White paper

How evolving design tools and specifications impact transformer longevity

The challenge faced by utilities

Planning engineers in North America are called on to build sound, cost-effective, 30- to 40-year asset plans to meet the needs of customers, employees, investors and the communities served. Those needs include appropriate levels of safety, reliability and efficiency. Another critical consideration is how the plans they formulate today will affect the long-term reputation and financial picture of their companies. Central to this planning is a prediction of asset longevity.

Of course planners must develop these plans within cost constraints, ensuring that the utility and its customers get the greatest possible return on investment (ROI). As planners do their cost analysis, there are many factors they must consider. Some are known and quantifiable, including initial purchase price and system losses. Other factors can be predicted with high levels of confidence, such as future power demand levels and price levels.

For power transformers, one of the high-confidence factors is asset life. Based on the large quantity of data documenting the life of transformers now in service or recently retired, it's possible to do a highly accurate job of predicting the life of a new transformer. The reliability of this factor is critical to the accuracy or validity of the asset plan because longevity is a primary factor in achieving the target ROI. Each additional year in service represents an increase in the ROI's denominator, boosting the return on the original investment. Likewise a failure of the asset in a shorter period than its expected or capital life can result in costs 6 to 10 times the initial cost of the transformer.

Concerns with lower costs

The power transformer is the highest cost item in a substation. As manufacturers have strived to bring the cost down, there has been some erosion in buyer confidence that the current generation of transformers will provide the same longevity as assets now in the fleet.

Some manufacturers may lower transformer costs by stretching design and material limits or relaxing production standards. As an example, one manufacturer minimized construction cost by using solid conductors for tap changer connections. The oil-filled, 5 MVA, 21 kV/4.16 kV transformer failed after only three years. The refinery had no backup, creating an extended production loss and leading to litigation to recover their losses.[1]

In another example, the investigation of a utility's step-up transformer failure was determined to "most likely be the result of a design, material or manufacturing defect in some component of the transformer, particularly since the transformer was only six years into what would typically be a 30 to 40 year lifetime." This despite the fact that the transformer had passed a factory acceptance test and was built to the customer's specifications.[2]

"Utilities have told me they don't believe today's transformers are going to last as long as they used to," said Scott Curley, ABB vice president for power transformers, North America. "They assume manufacturers are taking shortcuts to reduce costs in order to be more competitive. In fact, based on advanced tools and in-service knowledge, most power transformer manufacturers have the opportunity to create designs that are superior to, and even more cost-effective than, previous models."

With an appreciation for how lower costs have been achieved, and awareness of the need to create a well-written specification, utilities have every reason to believe they can develop asset plans that include reasonably priced power transformers able to deliver reliability and longevity comparable to the generations that came before them.

White paper overview

In order to develop sound asset plans, buyers need to closely evaluate the longevity expectations of, and risk associated with, the supplier. In this white paper, we will describe some of the common pitfalls of traditional long-term utility asset planning and longevity prediction. We will describe how new design tools have been a driver for a modern generation of transformers that offer new features and benefits, and often do so in a more compact envelop and at lower costs.

We will explain how specifications have evolved apace with design advances, and how planners need to modify their approach to specification development. Finally, we will introduce the concept of a "longevity quotient," a way to approach transformer life considerations in a more precise and accurate way.

Evolution of design tools

Design tools then

There are many examples of modern technologies that were unimaginable 40 years ago: Boiling a cup of water in a minute, geo-locating your position anywhere on the earth and perusing detailed aerial views of cities around the world. Similarly, engineers designing transformers in the 1970s couldn't begin to comprehend the many resources that today are taken for granted.

Back then, the primary design method was to submit the design input to the computer operator to be run on the mainframe computer and returned to them hours later, if not the next day. No doubt they were thrilled by the availability of the just-invented solid-state calculator, which greatly accelerated their calculations.

The engineering area included shelves housing the binders of rules and past designs used to guide the engineers' calculations. The collective experience of the organization's previous designs was compiled in these binders, creating a paper-based collection of analog algorithms used to guide future design.

"At Westinghouse, we had a design manual that was four inches thick," recalled ABB senior designer Scott Thomas. "There were rules and data related to windings, core, losses, cooling and more, all based on R & D efforts and historical performance of previous transformers. The more experience an organization had with transformer design, the higher the validity of that historical data. Past experience helped ensure that the next design would be an improvement over the last."

Design tools now

The designers' world fundamentally changed with the ready availability of greater computing power. First came increased access to mainframe computing via desktop network terminals and then PCs. The availability of these personal computing resources enabled more and better calculations.

Armed with a range of off-the-shelf and custom programs written for the PC, designers in the late 1980s for the first time had the

ability to quickly look at what-if scenarios and evaluate many design options or changes. They could now do this in the same time that would previously have allowed only one or two iterations. The relatively few calculations formerly done relying on the mainframe and design manuals were replaced by a range of off-the-shelf and custom software.

"Many transformer manufacturers had teams of computer programmers writing custom software to support finite element analysis and other complex calculations that were formerly available only to prove the technology or for special projects," Thomas said. "These programs let us verify, validate, and document the strengths of each transformer design. Today we can design to the actual, calculated limits of a material and selectively increase safety where it is most needed instead of checking a binder to see what we used in the last design and simply adding material to provide a safety margin."

Other computer-based resources commonly used by power transformer designers included tools to optimize materials versus customers' requirement for losses. With this widely used tool, a transformer buyer can specify losses to not exceed a certain dollar amount per kilowatt hour. The major transformer manufacturers have as many as 50 regularly used tools that include winding design, dielectric/voltage withstands calculations, force calculations, cooling/fluid flow and others to enhance their final designs. On the mechanical side, 2D drawings were replaced with 3D parametric CAD programs that can check for interference as well as structural strength.

"These tools help create better, more compact designs," Curley observed. "But it's important to realize that the smaller footprint doesn't mean they are any less robust. It's just that we've become smarter in our approach. We can pinpoint the highest stress locations to add margin where it's necessary and remove margin from places where it adds only size and cost with no functional benefit."

Tools vs. talent

The very best tools, however, won't assure the very best work. It is the talent of the person using the tool that largely determines the results.

"Those binders we used at Westinghouse were cumbersome, but they represented an invaluable collection of real-world experience," Thomas stated. "Today designers have tremendous calculation capabilities, but they still must rely on their personal experience and that of their coworkers to understand the appropriate inputs and to recognize flaws or improvement opportunities in the outputs."

With all of these tools, the design quality still comes down to experience. The most sophisticated tool is of little value if its margin of accuracy is not correctly understood by the designer. Engineers at organizations that are relatively new to transformer design rely on a fair amount of engineering approximation. They typically err on the side of more weight and margin and therefore create a sub-optimal design, or they focus on cost over reliability, incorporate insufficient margin, and create a less reliable transformer design.

"Most people understand that, with so many tools available, it's the talent and experience of the designer that ultimately makes the difference," Thomas said. "Buyers want to know that they can trust the people doing the design. It's as much about the designer and their process as it is the design."

As one proof of that statement, he points to the fact that a design review is almost always part of today's purchase process. That wasn't the case in the past. Today, buyers seem to want to interact with the designer. They want to feel confident that the design team has the competencies to deliver the transformer the customer is asking for.

Evolution of specifications

The fundamental elements of transformer technology have changed little in the last four decades. An engineer from the 1970s time-travelling to a modern engineering department would immediately recognize every basic transformer feature as being quite similar to the ones they designed. Still, there are many new features, materials and performance metrics available today.

Specifications have evolved to address changing customer requirements and expectations. This evolution has been less than perfect; as a result, most specifications don't do as good a job of ensuring the desired transformer life as they could.

"Factory acceptance testing and compliance to specifications can't guarantee longevity," Curley said. "One of best indicators of a design's robustness is short circuit testing your actual designs and looking at the history of tests from the same design system. That data provides a better reference for predicting longevity. When considering short circuit test data, however, it is important to remember that the ability to withstand short circuit currents is different between IEC and the more stringent IEEE."

Fear of change

A common misstep in specification creation is simply adding to past specs rather than looking critically at the actual performance requirements. In some cases, engineers take this approach because of the comfort level they get from relying on the specification for a proven transformer. In other cases, this approach has to do with talent drain. Some soon-to-retire designers, who began careers working off tables that showed what was tested and proven, feel that if it worked then it should work now. Relying on a proven design and specification seems like a safe approach.

"The technical owners may be afraid to change the way specifications are created," said Krzysztof Kulasek, vice president of power transformer engineering at ABB. "The new units are smaller, so they think they aren't as good. They are unsure of the advantages of the new technology. This thinking prevents them from capitalizing on newer technology. The fact is that, by drawing on the design experience and tools available today, suppliers can design and deliver smaller transformers that are just as reliable as older, larger and more expensive units."

If the specification includes a margin limit, every supplier will have to increase the price. Instead of asking for a general margin, Kulasek said they should consider specific limits for hot spot temperatures, local dielectric stress, and short circuit. A better option would be to increase specifications related to test BIL (higher kV), required direct hot spot measurement and short circuit reference. These tests are especially important when working with a new supplier or on a large project to reduce the risk of failure.

More of the same

"It's not unusual for a customer to want basically the same power transformer he bought 20 years ago," Thomas said. "It proved to be a reliable performer, so they want more of the same. They have confidence in the design and believe 'they don't build them like that anymore.' So they just add requirements to the old specification. In many cases, though, those additions don't really extend longevity. What makes more sense is understanding the application and requirements and then designing to the material limits while maintaining sufficient margins rather than increasing margins unnecessarily."

These recycled designs may also bring forward unneeded artifacts from the past. For example, the original 1980's design might have incorporated an on-load tap changer and a de-energized tap changer (DETC). The buyer won't remove the DETC in the current spec, even though it is never used, because they don't understand why it was there in the first place. It's like someone who buys a new desktop PC and pays extra to include a floppy disk drive. While that was a logical option in the past, it's unlikely to ever be used today, making it a waste of money.

As another example, customers may say they want to limit the flux density in the core steel to 17,000 gauss, the limit of the older electrical steel they previously specified. That ignores the fact that electrical steel manufacturers have improved their quality and performance, not to mention the improvements in core quality and construction developed by transformer manufacturers. If the buyer's goal is preventing operational issues relating to the core, a better way would be for the specification to state that the core hot spot and core surface temperature must be limited.

"When customers arbitrarily bring forward elements from past specs, it really ties the manufacturer's hands," Curley said.

A disturbing situation

Changing features and functions are one impetus for specs to evolve. Another is the need to address the changing power grid.

"Today's grid is more interconnected, with more sources and destinations," Curley observed. "That means more issues related to frequencies and more opportunities for electrical disturbances, the biggest source of failures for transformers and other transmission devices. You cannot specify a device be immune from all disturbances, but you can include language describing your requirements to ensure greater tolerance for disturbances. The point is to include things in the specification that will influence longevity."

"We see buyers seeking to protect their grid reliability by specifying items like infinite bus and stating 40-year life expectancy," Kulasek said. "That it is not a wise approach. Due to in-service conditions, you can't guarantee those things; you can only increase confidence in achieving them. By specifying infinite bus the buyer does gain an added margin of protection, but at a potentially large cost to protect against a condition that the transformer will probably never see. The added challenge is the fact that you can never test for these items, so buyers would do better to focus attention on other longevity indicators."

Curley added that "… infinite bus may actually cause problems in the overall system because it forces the buyer to look also at their downstream breakers and other devices."

Instead of adding infinite bus as boilerplate language, engineers would do better to commission a system study to assess the actual, probable demands on the transformer over its life, and then write the specification accordingly.

New manufacturers

When selecting a transformer design, it isn't always prudent to focus on history because much has changed and improved in the last 40 years. When selecting the transformer manufacturer, however, it can be very important to take a look backward.

"You want a supplier with a proven history for building long-life power transformers for the North American market," Curley said. "Even though a transformer passes a factory acceptance test and meets your specification, that doesn't mean it's going to last you 40 years. You need to feel confident in the systems and processes that will produce your next transformer."

He cites offshore manufacturers who entered the US market within the last 10 years.

"How can anyone really know how long their transformers are going to last when their experience on design for the US market and in-service history is less than the technical age of the installed base in the US?" Curley wondered.

Utilities concerned about the longevity of newly purchased transformers may want to consider the following checklist of items that will provide valid life-expectancy indicators:

- Does the manufacturer's design system integrate continuous improvement and incorporate both field failure and factory-test failures?
- Can they provide proven, third-party short circuit history and industry average or above pass rates?
- What is the field-failure rate for units installed in North America?
- Can they provide proof of North American-installed units still energized beyond current expected life cycle?
- Do they employ analytical design tools including 3D modeling, short circuit, field plots, dielectrics and others?
- What is the average age of their installed base for ANSI/IEEE designs?

The role of standards

References to the transformer manufacturer's quality system are increasingly, and appropriately, part of most current specifications.

"Thirty years ago, the customer would personally qualify the facility," Thomas said. "They would send a team of auditors to evaluate every function in the factory. Now buyers rely on paper documentation and standardized systems like ISO. They require documentation of the manufacturer's quality system and plan, their inspection and hold points. Buyers want to understand how quality is assured in the manufacturer's facility and processes. That's a critical requirement to include in a specification."

While reliance on national and international standards provides a good foundation for a specification, they don't cover all the special cases or specific parameters the customer may want, even for the active parts of the transformer.

"The standards provide the framework for a good specification, defining the majority of the parameters for what the manufacturer will deliver," according to Kulasek. "But just like a blueprint doesn't provide all the information needed to build a home, the standards alone don't provide all the information needed to meet the buyer's expectations. It is crucial that buyers stipulate detailed technical and non-technical parameters to ensure they take delivery of a unit that is more likely to meet their longevity expectations."

Even the tightest, best-written specification can't guarantee a 40-year transformer life. There is, or course, the critical issue of the manufacturer's ability to produce a transformer that fully complies with the specification and the buyer's expectations.

Once in service, there are a number of factors that could shorten the transformer's life. Will the buyer conduct the appropriate maintenance? Will the loads significantly increase? Will the transformer be subjected to frequent and intense disturbances? Still, a good specification executed by a proven manufacturer will provide the buyer with the strongest possible assurance of long life.

The longevity quotient

In doing their long-range planning, transformer buyers might consider the concept of a longevity quotient (LQ), a different way to think about the life of transformers that takes into consideration specific performance and cost metrics. With this longevity quotient, engineers may be able to better estimate the long-term viability and ROI of power transformers from commissioning through retirement. That makes the quotient a useful calculation when developing asset plans 25 to 40 years out. The LQ is based on the normal cost factors of initial price and losses but includes a factor for years of experience.

As an example:

LQ = MTBF (Mean Time Between Failures) / (37.4 years avg. age of transformers / years of market experience)

Using the LQ as a factor, a new evaluation methodology could be:

(First cost + Losses) + (Industry failure rate x (1000/LQ) x Average failure cost)

For example:

Transformer Rating: 250 MVA, 230 -115 kV

Supplier A		
First cost (10% higher than supplier B)		$1,980,000
Cost of losses		$500,000
Industry failure rate		1.30%
Mean time between failure (Years)		715
North American experience (Years)		80
Failure $ = $15,800 per MVA *		$3,950,000
LQ= MTBF / (37.4 years avg. industry age of transformers / years of North American market experience) **		1529
	Total evaluation >	**$2,513,575**

Supplier B		
First cost		$1,800,000
Cost of losses		$500,000
Industry failure rate		1.30%
Mean time between failure (Years)		550
North American experience (Years)		20
Failure $ = $15,800 per MVA *		$3,950,000
LQ= MTBF / (37.4 years avg. industry age of transformers / years of North American market experience) **		294
	Total evaluation >	**$2,474,950**

Difference in total evaluation	$38,950
% Difference in total evaluation	1.6%

* Hartford Steam Boiler Inspection and Insurance Company study of transformer losses 25MVA and above between 1997 and 2001 = $15,800 / MVA which includes business interruption

** Based on Doble Engineering Publications

Summary

As planning engineers build longevity considerations into their long-range asset plans, they often assume that transformer price is a good indicator of expected service life. Based on the lower, inflation-adjusted price of today's transformers, some engineers therefore assume that they should also lower their longevity expectations. To help ensure the desired longevity, they often build current specifications on old designs that have proven to be reliable.

But relying on specifications that don't focus on longevity factors won't assure that the transformer purchased today will match the long service life of those in the fleet still performing well after three or four decades. Achieving long and predictable life in newly purchased transformers requires that planning engineers first identify suppliers who are equipped with the accurate design tools and staffed by experienced, knowledgeable design engineers. These engineers also must focus on creating specifications incorporating appropriate parameters to ensure longevity. With this two-part approach, utilities can feel more confident about predicting asset life and more precisely execute their long-term asset plans.

In evaluating longevity predictions from the many competing suppliers in the market, transformer buyers should also calculate and understand the longevity quotient of each supplier to get a clearer view of the true potential transformer cost and projected performance.

"With continuously evolving power grids and increasing focus on long-term performance of power assets, it's clear that there is better value for both users and manufacturers when applying modern tools and production processes combined with relevant industry experience," said Curley. "Applying purchase-evaluation methodologies that include factors quantifying historically successful performance will result in lower overall costs and much improved."

References
[1] Case of the Double Transformer Failure, ecmweb.com

[2] Report on the Step-Up Transformer Failure and Fire at Palomar Unit 1, California Energy Commission

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