Investigating cost-benefit analysis for digital distribution transformers – Part II

ABSTRACT

Installation of the monitoring system or adding digital features to the distribution transformer fleet may seem like an unnecessary cost. Still, if it is appropriately conducted, it can be very beneficial in terms of the transformer's operation and cost reduction when looking at the transformer lifetime scale. This second part of the article focuses on the economic calculations to demonstrate how digitalization is cost beneficial and how it can extend the transformer's lifetime. Sustainable transformer ratings are introduced.

KEYWORDS:

cost analysis, digitalization, distribution transformers, monitoring systems, savings

IV. Economic Parameter Calculations

A. Annual costs reduction benefits

There are three distinct regions in a transformer failure bathtub curve (Fig. 8):

1. Infant mortality: indicated by a high failure rate in the first few years after manufacture, which decreases over time. These failures are generally attributed to inherent design defects or manufacturing errors.

2. Random failures: indicated by a flat region (constant failure rate) over the age range in the middle of the expected design life, where random failures are expected throughout the population.

> **Digitalization of the distribution transformers is beneficial in terms of transformer operation and long term cost reduction, although it is reluctantly adopted by users due to initial costs**

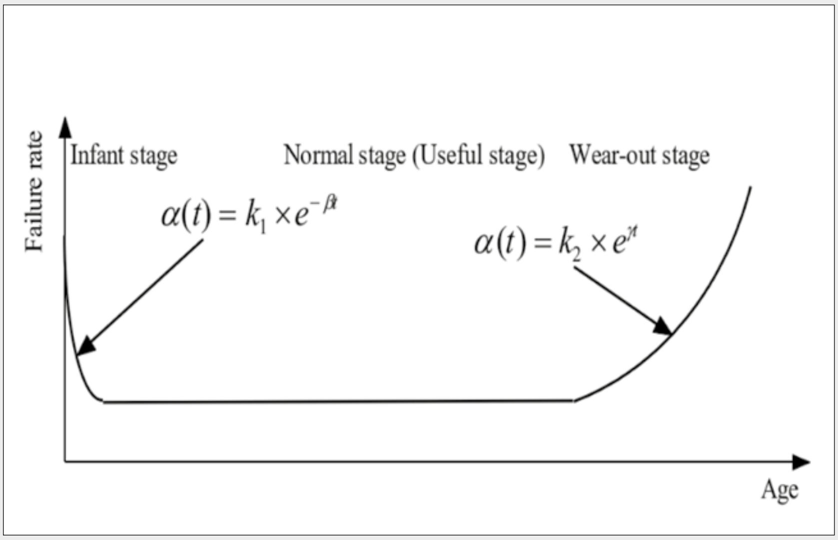

Figure 8. A usual transformer failure curve

Table 6. Typical failure rates of transformers

Failure rate	Inference
0 %–1 %	very good
1 %–2 %	good
2 %–3 %	marginal
3 %–4 %	poor
4 %–5 %	very poor
> 5 %	unacceptable

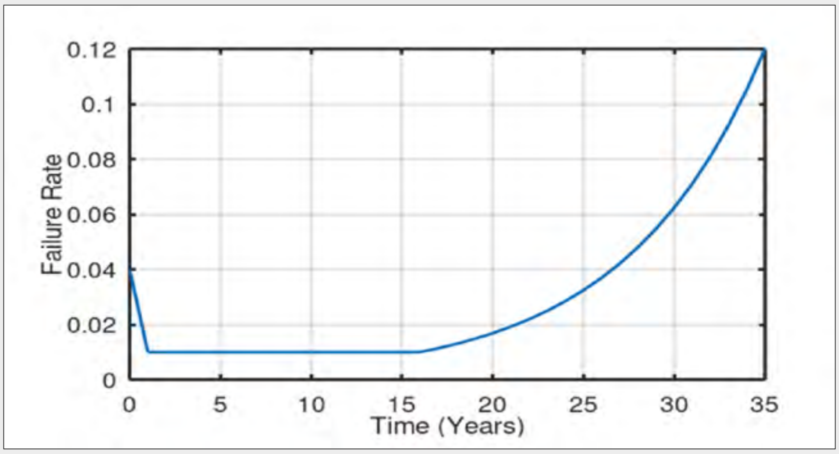

Figure 9. Industrial transformer failure curve [5].

Table 7. Failure rates for industrial transformers

Period	Failure rate
Infant stage	1st year, λ = 2 % (average)
Normal stage	2nd to 16th year, λ = 1 %
Wear out stage	17th year, λ = 1.06 %
Wear out stage	18th year, λ = 1.34 %
Wear out stage	19th year, λ = 1.55 %
Wear out stage	20th year, λ = 1.66 %
Wear out stage	21st year, λ = 1.92 %
Wear out stage	22nd year, λ = 2.36 %
Wear out stage	23rd year, λ = 2.64 %
Wear out stage	24th year, λ = 2.88 %
Wear out stage	25th year, λ = 3.29 %
Wear out stage	26th year, λ = 3.65 %
Wear out stage	27th year, λ = 4.17 %
Wear out stage	28th year, λ = 4.72 %
Wear out stage	29th year, λ = 4.88%
Wear out stage	30th year, λ = 6.35 %

The “normal life” stage for industrial transformers is around 16 years, after which the failure rate starts to increase, and it can reach 12 % at the end of life of 35 years

3. Wear-out: indicated by an increasing failure rate with an increase in age. This region has the highest failure rate. This area is related to wear-out and it is the area of the highest interest in this study.

Transformers are normally retired if the failure rate is assumed to be higher than the acceptable failure level. A typical classification can be as shown in Table 6.

The “normal life” stage for industrial transformers is around 16 years [5], after which

Table 8. Improvements made by digitalization in annual costs

Period	Failure rate	Total annual costs (non-digital)	Total annual costs (digital)	Annual benefit
Infant stage	1st year, λ = 2 %	$2,455	$1,254	$1,201
Normal stage	2nd to 16th year, λ = 1 %	$1,227	$627	$600
Wear out stage	17th year, λ = 1.06 %	$1,301	$665	$636
Wear out stage	18th year, λ = 1.34 %	$1,645	$840	$805
Wear out stage	19th year, λ = 1.55 %	$1,903	$972	$931
Wear out stage	20th year, λ = 1.66 %	$2,038	$1,041	$997
Wear out stage	21st year, λ = 1.92 %	$2,357	$1,204	$1,153
Wear out stage	22nd year, λ = 2.36 %	$2,897	$1,480	$1,417
Wear out stage	23rd year, λ = 2.64 %	$3,241	$1,655	$1,586
Wear out stage	24th year, λ = 2.88 %	$3,536	$1,806	$1,730
Wear out stage	25th year, λ = 3.29 %	$4,039	$2,063	$1,976
Wear out stage	26th year, λ = 3.65 %	$4,481	$2,289	$2,192
Wear out stage	27th year, λ = 4.17 %	$5,120	$2,616	$2,504
Wear out stage	28th year, λ = 4.72 %	$5,795	$2,960	$2,835
Wear out stage	29th year, λ = 4.88 %	$5,991	$3,060	$2,931
Wear out stage	30th year, λ = 6.35 %	$7,796	$3,983	$3,813

the failure rate starts to increase, as shown in Fig. 9. Typical failure rates are extracted as listed in Table 7 with failure rate = 12 % at 35 years [5]. Although this refers to power transformer, due to lack of data for distribution transformer failure curve the same has been used here.

The annual benefit is calculated by considering the failure rates from Table 7 and calculations illustrated in Section III.

The economic parameters (NPV, IRR and Payback) can now be calculated as listed in Table 9.

Table 9. Economic parameters calculation using (annual cost reduction)

Year	Cost reduction	Net income	Cost of monitoring	Cash flow	PV	Cumulative cash flow
0	$0	$0	($6,000)	($6,000)	$6,000	$6,000
1	$1,201	$1,201	$0	$1,201	$1,133	$4,867
2	$600	$600	$0	$600	$534	$4,333
3	$600	$600	$0	$600	$504	$3,829
4	$600	$600	$0	$600	$475	$3,354
5	$600	$600	$0	$600	$448	$2,906
6	$600	$600	$0	$600	$423	$2,483
7	$600	$600	$0	$600	$399	$2,084
8	$600	$600	$0	$600	$376	$1,707
9	$600	$600	$0	$600	$355	$1,352
10	$600	$600	$0	$600	$335	$1,017
11	$600	$600	$0	$600	$316	$701
12	$600	$600	$0	$600	$298	$403
13	$600	$600	$0	$600	$281	$121
14	$600	$600	$0	$600	$265	($144)
15	$600	$600	$0	$600	$250	($394)
16	$600	$600	$0	$600	$236	($631)
17	$636	$636	$0	$636	$236	($867)
18	$805	$805	$0	$805	$282	($1,149)
19	$931	$931	$0	$931	$308	($1,456)
20	$997	$997	$0	$997	$311	($1,767)
21	$1,153	$1,153	$0	$1,153	$339	($2,106)
22	$1,417	$1,417	$0	$1,417	$393	($2,500)
23	$1,586	$1,586	$0	$1,586	$415	($2,915)
24	$1,730	$1,730	$0	$1,730	$427	($3,342)
25	$1,976	$1,976	$0	$1,976	$460	($3,803)
26	$2,192	$2,192	$0	$2,192	$482	($4,284)
27	$2,504	$2,504	$0	$2,504	$519	($4,804)
28	$2,835	$2,835	$0	$2,835	$555	($5,358)
29	$2,931	$2,931	$0	$2,931	$541	($5,899)
30	$3,813	$3,813	$0	$3,813	$664	($6,563)

Table 10. Improvements made by digital transformers for oil sampling

Year	Normal DGA costs	Extended with DGA
1	$300	$0
2	$300	$0
3	$300	$300
4	$300	$0
5	$300	$0
6	$300	$300
7	$300	$0
8	$300	$0
9	$300	$300
10	$300	$0
11	$300	$0
12	$300	$0
13	$300	$300
14	$300	$0
15	$300	$0
16	$300	$300
17	$300	$0
18	$300	$0
19	$300	$300
20	$300	$0
21	$300	$0
22	$300	$300
23	$300	$0
24	$300	$0
25	$300	$300
26	$300	$300
27	$300	$300
28	$300	$300
29	$300	$300
30	$300	$300
Total	$9,000	$3,900
Savings (30 years)		$5,100
Savings/year		$170

The payback calculations for a digital transformer considering only the benefit due to annual cost reduction and the results are IRR = 12.51 %, NPV = $6,192 with a payback period less than 14 years

Table 9 lists the payback calculations for a digital transformer considering only the benefit due to annual cost reduction. The results are as follows:

- IRR = 12.51 %
- NPV = $6,192
- Payback period is less than 14 years.

B. Oil sampling reduction benefits

As part of the routine oil sampling maintenance procedure, oil is sampled once every year. The annual cost of oil sampling is $300 per sample. With digital transformers, manual oil sampling can be extended to once in 3 years on average. Table 10 lists the annual benefit earned by extending the manual oil sampling.

Table 11 lists the payback calculations for a digital transformer considering benefit due to annual costs reduction and reduced oil sampling. The results are as follows:

- IRR = 15.13 %
- NPV = $ 8,399
- Payback period is less than 10 years.

Improvements in all three parameters can be easily observed.

C. Life extension benefits – later replacement of transformer

As stated previously, transformers are normally retired if the calculated failure rate is higher than the acceptable failure level, i.e., λ = 3 % in this case.

Under the failure rate curve for non-digital transformers (Fig. 10), the acceptable age is close to 25 years, whereas for a digital transformer with 50 % efficiency, this age is around 30 years, which means a 5-year life extension is applicable.

Payback calculations for a digital transformer considering benefit due to annual costs reduction and reduced oil sampling show better results – IRR = 15.13 %, NPV = $8,399 with a payback period less than 10 years

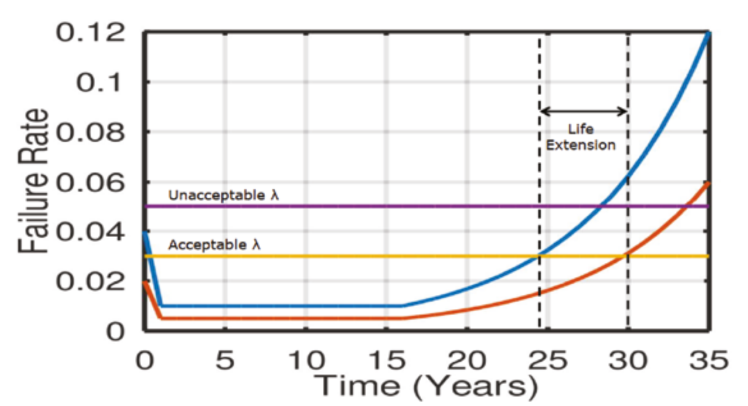

Figure 10. Life extension due to digital transformers

> **Since the failure rate of non-digital transformers are higher compared to digital transformers, a 5-year life extension can be expected**

Table 11: Economic parameters calculation using (failure reduction + oil sampling reduction)

Year	Failure benefit	Oil sampling	Net income	Cost of monitoring	Cash flow	PV	Cumulative cash flow
0	$0	$0	$0	($6,000)	($6,000)	$6,000	$6,000
1	$1,201	$170	$1,371	$0	$1,371	$1,293	$4,707
2	$600	$170	$770	$0	$770	$685	$4,021
3	$600	$170	$770	$0	$770	$647	$3,375
4	$600	$170	$770	$0	$770	$610	$2,765
5	$600	$170	$770	$0	$770	$575	$2,189
6	$600	$170	$770	$0	$770	$543	$1,647
7	$600	$170	$770	$0	$770	$512	$1,135
8	$600	$170	$770	$0	$770	$483	$651
9	$600	$170	$770	$0	$770	$456	$196
10	$600	$170	$770	$0	$770	$430	($234)
11	$600	$170	$770	$0	$770	$406	($640)
12	$600	$170	$770	$0	$770	$383	($1,023)
13	$600	$170	$770	$0	$770	$361	($1,384)
14	$600	$170	$770	$0	$770	$341	($1,724)
15	$600	$170	$770	$0	$770	$321	($2,045)
16	$600	$170	$770	$0	$770	$303	($2,349)
17	$636	$170	$806	$0	$806	$299	($2,648)
18	$805	$170	$975	$0	$975	$342	($2,989)
19	$931	$170	$1,101	$0	$1,101	$364	($3,353)
20	$997	$170	$1,167	$0	$1,167	$364	($3,717)
21	$1,153	$170	$1,323	$0	$1,323	$389	($4,106)
22	$1,417	$170	$1,587	$0	$1,587	$440	($4,547)
23	$1,586	$170	$1,756	$0	$1,756	$460	($5,006)
24	$1,730	$170	$1,900	$0	$1,900	$469	($5,476)
25	$1,976	$170	$2,146	$0	$2,146	$500	($5,976)
26	$2,192	$170	$2,362	$0	$2,362	$519	($6,495)
27	$2,504	$170	$2,674	$0	$2,674	$555	($7,049)
28	$2,835	$170	$3,005	$0	$3,005	$588	($7,637)
29	$2,931	$170	$3,101	$0	$3,101	$572	($8,210)
30	$3,813	$170	$3,983	$0	$3,983	$693	($8,903)

Table 12. Benefits due to later replacement of transformers

Age	Extension	End balance	Annual benefit
25	0	$40,000	
26	1	$40,800	$800
27	2	$41,616	$816
28	3	$42,448	$832
29	4	$43,297	$849
30	5	$44,163	$866

The life extension benefit can be evaluated as:

- For a 2 MVA non-digital transformer, the approximate cost is around $40,000.
- Current bank interest rate = 2 %
- Instead of replacing at the end of 25 years, the transformer will be replaced at the end of 30 years.

Table 13 lists the payback calculations for a digital transformer considering annual costs reduction, reduced oil sampling and later replacement benefit. The results are as follows:

- IRR = 15.317 %
- NPV = $9,168
- Payback period is less than 10 years.

D. Life extension benefits - increase in book value of transformer

An increase in book value can be calculated as [6]

$$= \frac{\text{Extended years}}{\text{Original years}} \times \text{Cost of transformer}$$

$$= \frac{5}{29} \times \$40{,}000 = \$6{,}897$$

(see Fig. 10)

Annual increase in book value = 6,897 / 30 = $230.

Table 13. Economic parameters calculation using (failure reduction + oil sampling reduction + later replacement)

Year	Failure benefit	Oil sampling	Later replacement	Net income	Cost of monitoring	Cash flow	PV	Cumulative cash flow
0	$0	$0	$0	$0	($6,000)	($6,000)	$6,000	$6,000
1	$1,201	$170	$0	$1,371	$0	$1,371	$1,293	$4,707
2	$600	$170	$0	$770	$0	$770	$685	$4,021
3	$600	$170	$0	$770	$0	$770	$647	$3,375
4	$600	$170	$0	$770	$0	$770	$610	$2,765
5	$600	$170	$0	$770	$0	$770	$575	$2,189
6	$600	$170	$0	$770	$0	$770	$543	$1,647
7	$600	$170	$0	$770	$0	$770	$512	$1,135
8	$600	$170	$0	$770	$0	$770	$483	$651
9	$600	$170	$0	$770	$0	$770	$456	$196
10	$600	$170	$0	$770	$0	$770	$430	($234)
11	$600	$170	$0	$770	$0	$770	$406	($640)
12	$600	$170	$0	$770	$0	$770	$383	($1,023)
13	$600	$170	$0	$770	$0	$770	$361	($1,384)
14	$600	$170	$0	$770	$0	$770	$341	($1,724)
15	$600	$170	$0	$770	$0	$770	$321	($2,045)
16	$600	$170	$0	$770	$0	$770	$303	($2,349)
17	$636	$170	$0	$806	$0	$806	$299	($2,648)
18	$805	$170	$0	$975	$0	$975	$342	($2,989)
19	$931	$170	$0	$1,101	$0	$1,101	$364	($3,353)
20	$997	$170	$0	$1,167	$0	$1,167	$364	($3,717)
21	$1,153	$170	$0	$1,323	$0	$1,323	$389	($4,106)
22	$1,417	$170	$0	$1,587	$0	$1,587	$440	($4,547)
23	$1,586	$170	$0	$1,756	$0	$1,756	$460	($5,006)
24	$1,730	$170	$0	$1,900	$0	$1,900	$469	($5,476)
25	$1,976	$170	$0	$2,146	$0	$2,146	$500	($5,976)
26	$2,192	$170	$800	$3,162	$0	$3,162	$695	($6,671)
27	$2,504	$170	$816	$3,490	$0	$3,490	$724	($7,395)
28	$2,835	$170	$832	$3,837	$0	$3,837	$751	($8,145)
29	$2,931	$170	$849	$3,950	$0	$3,950	$729	($8,874)
30	$3,813	$170	$866	$4,849	$0	$4,849	$844	($9,718)

Table 14. Economic parameters calculation using (failure reduction + oil sampling reduction + later replacement + book value)

Year	Failure benefit	Oil sampling	Later replacement	Book value	Net income	Cost of monitoring	Cash flow	PV	Cumulative cash flow
0	$0	$0	$0	$0	$0	($6,000)	($6,000)	$6,000	$6,000
1	$1,201	$170	$0	$230	$1,601	$0	$1,601	$1,510	$4,490
2	$600	$170	$0	$230	$1,000	$0	$1,000	$890	$3,600
3	$600	$170	$0	$230	$1,000	$0	$1,000	$840	$2,760
4	$600	$170	$0	$230	$1,000	$0	$1,000	$792	$1,968
5	$600	$170	$0	$230	$1,000	$0	$1,000	$747	$1,221
6	$600	$170	$0	$230	$1,000	$0	$1,000	$705	$516
7	$600	$170	$0	$230	$1,000	$0	$1,000	$665	($149)
8	$600	$170	$0	$230	$1,000	$0	$1,000	$627	($777)
9	$600	$170	$0	$230	$1,000	$0	$1,000	$592	($1,369)
10	$600	$170	$0	$230	$1,000	$0	$1,000	$558	($1,927)
11	$600	$170	$0	$230	$1,000	$0	$1,000	$527	($2,454)
12	$600	$170	$0	$230	$1,000	$0	$1,000	$497	($2,951)
13	$600	$170	$0	$230	$1,000	$0	$1,000	$469	($3,420)
14	$600	$170	$0	$230	$1,000	$0	$1,000	$442	($3,862)
15	$600	$170	$0	$230	$1,000	$0	$1,000	$417	($4,279)
16	$600	$170	$0	$230	$1,000	$0	$1,000	$394	($4,673)
17	$636	$170	$0	$230	$1,036	$0	$1,036	$385	($5,058)
18	$805	$170	$0	$230	$1,205	$0	$1,205	$422	($5,480)
19	$931	$170	$0	$230	$1,331	$0	$1,331	$440	($5,920)
20	$997	$170	$0	$230	$1,397	$0	$1,397	$436	($6,355)
21	$1,153	$170	$0	$230	$1,553	$0	$1,553	$457	($6,812)
22	$1,417	$170	$0	$230	$1,817	$0	$1,817	$504	($7,316)
23	$1,586	$170	$0	$230	$1,986	$0	$1,986	$520	($7,836)
24	$1,730	$170	$0	$230	$2,130	$0	$2,130	$526	($8,362)
25	$1,976	$170	$0	$230	$2,376	$0	$2,376	$554	($8,916)
26	$2,192	$170	$800	$230	$3,392	$0	$3,392	$746	($9,662)
27	$2,504	$170	$816	$230	$3,720	$0	$3,720	$771	($10,433)
28	$2,835	$170	$832	$230	$4,067	$0	$4,067	$796	($11,229)
29	$2,931	$170	$849	$230	$4,180	$0	$4,180	$771	($12,000)
30	$3,813	$170	$866	$230	$5,079	$0	$5,079	$884	($12,884)

Table 14 lists the payback calculations for a digital transformer considering annual costs reduction, reduced oil sampling, later replacement benefit and increase in book value. The results are as follows:

- IRR = 18.93 %
- NPV = $12,155
- Payback period is less than 7 years.

This analysis assumes a spare transformer is available and can be replaced in 8 hours. Also, this case study is based on a business branch where the loss of power supply leads directly to a considerable profit loss. As profit loss is different for each customer, we need to evaluate each scenario differently. However, there are common tangible outcomes–such as reduction in failure rate, oil sampling reduction, life extension, increasing book values, improved loading, improved NPV, among others, which are common to different scenarios.

A similar analysis under the N-1 redundancy criteria needs to be evaluated. It is typically assumed under N-1, there is usually no loss of supply, hence no profit loss. However, there are several instances when common cause failures (CCF) have been ignored, resulting in power loss even under N-1 criteria. This will be the subject of another article.

> **This case study is based on a business branch where the loss of power supply leads directly to a considerable profit loss**

E. Improved loading of the transformer

In general, transformer sizing is performed based on two methods:

- Connected load – where all the loads connected to the transformer are assumed to be operating at full load, i.e., operation without any demand or diversity.
- Operating load - where all the loads connected to the transformer are assumed to be operating at actual loading of the loads, i.e., operation with demand and diversity.
- In both cases, 20 % to 30 % reserve capacity is added for future growth.
- Selecting the next best standard available unit.
- This typically results in a unit selection that is operating anywhere between 40–50 % of its full capacity.

This approach has historically served the end customers well, and as such, majority of distribution transformers were unmonitored, i.e., non-digital. Loading at 50 % lowers the temperature, and as such, the residual life of the paper insulation may reach beyond 30–40 years of the expected life.

On the other hand, a digital transformer allows for the maximum load possible, based on real-time measured transformer temperatures, condition, and load. Instead of "flying blind", the digital distribution transformer provides timely and accurate information about the real thermal limit at any point in time. Thermal analysis, load analysis and ageing analysis of the transformer provide this vital information to the customer. The improvement in loading characteristic without compromising on the paper life dramatically improves the value proposition for digital transformers. The benefit can be quantified as follows for a 10 % improvement in loading capability–let us consider the following transformer characteristics:

kVA	No-load loss, watts	Load loss, watts
2,000	1,760	17,000

The following efficiency curve is obtained for this design:

Figure 11. Efficiency vs loading curve for 2 MVA transformer (NLL = 1.76 kW, LL = 17 kW)

Table 15. Transformer characteristics for TCO evaluation

Transformer rating	MVA	2
No-load loss	kW	1.76
Load loss	kW	17
Rated top oil temperature rise	K	60
Ambient temperature	°C	40
Oil temperature exponent		0.8
Winding exponent		1.6
Hot spot factor		1.1
Gradient	K	15

Table 16. Hot spot temperature and the ageing rate at different loading

Load %	Hot spot temperature (°C)	Ageing rate	Expected transformer life*
50 %	69.6	0.038	395 years
60 %	77.3	0.091	136 years

*Under "free from air" and 0.5 % moisture values

Table 17. Loss evaluation factor for non-digital transformer at 50 % load

Energy cost	0.1	$/kWh
% increase in energy cost every year	6	%
No of years	30	years
Inflation rate	6	%
Loading	0.5	pu
A	12,057.99	$/kW
B	3,014.498	$/ kW

Table 18. Loss evaluation factor for the digital transformer at 60 % load

Energy cost	0.1	$/kWh
% increase in energy cost every year	6	%
No of years	30	years
Inflation rate	6	%
Loading	0.6	pu
A	12,057.99	$/kW
B	4,340.877	$/kW

> **The concept of digital transformer is to bridge the technical and economic end of transformer life!**

The parameters listed in Table 15 are assumed to calculate the ageing rate and hot spot temperature.

The hot spot temperature and the ageing rate at 50 % and 60 % loading are shown in Table 16.

The typical desired transformer life is 30 years. Hence, even with additional loss of paper life at extra 10 % loading, the technical end of transformer life will be the desired transformer life of 30 years. Thus, the cost attributed to loss of life from improved loading will only be applicable if the loading decreases the life below 30 years, or 50 years as a safety margin, i.e., around 85 °C. After 50 years, the transformer will be anyway replaced due to other factors: the physical end of life or the economic end of life. The concept of digital transformer is to bridge the technical and economic end of transformer life!

A digital transformer comprised of load, temperatures, hydrogen, and moisture sensors; can support the end-user to calculate the maximum safe load the transformer can carry from a thermal perspective.

Considering Total Cost of Ownership (TCO):

$$TCO = C_{pp} + (A \times P_0) + (B \times P_k) + \textit{Commisioning cost} + \textit{Maintenance cost}$$

Since commissioning costs is the same, it is not included in calculation below:

A) Cost of losses for non-digital transformer at 50 % load

TCO for operation at 50 % load of non-digital transformer ($40,000) with A and B parameters calculated in Table 17.

B) Cost of annualized maintenance for non-digital transformer

Maintenance costs vary with the lifetime of the transformer, as the failure rate varies.

From Table 8, the total annual costs for non-digital can be calculated as - $73,000.

C) Cost of fixed DGA for non-digital transformer

Lab DGA costs are fixed (typically) with the lifetime of the transformer unless extreme values are encountered.

From Table 9, the total annual costs for non-digital can be calculated as - $9,000.

$$\text{TCO} = \$40{,}000 + (12{,}057.99 \times 1.76) + (3{,}014.498 \times 17) + (\$73{,}000) + (\$9{,}000)$$

$$\text{TCO}_{\text{(non-digital)}} = \$194{,}468.50$$

D) Cost of losses for digital transformer at 60 % load

TCO for operation at 60 % load of the digital transformer ($46,000) with A and B parameters calculated in Table 18.

E) Cost of annualized maintenance for digital transformer

Maintenance costs vary with the lifetime of the transformer, as the failure rate varies. From Table 8, the total annual costs for digital transformer can be calculated as - $37,293.

F) Cost of fixed DGA for digital transformer

From Table 9, the total annual DGA costs for a digital transformer is $3,900.

G) Cost of field replacement of sensor module at end of 15 years: $5,000

$$\text{TCO} = \$46{,}000 + (12{,}057.99 \times 1.76) + (4{,}340.877 \times 17) + (\$37{,}293) + (\$3{,}900) + (\$5{,}000)$$

$$\text{TCO}_{\text{(digital)}} = \$\ 187{,}209.97$$

> **Even with 10 % higher loading, the cost of operating a digital transformer is lower than a non-digital transformer**

In summary, it can be concluded as shown in Table 19.

Even with 10 % higher loading, the cost of operating a digital transformer is lower than a non-digital transformer. The benefit of specifying a digital distribution transformer with ester fluid will be the subject of another article. Now, let us see the benefits - considering 10 % extra loading for 24 hours in a day for 365 days, continuously.

Table 19: TCO comparison between the digital and non-digital transformer

	TCO (30 years)	Loading
Non-digital 2 MVA	$194,468.50	50 %
Digital 2 MVA	$187,209.97	60 %

Table 20. Income generated from the digital transformer

Non-digital transformer	2 MVA
Power factor	0.9
Transformer real power	1.8 MW
Loading without monitoring	50 %
Energy transferred	0.9 MW
Duration (hours)	8,760
Total load (kWh) in 1 year	7,884 MWh
Value of energy delivered ($/MWh)	$100/MWh
Total value of energy delivered ($)	$788,400
Cost of extra loss of life	$0
Net income per year from a **non-digital transformer**	**$784,400**
Digital transformer	2 MVA
Power factor	0.9
Transformer real power	1.8 MW
Loading with monitoring	60 %
Energy transferred	1.08 MW
Duration (hours)	8,760
Total load (kWh) in 1 year	9,460.8 MWh
Value of energy delivered ($/MWh)	$100/MWh
Total value of energy delivered ($)	$946,080
Cost of extra loss of life	$0
Net income per year from a **digital transformer**	**$946,080**

Table 21. Sustainable transformer rating with digitalization

	Loading	Load	Price	No-load loss and load loss (Watts)
Non-digital 500 kVA	50 %	250 kVA @ 0.9 pf 225 kW	$10,000	510/5,500
Digital 400 kVA	62.5 %	250 kVA @ 0.9 pf 225 kW	$12,000	430/4,600

Table 22. Annualized failure-related costs for sustainable transformer rating with digitalization

Period	Failure rate	Total annual costs (non-digital)	Total annual costs (digital)
Infant stage	1st year, λ = 2 %	$2,188	$1,103
Normal stage	2nd to 16th year, λ = 1 %	$1,094	$551
Wear out stage	17th year, λ = 1.06 %	$1,160	$584
Wear out stage	18th year, λ = 1.34 %	$1,466	$739
Wear out stage	19th year, λ = 1.55 %	$1,696	$855
Wear out stage	20th year, λ = 1.66 %	$1,816	$915
Wear out stage	21st year, λ = 1.92 %	$2,101	$1,059
Wear out stage	22nd year, λ = 2.36 %	$2,582	$1,301
Wear out stage	23rd year, λ = 2.64%	$2,889	$1,456
Wear out stage	24th year, λ = 2.88 %	$3,152	$1,588
Wear out stage	25th year, λ = 3.29 %	$3,600	$1,815
Wear out stage	26th year, λ = 3.65 %	$3,994	$2,013
Wear out stage	27th year, λ = 4.17 %	$4,564	$2,300
Wear out stage	28th year, λ = 4.72 %	$5,165	$2,603
Wear out stage	29th year, λ = 4.88 %	$5,341	$2,692
Wear out stage	30th year, λ = 6.35 %	$6,949	$3,503
	Total (1st to 30th year)	$65,073	$32,791

The net benefit of using the digital transformer rated at 2 MVA is $157,680 per year, but it will vary depending on the usage of the transformer

The net benefit of using the digital transformer per year is $157,680. The net benefit will vary depending on the usage of the transformer. However, with optimal loading capability, the benefit of extra income will always aid in the payback of the upfront costs. In the above scenario, the payback is in less than 1 year.

E. Sustainable transformer ratings

Another benefit of digital distribution transformer is illustrated here – sustainable transformer rating. In this scenario, it is investigated if a 400 kVA transformer is delivering the same load as 500 kVA, is it worth digitalizing or not? Characteristics shown in Table 21 are assumed.

Keeping the failure costs the same as the previous example and updating the purchase price, the total annual costs can be calculated as in Table 22.

The TCO factors can be calculated as in Table 23.

Keeping the same DGA requirements as in the previous cases and an extra $5,000 for mid-life sensor replacement, the following can be computed as shown in Table 24.

Purchasing a smaller digital transformer and using real-time thermal loading will reduce the total cost of operation while delivering the same load. Digital transformers help in the life extension of the transformer, thus additionally having an NPV saving due to later replacement. It will also help in reducing the carbon footprint due to fewer construction materials and less transformer oil. Assuming for distribution transformer oil / kVA ratio is around 0.9 liters / MVA, i.e., for 500 kVA = 450 liters of oil and for 400 kVA = 360 liters of oil, which means we are saving close to 90 liters of mineral oil = 170 kg of CO_2. Imagine buying 100 x sustainable transformers = 17 tons of CO_2 reduction during mineral oil production!

Conclusions

Monitoring for distribution transformers is still not widely accepted, the common notion being that these transformers can be easily stocked and replaced upon failure. Hence, there is no additional benefit which monitoring will bring. This strategy is suitable in the traditional power net-

Table 23. Loss evaluation factors for sustainable transformer rating with digitalization

	500 kVA	400 kVA	Units
Energy cost	0.1	0.1	$/kWh
% increase in energy cost every year	6	6	%
No of years	30	30	years
Inflation rate	6	6	%
Loading	0.5	0.625	pu
A	12,057.99	12,057.99	$/kW
B	3,014.498	4,710.153	$/kW

work with unidirectional power flow. Due to the changing dynamics and increasing complexity of today's electricity grid, the need for monitoring to prevent loss of revenue is very important. Even for industrial applications, with the proliferation of variable speed drives and other power electronic-based machines, the need for self-monitored transformers is evident.

In a sustainable transformer rating scenario, it is investigated if it is worth digitalizing a 400 kVA transformer, which is delivering the same load as 500 kVA

Many end users are yet to adopt digitalization at the distribution transformer level simply because of the extra upfront price, i.e., the additional price of monitoring. This is particularly true when agents or electrical contractors make purchase decisions based on the low first cost for commercial and industrial end-users. A digital distribution transformer can significantly reduce the capital upfront cost as it will allow the transformer to operate with the maximum load possible, based on real-time measured transformer temperatures and conditions. Instead of "flying blind" when operating close to the limits, the digital distribution transformer provides timely and accurate information about the real thermal limit at any point in time. However, if a thorough economic investigation based on the total cost of ownership / operation is carried out, it shows that it is economically beneficial to pay for the upfront investment.

As new technologies continued to be developed and the more push towards a decarbonized grid, the optimization of transformer utilization is apparent. The only way this optimized utilization can be achieved is by increased use of data and information, which a digital distribution transformer provides. This data can be used effectively by utilities, industries, and other businesses to manage their networks and plants.

It is imperative that each sensor used in the digital distribution transformer has an MTBF (mean time between failure) greater than 15 years to ensure one mid-life field replacement. The sensor module must be designed in such a way that, without draining the oil of the transformer, field replacement can be done. Also, for oil type, the service time required should be less than 2 hours of interruption, and for dry type, this should be less than 1 hour of interruption.

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Table 24. TCO comparison with sustainable transformer rating with digitalization

	TCO (30 years)	Loading
Non-digital 500 kVA	$10,000 + (12,057.99 x 0.51) + (3,014.498 x 5.5) + $65,073 + $9,000 = **$106,950**	50 %
Digital 400 kVA	$12,000 + (12,057.99 x 0.43) + (4,710.153 x 4.6) + $32,791 + $3,900 +$5,000 = **$80,542**	62.5 %

> **A digital distribution transformer can significantly reduce the capital upfront cost as it will allow the transformer to operate with the maximum load possible, based on real-time measured transformer temperatures and conditions**

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Author

Bhaba P. Das is the Lead Digital Business Developer for Transformers Business Line, HUB (Asia-Pacific, Middle East and Africa), Hitachi ABB Power Grids, based in Singapore. He is part of the Application Engineering Team and spearheads the digital transformation efforts of transformers in the Asia Pacific, Middle East and Africa region. Prior to Hitachi ABB Power Grids, he worked as the R&D engineer for ETEL Transformers Ltd in New Zealand. He was awarded the Young Engineer of the Year 2017 by the Electricity Engineers Association of New Zealand for his work on the design and development of smart distribution transformers, fibre optics-based sensors for transformers, and diagnostic software for fleet condition monitoring. He is a Senior Member of IEEE and Young Professional of IEC. He completed his PhD in Electrical Engineering from the University of Canterbury, New Zealand.