Digital Distribution Transformers – A Smart and Economical way to manage the LV Network

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***Abstract*— Distribution transformers are one of the key components of a successful electrical grid. They serve as a major hub for collection and distribution of power. If the right intelligence is added to the distribution transformer, it provides the utility a clear view of how the transformer is utilized. Historically however, most distribution transformers were unmonitored to minimize costs. Typically, monitoring was done at the zone substation with the assumption that power flow was unidirectional. However, this assumption is no longer true with photovoltaic rooftop penetration, increased uptake of electric vehicles and greater use of non-linear power electronic based loads, and a new strategy is needed. In this paper, we will discuss what is a digital distribution transformer, why we need to invest in digital distribution transformer from a purchasing policy perspective, and how we can use digital distribution transformers to evaluate the social cost of operation of the low voltage (LV) network.**

Keywords— *Digital Distribution Transformer, Total Cost of Ownership, Social Cost.*

I. Introduction

The distribution transformer is an important link in the power distribution system. Without this, neither is the utility able to supply electricity to consumers or are industries able to deliver production. In the event of failure of the distribution transformer, apart from the loss of capital/production, the consumer suffers due to inconvenience caused by the interruption of power supply. Though failure of a distribution transformer is simpler when compared to the power transformer, there is a chain of adverse effects such lengthy investigations, sometimes government penalties. Thus, the risk of unplanned outages and resulting losses can be significant. This challenge is far more serious for transformers that are in mission-critical applications or where there is large loading variability as seen in the chemical, oil and gas, renewables, semi-conductor, data centers, 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.

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

- Distribution transformers are inexpensive in relation to power transformers.
- End-users often maintain standard stock, and swap distribution transformers in case of failures.
- Majority distribution transformers are scrapped without attempts to repair.

Traditionally, 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 which is operating anywhere between 40-50% of its full capacity.

Both these approaches have historically served end customers well and provided much-required reliability of the network [1]. However, these methods lead to selection of higher sized transformers. Now, there is an opportunity to save in investments and operations by rightly sizing transformers to actual load, while still operating with safety margins and acceptable risks. Apart from operational costs, the social costs of ownership of transformers must also be analyzed and included in the sizing calculations. Transformer specifiers and owners should assume these social costs as higher losses of oversized units directly correspond to the additional energy that must be generated by the existing generation mix of the power system of that country. The social cost translates into the future harm inflicted by the release of one additional ton of carbon dioxide (CO_2) into a present monetary value

To understand these aspects, the first and most crucial step is to get the loading data of distribution transformers. This is where the digital distribution transformer comes into the fray. To illustrate the above points, this paper is divided into the following sections -

1. What is a digital distribution transformer?
2. Why invest in digital distribution transformer? Social cost of ownership of transformers
3. Evaluating the social costs of two digital transformers with different losses.

II. Digital Distribution Transformer

A digital distribution transformer is a transformer which 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,
- Moisture 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.

The digital distribution transformer allows real time monitoring that identifies potential failure cases and instantly generates and sends notifications to help avoid unplanned outages. It helps businesses utilize a data-driven approach to move from time-based to condition-based maintenance strategy and optimize operations by focusing on the transformers that need attention. It also helps in justifying new capital expenditure decisions among other features.

III. Why Invest in Digital Distribution Transformer?

Understanding the loading profile is crucial in selecting the right sizing of the transformer. This traditionally has been unavailable as most distribution transformers were unmonitored. Typically, when electrical distribution utilities purchase distribution transformers, it is based on specified rating, specific design considerations and some type of loss evaluation procedure. This loss evaluation concept is called the Total Cost of Ownership (TCO) method. TCO is based on the following formula:

$$TCO = PP + A \times NLL + B \times LL \quad (1)$$

where PP refers to the purchasing price of the distribution transformer in \$, A indicates the equivalent no-load loss cost rate in \$/kW, NLL refers to no-load loss in kW, B indicates the equivalent load loss cost rate in \$/W, and LL refers to load loss in kW. A typical formula from a South African utility [2]:

$$TCO = PP + 31{,}200 \times NLL + 6{,}700 \times LL \quad (2)$$

From the Eqn. (2), the loading this transformer is expected to see can be calculated as:

$$k = \sqrt{\frac{6700}{31{,}200}} = 46.34\% \quad (3)$$

Let us consider a 100kVA transformer as per SANS 780 [3] for distribution transformers. The loss specified are:

Table 1: 100 kVA Transformer Losses

SANS 780	No- Load Loss (W)	Load Loss (W)
100 kVA (<12kV)	300	1700

For a 25-year period, the total loss for this 100kVA transformer can be calculated as:

Table 2: 100 kVA Transformer Losses For 25 Years

100 kVA	MWh
Total Loss in 25 years	145.64

To translate these losses into social cost of carbon (SCC), a conversion factor of 0.97 $tonCO_2$/MWh is applied [4]. The social cost of carbon translates the future harm inflicted by the release of one additional ton of CO_2 into a present monetary value. It answers the question: How much damage will a ton of CO_2 emissions released today cause in the future? Transformer specifiers and owners should assume these social costs as the losses directly correspond to the additional energy that must be generated by the existing generation mix, calculated in Table 3.

Table 3: Evaluating Social Cost from Specification

100 kVA	MWh	$tonCO_2$	Cost/ $tonCO_2$	SCC (\$)
Total Loss in 25 years	145.64	141	US\$50/tCO_2	US\$ 7,050

Now, we have a digital transformer which allows us to get the thermal, load and ageing data in real time. Figure 1 shows the actual transformer loading for a 24-hour period, with an average load of 40%. This load curve forms the basis of total cost of ownership with a 25-year lifetime.

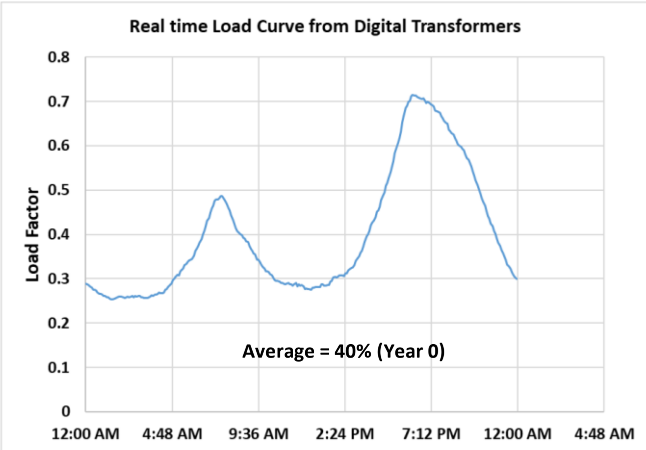

Fig. 1. Real time load curve from Digital Transformers.

Assuming a 3% annual increase in load, the loading pattern for 25 years can be estimated, with average load increasing to 83.5% at the end of 25 years.

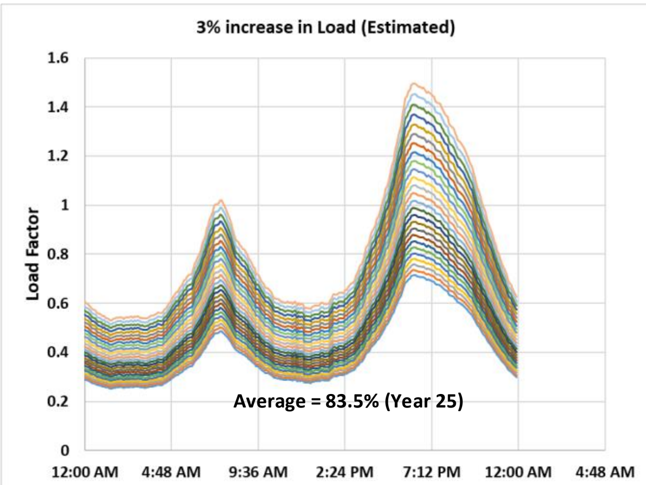

Fig. 2. Estimated loading profile for 25 year period (3% annual growth).

TABLE 4: EVALUATING SOCIAL COST FROM REAL TIME LOAD

100 kVA	MWh	$tonCO_2$	Cost/ $tonCO_2$	SCC ($)
Total Loss in 25 years	228.25	221.4	US$50/$tCO_2$	US$ 11,070

Table 4 lists the SCC for this 100kVA transformer (obtained using real time loading and 3% annual growth) equal to US$ 11,070, which is 57% higher than SCC calculated at estimated load of 46.43% based on TCO formula alone. Thus, without real time load from digital distribution transformers, estimating the environmental costs of operating transformers may result in lower values. Apart from benefits from a purchasing policy perspective, there are several other benefits of digital distribution transformers as well [5].

The TCO equation can now be updated as:

$$TCO = PP + A \times NLL + B \times LL + C_{env} \qquad (4)$$

Where C_{env} is the cost of environment (social cost of carbon).

IV. EVALUATING TWO DIFFERENT 100KVA DESIGNS

In this section, two different 100kVA digital distribution transformers are evaluated using the loading conditions shown in Fig. 2. Design 1 is CRGO steel while Design 2 is Amorphous steel. The loss values are listed in Table 5.

TABLE 5: 100 KVA TRANSFORMER LOSSES

Design #	No- Load Loss (W)	Load Loss (W)
1	250	1300
2	70	1650

The efficiency against loading for both the designs are shown in Fig. 3.

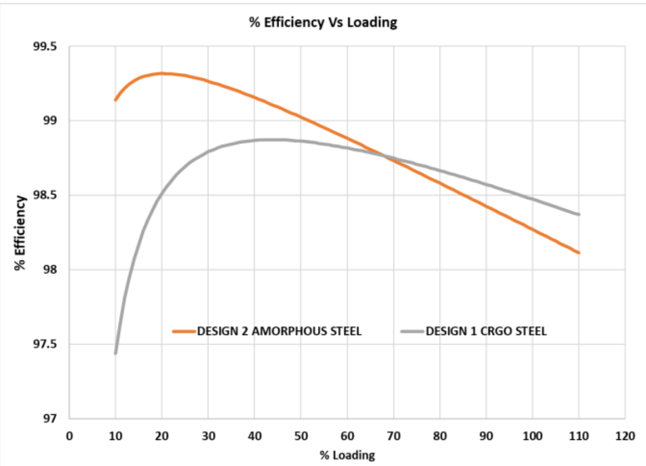

Fig. 3. Efficiency vs loading for Design 1 and Design 2.

Due to an increased interest in producing sustainable and environmentally friendly equipment in line with the global movement of environmental protection; pressure and demand for a solution which offers improved energy savings has been a key issue. Inevitably, materials which exhibit the qualities of low core loss and low magnetostriction, such as amorphous steel, has been of interest. This is the logic for selecting Design # 2 with amorphous core transformer.

TABLE 6: EVALUATING SOCIAL COST OF TWO DESIGNS

Design	MWh 25 years	$tonCO_2$	Cost/ $tonCO_2$	SCC ($)
1	179	173.85	US$50/$tCO_2$	US$ 8693
2	171.16	166	US$50/$tCO_2$	US$ 8301

From Table 6, although amorphous steel is excellent in reducing the no-load loss, the environmental costs of operation are very similar. What is more important is to understand the loading pattern of the transformer. Without the loading analysis from digital transformers, it is difficult to estimate the actual environmental costs of operating transformers. Based on the efficiency vs loading characteristics as shown in Fig 2, the amorphous core transformer is very efficient when the transformer is lightly loaded while the actual load is on the higher side. The TCO can be calculated in Table 7. It is seen the difference is only 2%.

TABLE 7: TCO OF TWO DESIGNS WITH A = $31,200 AND B = $6,700

Design	Loss (W)	PP ($)	TCO Without C_{env}	TCO With C_{env}
1	250/1300	$8,000	$24,510	$33,202
2	70/1650	$11,200	$24,439	$ 32,740

Thus, it is extremely important to understand the design as well as the loading analysis to shift from CRGO steel to Amorphous steel. Given the challenges in securing real time data to correctly size and procure transformers, the priority should be to digitalize transformers to understand their actual loading pattern. Once the patterns are well understood, the move towards material improvement in terms of low loss core steel can be easily justified.

V. CONCLUSIONS

The electricity industry is under pressure to reduce operational costs and reduce CO_2 emissions. Years of cheap electricity, an abundance of coal has led to an industry that uses outdated transformer sizing techniques. There is a reluctance in adopting monitoring for distribution transformers, as this cost is seen as an unnecessary. However, if the data is analyzed while placing orders for new transformers, digitalization of transformers are cost beneficial.

A digital distribution transformer can significantly reduce the capital upfront cost. This 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. When a thorough economic investigation based on the total cost of ownership / operation is carried out, it shows that in some cases, even adopting low loss material may not reduce the total costs by significant amount. When the loading patterns are well understood, and transformers are specified accordingly, are actual financial and sustainable benefits visible. The only way this can be achieved is by increased use of data and information, which a digital distribution transformer provides.

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