Enhancing transformer sustainability through dynamic rating algorithms

ABSTRACT

Material production and energy supply are becoming increasingly interconnected. The large-scale deployment of solar energy, wind turbines, electric vehicles, and fuel cells is essential to limit global temperature rise to 1.5°C. However, these technologies require significant raw materials, including steel, copper, aluminum, and concrete, driving demand at an unprecedented rate. Transformers, as critical, long-lasting, and resource-intensive components of the electrical grid, must be designed to address this energy-materials challenge. This article critically examines how transformer digitalization, through dynamic rating algorithms, can optimize resource use, using a 20 MVA transformer as a case study.

KEYWORDS:

dynamic rating, digitalization, carbon footprint, load capacity, thermal monitoring


DYNAMIC RATINGS
C50 SERIES

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1. Introduction

Among the different operating limits of transformers, loadability is usually determined by maximum oil temperature, hot spot temperature, aging insulation, oil degradation and external weather conditions. If these limits are exceeded, the transformer insulation life expectancy is affected and, in some extreme cases, results in permanent damage to the transformer. Thus, to ensure operational reliability, the rated power of the transformer has been traditionally kept constant [1]. However, temperatures are influenced by environmental conditions, which are usually different from design assumptions. This results in uncertainty in the actual maximum allowed rated power under real operating conditions. To overcome these limitations, thermal monitoring is widely recommended to enhance transformer performance [2].

Thermal monitoring is a solution that enables the dynamic rating of transformers. The dynamic rating allows the calculation of top oil and hot spot temperatures, considering the load and ambient temperature, to estimate and predict the maximum transformer rated power under both a steady state and a transient state. Dynamic rating is defined in [1] as: “The maximum loading which the transformer may acceptably sustain under time-varying load and/or environmental condition”. The typical nameplate definition is the output power at the secondary side, which the transformer can deliver on a continuous basis at a rated frequency, rated voltage, and ambient of either 20°C (IEC) or 30°C (IEEE) resulting in continuous hot spot temperature of 98°C (IEC) or 110°C (IEEE).

Now, theoretically, when ambient temperatures are lower than design values, it is possible to load the transformer above its nameplate rating without breaching the hot spot limits of either 98°C (IEC) or 110°C (IEEE). The dynamic rating calculated will be higher than the nameplate rating in this scenario. On the other hand, when ambient temperatures are higher than design values, the dynamic rating calculated will be lower than the nameplate rating. This ability to extract the maximum transformer rated power using thermal monitoring and dynamic rating is extremely beneficial in terms of reducing the material carbon footprint of transformers. This functionality of adding sensors, online monitoring, and the use of a dynamic rating algorithm helps to meet higher continuous load or even peak demands for certain periods in a day without the need to invest in “larger” capacities in terms of the static rated transformers.

Larger capacity static rated transformers need more material. Material production and energy supply are becoming increasingly interlinked and interdependent. Solar energy, wind turbines, electric vehicles, fuel cells, and other key infrastructures must be deployed on a large scale to hold global temperature rise within 1.5°C. However, these infrastructures are much more material intensive, i.e., demand for steel, copper, aluminum, concrete, etc., and are all increasing at a rapid rate.

> **Larger capacity static rated transformers need more material, and material production and energy supply are becoming increasingly interlinked and interdependent**

Transformers, being key, long-lasting, energy- and material-intensive components of the electricity grid, need to be designed to address the energy-materials nexus challenge. Digitalization of the power transformer unlocks this potential of making the static rating dynamic and doing more with less.

The ability to use digital technology to improve sustainability is known as sustainable digitalization. This involves using digital tools to make sustainability improvements, such as reducing environmental impact or increasing material efficiency. This study demonstrates the tangible material savings potential by applying dynamic rating to a 20 MVA, 33/11.5 kV transformer, analyzing real operational data and comparing material carbon footprints.

The dynamic rating algorithm calculates the maximum hotspot and top oil temperature considering the loading curve profile, as well as equivalent aging for the different time durations: 5 min, 15 min, 30 min, 1 hour, 2 hours, 4 hours, 8 hours. The thermal model uses top oil temperature and load and calculates the winding hot spot temperature by using either IEC 60076-7 [3] or IEEE C57.91-2011 [4]. The ageing calculation calculates the insulation aging based on hot spot temperature. Total ageing is calculated by accumulating aging hours. Similarly, the 24-hour maximum allowable continuous load is also calculated.

The dynamic rating algorithm also verifies if any one of these three outputs exceeds the limits imposed by the end user. It then provides the operational rating of the transformer under time varying conditions with a maximum limit of 1.5 p.u of the load current.

2. Transformer under investigation

The static nameplate rating of the transformer is listed in Table 1.

3. Sustainable digitalization

3.2 Dynamic rating capability of dynamic rating algorithm

3.1.1 Ambient temperature

While the digitalized transformer has been operational for over a year, for clar-

Table 1. Nameplate rating of the 20 MVA transformer

Rating	20 MVA	Voltage	33/11.5 kV
Phase	3	Impedance	12.35%
Frequency	50 Hz	Cooling method	ONAN
Vector group	Dyn11	Oil/Winding rise	44/55 K
Insulation	TU Paper/Mineral oil	Max ambient	50°C

ity, two weeks of data for Sep 2023 has been selected. The load data plot is shown in Figure 1. It can be seen from Fig 1 that this transformer operates around 80% of the nameplate rating.

> **The dynamic rating algorithm provides the operational rating of the transformer under time varying conditions with a maximum limit of 1.5 p.u of the load current**

3.1.2 Ambient temperature

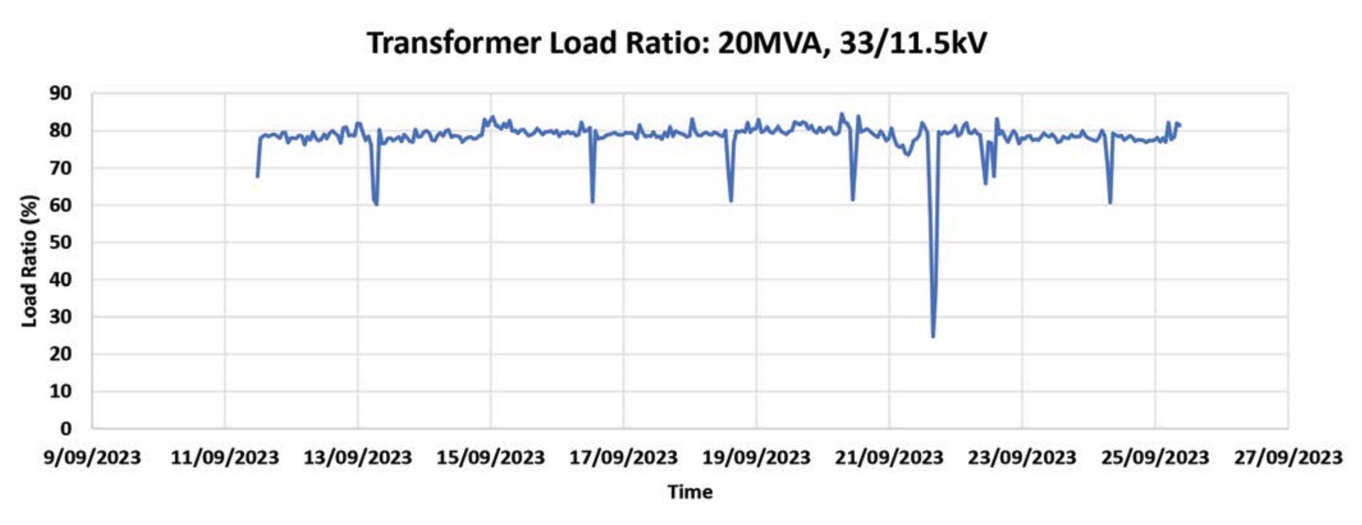

Figure 1. Load profile for 2 weeks: 20 MVA, 33/11.5 kV

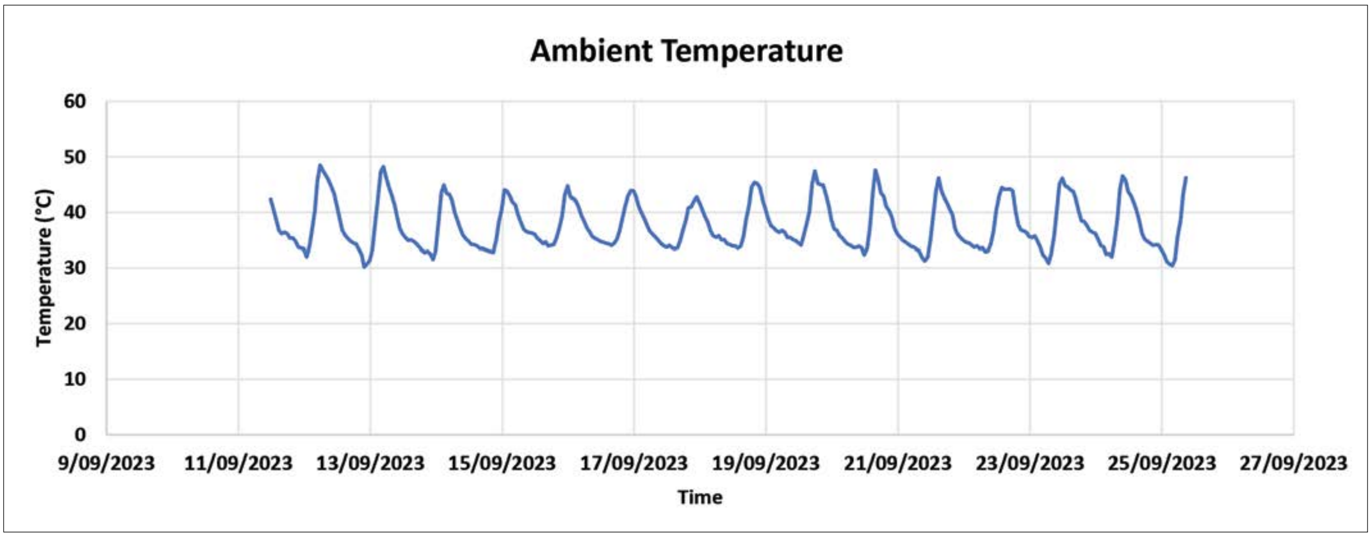

Figure 2. Ambient temperature profile for 2 weeks: 20 MVA, 33/11.5 kV

> **On average, a dynamically rated 20 MVA transformer can operate as a 24 MVA static rated transformer without top oil temperature, hotspot temperature and loss of life violations**

3.1.3 Measured top oil and calculated hot spot temperature

Figure 3 shows the measured top oil and calculated hot spot temperatures for two weeks. The hot spot temperature is well below the 110°C limit imposed as maximum, and the top oil temperature is well below the 85°C limit imposed as maximum.

3.1.4 Continuous loadability of the transformer

The calculated continuous loadability of the transformer calculated by the dynamic rating algorithm is shown in Figure 4. From Figure 4, it can be calculated that, on average, this 20 MVA transformer can operate as a 24 MVA transformer without top oil temperature, hotspot temperature and loss of life violations based on the Arrhenius ageing study as per [3] or [4].

The maximum hotspot temperature calculated for continuous loadability of 20 MVA, as shown in Figure 4, is shown in Figure 5.

The ability of the dynamic rating algorithm to readily calculate the rating of the transformer helps in addressing the energy-materials nexus challenge. The digitalization of the transformer using a dynamic rating algorithm provides an

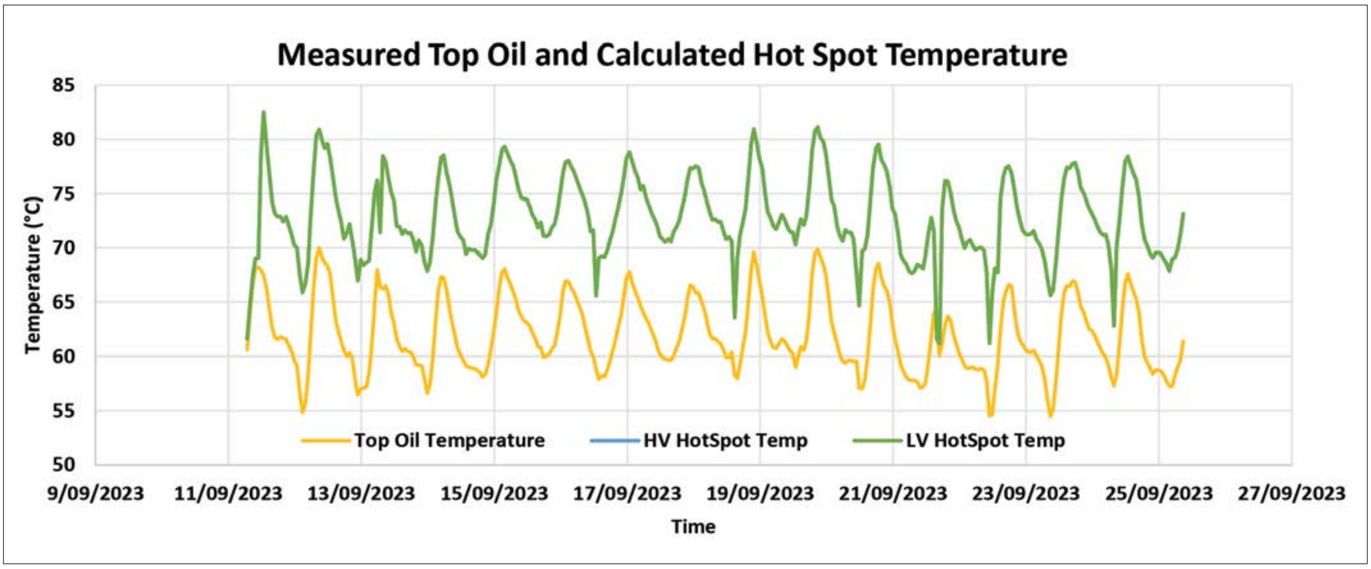

Figure 3. Top oil and hot spot temperature for 2 weeks: 20 MVA, 33/11.5 kV

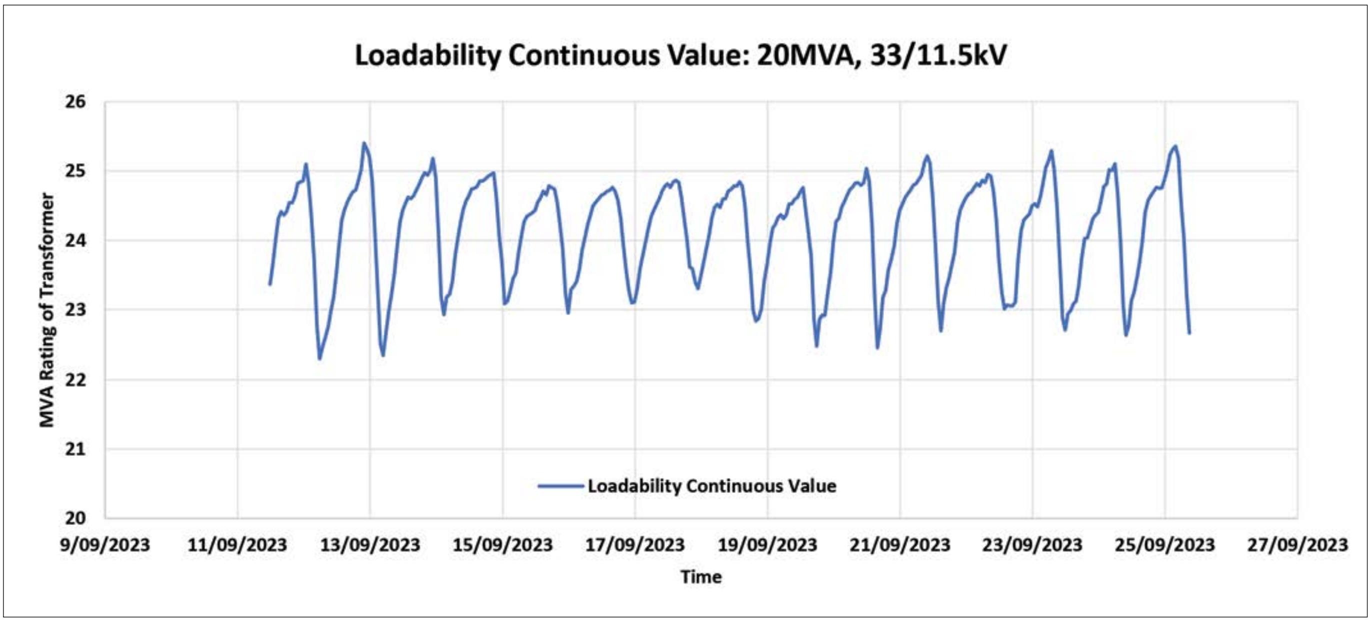

Figure 4. Continuous loadability of the 20 MVA, 33/11.5 kV using dynamic rating algorithm

opportunity to upgrade the transformer rating:

- While keeping the lower unit dimensions, meeting space restrictions.
- While not over-rating the transformer - lowering raw material consumption.
- While decreasing the upfront transformer purchase price.

Section 4 calculates the savings in material carbon footprint, which can be achieved by utilizing a dynamic rating algorithm.

4. Material carbon footprint reduction

Table 2 presents the comparison of the transformer component mass and material carbon footprint between 20 MVA and 24 MVA transformers. The total mass can be reduced by 4,420 kg. The calculated material carbon footprint of the 20 MVA transformer is 97.71tCO$_{2e,}$ while that of the 24 MVA transformer is 112.57 tCO$_{2e}$, an equivalent material carbon footprint reduction of 15%. This is achieved by one transformer utilizing the dynamic rating algorithm. The potential will be immense if the dynamic rating algorithm is more widely used. The barriers to widespread adoption currently include:

1. Highly dependent on environmental conditions (e.g., if ambient temperatures remain consistently high, dynamic rating provides little to no benefit).
2. Limited by power system constraints (e.g., in networks with high short-circuit levels, increasing transformer loading may not be feasible).

> **The ability of the dynamic rating algorithm to readily calculate the rating of the transformer helps in addressing the energy-materials nexus challenge**

Conclusion

Dynamic rating algorithms unlock substantial efficiency and sustainability benefits in transformer operations, demonstrating that real-time optimization can reduce material use while maintaining reliability. The study concludes:

1. Dynamic rating enables transformers to handle 20% higher loads without exceeding thermal limits.
2. Significant material and carbon footprint savings (15%) are achievable.
3. Wider adoption of dynamic rating can defer new investments and optimize grid operations.

The future research directions include:

1. Investigating the benefits on the operational carbon footprint of transformers due to increased loading under different grid emission factors.
2. Carbon footprint implications on the use of higher-rated bushings, leads, and tap changers when compared to benefits gained from core, steel, oil, etc.
3. Extending dynamic rating to fleet-wide transformer operations to maximize grid-wide benefits.
4. Assessing the impact of dynamic rating algorithms under extreme weather conditions.
5. Exploring AI-driven predictive models for further optimization.

> **The material carbon footprint of the 20 MVA transformer is 97.71tCO2e, while the equivalent static rated 24 MVA transformer has 112.57 tCO2e**

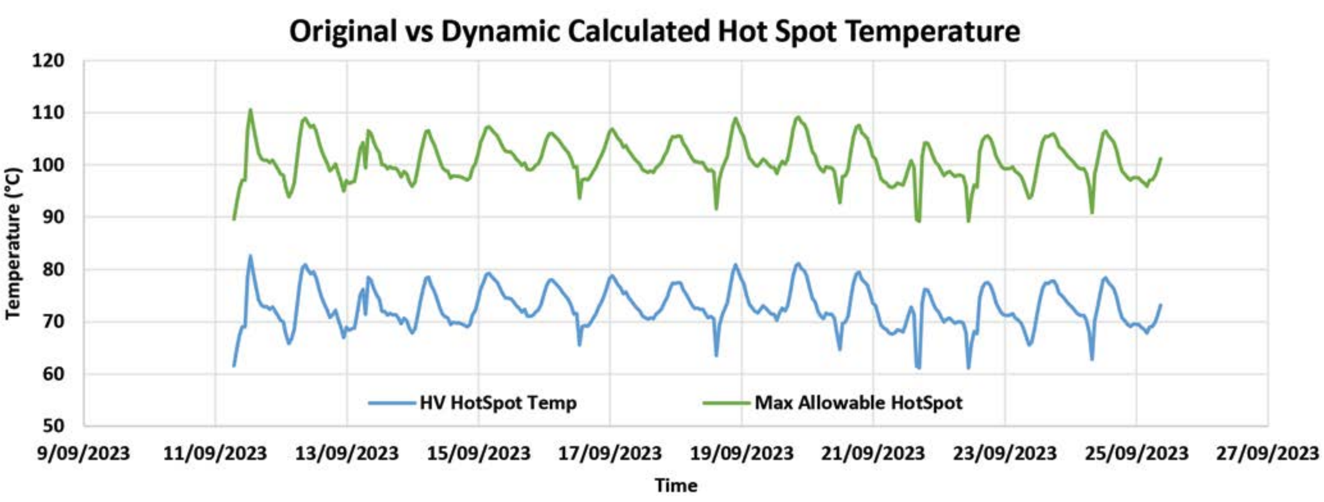

Figure 5. Max hot spot temperature of the 20 MVA, 33/11.5 kV using dynamic rating algorithm

Table 2. Mass and material carbon footprint comparison between two designs – 20 MVA & 24 MVA transformer

Material	Mass (kg) 20 MVA, 33/11.5 kV	Mass (kg) 24 MVA, 33/11.5 kV	Emissions factors used	Material carbon footprint 20 MVA	Material carbon footprint 24 MVA
Core coil assembly	20,000	23,150	Copper@4.88kgCO$_{2e}$/kg Core Steel@2.38kgCO$_{2e}$/kg Pressboard @0.29kgCO$_{2e}$/kg Paper@1.74kgCO$_{2e}$/kg Wood@1.5kgCO$_{2e}$/kg Carbon Steel@2.42 kgCO$_{2e}$/kg	60.53 tCO$_{2e}$	73.12 tCO$_{2e}$
Oil	8350	8970	Mineral Oil@1.12 kgCO$_{2e}$/kg	9.35 tCO$_{2e}$	10.04 tCO$_{2e}$
Tank	6570	7000	Carbon Steel@2.42 kgCO$_{2e}$/kg	15.89 tCO$_{2e}$	16.94 tCO$_{2e}$
Radiator	4930	5150	Carbon Steel@2.42 kgCO$_{2e}$/kg	11.93 tCO$_{2e}$	12.46 tCO$_{2e}$
Transformer's total transport mass	**39,850**	**44,270**	Total material carbon footprint	**97.71 tCO$_{2e}$**	**112.57 tCO$_{2e}$**

> **Dynamic rating algorithms unlock efficiency and sustainability benefits in transformer operations, demonstrating that real-time optimization can reduce material use while maintaining reliability**

Reference

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[3] IEC 60076-7:2018, Power transformers - Part 7: Loading guide for mineral-oil-immersed power transformers

[4] IEEE C57.91-2011 - IEEE Guide for Loading Mineral-Oil-Immersed Transformers and Step-Voltage Regulators

Author

Dr. Bhaba P. Das is the Regional Manager (Asia Pacific) for Dynamic Ratings Australia, based in Wellington, New Zealand.

He is a Senior Member of IEEE, Young Professional of IEC, Member CIGRE NZ A2 panel, Member of Engineering New Zealand and Executive Editor of Transformers Magazine. He has published 35+ technical articles in various peer reviewed international journals and magazines. He has three patents in New Zealand & Australia related to condition monitoring. He has been awarded the best author of 2023 by voters of Transformers Magazine, a leading worldwide publication on Transformers.

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