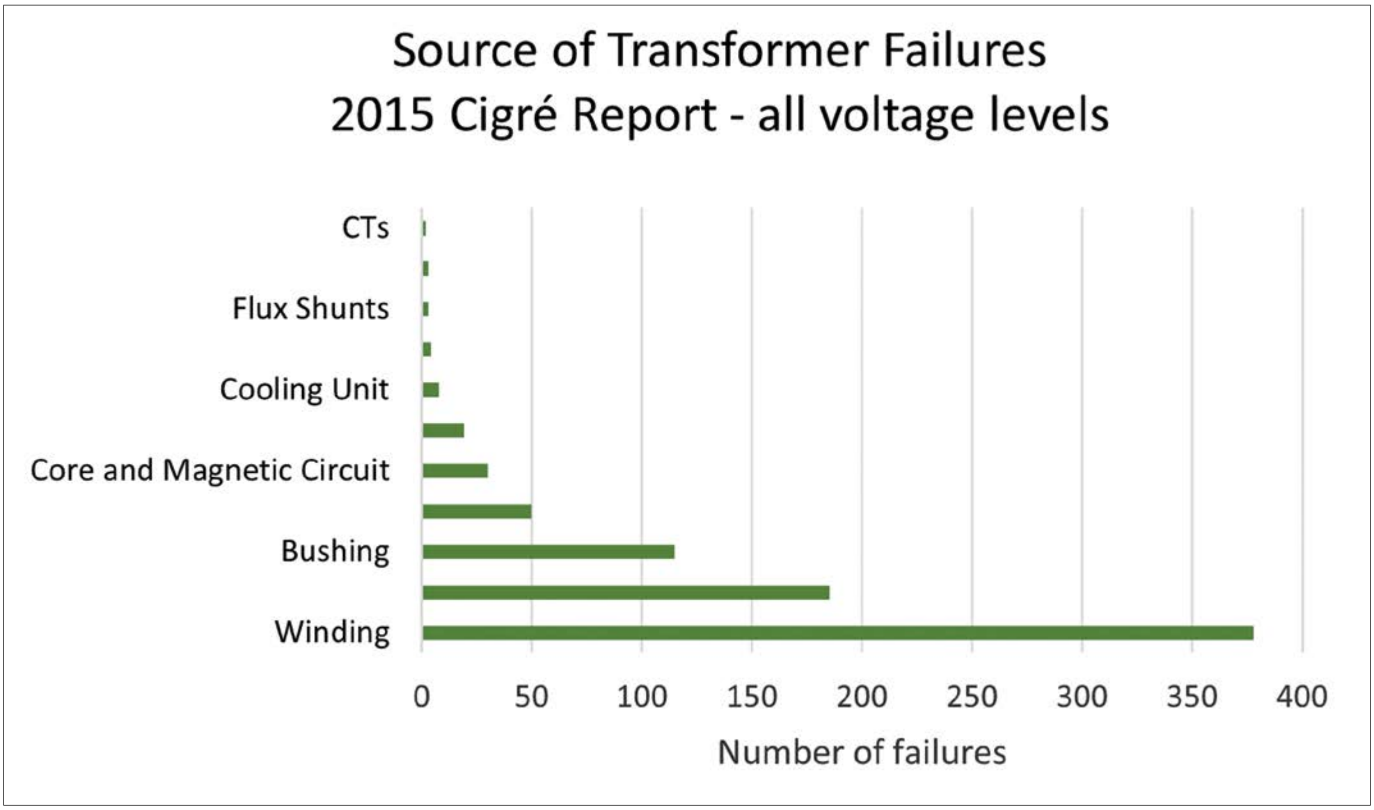

Figure 1. Transformer Failures – 2015 Cigre Report

Worldwide and at the Southern California Edison Company, HV and EHV transformers have a good reliability history with annual failure rates in the neighborhood of 0.5 %

ed to be clearly understood by diverse readers.

- **Realistic.** The expected benefits needed to be reasonable and likely achievable.
- **Objective.** Online monitoring will not prevent all future transformer failures and provide exact transformer health assessments. It will reduce failures but not entirely eliminate them.
- **Transparent.** All initial investment and long-term operational and maintenance costs needed to be identified and estimated.
- **Financially attractive.** The investment in transformer online monitors must have an attractive IRR (Internal Rate of Return), NPV (Net Present Value), and a reasonable payback period.

4. Transformer reliability

Worldwide and at the Southern California Edison Company, HV and EHV transformers have a good reliability history. Annual failure rates in the neighborhood of 0.5 % are typical; unfortunately, most transformer reliability surveys in the public domain are limited in scope and detail.

In 2015, a second worldwide transformer reliability study by Cigré was completed. This second study was a significant step forward in statistically analyzing the reliability of power transformers. Key findings relevant to SCE are:

- Nearly 84 % of all reported transformer failures involve:
  - windings
  - load tap changers
  - bushings.
- Power transformer failures do not show a strong age dependency
- Standard utility practice is to replace older power transformers before failure occurs. Because wear-out rarely happens, it is impossible to place an exact age when the end-of-life is expected.
- Bushing failures most likely initiate transformer fires.
- The study population is biased with oil-impregnated paper (OIP) condenser design bushings. Newer, resin-impregnated paper (RIP) and resin-bonded paper (RIB) bushings should reduce the probability of fire but have substantially different aging characteristics.
- Condition assessment and online monitoring is the most effective way of ensuring that the transformer operates correctly and that its predicted life expectancy is realized.
- Because the dominant transformer failure mechanisms are not time-dependent, time-based maintenance is not an economically or technically effective method for assuring transformer reliability. When failure mechanisms evolve slowly, periodic condition assessment tasks are efficient. When failure mechanisms develop relatively quickly, online monitoring is required.

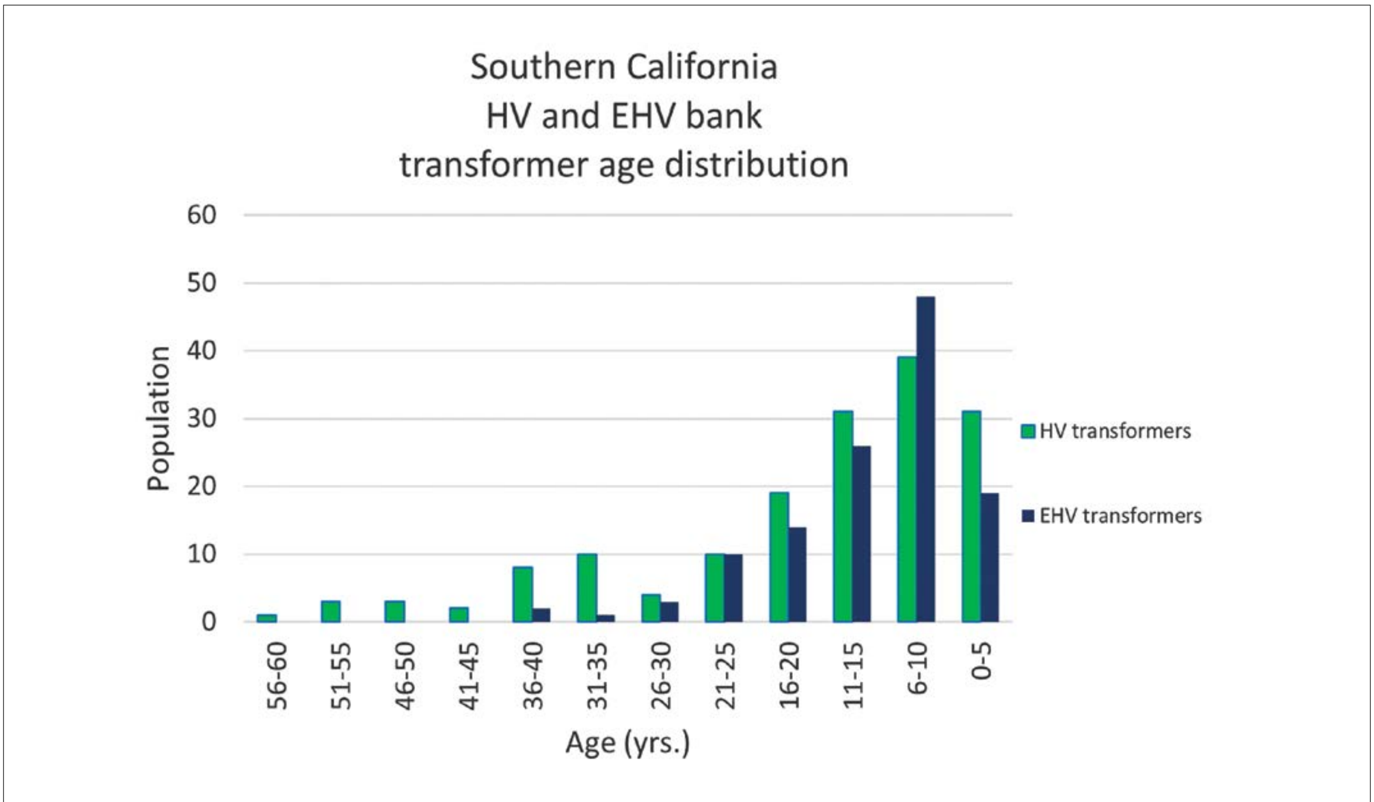

Figure 2. SCE HV and EHV transformer age distribution

Continuous assessment allows for early identification of incipient faults and significantly improves understanding of active aging mechanisms allowing for a timely and targeted response

The Electric Power Research Institute (EPRI) study of 1,112 transformer failures yielded similar findings.

5. The value of transformer online monitoring

Power transformers have a nominal life of thirty (30) to forty (40) years. The actual useable life of a transformer is mainly dependent on:

- temperature, a function of loading,
- the oxygen and moisture content of the oil and insulating paper,
- the number of LTC operations,
- aging of the bushing core insulation,
- through faults,
- transient overvoltage (switching and lightning surges),
- design and manufacturing quality.

Legacy maintenance practices and diagnostic technologies only allow periodic transformer condition assessments. Some assessments like DGA and thermal imaging can occur when the transformer is in service. Full condition assessment requires transformer de-energization occurring every three to eight years with increasing operating pressure to lengthen these intervals. The net result is an increased uncertainty of the actual transformer's condition.

Online DGA, moisture measurement, and bushing monitoring reverse the situation by providing a continuous assessment of three dominant sources of transformer failure:

- windings,
- load tap changers,
- bushings.

Continuous assessment allows for early identification of incipient faults and significantly improves understanding of active aging mechanisms allowing for a timely and targeted response.

6. Modeling transformer life

When dealing with an unreliable asset, it is easy to show the benefits of improved reliability. When dealing with a reliable asset like a power transformer, it is substantially more challenging to show the benefits of incremental improvements in reliability. To do so requires the development of models that predict future transformer operational reliability. No model is 100 % accurate; good models provide helpful insight.

To mitigate uncertainty, the SCE study employed two general transformer reliability models. The two general reliability models provide the reader with a range of reliability predictions that are meant to apply to most HV and EHV transformers. The two models are summarized as follows:

- **Asset Health Model:** This general model predicts when the transformer should be removed from service because it has deteriorated to a condition where the risk of failure is excessive, and planned replacement is in the best interest of all stakeholders. This model is based on SCE transformer health and reliability data and was used in the economic analysis.
- **Failure Model:** This general model predicts when a functional failure will occur, requiring immediate repair or replacement. This model is based on a composite of industry data; it was not used for the economic analysis. When compared to the Asset Health Model, it showed that useable transformer life could be extended at low risk.

Determining a power transformer's future reliability and remaining life is not an easy task and includes much uncertainty

A simple example of the benefit of having two different models is demonstrated by the fictitious example of developing an automobile tire replacement policy.

The nominal expected life of a passenger tire is 40,000 miles (64,000 km); at this distance, the tires are considered to be "unhealthy" even if they have not functionally failed. Experience has shown that the tires may not fail until 70,000 or more miles depending on the driving conditions. Implementing a policy of performing a detailed visual inspection each day, not driving in wet conditions, and limiting speeds to 40 MPH could result in 10,000 to 20,000 additional miles. While designed to maximize tire utilization and reduce costs, this tire replacement policy may be risky.

Another approach for determining when to replace tires is to look at tread depth. In the USA, passenger car tires are required to be replaced when the tread depth is 1/16th inch (1.6 mm) or less. A tread depth of 1/16th inch represents the point when the tire's useful life has been expended; the tires are considered to be "unhealthy." Having the policy to change tires when the tread depth is 3/32^{nds} inch (2.4 mm) dramatically reduces the chance of a blowout and significantly reduces the likelihood of hydroplaning on wet roads. An "early wear" replacement policy would likely reduce risk but may be considered overly conservative.

Both the above tire replacement policies have merit. They may represent a broad range of consequences and provide policymakers with helpful information for making informed decisions.

Determining a power transformer's future reliability and remaining life is not an easy task and includes much uncertainty. One must recognize that a very small transformer winding or bushing insulation defect can lead to an unrepairable failure but not captured in a predictive model. Accurate modeling requires the development of a "digital twin." Conversely, anecdotal experience has shown that, in general, power transformers have provided utili-

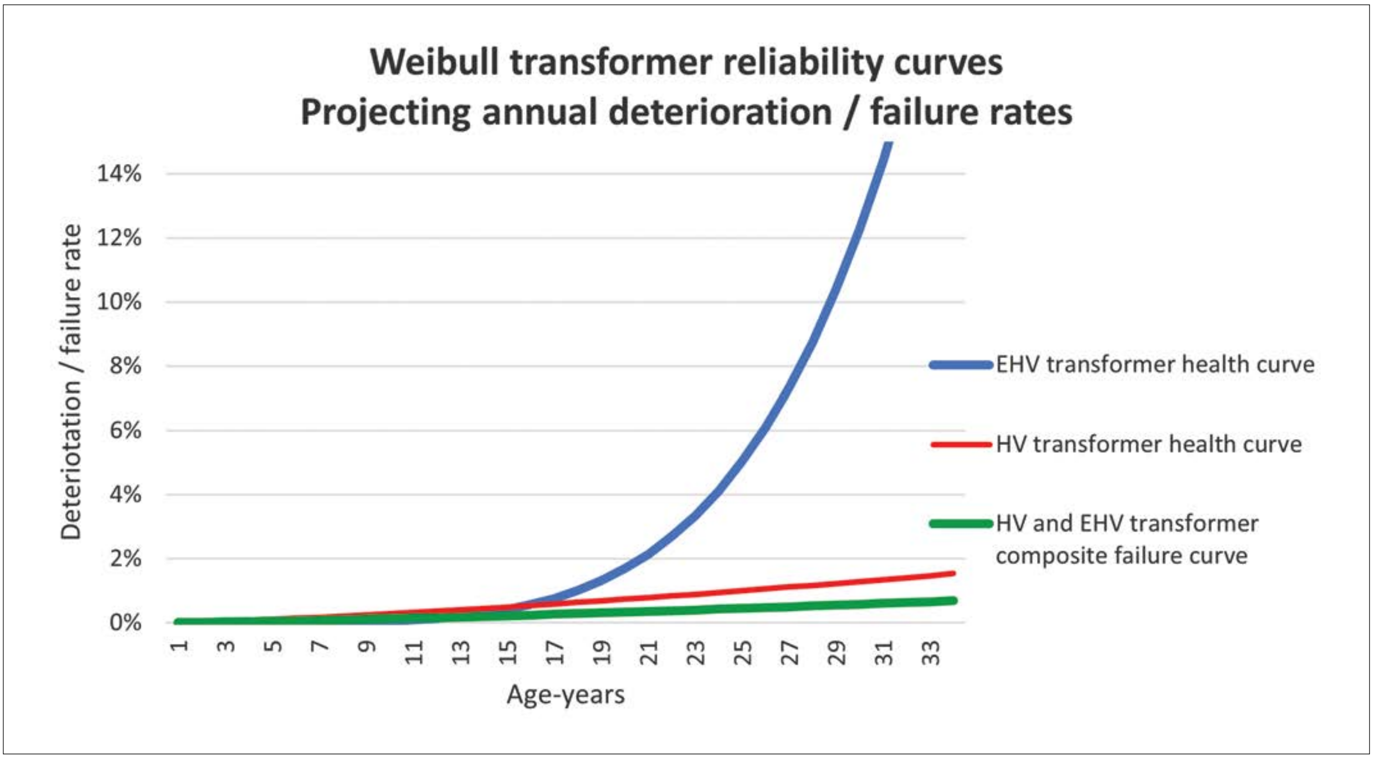

Figure 3. Weibull aging model for SCE EHV transformers

ties around the world with decades of reliable performance; modeling "average fleet performance" is a much easier task.

For the SCE study, two transformer populations (HV and EHV banks) and two reliability models (Asset Health and Asset Failure) were initially considered. This combination of population and reliability models results in four (4) different analyses. While SCE developed independent health models for HV and EHV banks, only a single failure model for both HV and EHV transformers was used.

Three sets of Weibull reliability curves were developed and used for SCE's online monitoring study. These curves are displayed above (Fig. 3) and predict the annual HV and EHV transformer deterioration / failure rates. Transformer populations with low deterioration / failure rates and long useful lives benefit less from online monitoring than those with higher deterioration / failure rates and shorter useful lives.

The three Weibull reliability curves are described as follows:

- **EHV and HV transformer asset health curve.** The blue and red curves in Fig. 3 show how the health of EHV and HV transformers, respectively, deteriorate with age. End-of-life occurs when the health has deteriorated beyond a threshold where failure is imminent. This curved was developed and is used by SCE Asset Management.
- **HV transformer and EHV transformer failure curve.** The green curve shows the probability of functional transformer failure with age. The same curve is used for both HV and EHV transformers and is based on a composite SCE failure Cigré data. Logically, failures occur after a transformer's health has deteriorated.

To quantify the benefits of online monitoring, a business case was developed with typical HV and EHV transformers installed on the Southern California Edison grid

The above deterioration / failure curves provide a reasonable optimistic view of the maximum functional life of a transformer as well as a realistic pessimistic view of its useful life. The two views were used in the online monitor benefit model; they provided the reader with a better understanding of costs and benefits from two distinct vantage points:

- A view that emphasizes transformer reliability and strives to reduce overall risk.
- A view that attempts to maximize transformer utilization and accepts more risk.

7. The business case analysis

To quantify the benefits of online monitoring, a business case was developed. This business case considered typical HV and EHV transformers installed on the Southern California Edison grid. A transformer Failure Mode and Effect Analysis (FMEA) was performed. The FMEA identified the dominant causes of transformer failure and the failure prevention effectiveness of various monitoring and maintenance strategies. Weibull models derived from SCE's historical transformer failures and health assessments projected transformer aging. The study estimated transformer operating / replacement costs, maintenance expenditures, and benefits expected over 20 years for various scenarios:

1. **Run-to-failure scenario:** No periodic DGA, dielectric system assessments, or planned maintenance.

Compared to the run-to-failure scenario, periodic DGA has proven to be a technically and financially viable approach to achieving long power transformer life

2. **Status quo scenario:** Yearly DGA performed on manually extracted oil samples from the main tank and LTC. Bushing tests only occurred when the transformer was offline for other reasons.
3. **Decreased DGA interval:** Periodic DGA sampling intervals as short as one month were analyzed.
4. **Online monitoring:**
   - DGA main tank,
   - DGA LTC,
   - bushing leakage current and capacitance.

Important parameters and assumptions used for comparing the above scenarios are included in Table 1.

Compared to the run-to-failure scenario, periodic DGA has proven to be a technically and financially viable approach to achieving long power transformer life. Its historical success is due to its ability to detect many causes of dielectric failure in a developing stage. For those fewer cases of fast-evolving failure mechanisms, periodic DGA is less effective, and online DGA analysis is the most viable detection solution.

DGA is not an effective tool for detecting incipient bushing failures. Offline capacitance and power / dissipation factor measurements are technically effective in identifying bushing deterioration but are an operational challenge. Online bushing monitors are a real solution for assessing bushing health.

The SCE online monitoring business case provided asset managers and decision-makers with viable options for improving power transformer reliability and decreasing life-cycle costs. It was shown that the incremental investment of money or labor resources for each of the analyzed reliability improvement scenarios was prudent. The investment in online monitoring provided the greatest financial benefit and also strategically:

- Reduces overall risk of transformer failure.
- Allows precious labor resources to be used on other important tasks / projects.
- Extends transformer operating life.
- Significantly improves health assessments and the planning of transformer replacements.

Table 1. Key business case parameters and assumptions

Parameter	Value
Targeted transformer failure modes	Dielectric (main tank, LTC, and bushings)
Average transformer age: **• HV transformers** **• EHV transformers**	 16 years 12 years
Transformer replacement cost (fully burdened with transformer placed on the pad) **• HV transformers-three phase units** **• EHV transformers-single phase units**	USD 5.5 M to USD 6.5 M
Cost of non-catastrophic repair	25 % of replacement cost
Percent of major failures being unrepairable	90 %
Probability of collateral damage	40 %
Aging and failure model	Weibull characteristic life and shape parameters based on SCE failure experience and transformer health assessment.
Main tank and LTC dielectric failure mode detection effectiveness – annual DGA sample	63 %
Main tank, LTC and bushing dielectric failure mode detection effectiveness – online monitoring	99 %
Insurance coverage	Self-Insured
Fully loaded cost of a manual main tank and LTC DGA test	USD 700 to USD 1.000
Weighted average cost of capital (WACC)	10 %
Annual inflation rate	2.2 %

8. Quantified benefits of online monitoring

The SCE business case concluded that implementing continuous multi-gas, moisture, and bushing online monitoring on HV and EHV transformers is beneficial to all Edison stakeholders. The key quantified benefits the suite of monitoring technologies provides are:

Economic: Online monitoring dramatically reduces the impacts of failure on all stakeholders. A payback period of five (5) years is conservatively expected for each multi-gas, moisture, and bushing monitor installation. Economic metrics included:

- **IRR** (Internal Rate of Return): The annual rate of growth that an investment is expected to generate. IRR is ideal for analyzing capital budgeting projects to understand and compare potential rates of annual return over time.
- **NPV** (Net Present Value): The current total value of a future stream of payments. If the NPV of a project or investment is positive, it means that the discounted present value of all future cash flows related to that project or investment will be positive and therefore attractive. In the table below, it is expressed in terms of the initial installed cost.
- **Payback:** The future year when the value of the benefits equals the project's cost. From that point in time forward, the investment is producing net positive cashflow.

The SCE business case concluded that implementing continuous multi-gas, moisture, and bushing online monitoring on HV and EHV transformers is beneficial to all Edison stakeholders

Asset health visibility: Considerable improvement in situational awareness results from the implementation of online monitoring. Detailed health assessments are not dependent on infrequent transformer maintenance and condition assessment outages.

Minimize rare and extreme events: Rare events encompass natural phenomena (major earthquakes, tsunamis, hurricanes, floods, asteroid impacts, solar flares, etc.) as well as unlikely or sudden causes of transformer failure. Periodic DGA has been highly effective in detecting incipient faults for numerous reasons, one being that most faults evolve slowly. Slow evolving faults make successful application of the "P-F" curve possible. Slow evolving faults allow yearly DGA to identify potential failures early enough to take action before the actual functional failure occurs, see the theoretical P-F Curve in Fig. 4.

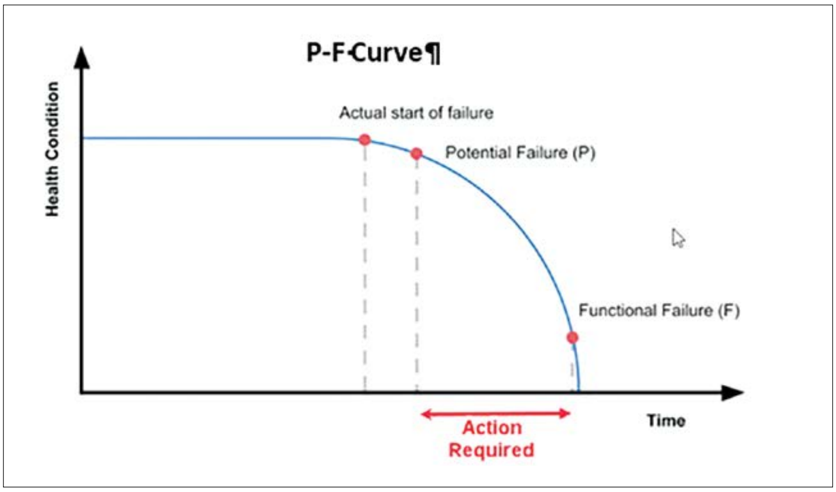

Figure 4. Theoretical P-F curve

Table 2. Summary of online monitoring costs and benefits

	EHV transformers	EHV transformers
Average age	12 years	16 years
Monitor investment cost (hardware, planning, engineering, communication, installation, commissioning, etc.)	USD 150,000 to USD 250,000	
Annual operating costs	USD 700 to USD 1,100	
IRR	40 % to 65 %	
NPV	1.5 to 6 times the installed cost of the monitors	
Payback	4 to 7 years	

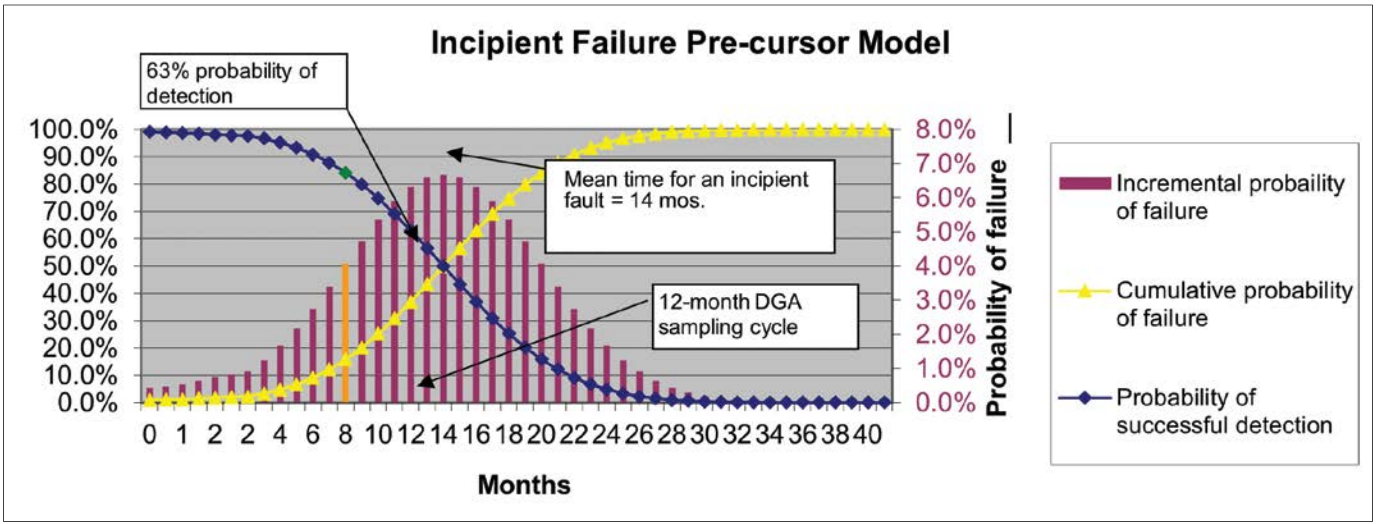

Figure 5. Incipient Failure Pre-cursor Model

Significant reductions in the overall risk of transformer failure result from online monitoring implementation, even when all modes of failure and current maintenance practices are included

Not all transformer functional failure mechanisms are the same. Many failures take months to manifest themselves; few only take weeks, days, hours, or even seconds to go from functionality to failure. For this analysis, SCE assumed that the time from the start of failure to complete functional failure followed a Normal Distribution (see the Incipient Pre-Cursor Model below).

Arguably, the SCE Incipient Pre-cursor Model is highly subjective; it does recognize that for incipient faults that create combustible gas:

- Periodic manual DGA cannot detect all failures.
- Increasing the manual DGA sampling frequency will improve the likelihood of failure detection.
- From a cost standpoint, increasing the DGA sampling frequency has diminishing returns.
- For online DGA, higher sampling frequencies have little impact on operating and maintenance costs.
- Only incipient failure mechanisms with gestation periods of less than a day fall into the category of "Rare Events."

Figure 5. Incipient Failure Pre-cursor Model

Risk reduction: Significant reductions in the overall risk of transformer failure result from online monitoring implementation, even when all modes of failure and current maintenance practices are included. More than a 60 % reduction in the annual failure risk for the existing fleet is anticipated (Fig. 6 and 7).

Maximizing transformer useful service life: Online bushing and multi-gas monitors allow Edison to operate transformers beyond a nominal life of 40 years without failure. A conservative estimate of one (1) additional year of working life was assumed; many additional years should be expected. From a financial point of view, this can be the dominant benefit of online monitoring, especially for older transformers. Delaying the replacement of a very costly asset frees precious capital funds for investment in other vital projects.

9. Conclusions

HV and EHV transformers represent a significant and substantial investment at Southern California Edison. While the Edison Electric system's design is robust enough to mitigate the impacts of a failure on most customers, the effects are not eliminated. Therefore, the direct implications of an HV or EHV transformer failure for Edison are significant, resulting in a sizeable monetary outlay to replace a failed unit.

Even though the fleet of transformers was relatively young, Edison was at risk of

Even though the fleet of transformers was relatively young, Edison was at risk of randomly suffering multiple failures over a short period, resulting in a severe strain on portions of the electrical system. To reduce this risk, a program to install online multi-gas, moisture, and bushing monitoring systems

> **Installation of online multi-gas, moisture, and bushing monitoring systems will result in the improved HV and EHV transformer reliability, reduced failure impacts, and prolonging of the transformer's lifetime, among other benefits**

randomly suffering multiple failures over a short period resulting in potentially a severe strain on portions of the electrical system. To reduce this risk, a program to install online multi-gas, moisture, and bushing monitoring systems is expected to result in:

- improved HV and EHV transformer reliability,
- reduced failure impacts,
- realization of complete transformer useful life, potentially several years beyond the nominal expected life,
- identification of units in urgent need of repair / replacement,
- early recognition of problems that the OEM's warranty should cover,
- substantial reduction in overall transformer operating risks,
- improved accuracy of transformer health assessments.

The models utilized in this analysis are, at times, overly conservative but demonstrate the technical and economic value that online multi-gas, moisture, and bushing monitoring would provide to Edison.

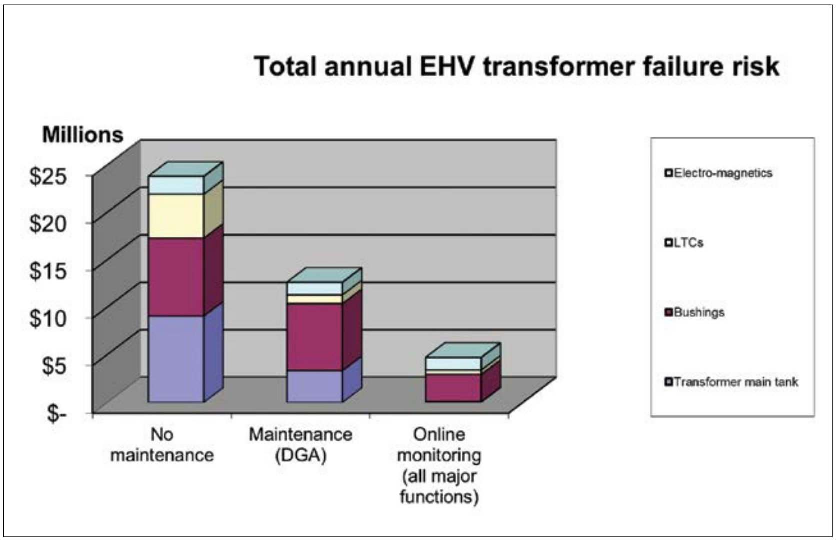

Figure 6. EHV transformer risk comparison

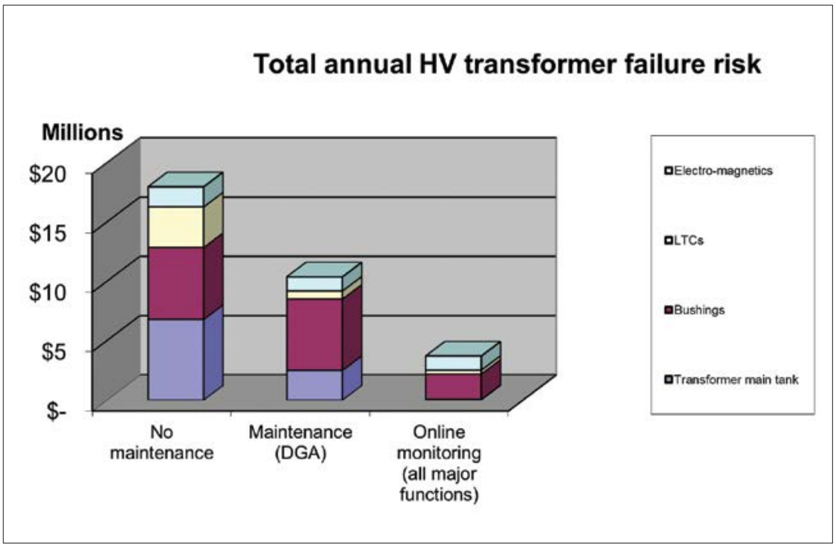

Figure 7. HV transformer risk comparison

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