TECHNICAL, ECONOMIC AND STRATEGIC LOADING ISSUES INVOLVING THE EXPLOITATION OF POWER TRANSFORMERS: A PROPOSAL FOR THE NEW MILLENNIUM

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Abstract

The paper discusses operation and maintenance criteria for an optimized loading policy. A proposal for an assessment of transformer reliability for loading to be conducted in conjunction with an economic study is also presented. Strategic issues involving asset management aspects referring to the operation, maintenance, life assessment and economics of power transformers are discussed.

Operating Power Transformers from a Technical Point of View

In recent years there has been much concern among power utilities on the development of new techniques in order to obtain a better life assessment of the transformers on their power systems.

It has been widely discussed that not only the effect of heat due to loading, but also contaminants like moisture, oxygen, and oil acids, work synergistically to reduce the remaining useful life of Kraft paper. Consequently the life of the transformer diminishes.

One of the ways to increase the life of transformers is to minimize the effects of paper and oil degradation agents by properly designing, operating, and maintaining power transformers. An effective oil preservation system (e.g., nitrogen-gas blanket) is very useful to prevent atmospheric contaminants from entering transformers and thus accelerating the oil degradation. In cases when moisture and oxygen have already caused some damage, it is usually convenient both to reclaim the oil and to dry out the solid insulation.

Well-preserved transformers with a low oil oxygen content (e.g., lower than 3,000 ppm), a low oil acid number (e.g., lower than 0.1 mg KOH/g), and a low water content of the solid insulation (e.g., lower than 1%), can be loaded according to their specification with a minimum of life consumption[1]. In such cases it is possible to load the unit beyond nameplate values under contingencies. It is important to emphasize that overloading limits are established in loading guides according to the contingency time duration and overload values. For example, IEEE

Loading Guide C57.91-1995[2] suggests a maximum hottest-spot conductor temperature of 180 °C for loading above nameplate transformers with 65 °C rise when a short-time emergency loading occurs. The adverse effect of such a very high temperature level on the life expectancy should be compensated when the transformer operates at much lower temperature levels during normal loading if the Kraft paper and insulating oil are maintained at an excellent preservation condition. However, if the solid insulation is wet and the oil is acidic, the consequences of high loading temperatures can be catastrophic. When this is the case of any transformer, it is critical to bring the unit back to good maintenance conditions before any aggressive loading program is put into practice.

We have observed that there are utilities which are very conservative concerning their loading practices although they spend much maintenance money to keep the oil of their power transformers with a low acid number and the Kraft paper with a low water content. We always recommend these utilities to be more aggressive in terms of loading practices in order to compensate for the money spent in oil and Kraft paper maintenance.

There are also utilities that are very liberal in terms of loading practices and have budget limitations to maintain the oil of their power transformers with a low acid number and the Kraft paper with a low water content. We try to demonstrate to these utilities which are the more critical points where they will have a better return ratio for their maintenance dollars.

Figure 1 shows an example of the importance of conducting the analysis of maintenance data. The acid number growth trend of transformer #1 versus the average acid number growth trends of membrane and nitrogen-gas blanketed power transformers are presented in the figure. Transformer #1 had its oil reclaimed after 11 years in service. During the following 6 years, the acid number of its oil was recorded on a yearly basis. As can be seen in the figure, only after roughly three years that the oil had been reclaimed, it had already reached the limit value of 0.1 mg KOH/g. Though this limit value can be considered as very low, it is important to emphasize that the higher the acid number the more severe paper degradation due only to acids will occur. It can also be observed in the figure that the velocity of the acid number growth was extremely high as compared to average values obtained for a total of 113 membrane type transformers installed on the power system of a Brazilian power distribution utility[3]. In short, just the data analysis of the acid numbers of a reclaimed oil has sparked the attention on the actual benefits of a specific maintenance procedure, like oil reclamation, and what should be done to overcome the problems detected, how could they be prevented to happen again, and consequently how could maintenance dollars be spent more reasonably in order to have a better benefit/cost ratio.

The Use of Power Transformers as an Asset

From a merely technical standpoint, a transformer life should always be preserved by proper maintenance practices and safe operation policies. Though a general consensus on the validity and importance of this statement can be easily achieved, it should be noted that a power transformer must pay for itself, and its use must also generate profit to the utility, like any other of its assets.

When economic aspects are taken into consideration while analyzing both operation and maintenance philosophies, old paradigms can start being questioned. For example, is it proper economically speaking to reclaim the oil or even to impose conservative hottest-spot conductor temperature limits to preserve the life of a transformer 40 years in service? Or even, what are the long-term economic advantages of maintaining the oil acid number of a 15-year old transformer below 0.1 mg KOH/g by conducting its oil reclamation on a regular basis?

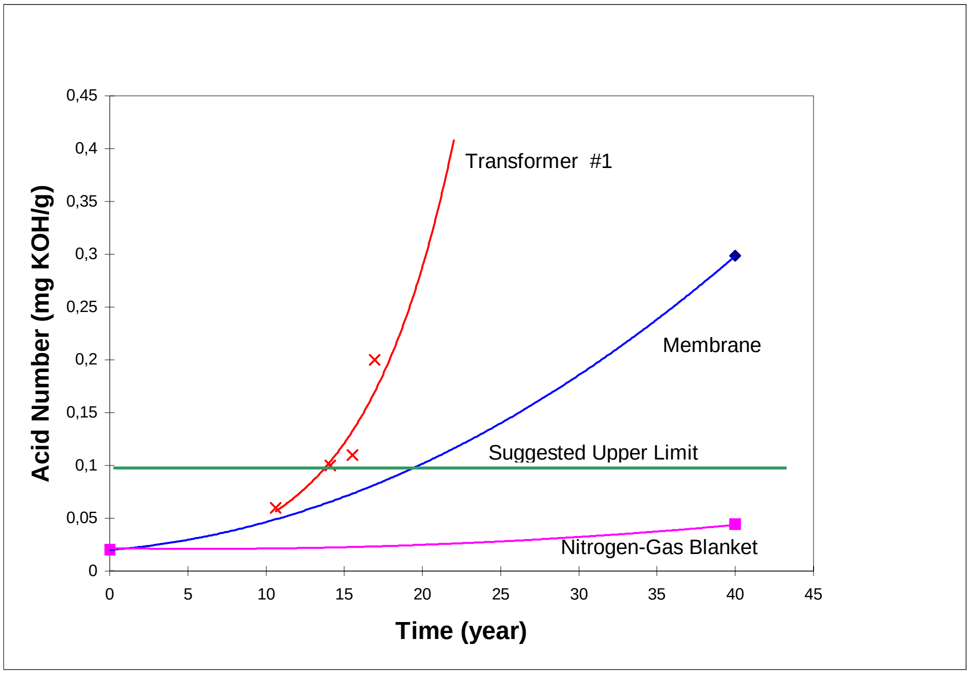


Figure 1
Comparison of the Acid Number Growth Trend of Transformer #1 Versus the Average Acid Number Growth Trends of Membrane and Nitrogen-Gas Blanketed Power Transformers

Table 1 presents the necessary data to assess the economic advantages and disadvantages of conducting typical oil and Kraft paper preventive maintenance procedures of a Brazilian power transformer, rated 138/13.8 kV, 18,750 kVA. In this specific case, the analysis was performed in order to assess the benefits of installing an oil preservation system consisting of a plastic bladder filled with dry nitrogen gas at atmospheric pressure in replacement to a rubber bag system. The unit had been in service for 19 years. Table 2 and Figure 2 show the dollars that have to be spent on average on transformers like the one referred to in the example, taking into consideration market prices and the time frame when the maintenance procedures analyzed, like oil reclamation, oil and winding drying-out, rubber bag replacement, etc. have to be conducted. For example, rubber bags have to be replaced every 12 years on average due to cracks.

Table 1

Input Information for an Economic Assessment of Maintenance Procedures to Extend the Life of the Kraft Paper and Insulating Oil of an 18,750-kVA Transformer

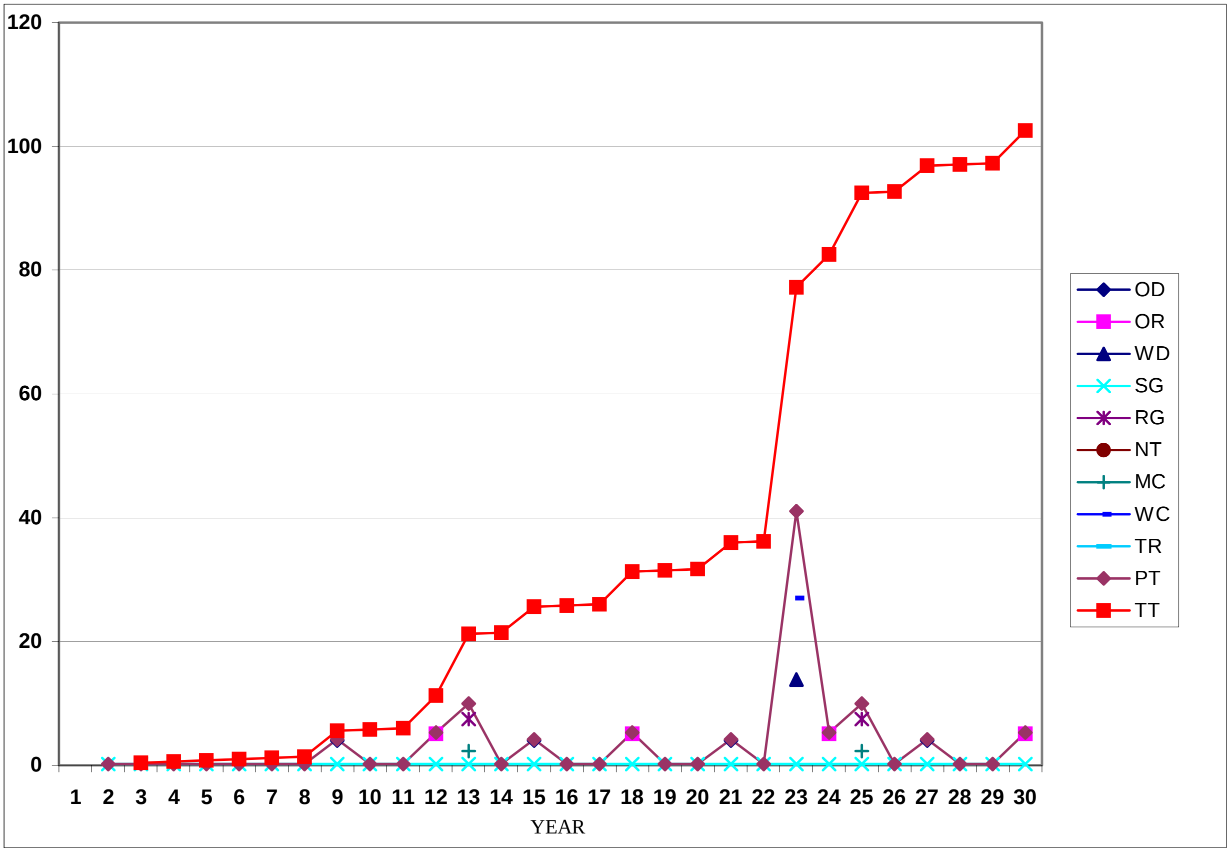
TRANSFORMER DATA	**US$**
Price:	325,000
Oil Volume (Liter):	13,370
Rated Capacity (kVA):	18,750
GENERAL EXPENDITURES	**US$**
Oil Degassing and Drying (US$ 0.30 per liter):	4,011
Oil Reclamation (US$ 0.38 per liter):	5,081
Winding Drying-Out:	13,900
Silica Gel Replacement:	0.2
Rubber Bag Replacement:	7,500
Additional Costs Referring to Rubber Bag Replacement:	2,250
Additional Costs Referring to Winding Drying-Out Procedure:	27,000
New Transformer Assembling/Commissioning:	65,000
Installation of Plastic Bladder System Filled with Dry Nitrogen-Gas at Atmospheric Pressure:	6,500
ANNUAL INTEREST RATE	**%**
Value Used in the Calculation	10

Table 2

Average Costs (US$ x 1,000) of Maintenance Procedures to Extend the Life of the Kraft Paper and Insulating Oil of an 18,750-kVA Transformer

Year	1	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
OD					4.0						4.0						4.0						4.0				
OR								5.1						5.1						5.1						5.1	
WD																			13.9								
SG	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
RG									7.5												7.5						
NT																											325.0
MC									2.3												2.3						
WC																			27.0								
TR																											65.0
PT	0.2	0.2	0.2	0.2	4.2	0.2	0.2	5.3	10.0	0.2	4.2	0.2	0.2	5.3	0.2	0.2	4.2	0.2	41.1	5.3	10.0	0.2	4.2	0.2	0.2	5.3	392.0
TT	0.2	1.0	1.2	1.4	5.6	5.8	6.0	11.3	21.2	21.4	25.7	25.9	26.1	31.3	31.5	31.7	35.9	36.1	77.2	82.5	92.5	92.7	96.9	97.1	97.3	102.6	492.8

OD – oil drying-out; OR – oil reclamation; WD – solid insulation drying-out; SG – silica gel replacement; RG – rubber bag; NT – price of a new transformer; MC – costs associated with rubber bag replacement; WC - costs associated with solid insulation drying-out process; TR – costs associated with installation/commissioning of a new transformer; PT – partial total; TT-total



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Both the technical and economic advantages of installing the plastic bladder system with dry nitrogen gas at atmospheric pressure are presented in Table 3. The installation of this system is still economically interesting even for units that have been more years in service. Table 4 shows the pay-back times for similar transformers up to 30 years in service.

The limits imposed by operation and maintenance criteria are established based on technical parameters such as voltage level, year of manufacture, type, etc. It is quite unusual to correlate such limits with economic calculations.

From an accounting point of view, any asset depreciates at a determined yearly depreciation rate for a certain period of time until its accounting end of life is reached. In the case of transformers, for example, the depreciation time can be 30 years. During the depreciation period of time, the amount of money obtained by multiplying the purchase price by the yearly depreciation rate of all assets can be deduced from the company's cash flow. This deduction permits the company to pay less income tax because the final balance of its cash flow will be lower.

Table 3

Cost Comparison between the Installation/Maintenance of a Plastic Bladder Filled with Dry Nitrogen Gas at Atmospheric Pressure and the Maintenance of a Rubber Bag as Oil Preservation Systems in an 18,750 kVA Transformer

SCENARIO	**US$ SPENT TO DATE**	**US$ TO BE SPENT**	**TOTAL US$**	**BENEFITS/ PROBLEMS**
Present condition of a rubber bag type transformer 19 years in service	31,733	70,833	**102,566**	Excessive loss of life of the transformer, and high maintenance costs
Condition of a transformer 19 years in service after the installation of a plastic bladder system filled with nitrogen gas at atmospheric pressure	31,733	31,571 (pay-back time 1.8 years)	**63,304**	Additional benefits worth US$ 500,000 to be obtained due to the calculated life extension (from 30 to 41 years), higher loading limiting values, investment postpone in the construction of a new substation
Condition of a new transformer supplied by the manufacturer with the plastic bladder system filled with nitrogen gas at atmospheric pressure	6,500 (pay-back time 0.7 year)	1,952	**8,452**	Extended service life and reliability for higher load limit values, maintenance costs reduction, and savings worth 30% of the price of a new transformer after 30 years

After the depreciation period of time is over, all of the costs involved in maintaining and operating a transformer, for example, cannot be taken into consideration in terms of accounting since the unit has already been depreciated. Also, no depreciation deduction can be done in the cash flow, and consequently more income tax will have to be paid. Ideally, the technical and accounting end of life should occur at the same time.

Strategic Aspects Involving the Exploitation of Power Transformers

Another very well-accepted paradigm concerning the operation of power transformers establishes that an old transformer should be taken out of service only after a significant failure. It is usually said that the cost of replacement of these pieces of equipment is very high, and it is difficult to justify the replacement before a failure due to the end of life occurs.

Table 4

Economic Assessment of the Installation of a Plastic Bladder System Filled with Nitrogen Gas at Atmospheric Pressure in an 18,750 kVA Transformer

YEAR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
IRR	21.6	21.6	21.6	21.6	21.6	21.6	21.6	21.6	21.6	21.6	21.6	21.6	21.6	21.6	21.6
NPV	164.5	205.4	257.8	324.4	408.8	515.2	649.7	818.4	1,030	1,293	1,621	2,026	2,527	3,141	3,892
Pay Back Time	0.67	0.66	0.64	0.62	0.61	0.63	0.62	0.60	0.57	0.55	0.54	0.52	0.49	0.47	0.44

YEAR	16	17	18	19	20	21	22	23	24	25	26
IRR	21.6	19.4	19.2	18.9	17.4	16.1	16.0	17.6	13.6	6.8	8.7
NPV	4,805	5,886	7,204	8,769	10,602	12,720	15,119	17,.762	20,547	23,304	25,719
Pay Back Time	0.41	1.59	1.76	1.82	2.64	3.62	3.35	2.44	3.74	5.59	8.07

YEAR	27	28	29	30
IRR	7.3	6.4	5.9	5.2
NPV	30,486.8	27,134.5	25,472.8	25,472.8
Pay Back Time	7.26	3.58	3.78	3.58

IRR- investment return rate NPV – net present value

Though it is very hard to predict the day of an end-of-life failure, it is possible to make diagnostic assessments so as to have more available data to assist determining how potentially close that day can be. Then, the costs involved in each possible solution to the problem can be calculated. The final decision will depend not only on economic aspects, but also on technical and strategic ones.

In the past few years we have adopted our own approach to assist utilities to live with service-aged power transformers, while increasing their service reliability, and having a better invest return from these pieces of equipment.

Typically transformers should have their loading reliability assessed before making decisions which loading limit values should be imposed on them. A loading reliability assessment involves initially the diagnostics of both the Kraft paper and oil aging condition and its long-term impact on the useful life in view of the loading pattern of the unit. An economic study, like the one presented in the paper, is also conducted to determine the benefits of typical preventive maintenance procedures like oil reclamation, winding drying-out, oil preservation system maintenance, etc.

Based on the results of the loading reliability assessment, it is possible to replace an old transformer before a catastrophic failure occurs. The replacement can be programmed in order to reduce the costs and technical disadvantages of a contingency due to a transformer failure. Also, the decision to scrap an old transformer can be based on economic criteria. In other words, a transformer considered to be not so old by technical criteria could be taken out of service if the costs associated with its failure would justify to replace it by a more reliable unit. In case there were no other facilities where to install such an old transformer on the system, it could be scrapped.

Among the more important characteristics of the proposals discussed here, there is the possibility to help different working groups within the company structure, such as power system planning, operations, maintenance, asset management, construction, specification & procurement, etc., to work synergistically and more effectively to improve power quality, while reducing maintenance costs and optimizing the return rates of investments on the power system expansion.

In accord with an Electrical World article, an estimated 65% of all power transformers in North America are more than 25 years old[4]. This means that a considerable amount of transformers in service can be beyond their depreciation period of time (e.g., 30 years). In cases like these, it important to try to determine which are the more reliable units for their present normal and possible contingency loading patterns. It should also be established the amount of money required to bring and/or to keep them reliably for their present and future loading patterns. It is probable that a compromise will have to be sought between the amount of money to be spent on maintenance versus the load to be carried by the unit.

The critical aspects involved in the analysis of the reliability of service-aged power transformers are related with which tests and limit criteria must be used to prioritize the maintenance dollars available. We have dedicated time and efforts in conducting joint studies with utility personnel in assessing their database both for oil and Kraft paper test results, in performing new types of paper and oil testing, and in making economic assessments of the several technical solutions to the problems found in order to improve the maintenance prioritization process.

New transformers and those still in their early years should have their load increase estimated over the time under different scenarios in order to obtain a better investment return ratio by trying the best to use their technical service life fully within its depreciation period of time. The scenarios have to include not only different load growth rates, but also different levels of both oil and paper degradation. Based on these results it is possible to track the insulation system degradation, and the remaining service life associated with the load evolution. Then, strategic decisions can be made based on economic criteria. For example, to spend more maintenance dollars when the pay-back time is adequate or to add an additional transformer at an existing substation.

Conclusion

A proposal for an assessment of transformer reliability for loading to be conducted in conjunction with an economic study was presented. Real examples showed the importance of assessing maintenance data to make better use of maintenance dollars, as well as the technical and economic advantages to replace a rubber bag oil preservation system of an 18,750 kVA transformer for a plastic bladder filled with nitrogen gas at atmospheric pressure.

Strategic issues involving asset management aspects referring to the operation, maintenance, life assessment and economics of power transformers have to be analyzed all together. Consequently, transformers should have their loading reliability assessed before making decisions which loading limit values should be imposed on them. In the case of service-aged transformers, their database both for oil and Kraft paper test results should be evaluated while making economic assessments of the several technical solutions to the problems found in order to improve the maintenance prioritization process. New transformers and those still in their early years should have their load increase estimated over the time under different scenarios in order to obtain a better investment return ratio by trying the best to use their technical service life fully within its depreciation period of time.

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Biographies

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