

Impact of Reactive Power Fluctuation on the Performance and Insulation Loss-of-Life Rate of Industrial Power Transformers: A Case Study of the PT Semen Tonasa Electrical System

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Abstract – Power transformer performance is strongly influenced by reactive power (VAR), yet the quantitative link between VAR fluctuation and insulation loss-of-life in heavy industrial systems remains under-documented. This study analyzes that link for six 70 kV power transformers (three at the Tonasa IV and three at the Tonasa V substations, 31.5–40 MVA) in the electrical system of PT Semen Tonasa, combining SCADA operational data, an ETAP load-flow simulation, and an analytical ageing-rate calculation based on IEC 60076-7. Varying reactive power from 1 to 10 MVAR at a fixed active power of 10 MW increased the loading level from 31.41% to 44.19% of the 80% operating limit, consistent with $S = \sqrt{P^2 + Q^2}$. SCADA records showed current rising and primary-side voltage falling as VAR increased, with all voltages (66.68–68.95 kV) remaining within $\pm 10\%$ of nominal. For the three Tonasa V units, hotspot temperatures of 65.42–75.23°C and loss-of-life rates of 0.022–0.069 pu/day were obtained, well below the $98^\circ\text{C}/V = 1$ design reference; Transformer #1 aged roughly 3.1 times faster than Transformer #2, reflecting its higher average loading (63.4% vs. 36.5% of the operating limit). The extrapolated remaining-life figures (79.7–250 years) are indicative rather than literal, given the short (3–5-day) SCADA window; the loss-of-life rate is therefore treated as the primary, more defensible indicator. Reactive-power compensation via capacitor banks or static var compensators is recommended to limit current, hotspot temperature, and insulation ageing.

Keywords: ETAP, insulation ageing rate, power factor, power transformer, reactive power.

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I. INTRODUCTION

Transformers are among the most critical pieces of equipment in a power system because they transfer and convert electrical energy between voltage levels through the principle of electromagnetic induction [1]. In large-scale industries such as PT Semen Tonasa, the reliability of power transformers is a primary determinant of continuity of production.

One factor that significantly affects transformer performance is reactive power (VAR), needed to establish the magnetic field in inductive equipment such as the transformer itself [2]; excessive reactive-power flow increases current, power losses, and winding heating, and disturbs voltage stability [3], [4]. This matters for insulation ageing because IEC 60076-7 and IEEE C57.91 correlate paper ageing directly with hottest-spot temperature (HST): higher losses raise HST and accelerate degradation [10], [11], an effect compounded by overloading, non-sinusoidal supply, or high ambient temperature [5].

PT Semen Tonasa, one of the largest cement producers in Indonesia, operates a complex internal electrical system with highly variable industrial loads, including its own generating units (a coal-fired power plant) and distribution through several 70 kV power transformers. Variable inductive loads from large-scale motors — raw mills, kilns, coal mills, and finish mills — produce reactive-power fluctuations that have the potential to significantly affect transformer performance.

While reactive-power effects on transformer loading and ageing have been studied through simulation and utility-substation data (reviewed in

Section 2.3), quantitative validation using actual SCADA measurements from a heavy industrial system with highly variable reactive loads — such as a cement plant driven by large-scale motors — remains limited. This study addresses that gap by combining SCADA data, an ETAP load-flow simulation, and an IEC 60076-7 ageing-rate calculation, while explicitly discussing the limitations of extrapolating long-term remaining life from short-term observation data.

Based on the above, this study aims to: (1) analyze the effect of reactive power (VAR) on transformer performance parameters, including current, voltage, and power factor; and (2) evaluate the impact of reactive-power variation on the insulation ageing rate of 70 kV power transformers in the electrical system of PT Semen Tonasa, through ETAP simulation and analytical calculation based on IEC 60076-7, together with a discussion of the limitations of the remaining-life extrapolation method used.

II. LITERATURE REVIEW

A. Reactive Power and Transformer Loading

In a three-phase AC system, active power (P), reactive power (Q), and apparent power (S) form the power triangle with power-factor angle ϕ [2],

$$P = \sqrt{3} VI \cos \phi \quad (1)$$

$$Q = \sqrt{3} VI \sin \phi \quad (2)$$

$$S = \sqrt{P^2 + Q^2} \quad (3)$$

$$PF = \frac{P}{S} = \cos \phi \quad (4)$$

where V is line-to-line voltage, I is line current, and $\cos \phi$ is the power factor. Reactive power performs no real work but is required to establish the magnetic field in inductive equipment such as motors and transformers [3]. Excess reactive power in a system therefore (1) lowers the power factor and raises the apparent power the transformer must carry per Equation (3); (2) increases current; (3) increases copper losses (I^2R); and (4) raises operating temperature, accelerating insulation degradation [4]. A high reactive component combined with load imbalance can additionally raise neutral current and cause uneven winding heating [14].

Transformer losses consist of core (no-load) losses P_0 and load-dependent copper losses,

$$P_{cu} = I^2 R \quad (5)$$

which scale with the square of the load factor $K = S_{avg}/S_{FL}$,

$$K = \frac{S_{avg}}{S_{FL}} \quad (6)$$

$$P_{cu} = \left(\frac{S_{avg}}{S_{FL}} \right)^2 P_{cu, FL} \quad (7)$$

Transformer heating is dominated by this load-dependent copper loss [8], [19], making the hotspot temperature (HST) — considered safe up to 98°C at a 20°C ambient under IEC 60076-7 [10] — the primary driver of insulation ageing.

B. Transformer Thermal Ageing and Loss of Life

The hotspot temperature is obtained from the loss ratio $D = P_{cu}/P_0$, the top-oil temperature rise, and the hotspot–top-oil difference,

$$D = \frac{P_{cu}}{P_0} \quad (8)$$

$$\theta_{to} = \Delta \theta_{to, r} \left[\frac{1 + dK^2}{1 + d} \right]^x \quad (9)$$

$$\Delta \theta_h = H \Delta \theta_{wo} K^{2y} \quad (10)$$

$$\theta_h = \theta_a + \theta_{to} + \Delta \theta_h \quad (11)$$

where $\Delta \theta_{to, r} = 55^\circ\text{C}$ and $x = 0.9$ for ONAN/ONAF cooling, $H = 1.3$ is the hotspot factor, $y = 0.8$, and θ_a is the ambient temperature [10]. IEC defines the transformer base life as 20–20.5 years (7,300 days), with a normal loss-of-life rate of 0.0137%/day at the reference condition ($\theta_h = 98^\circ\text{C}$, $V = 1$) [10], [11]. The relative thermal ageing rate follows the Montsinger relationship [8],

$$V = 10^{\frac{\theta_h - 98}{19.93}} \quad (12)$$

equivalent to the IEEE C57.91 rule that ageing doubles for roughly every 6°C rise in HST. The loss of life (L) is obtained by integrating V over the observation period using Simpson's rule, and the projected remaining life (n) from the ratio of remaining base life to L [8], [9],

$$L = \frac{1}{3n} [V_0 + 4\sum V_{odd} + 2\sum V_{even} + V_n] \quad (13)$$

$$n = \frac{T_{base} - T_{used}}{L} \quad (14)$$

The validity of n depends heavily on how representative the time base and loading profile are, a limitation discussed in Section 4.6.

C. Research Gap

Prior studies have examined transformer ageing under reactive-power variation mainly through simulation on standard test networks [12] or physical thermal modeling on residential distribution systems with distributed-generation or EV-charging profiles [13], [16], and through reactive-power-compensation studies that stop short of relating results to transformer life [14]. Studies using field data are typically drawn from utility substations with comparatively stable, well-characterized load profiles [15]. Quantitative validation using actual SCADA measurements from a heavy industrial system with highly variable reactive loads — such as a cement plant driven by large synchronous and induction motors — remains limited. This study addresses that gap by integrating SCADA measurements, a controlled ETAP Q-sensitivity simulation, and IEC 60076-7 thermal ageing calculations to quantify the relationship between reactive power, transformer loading, hotspot temperature, and loss-of-life rate, while explicitly discussing the limitations of extrapolating long-term remaining life from short-term observation data.

III. METHOD

A. Research Flow

This study was conducted on the electrical system of PT Semen Tonasa, with six 70 kV power transformer units at the Tonasa IV and Tonasa V substations as the research object (Section 3.4). The research followed a closed-loop flow, in which each stage was checked against the objectives before proceeding, so that inconsistent results triggered a repeat with adjusted parameters: (1) literature review; (2) SCADA data collection; (3) ETAP modeling; (4) load-flow simulation with MVAR variation at fixed active power; (5) analytical ageing-rate calculation (Montsinger/IEC 60076-7); (6) consistency check, repeating (4)–(5) if needed; (7) analysis of VAR effects on current, voltage, power factor, and loss of life; and (8) conclusions and recommendations.

B. Data Collection Technique

Data were collected through three complementary methods. First, technical discussions with operators and engineers at PT Semen Tonasa to understand the system configuration and the operational history of the transformers. Second, retrieval of historical data from the SCADA system, which logs current, voltage, active power, reactive power, apparent power, power factor, frequency, and ambient

temperature at 10-minute intervals; because of data-access constraints on the production system, a continuous window of 3–5 days per transformer was exported, chosen to include normal daytime and night-time production shifts (with their associated peak- and low-load conditions) rather than a shutdown or start-up period, so that the sampled loading and reactive-power range is representative of routine operation even though it does not span all seasons. This constraint is revisited as a limitation in Section 4.6. Third, a review of the relevant standards (IEC 60076-7, IEEE C57.91) and prior literature as the theoretical basis for the calculations.

C. Data Analysis Technique

The analysis used two complementary approaches. First, a load-flow simulation in ETAP, varying the reactive power from 1 to 10 MVAR at a fixed active power of 10 MW to isolate, in a controlled manner, the relationship between reactive power and transformer loading; the model retains the inter-phase load imbalance already present in the PT Semen Tonasa one-line diagram, though phase-resolved imbalance indices are outside the present scope. The loading indicator used throughout this study, denoted “loading relative to the 80% operating limit,” is defined as $(S / 0.8 \cdot S_{\text{nominal}}) \times 100\%$, i.e. apparent power S expressed as a percentage of 80% of the transformer's rated capacity S_{nominal} (the healthy-loading limit defined in Section 2.1) — not as a percentage of the full nameplate rating — with S obtained from the ETAP output consistent with Equation (3). Second, an analytical calculation of the transformer ageing rate from actual SCADA loading data, using Equations (6)–(11) for the hotspot temperature and Equations (12)–(14) for the thermal ageing rate and remaining-life projection.

These two approaches are deliberately kept separate rather than merged into one combined Q-to-loss-of-life sensitivity table. The ETAP sweep is a controlled, instantaneous simulation used only to isolate how Q affects loading (Section 4.1); it produces no time series, whereas the ageing calculation in Equations (12)–(13) is a Simpson-rule integration requiring a chronological loading and temperature record. Because the ETAP scenarios and the SCADA-logged loading of each unit are not time-synchronized, propagating simulated loading directly into Equations (6)–(14) would assume a sustained condition never actually observed. The reactive-power-ageing relationship is therefore established mechanistically via Equations (1)–(14) and evaluated at actual operating points (Sections 4.2–4.5); a field

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trial recording Q, loading, and hotspot temperature simultaneously and continuously is identified as a priority for future work (Section 4.6).

D. Specifications of the Research Object

Table 1 presents the technical specifications of the power transformers studied. All six units use a primary-side voltage of 70 kV and a secondary-side voltage of 6.3 kV with an ONAN/ONAF cooling system. The Tonasa V units are dual-rated 30/40 MVA (ONAN/ONAF); the higher, ONAF value (40 MVA) is used as Snominal, i.e. the reference rating

for the 80% operating limit (32 MVA) and for the load factor K in Section 4.3, since ONAF is the cooling mode normally in service. Complete loss data (load and no-load losses) are available only on the Tonasa V nameplates; equivalent data for Tonasa IV could not be obtained during the study because of limited nameplate documentation in the field. Consequently, all six units are used for the loading-level analysis in Section 4.1–4.2, while the ageing-rate calculation in Section 4.3–4.5 is restricted to the three Tonasa V units, for which complete loss data are available.

Table 1. Specifications of the 70 kV Power Transformers at PT Semen Tonasa

Unit	Transformer	Capacity (MVA)	Voltage (kV)	Cooling System	Load Losses (kW)	No-Load Losses (kW)
Tonasa IV	#1	31.5	70/6.3	ONAN/ONAF	n/a *	n/a *
Tonasa IV	#2	31.5	70/6.3	ONAN/ONAF	n/a *	n/a *
Tonasa IV	#3	40	70/6.3	ONAN/ONAF	n/a *	n/a *
Tonasa V	#1	30/40	70/6.3	ONAN/ONAF	170	20
Tonasa V	#2	30/40	70/6.3	ONAN/ONAF	170	20
Tonasa V	#3	30/40	70/6.3	ONAN/ONAF	170	20

* Loss data for the Tonasa IV transformers were not available on site during the study.

IV. RESULTS AND DISCUSSION

A. Effect of VAR on Transformer Loading Level (ETAP Simulation)

The simulation was performed in ETAP by varying the reactive-power value (MVAR) from 1 to 10

Table 2. Simulation Results of Transformer Loading Level versus MVAR Variation

No.	Active Power (MW)	Reactive Power (MVAR)	Loading Level (%)
1	10	1	31.41
2	10	2	31.88
3	10	3	32.63
4	10	4	33.66
5	10	5	34.94
6	10	6	36.44
7	10	7	38.16
8	10	8	40.03
9	10	9	42.03
10	10	10	44.19

Table 2 and Figure 1 show that increasing the MVAR value consistently increases the transformer loading level, from 31.41% at MVAR = 1 to 44.19% at MVAR = 10. This increase is consistent with the rise in apparent power (S) that the transformer must carry as the reactive component of the load increases, in accordance with Equation (3): even though the

10 under a fixed active-power condition of 10 MW, on a load-flow model that retains the actual inter-phase load imbalance of the PT Semen Tonasa network; a full phase-resolved imbalance analysis is left for future work. Table 2 and Figure 1 present the results of the MVAR-variation scenario.

active power remains constant at 10 MW, the increase in the Q component raises the total load that the transformer must deliver. As explained in Sections 3.3 and 3.5(d), this 10 MW scenario is a controlled illustration, not a replication of the actual loading condition of each unit.

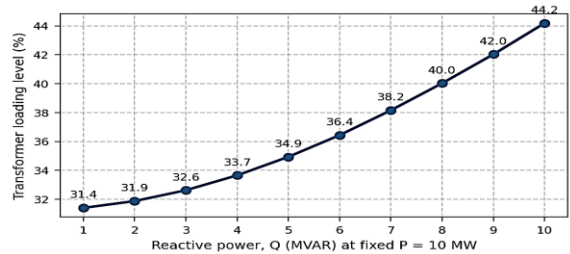


Figure 1. Transformer loading level versus MVAR variation at a fixed P = 10 MW.

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B. Effect of VAR on Voltage, Current, and Power Factor

Based on the SCADA operational data collected during the study period, voltage and current profiles were obtained for the transformers studied. For the Tonasa V transformers, the phase-to-phase (L-L) voltage was measured in the range of 66.68–68.95 kV. With a tolerance of $\pm 10\%$ of the 70 kV nominal voltage (lower limit 63 kV, upper limit 77 kV), all voltage values fall within the safe range, so that no undervoltage or overvoltage condition occurred.

A tendency toward decreasing voltage as the MVAR value increases was observed, consistent with power-system theory, in which an inductive load that absorbs reactive power causes the voltage profile to decline. The average current on the Tonasa V transformers ranged from 164–183 A and tended to

increase with increasing reactive load, because the transformer must deliver a larger apparent power in accordance with Equation (3) — with implications for increased copper losses per Equation (5) and the potential for a rise in operating temperature.

The effect of VAR on power factor is also evident: transformers with a higher MVAR value (Tonasa IV: 5.5–6.1 MVAR) have a power factor of around 0.90–0.91, while transformers with a lower MVAR value (Tonasa V #2: 0.5 MVAR) reach a power factor of 1.00, confirming the inverse relationship between reactive power and power factor described by Equation (4).

Table 4 summarizes the range of operational parameters observed from the SCADA data during the monitoring period, consolidating the values reported above for both substations.

Table 4. Summary of SCADA-Recorded Operating Parameter Ranges During the Monitoring Period

Substation	Reactive Power (MVAR)	L-L Voltage (kV)	Average Current (A)	Power Factor
Tonasa IV	5.5 – 6.1	n/a *	n/a *	0.90 – 0.91
Tonasa V	0.5 – 6.0 **	66.68 – 68.95	164 – 183	0.90 – 1.00

* Per-unit L-L voltage and current logs for the Tonasa IV transformers were not itemized in the SCADA export used for this study. ** Range inferred from the reported extremes among the Tonasa V units (0.5 MVAR for Unit #2 up to the higher-loaded units); see Section 4.3 for the per-unit ageing-rate calculation. Day-by-day SCADA logs and the complete ETAP load-flow case file underlying Tables 2–4 are archived by the authors and are available from the corresponding author upon reasonable request, subject to PT Semen Tonasa's data-sharing policy.

These trends are reported as ranges rather than a fitted regression of voltage, current, or power factor against Q , because the SCADA export available provides aggregate minimum–maximum values per transformer over the observation window rather than a timestamp-matched series of Q with the

corresponding V , I , and PF at each instant. A regression of the form $V, I, PF = a + bQ$, with reported slope, R^2 , and significance, is therefore left for future work using continuously logged, time-synchronized SCADA records (Section 4.6).

C. Ageing-Rate Calculation for the Tonasa V Transformers

Ageing-rate calculations were performed for the three 40 MVA Tonasa V transformer units using actual loading data from SCADA and Equations (6)–(14), because these three units have complete loss data on their nameplates (see Section 3.4). The calculation results are presented in Table 3 and Figure 2.

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Table 3. Summary of Ageing-Rate Calculation Results for the Tonasa V Transformers

Parameter	Transformer #1	Transformer #2	Transformer #3
Average load (MVA)	20.30	11.68	10.97
Load factor (K)	0.50	0.29	0.27
Loss ratio (D)	0.72	0.72	0.63
Top-oil temperature θ_{to} (°C)	39.23	35.60	36.89
Hotspot–top-oil difference $\Delta\theta_h$ (°C)	9.00	3.82	3.41
Hotspot temperature θ_h (°C)	75.23	65.42	67.30
Thermal ageing rate (V)	0.072	0.023	0.028
Loss of life L (pu/day)	0.069	0.022	0.027
Projected remaining life n (years) *	79.7	250	203

* The value of n is obtained from Equation (14), following Anca et al. [9] and the convention commonly used in the transformer loss-of-life literature based on IEC 60076-7 [8]. As explained in Section 3.5(c), this value is indicative and comparative in nature, not a literal life-expectancy prediction; a further discussion is given in Section 4.6.

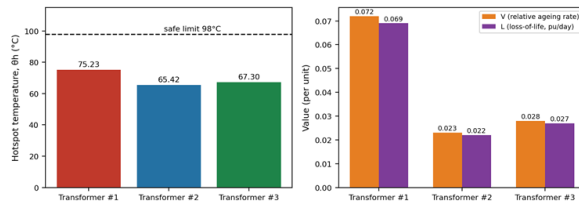


Figure 2. Comparison of (a) hotspot temperature and (b) ageing rate (V) and loss of life (L) for the three Tonasa V transformer units.

The calculation results show that the hotspot temperature of all three transformers is below the 98°C safety limit defined by IEC 60076-7. Transformer #1, with the highest average load (20.30 MVA, or 63.4% of the 32 MVA safe operating capacity), produces the highest hotspot temperature (75.23°C) and the highest thermal ageing rate ($V = 0.072$). Conversely, Transformer #2, with the lowest average load (11.68 MVA, or 36.5% of the safe operating capacity), produces the lowest hotspot temperature (65.42°C) and the lowest thermal ageing rate ($V = 0.023$). This pattern is consistent with the basic principle that a higher loading level — which in turn is associated with a larger reactive-power flow — accelerates the insulation ageing rate.

D. Interpretation of Loss of Life and Inter-Unit Comparison

The loss-of-life rate (L) in Table 3 — 0.022–0.069 pu/day — is the most direct and defensible result, since it follows directly from the measured

hotspot temperature without long-term extrapolation. For comparison, Juwita and Liliana [15] reported $L = 1.07$ pu/year for a substation transformer loaded at 89.5% of capacity — much closer to the design reference ($V = 1$ at 98°C) — while Rosyidi et al. [18] and Maruf and Primadiyono [19] likewise reported higher loss-of-life values as loading approached rated capacity. Although differing time bases and objects prevent a direct numerical comparison, these studies confirm that the Tonasa V units, operating far below their rated capacity, age correspondingly more slowly than the design reference condition.

Among the three units, Transformer #1 shows the highest thermal stress ($V = 0.072$; $L = 0.069$ pu/day), about 3.1 times that of Transformer #2 ($V = 0.023$; $L = 0.022$ pu/day), consistent with its higher load factor ($K = 0.50$ vs. 0.29; Table 3). This indicates the load distribution among units is not yet fully balanced: if the present loading pattern persists without reactive-power compensation or load-balancing, Transformer #1 will continue to age faster than the other two units, regardless of the absolute uncertainty in its projected remaining life (Section 4.6) — underscoring the need for proactive VAR management and load balancing, and for prioritizing Transformer #1 in condition monitoring.

E. Limitations and Directions for Future Work

The projected remaining-life values (79.7, 250, and 203 years) far exceed the transformer's design base life (20–20.5 years) and should not be read as literal service-life estimates: paper-insulation degradation is also driven by non-thermal factors — moisture, oxygen, contaminants, mechanical and chemical stress — not captured by the Montsinger/IEC 60076-7 thermal model [11], and the very large n values here simply reflect a relative ageing rate far below the design reference ($V = 1$ at 98°C) under the light loading observed. The result's

main value therefore lies in (1) confirming safe thermal operation throughout the observation period and (2) the relative ageing-rate comparison that flags Transformer #1 for monitoring priority, rather than in the absolute year figures. A longer observation period — ideally a 24-hour profile across multiple seasons, consistent with the Simpson-integration basis of IEC 60076-7 — would yield a more reliable projection.

A second limitation, noted in Sections 3.3 and 4.2, is that the reactive-power-ageing relationship here is established mechanistically ($Q \rightarrow S \rightarrow I \rightarrow P_{cu} \rightarrow HST \rightarrow V \rightarrow L$ via Equations (1)–(14)) and evaluated at actual operating points, rather than as one continuous sensitivity curve or regression fitted directly to Q , because the controlled ETAP sweep and the SCADA-based ageing calculation draw on two non-synchronized data sources, and the SCADA export summarizes V , I , and PF as observation-window ranges rather than a series matched to Q . Continuous, time-synchronized logging of Q , loading, and hotspot temperature across a wider operating range would allow this relationship to be quantified directly — e.g., a Q -versus-hotspot-temperature sensitivity table analogous to Table 2, and a regression of V , I , PF , and loss of life against Q with slope, R^2 , and significance — yielding a direct numerical link between reactive power and insulation loss of life.

V. CONCLUSION

Reactive power has a measurable, mechanistically consistent effect on both the performance and the insulation ageing of the 70 kV transformers at PT Semen Tonasa. Raising VAR from 1 to 10 MVAR at a fixed 10 MW active load increased loading (relative to the 80% operating limit) from 31.41% to 44.19%, with a concurrent tendency of rising current, falling primary-side voltage, and a power factor decreasing from near unity to 0.90–0.91 — all voltages remaining within $\pm 10\%$ of nominal. For the three Tonasa V units with complete loss data, the resulting hotspot temperatures (65.42–75.23°C) stayed below the 98°C IEC 60076-7 limit, with loss-of-life rates of 0.022–0.069 pu/day; Transformer #1, the most heavily loaded, aged roughly 3.1 times faster than Transformer #2, identifying it as the priority unit for condition monitoring. The extrapolated remaining-life figures (79.7–250 years) are indicative only, given the short (3–5-day) SCADA window and the constant-loading assumption used; the loss-of-life rate remains the primary, more defensible indicator. Reactive-power

compensation — via capacitor banks or, for more variable loads, a static var compensator [20] — together with load balancing across units and routine hotspot monitoring — which can be integrated with an Internet-of-Things-based capacitor-bank monitoring system [7] — is recommended to limit current, contain insulation ageing, and extend transformer service life.

The transformer loading and hotspot-temperature calculations reported in Tables 2–4 and Figures 1–2 are derived from SCADA operational records and an ETAP load-flow case file belonging to PT Semen Tonasa. These underlying daily records contain internal operational details of the company's electrical system and are therefore not published in full as a public dataset. The processed summary values used in this study, together with the ETAP case file, are archived by the corresponding author and can be made available to editors, reviewers, or other researchers upon reasonable written request and subject to PT Semen Tonasa's internal data-sharing policy.

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