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

ABSTRACT

Monitoring for distribution transformers is still not widely accepted, the common notion being that these transformers can be easily stocked and replaced upon failure. Although data-driven transformer asset management advantages are recognized, many end users are reluctant to adopt, simply because of the extra upfront price. This article brings many case studies that show that digitalization is cost-effective and lead to savings. Sustainability is also addressed in part II of the article since the digitalized transformers can be utilized in a more efficient way.

KEYWORDS:

asset management, digital transformers, distribution transformers, economics, sustainability

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I. Introduction

Due to the changing dynamics and increasing complexity of today's electricity grid, the need for dynamic asset management strategies is very evident, especially for distribution transformers. However, asset management strategies have not evolved accordingly and still rely on the same time-based maintenance strategies that have been used for decades. Others have relied on N-1 contingency or maintaining surplus stock.

Sometimes, these strategies are insufficient for today's needs and lead to uninformed investments and operational decision by businesses. An example of such a strategy is transformer sizing in residential applications. This selection is based on a number of assumptions and the fact that distribution transformers can be easily stocked and replaced when the failure occurs. One such assumption is to provide an average load based on home size, while a second assumption involves sizing the transformer based on a peak period (e.g., few hours). An unofficial policy adopted by many is to install a higher rated transformer than necessary and rely on the fact that most transformers see only around 40-50 % of its rated load. Based on this, end-users have enjoyed very long lives from transformers that have only been loaded heavily at times of peak load and high temperatures. However, there is a growing concern that such transformers may become overloaded than when they were originally planned due to new types of load, such as electric vehicles [1], and the question is – how much higher sized transformer would be appropriate?

Over time, these simple decisions become more expensive to correct. Thus, increasing the risk of unplanned outages and resulting losses. This challenge is more serious for transformers in mission-critical applications or large loading variability as seen in the chemical, oil and gas, renewables, semi-conductor, data centres, and marine and mining industries. Without the right kind of data, only a small percentage of transformer issues can be proactively addressed. Availability of accurate and timely data about a transformer's performance helps in making informed operations and maintenance decisions that not only help in avoiding unplanned downtime but also increase the return on investment in transformers.

While it is becoming very common for power transformers to be monitored in real-time, monitoring for distribution transformers are rare. This can be typically attributed to:

- Distribution transformers are far less costly than a power transformer.
- End-users often maintain standard stock and swap distribution transformers in case of failures.
- Majority distribution transformers are scrapped without attempts to repair.
- Cost of installation usually exceeds the cost of the transformer when the transformer fails.

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front price, i.e., the additional price of monitoring. This is typically true when the purchases of the transformer are only based on the initial cost (without any consideration of long-term economics), agents / contractors would choose the lowest price. Agents or contractors may have little incentive to take into consideration any economic factors other than the transformer's first cost. End-user concerns about higher first costs discourage original equipment manufacturers (OEMs) and contractors from offering or recommending the more expensive monitoring options to the customer who does not specifically request them.

In this article, a scenario is evaluated to calculate the financial implications if 2 MVA transformers were to fail. Under this scenario, is it economically justified to have digital distribution transformers? What economic benefits will digital distribution transformers bring to the table? The comparisons for different scenarios are carried out using the following initial upfront extra cost:

- 2 MVA, non-digital ($40,000)
- 2 MVA, digital ($46,000)

For any commercial person, when comparing different options and decide which one to invest in, there are generally three options available: internal rate of return (IRR), payback period, and net present value (NPV). Three parameters are:

- NPV is the value of all future cash flows (positive and negative) over the entire life of an investment discounted to the present.
- IRR is the discount rate that makes the NPV = 0. This equates to the expected compound annual rate of return that will be earned by going for digitalization.
- The payback period is the time taken to recover the cost of an investment in the digital transformer.

These three parameters are evaluated under different benefit categories earned by digital distribution transformers.

II. What is a digital distribution transformer?

The distribution transformer is a very important link of the power distribution system, without which the utility would not be able to supply electricity to consumers, or industries would not be able to cater production. In the event of the failure of distribution transformers, apart from the loss of capital / production, consumers suffer due to inconvenience caused by the interruption of power supply which is an integral part of our lives. Though failure of a distribution transformer is simpler when compared to the power transformer, there is a chain of adverse effects – manufacturer, investigations, sometimes government penalties.

In [2], the failure rate of distribution transformers in India is reported to be at 12-17 % as compared to the global average of 1-2 %. To bring this into perspective, if a small utility has 10,000 distribution transformers globally, the repair / replacement would be done for around 200 transformers each year, while for India, it will be 1,700 transformers. Apart from the money spent in repairing / replacing, the loss becomes enormous if the loss for revenue due to outage is also taken into consideration. So, it is of paramount importance that these unplanned outages are avoided. Similar statistics can be checked for different countries as well. A reported Australian utility which operates around 150,000 distribution transformers, 2018 spent AU$60 M on replacement and AU$3 M on maintenance [3].

There are a lot of different causes of failure of distribution transformers worldwide – the sources can be broadly divided into 5 categories as listed in Table 1:

Table 1. Typical failure causes for distribution transformers

External	End-user	Manufacturer	Procurement	Ageing
1. Unauthorized tapping 2. Arson, vandalism 3. Oil leaks 4. LV system faults 5. Weather: lightning strike, storm, extreme ambient, etc. 6. External short circuit: cables connected 7. Animals 8. Vegetation 9. Ground tilting	1. Improper pre-check and installation 2. Improper terminations 3. Faulty earth connections 4. Bypassing of protection systems 5. Protection malfunction 6. Inadequate maintenance 7. Prolonged overloading or unbalancing	1. Faulty design 2. Quality of raw material 3. Poor workmanship 4. Improper manufacturing process 5. Improper transportation 6. Underrated connectors	1. Improper technical specifications 2. Improper inspection process 3. Choice of lowest price first before proper evaluation	1. Insulation property deterioration 2. Moisture ingress 3. Natural wear out

Despite the wide range of causes, there are some common parameters that would indicate early warning signals from the transformer, which would enable the end-user to take corrective actions. These would include thermal, electrical, mechanical, and chemical categories as listed in Table 2:

The global average failure rate of distribution transformers is 1-2 %, which means, if a small utility has 10,000 distribution transformers, the repair/replacement would need to be done for around 200 transformers each year

Table 2. Early warning categories for distribution transformer warnings

		Early warnings	Thermal	Electrical	Mechanical	Chemical
Main Tank	Mechanical faults	Short circuit	✓	✓	✓	✓
		Winding displacement	✓		✓	✓
		Winding loose	✓		✓	✓
	Electrical faults	Partial discharge		✓		✓
		Overvoltage	✓	✓		✓
		Arcing	✓	✓		✓
	Thermal faults	Cooling	✓			✓
		Insulation ageing				✓
		Overloading	✓	✓		✓
		Overheating	✓			✓
Accessories		Cooling system	✓		✓	✓
	If applicable	Bushings	✓	✓	✓	✓
	If applicable	Tap changers	✓	✓	✓	✓
	If applicable	Oil Preservation systems	✓			✓

Based on the above Table 2, the typical parameters to be monitored in a distribution transformer include (Table 3):

Table 3: Main parameters for distribution transformer monitoring

Sl. no	Main parameters	Early warning category
1.	Temperature	Thermal, chemical, mechanical
2.	Moisture	Chemical
3.	Tank pressure	Mechanical
4.	Hydrogen	Chemical, electrical
5.	Oil Level	Mechanical, electrical
6.	Voltage and current	Electrical
7.	Harmonics	Electrical

In the event of the failure of distribution transformers, apart from the loss of capital / production, the consumers suffer due to inconvenience caused by the interruption of power supply which is an integral part of our lives

Investment decision is based on how much improvement can be offered by adopting digital distribution transformers, and the comparison of different options is meaningless unless the costs are brought to the same basis

So, a digital distribution transformer is a transformer that can perform the following functionalities:

- A transformer which is equipped with an array of sensors that collate data which is then utilized by the processing unit in the transformer to deliver actionable intelligence by providing valuable information on how the transformer is operating.
- Actionable intelligence includes
  - Thermal analysis of the transformer,
  - Load analysis of the transformer,
  - Ageing analysis of the transformer,
  - Harmonic distortion analysis of the transformer,
  - Hydrogen detection and trending analysis of the transformer,
  - Watch alarms – oil level, tank pressure, voltage, current, temperature etc.,
  - Time-stamped GPS location for ease of transformer identification,
  - Ambient temperature measurements, among others.
- A transformer that allows real-time monitoring identifies potential failure cases and instantly generates and sends notifications of these to help avoid unplanned outages.
- A transformer that helps businesses utilize a data-driven approach to move from a time-based to condition-based maintenance strategy, identify the risk of failure and optimize operations by focusing only on the transformers that need attention.
- A transformer that helps in justifying new capital expenditure (CAPEX) decisions, among other features.
- To evaluate the digital distribution transformer efficiency, specific values in [2] are used as below:

The efficiency of a digital distribution transformer can be estimated to be 50 %, as listed in Table 4. Each end-user should calculate the efficiency as per their own failure statistics!

III. How much investment is justified?

Each investment decision is based on how much improvement can be offered by adopting digital distribution transformers. The comparison of different options is meaningless unless the costs are brought to the same common basis. One common ground that is usually used is the ANNUAL REPLACEMENT COSTS – under non-catastrophic and catastrophic failures. To calculate ANNUAL COSTS, we need to know: Failure rate λ/per year, mean time to replace / repair (MTTR) – can be repaired (onsite / offsite) or replace, costs associated etc.

In this case, the following characteristics are assumed for an oil and gas facility:

- This facility has a capacity of 50,000 barrels per day (bpd).
- There are 5 well pads with an average production capacity of 10,000 bpd.
- Western Texas Intermediate (WTI) crude oil spot price = $55 per barrel.

Table 4. Efficiency evaluation of digital distribution transformer

Component (failure)	Statistics	Digital distribution transformer detection probability
Insulation	26.44 %	70 %
Manufacturing	6.32 %	70 %
Overloading	8.62 %	100 %
Line surge	20.11 %	0 %
Improper maintenance	5.46 %	50 %
Lightning	4.02 %	0 %
Sabotage / vandalism	0.57 %	0 %
Moisture	6.03 %	100 %
Oil contamination	5.75 %	10 %
Others	16.67 %	50 %
Overall efficiency		49.2 % (~50 %)

- Production cost per barrel = $30 per barrel.
- There is a spare transformer available at the site.
- Average time to replace transformer for non-catastrophic failure = 8 hours.
- Typical failure rate of transformers = 1 % (assumed constant)
- Typical failure rate distribution is shown in Fig. 1.
- Transformer expected lifetime = 30 years
- Maximum cost of replacing the transformer for non-catastrophic outage = $8,000 (20 % of new non-digital transformer cost, $40,000).
- Maximum cost of digitalization = $6,000 i.e., additional cost of digital transformer = $46,000.

Despite the wide range of cause of the failures, there are some common parameters that would indicate early warning signals from the transformer, which would enable the end-user to take corrective actions

Assuming one of the good pads fail due to transformer failure! Based on this, the following can be computed for non-catastrophic failure:

a) Production loss/h = 10,000 bpd x ($55-$30) / 24 = $10,417/h
b) Total replacement costs = ($10,500/h x 8 h) + $8,000 = $ 91,336
c) Non-catastrophic failure rate = 1 % x 70 % x 90 % = 0.0063
d) Annual non-catastrophic replacement cost = 0.0063 x $91,336 = $575

Time value of money for non-catastrophic outage can be computed as follows:

a) Transformer expected life (n) = 30 years
b) Discount rate = 6 %
c) Annual non-catastrophic replacement cost = $575
d) Present value (NCNon-Digital) = $7,920

Similarly, the following can be computed for catastrophic failure:

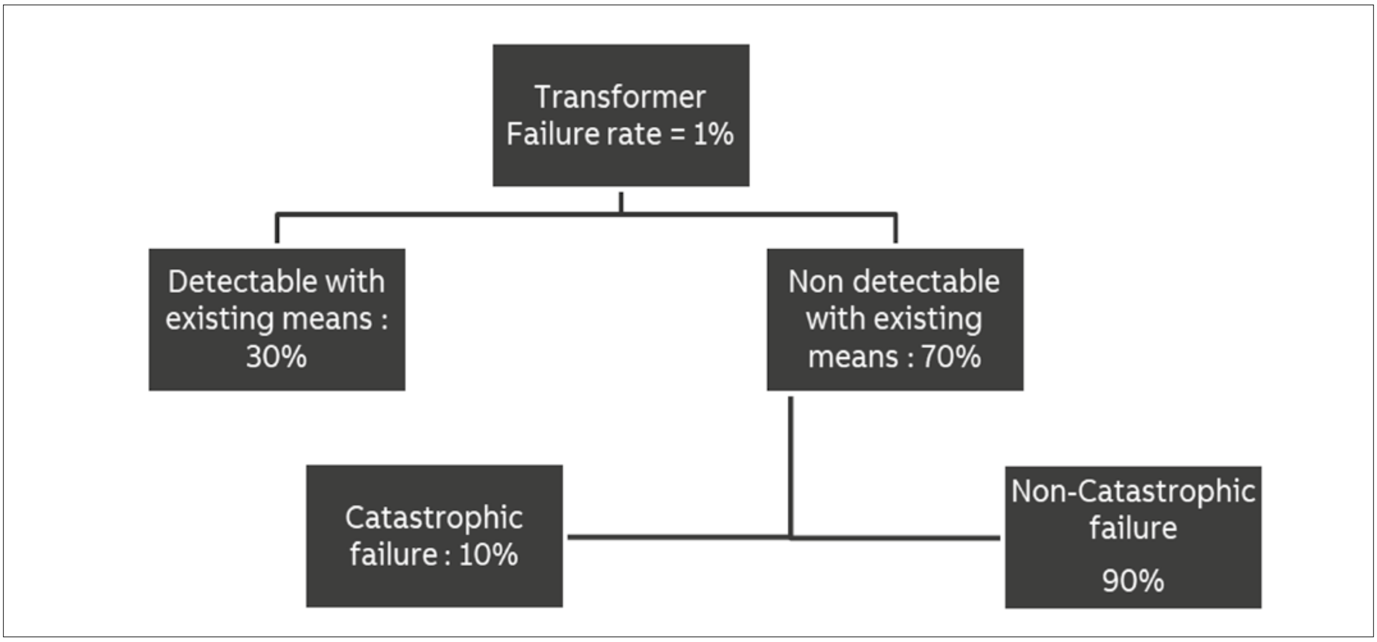

Figure1. Typical transformer failure rate distribution [4]

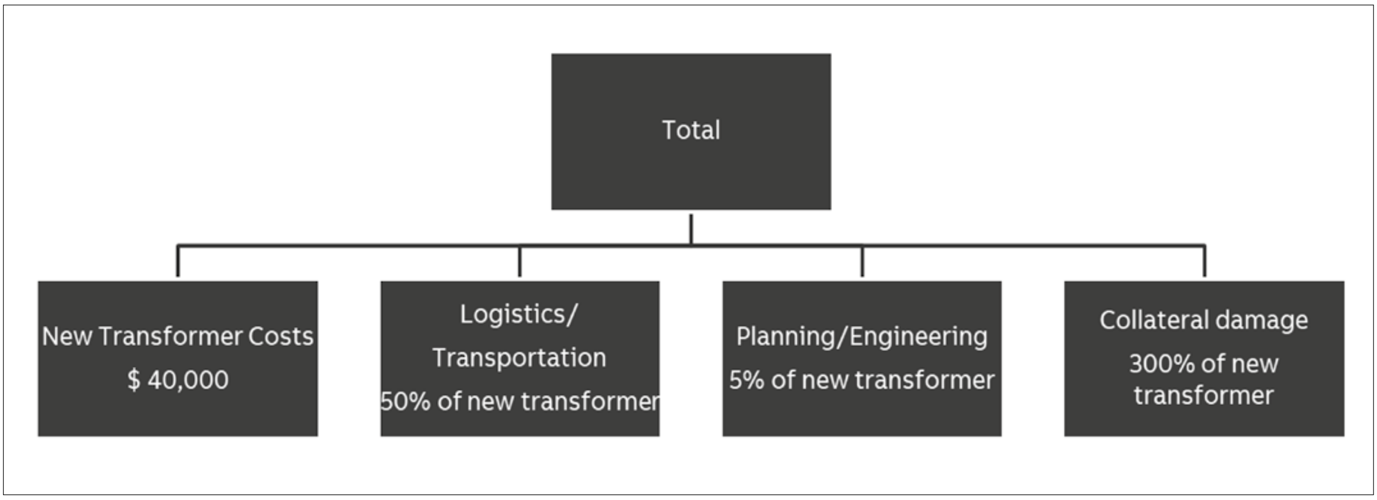

Figure 2. Costs under catastrophic transformer failure

a) Disposal and new transformer costs including collateral = $182,000
b) Average time to replace transformer for catastrophic failure = 72 hours
c) Total replacement costs = ($10,500/h x 72 h) + $182,000 = $932,000
d) Catastrophic failure rate = 1 % x 70 % x 10% = 0.0007
e) Annual catastrophic replacement cost = 0.0007 x $ 932,000 = $652

Time value of money for catastrophic outage can be computed as follows:

a) Transformer expected life (n) = 30 years
b) Discount rate = 6 %
c) Annual non-catastrophic replacement cost = $652
d) Present value (CNon-Digital) = $8,980

Once calculated, the present value of replacing one transformer is equal to $16,900 (PV of NC + PV of C). In other words, we should spend $16,900 today in capital costs to mitigate a future transformer failure. The $16,900 can be used to increase either the protection of the transformer or the frequency of maintenance, i.e. invest in digital transformers.

For digital transformers, the following can be computed:

a) With a digital transformer, assuming efficiency at 50 %, failure reduction calculations show that with the digital transformer, it is possible to prevent 65 % of all possible failures, while for a non-digital transformer, only 30 % is detectable, which is a major improvement, as listed in Table 5.
b) Non catastrophic failure rate = 1 % x 70 % x 50 % x 90% = 0.00315
c) Catastrophic failure rate = 1 % x 70 % x 50 % x 10 % = 0.00035

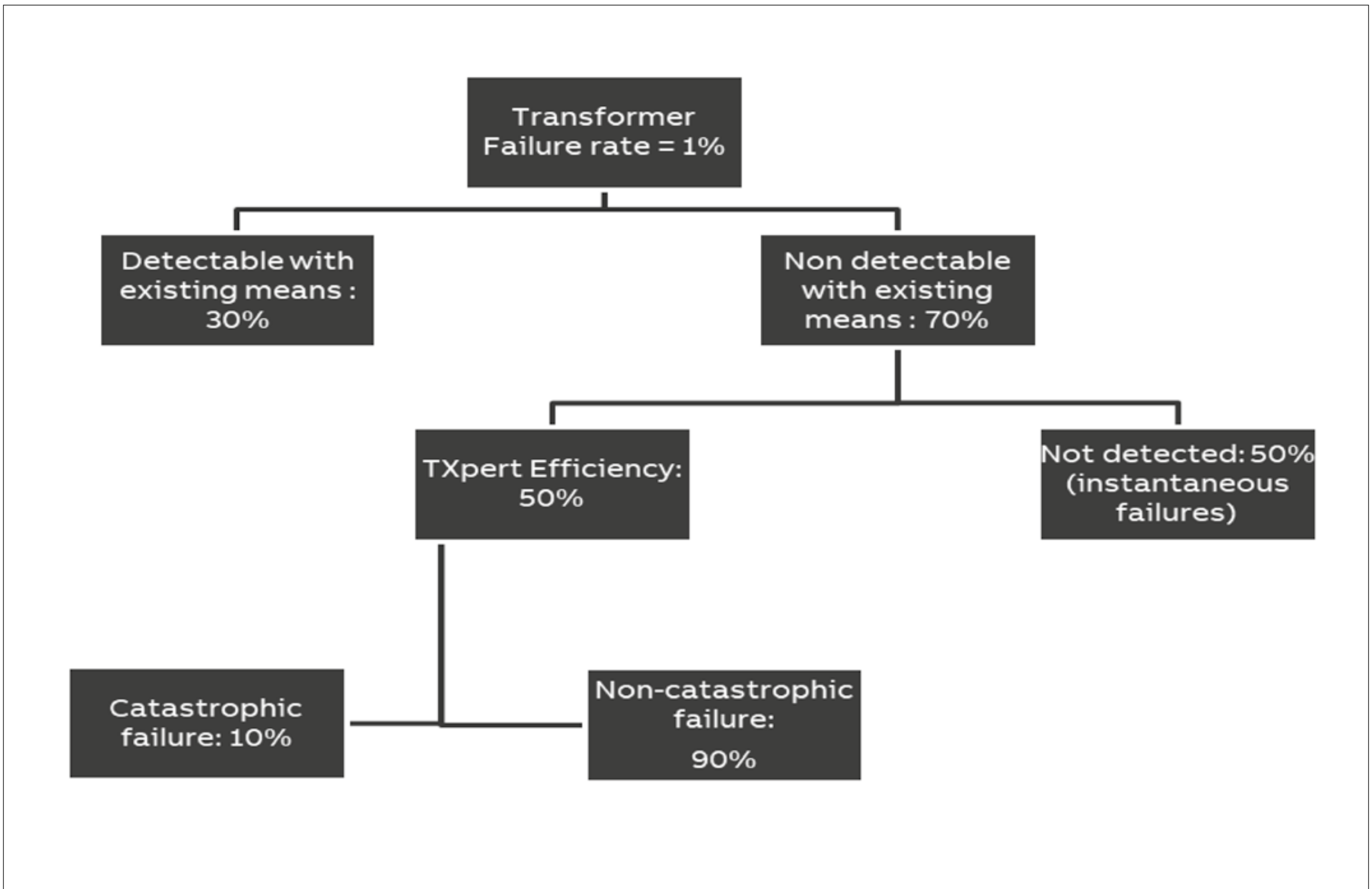

Figure 3. Failure improvement due to digital transformers [4]

Table 5: Improvements made by digitalization

	Non-digital	Digital	Absolute relative improvement
Failure occurring	70 %	35 %	Decrease by 66 %
Failure prevented	30 %	65 %	Increases by 73 %

A comparison can be made between the two types of transformers considering the Total Present Value:

Cost of non-digital transformer = $40,000 Annual maintenance cost = $1,227	Cost of digital transformer = $46,000 Annual maintenance cost = $627

The variation in Total Present Value for different discount rates vs different lifetimes is plotted in Fig 4, 5 and 6.

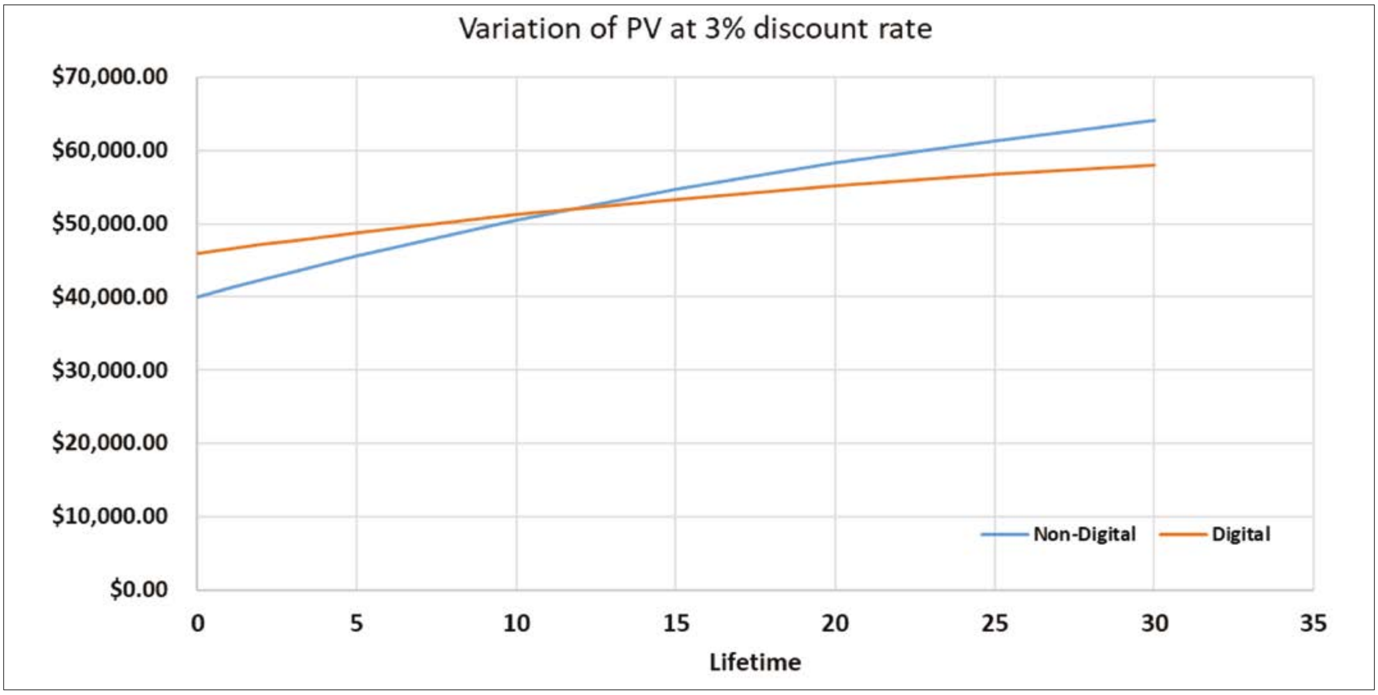

Fig. 4: Break-even year between non-digital and digital transformers (λ = 1 %, = 50 % and *i* = 3 %)

The break-even period is listed in Table 6:

Table 6: Effect in the variation of discount rate in calculation of PV

Parameters	Break-even period
λ = 1 %, η = 50 % and i = 3 %	11 years
λ = 1 %, η = 50 % and i = 6 %	16 years
λ = 1 %, η = 50 % and i = 10 %	25 years

A case study of the costs due to transformer failure and saving that can be achieved by utilization of the digitalized distribution transformer has been conducted using the typical data, users are encouraged to use own data to calculate the break even periods!

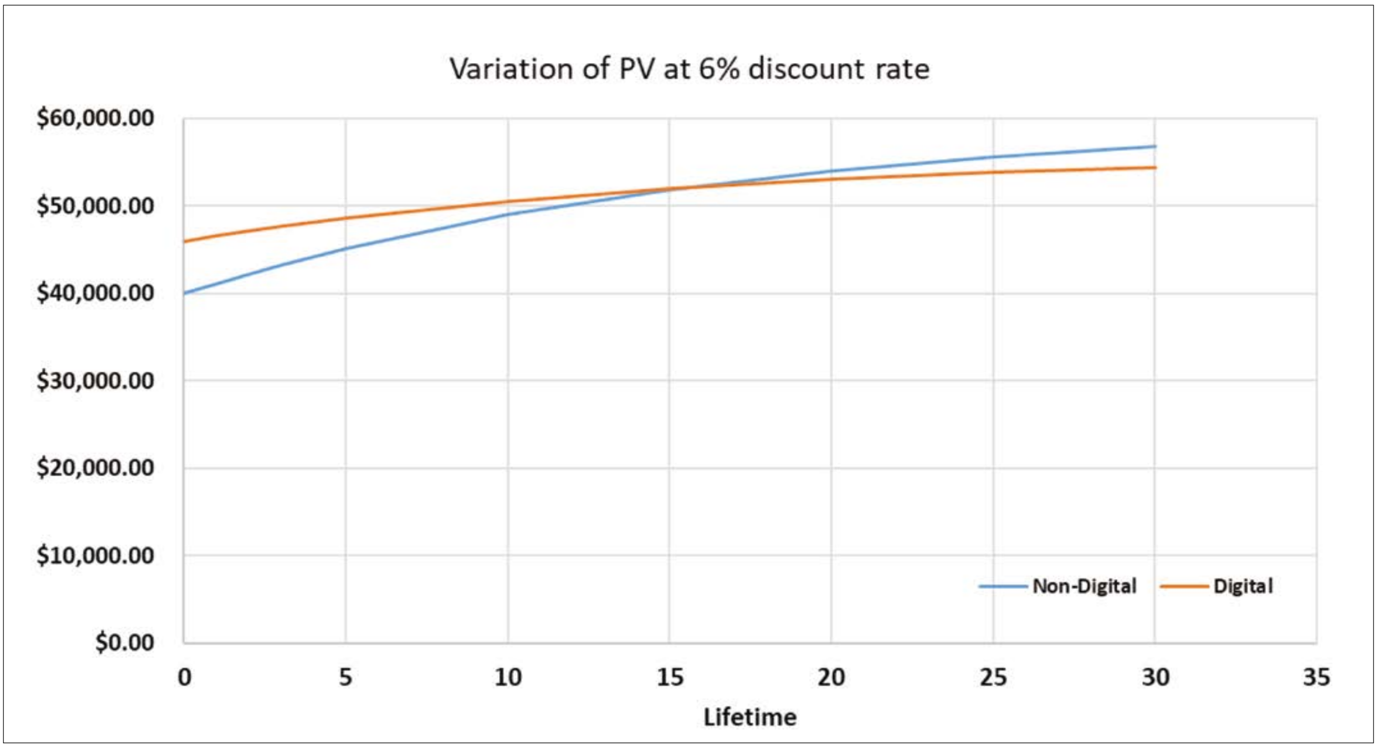

Figure 5. Break-even year between non-digital and digital transformers (λ = 1 %, = 50 % and *i* = 6 %)

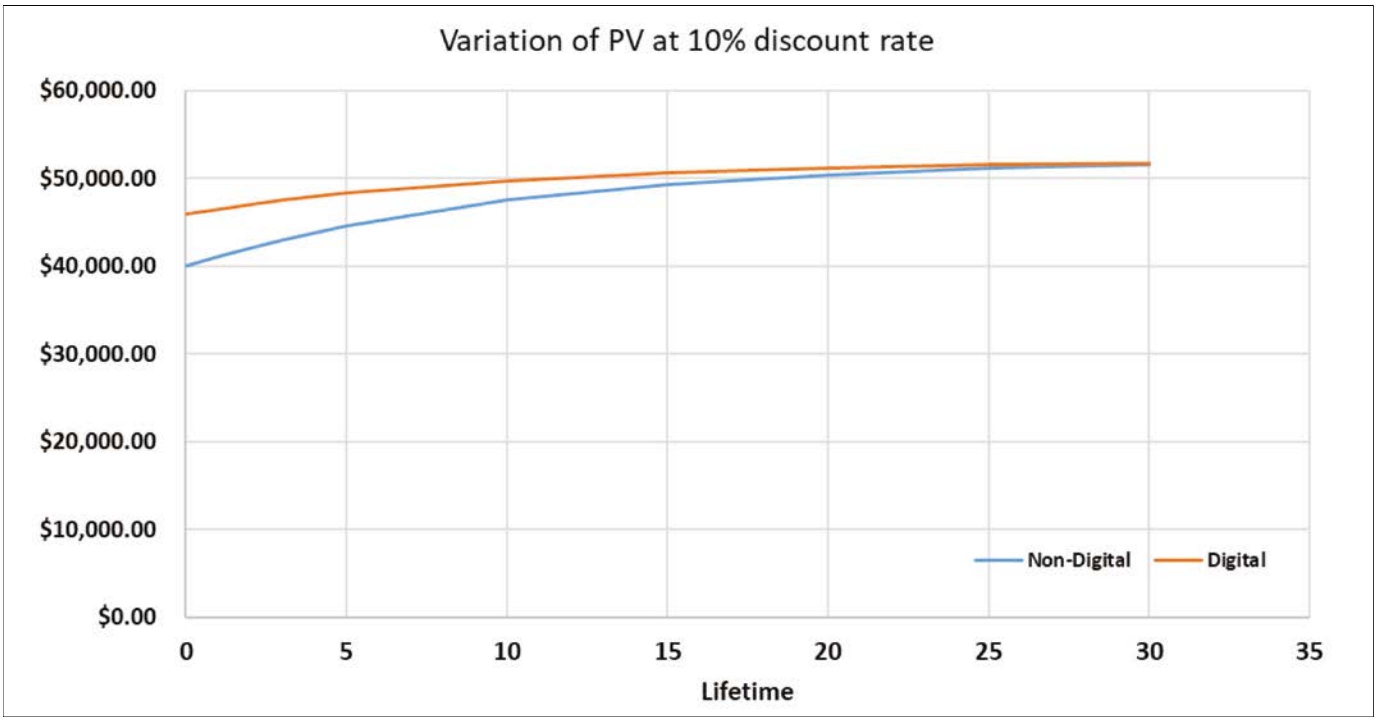

Figure 6. Break-even year between non-digital and digital transformers (λ = 1 %, = 50% and i = 10 %)

Similarly, the break-even period with λ = 2 % is listed in Table 7:

As the discount rate and failure rate varies for different end-users, country by country, it is advisable to perform a full sensitivity analysis.

Table 7: Effect in the variation of discount rate in calculation of PV

Parameters	Break-even period
λ = 2 %, η = 50 % and i = 3 %	5 years
λ = 2 %, η = 50 % and i = 6 %	6 years
λ = 2 %, η = 50 % and i = 10 %	8 years

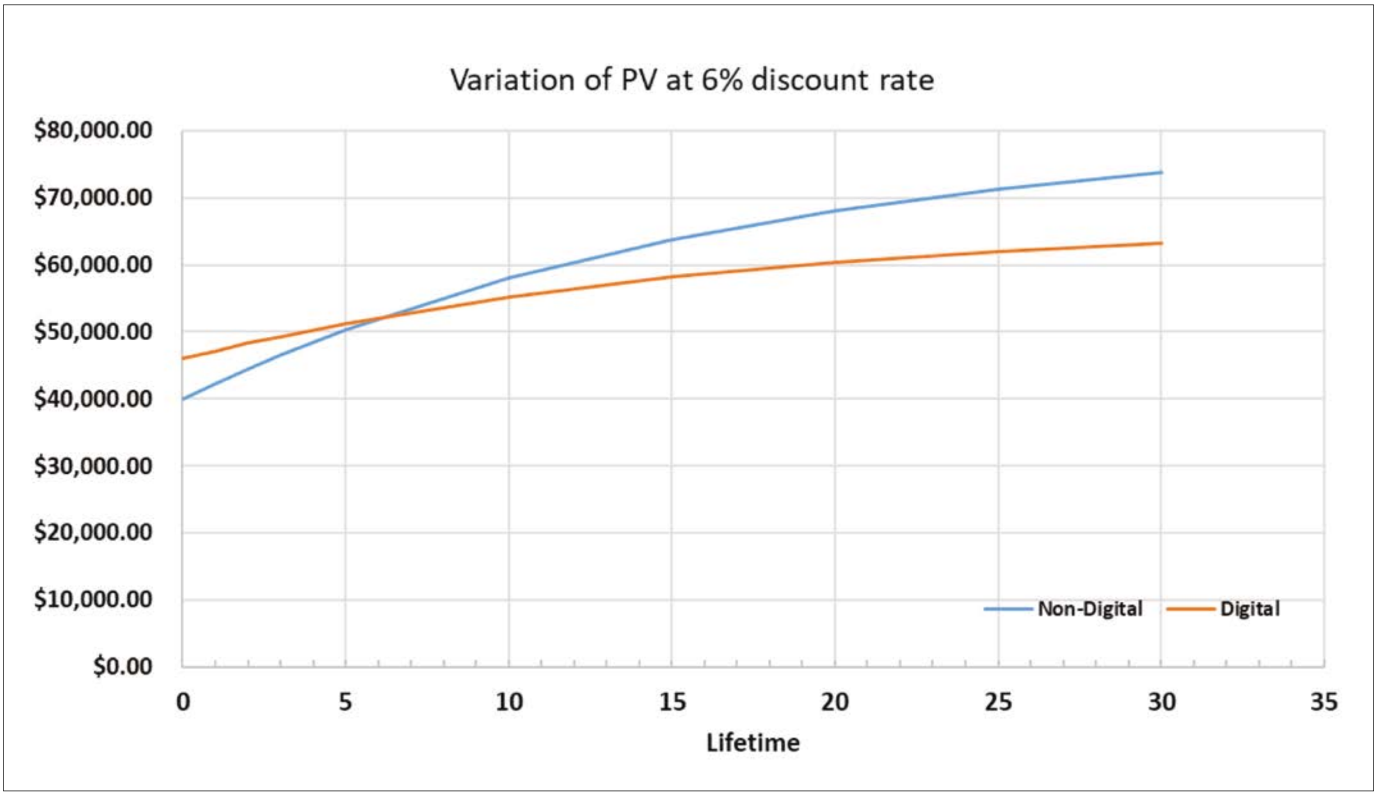

Figure 7. Break-even year between non-digital and digital transformers (λ = 2 %, = 50 % and *i* = 6 %)

In part 2 of this article, we will see how the break even period can be further improved when other benefits are considered in the return calculations. We will also investigate how digital transformers can help optimize the loading of transformers and introduce the concept of sustainable transformer ratings while maintaining the same level of network reliability.

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