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Immediate Benefits of Winding Direct Hot-Spot Temperature Measurements

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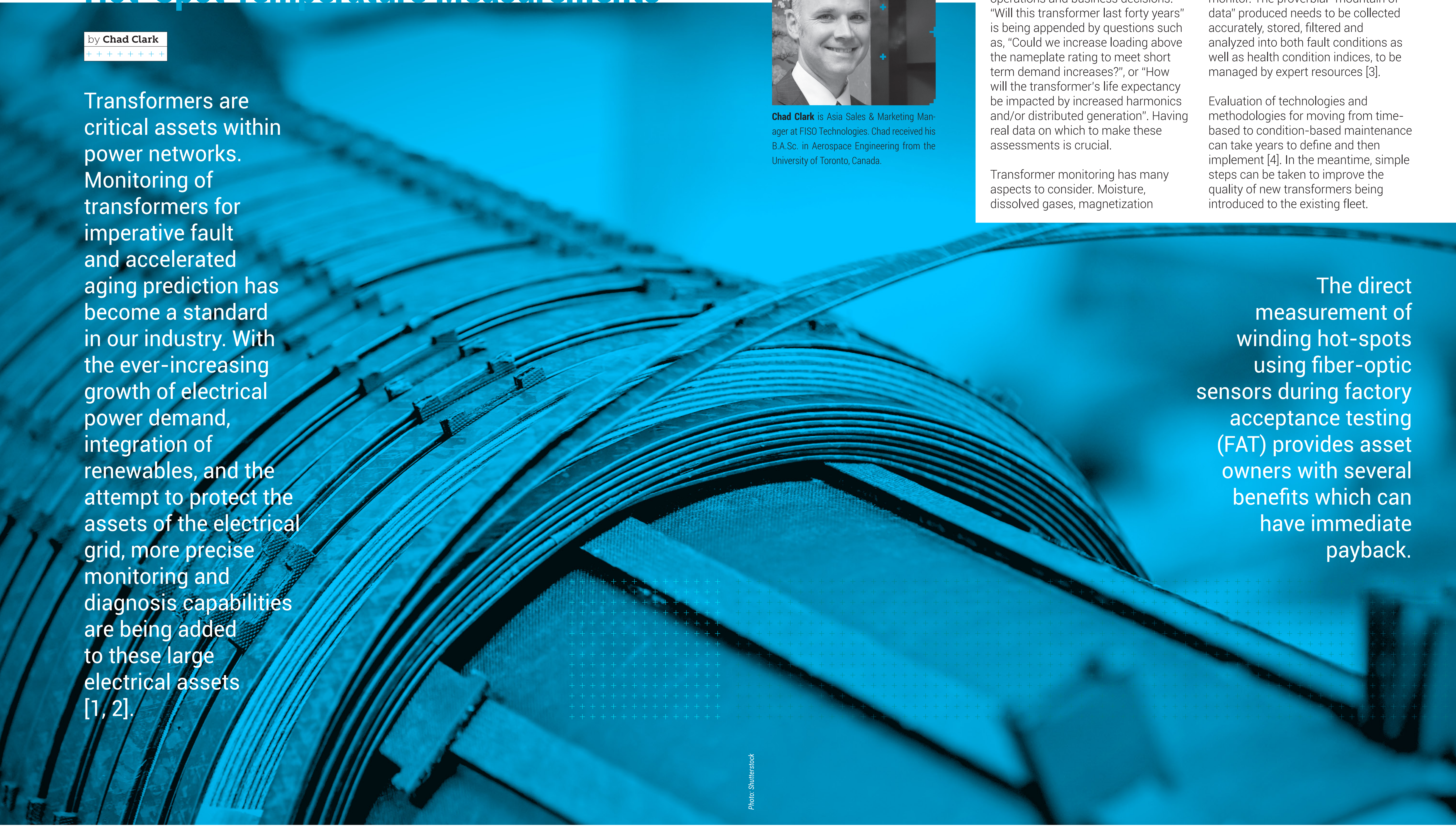
by **Chad Clark**



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Transformers are critical assets within power networks. Monitoring of transformers for imperative fault and accelerated aging prediction has become a standard in our industry. With the ever-increasing growth of electrical power demand, integration of renewables, and the attempt to protect the assets of the electrical grid, more precise monitoring and diagnosis capabilities are being added to these large electrical assets [1, 2].

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There is an evolution of monitoring strategy occurring right before our eyes. Monitoring systems are not only employed to ensure the asset lasts longer, but they are also being deployed to enable more efficient operations and business decisions. "Will this transformer last forty years" is being appended by questions such as, "Could we increase loading above the nameplate rating to meet short term demand increases?", or "How will the transformer's life expectancy be impacted by increased harmonics and/or distributed generation". Having real data on which to make these assessments is crucial.

Transformer monitoring has many aspects to consider. Moisture, dissolved gases, magnetization current, partial discharge, bushing capacitance and power factor, OLTC loading, movement and contact care, load current, cooling operation, oil, tank and winding temperatures are the most well-known parameters to monitor. The proverbial "mountain of data" produced needs to be collected accurately, stored, filtered and analyzed into both fault conditions as well as health condition indices, to be managed by expert resources [3].

Evaluation of technologies and methodologies for moving from time-based to condition-based maintenance can take years to define and then implement [4]. In the meantime, simple steps can be taken to improve the quality of new transformers being introduced to the existing fleet.

The direct measurement of winding hot-spots using fiber-optic sensors during factory acceptance testing (FAT) provides asset owners with several benefits which can have immediate payback.

Better to spend time on weeding out the problems at the beginning or you'll pay for it later. Installing fiber-optic sensors and relying on their data for temperature rise testing was a wise decision we made and we would never go back to not using them.

Quote from a Major Australian Transmission System Operator (TSO)

Here we propose one of those simple steps: *The direct measurement of winding hot-spots using fiber-optic sensors during factory acceptance testing (FAT) provides asset owners with several benefits that can have an immediate payback*. In short, even if the benefit of safely loading the transformer during service life and the long term benefits related to on-line real-time condition monitoring are excluded, the immediate benefits of installing these sensors can justify the investment.

You don't necessarily need a mountain of data to improve the safe-use and health of the transformer asset, just a select few smart data choices can sometimes suffice. Measuring winding hot-spot temperatures directly during temperature rise testing is one of those "smart data" choices.

Informative IEC 60076-2 Annex E

The application of winding direct hot-spot measurements using fiber-optic sensors has been around since the 1980s, with one of the pioneers being FISO's Nortech brand [5]. Today's state-of-the-art EasyGrid system utilizing IEC/ITU/TIA standard optical fiber is pictured in Figure 1 with the elements which are part of transformer (sensors, tank-wall plate, fiber-optic feedthroughs, and cover) along with the elements outside the tank (fiber-optic cable extensions and monitor) illustrated.

In 2011 IEC released an update to IEC 60076-2 "Temperature rise for liquid-immersed transformers" with a new Appendix E, "Application of optical fiber sensors for winding hot-spot measurements". Now recognized by authorities, this important publication by IEC changed the perception and future adoption rate significantly. Table 1 is an example of the recommended minimum number of sensors to be installed in different types of transformers depending on rated power, cooling system, and number of phases, according to IEC [6].

Immediate Return on Investment

One of the largest users of fiber-optic (FO) sensors today for direct hot-spot monitoring did not plan a detailed condition monitoring strategy and install sensors from the beginning with a completely defined health index grading program in place. Instead, they became a super-user quite by accident.

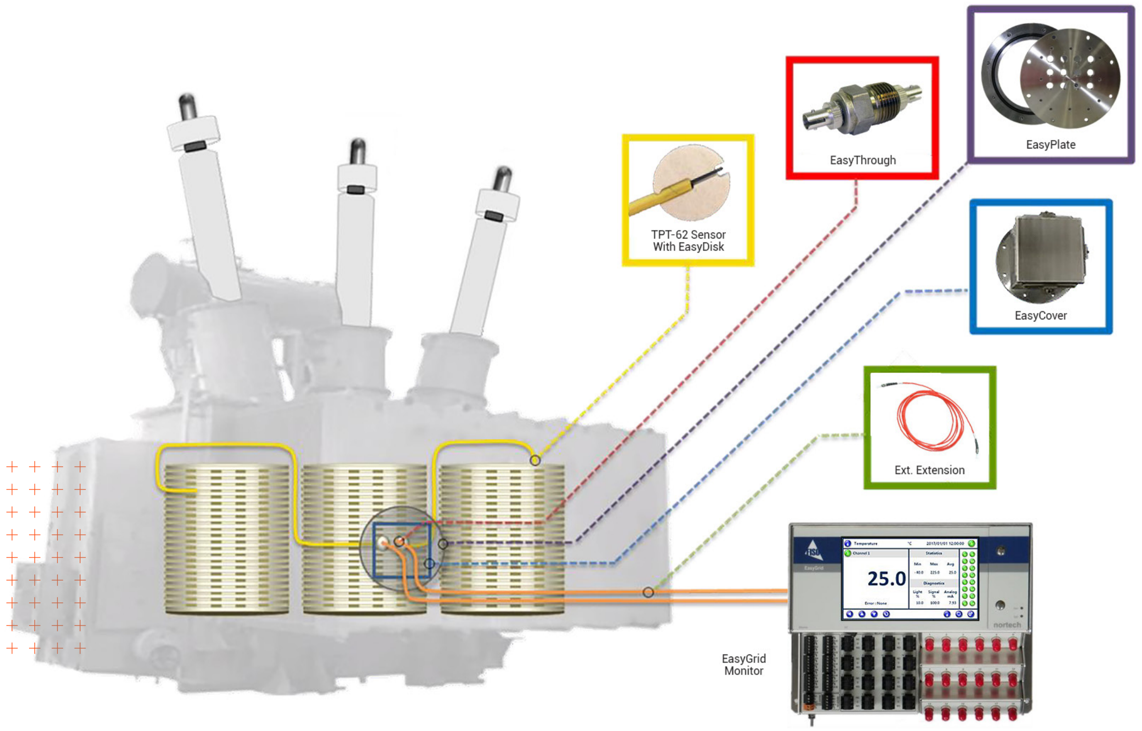

Figure 1. Complete winding direct hot-spot temperature monitoring system

Rated power MVA	Cooling system	Number and phases of installation					
		Total	On central phase		On each lateral phase		
			HV winding	LV winding	HV winding	LV winding	
≥100	All system	8	2	2	1	1	
From ≥ 20 to <100	ON... - OF..	6	1	1	1	1	
	OD..	8	2	2	1	1	

Table 1. Table E.1 from IEC 60076-2 Annex E defining minimum number of sensors based on transformer type

After the release of the new IEC 60076-2 standard this utility decided to install fiber-optic sensors as part of a Type Test of a new transformer design coming from a large multi-national transformer manufacturer. Temperature Rise test was conducted following IEEE PC57.12.90 and the results were surprising [7].

Temperatures were far higher than expected from the thermal modeling. After the first Type Test result, the utility requested that all transformers in a new order be fitted with FO sensors and data again acquired during the temperature rise test. When the results came in, all the transformers were well above the thermal model. What happened next is a matter of contract renegotiation and remains proprietary, but the result was the cost of sensor installation was paid back immediately through discounts provided for transformers which would not last 40+ years at the nameplate rated load.

After this experience, this asset owner required fiber-optic sensors to be installed on all new power transformers from all suppliers, and in the last few years has moved to continuous real-time monitoring on all transformers. This user case follows well the "Evolution of Adoption" that the typical user of fiber-optic temperature sensors experiences, see Figure 2.

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Figure 2. Evolution of adoption

Temperature rise over the permissible limit (°C)	Compensation as a percent of total FOB price of the transformer
0-2.99	0%
3.00-4.99	3.00-4.99
5.00-6.99	10%
7.00-8.99	14.50%
9.00+	Right of refusal

Table 2. Compensation from temperature rise test results

Start with Type Testing

Type testing is an inexpensive means by which to assess the OEM manufacturer's design accuracy and in the case of winding temperatures to confirm the thermal model provided during the design review is accurate. IEEE standard 1538a-2015, "IEEE Guide for determination of maximum temperature rise for liquid immersed transformers" has detailed instructions on where and how many fiber-optic sensors to install on a transformer for this purpose.

With regards to the quote attributed earlier to a large Australian utility, the concept of "spending time at the beginning to avoid the problems later" has its origin from Type Testing. During Temperature Rise tests one of the sensors on the first transformer of a multiple transformer substation project was measuring 7°C hotter than expected at rated load. The traditional winding temperature indicator (WTI) which was to be used for control (alarming & cooling) showed a normal temperature. "That sensor is running a bit hot today" was the explanation from the transformer OEM. In this case the utility was not accepting the explanation and asked for the oil to be drained and the transformer to be investigated. This was not a small task, but the 7°C difference could not be explained and so the OEM reluctantly agreed.

The resulting investigation revealed that the outer surface on an oil duct used to direct flow at the bottom of the windings had delaminated. The delaminated material wedged itself in the oil flow and diverted the cooler oil away from a portion of the winding where one of the sensors had been installed. All the transformers on that order were drained and all were found to have the same delamination on the oil ducts causing the same type of blockage. The OEM changed the oil ducts to a new material, tests were redone, and the transformers subsequently passed.

If the Type Test had not been done with such accuracy, the original transformers would have been energized in the field and had a lifetime shorter than expected. Finding the design problem at the beginning avoided the financial loss associated with their early replacement, easily equivalent to a few hundred fiber-optic monitoring systems. That Australian Utility has since progressed to 100% Temperature Rise Quality Check during FAT using the data from the fiber-optic sensors.

Photo: Shutterstock

Our Ideal transformer includes direct hot-spot monitoring using fiber-optic sensors. The temperature tests done during FAT provide the beginning of life fingerprint against which to compare the on-line temperature data.

Senior Risk Consultant of a Major Commercial Property Insurer

100% Quality Check during FAT

Transformer design and material workmanship are major causes of transformer failures. Since an asset owner cannot be on-site the entire time a transformer is being manufactured, factory acceptance tests witnessed by the asset owner or contracted delegate are vital [8, 9].

What to do if the results are not as expected? Higher temperatures mean that either the transformer cannot be run at rated load, or if run at rated load the lifetime of the transformer will be reduced. Compensation for reduced life expectancy can be calculated and financial penalties can be assessed and pre-agreed contractually. An example of such a financial agreement is described in Table 2.

If a deviation of 3+ degrees is measured, then payback on the installed sensors is immediate. Further, after being installed and used in the factory test, the sensors could be made accessible for connection later on site. The temperature probes can be measured using a portable monitor before the transformer warranty period ends and compared to its beginning of life "fingerprint" performance. Having field-tested transformers enables a second opportunity for the transformer manufacturer quality check and more data by which the asset owner can base future transformer purchasing decisions. Are there some transformer OEMs that perform better or worse than others? Having real-time field data from the fiber-optic temperature sensors can help provide the answer.

Other Immediate Side Benefits

Although quality check of the transformer OEM is the key motivation for Type Test and 100% Temperature Rise QC adoption strategies there are other compelling technical and commercial benefits.

Benefit: Used to Correct Hot-Spot Simulators

Listing the deficiencies of traditional winding temperature indicators (WTI) is beyond the scope of this article, but for any user of these devices the process of calibrating them is seen as a bit of a dark art. Their precision is dependent wholly on parameters entered by the transformer OEM. Sources of error exist, such as the calculated value being dependent on ambient temperatures, due to changes in oil viscosity, and that variation is not considered in the model [10]. Further, the calculations made to estimate winding temperatures using this method are based on below rated load conditions, and in order to know the actual accuracy at above rated load requires further modeling and validation testing for that specific transformer class and design.

Some clever asset owners have taken to use the accurate fiber-optic probe measurements obtained during the temperature rise tests and use that to fine tune the thermodynamic model of the transformer in the WTI at the rated load condition. The real measurement from the fiber-optic sensors essentially corrects the WTI measurement at a critical temperature where cooling of the transformer is critical and the loading of the transformer needs to be managed closely.

Benefit: Recognized by Insurance Companies

The installation of fiber-optic temperature probes can result in a higher confidence level for the newly energized transformer. As a bonus, the sensors then provide the ability to monitor in future years to safely manage the loading and thus the life of the transformer. A multinational property insurer, covering over 100,000 power transformers worldwide, lists the fiber-optic direct hot-spot monitor as part of their ideal transformer.

Now that the immediate benefits are more clearly understood, the conversation inevitably turns to the cost of implementation.

Associated Costs

Pricing of systems can vary depending on the transformer, mainly due to the number of channels, length of cables, and monitor communications required. A rule of thumb is that the external monitoring components (external cables and monitor) are 50-60% of the total cost of the system. Therefore, asset owners can achieve the benefits of the fiber-optic sensor installation at less than half the cost they initially would have imagined. Table 3 compares the relative costs associated with each adoption strategy.

The concept of installing sensors without monitoring at the energized transformer site we refer to as "Dark Sensor" installations. Dark Sensors are one of the least guarded secrets of our industry, however, many end-users and asset owners are unaware of this strategy which is available at just 10-50% of the material costs related to continuous on-line monitoring.

Since fiber-optic sensors need to be installed in the windings at the time of manufacture, investing in the immediate benefits also comes with the ability to reap the long term benefits later. Consider the installed sensors as an "Insurance policy" which can be cashed in later.

The Insurance Policy

Consider the following cases which are likely to occur in the future, and which the existing fiber-optic sensors would then be utilized. As Figure 3 [11] helps illustrate, managing the temperatures of the hot-spots through dynamic loading and efficient cooling in order to avoid rapid loss of life is critical. Having real-time, accurate temperature data from fiber-optic sensors would be invaluable. Where on the dotted line of Figure 3 are your transformers?

New Regulations and Laws

As national energy policies evolve, new requirements can be introduced which require the understanding of how the transformer will fare under emergency loading conditions. What happens when one transformer fails and others have to carry a higher load?

Strategy / Parameter	Type Test	100% quality check during FAT	Monitoring pilot project	Continuous monitoring
Sensors installed?	12-30 on one transformer	All transformers	All transformers	All transformers
Monitor needed?	No	No	One transformer per site	All
Investment	10-15%	40-50%	60-70%	100%

Table 3. Cost of adoption

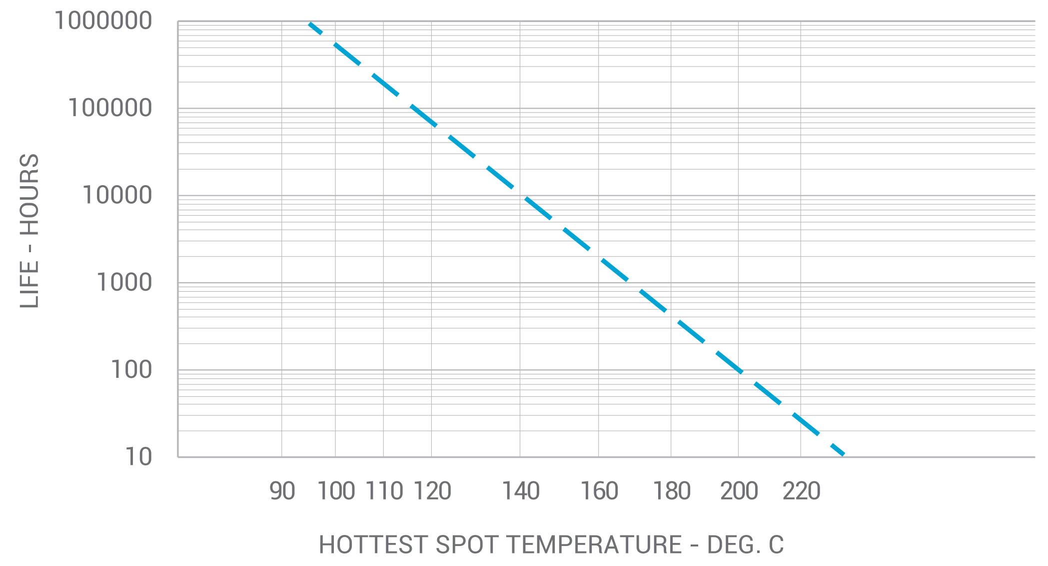

*Figure 3. A Transformer's life expectancy is dependent on winding hot-spot temperature [11]**
Minimum life expectancy curve for liquid-immersed distribution, power, and regulating transformers rated in accordance with Clause 5 IEEE Std C57.12.00-2015, at 65°C average winding rise, 80°C hottest-spot rise

The transformer previously running at just 55% may now need to run above 100% rated load. Ten, twenty, thirty years after first being energized can it do so *safely?*

Increasing Demand

Most transformers when put into service are not heavily loaded, perhaps only loaded to 40-60% of the nameplate value. This may last for 5 years or 15 years, but eventually the transformer can become heavily loaded and subject to stresses from overload or dynamic loading situations. As populations increase, space constraints occur, and/or economic realities change the situation can quickly become even more severe. In some countries today the electrical T&D networks run close or at maximum capacity. There are times when transformers in the network will be over rated load and the owner will want to efficiently cool, or reduce loading when the transformer temperature gets too hot. Catastrophic failures also need to be avoided. India is one country where managing overload conditions is the main driver for adoption.

Revenue Opportunity from Overcapacity

The economic benefit for owners to run their transformers over rated load for short periods of time to capture additional revenues can be calculated directly using only a few variables. Net yearly benefits of several hundreds of thousands of dollars can be realized with on-line monitoring, adding typically less than 1% to the cost of the transformer. In places like Australia and the United States this is one of the reasons why direct measurements and comprehensive monitoring systems are employed. Utilities can make better-informed decisions with the accurate data the real-time, direct temperature measurements provide.

The Age of Dark Sensors

The complexity of on-line condition monitoring coupled with the rigors of asset maintenance can paralyze an organization when evaluating new technologies for incorporation into their future plans. Long term benefits do need to be understood, but in the case of direct real-time hot-spot monitoring the immediate benefits provided during factory acceptance testing make their specification and installation into new power transformers a smart decision by owners of these assets.

The immediate benefits include:

- Identify design flaws and root out material and workmanship issues before acceptance from manufacturer
- Used as a basis on which to receive a pre-negotiated discount, or even reject entirely
- Used to correct the existing hot-spot indicators (WTI) which may still be used to control cooling
- Provide beginning-of-life performance "fingerprint" against which to compare energized transformers on-site before their warranty expires

Further, the medium and long-term benefits experienced from efficiently managing the load on a transformer due to increasing demand, economic benefit, or to comply with new regulations are non-debatable. *Transformers with fiber-optic sensors providing real-time accurate hot-spot temperature measurements will operate safer and last longer.*

Take a step back from the concept of condition-based asset maintenance for a moment and focus on the immediate benefits to your transformer fleet. The short-term benefits and the corresponding insurance policy for the future that direct hot-spot monitoring provides are clear. The installation of fiber-optic sensors into your power transformers for direct winding hot-spot temperature measurement could be your next bright idea [12].

Acknowledgments

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