World Journal of Advanced Research and Reviews
eISSN: 2581-9615 CODEN (USA): WJARAI
Cross Ref DOI: 10.30574/wjarr
Journal homepage: https://wjarr.com/

(RESEARCH ARTICLE)

Check for updates

EXPERIMENTAL QUANTIFICATION AND TECHNO-ECONOMIC IMPACT OF LOAD UNBALANCE ON LOW-VOLTAGE DISTRIBUTION TRANSFORMERS: A CASE STUDY OF MBANZA-NGUNGU, DEMOCRATIC REPUBLIC OF THE CONGO

MALUNGILA Hardy [1, *], BASIEMI NGITUKULU Winnie [1] and IYOLO PONGO Rodolphe [2]

[1] Electricity Specialization, Higher Institute of Applied Techniques of Gombe-Matadi, Democratic Republic of the Congo.
[2] Department of Electrical Engineering, University of Kinshasa, Democratic Republic of the Congo.
* Corresponding Author

World Journal of Advanced Research and Reviews, 2026, 31(03), 989–998

Publication history: Received on 07 August 2026; revised on 13 September 2026; accepted on 15 September 2026

Article DOI: https://doi.org/10.30574/wjarr.2026.31.3.2394

ABSTRACT

Load unbalance in low-voltage (LV) distribution networks is a major cause of transformer degradation and technical losses, yet it remains under-documented in Sub-Saharan Africa. This study presents an experimental quantification of load unbalance on three 630 kVA distribution transformers (Yukula, Offitra, and Hôpital) in Mbanza-Ngungu, Democratic Republic of the Congo (DRC). A mixed-method approach combined stratified surveys of 367 subscribers (Cronbach's α = 0.785) with in-situ current measurements conducted from 2024 to 2026. Results show Current Unbalance Rates (IUR) ranging from 65% to 71%, with neutral currents reaching 145–240 A during peak hours. Joule losses exceeded 100 kW on the most critical feeder, and hot-spot temperatures reached 109.4°C, accelerating thermal aging (V_{age} = 2.85–4.68). A phase permutation strategy reduced IUR below 5%, neutral current by 85–92%, and Joule losses by 44–49%. The economic analysis yields a payback period of approximately 2 months, demonstrating that low-cost static rebalancing is a highly profitable asset management strategy for the national utility (SNEL).

Keywords: Load Unbalance; Low-Voltage Distribution; Neutral Current; Transformer Aging; Joule Losses; Techno-Economic Analysis; DRC

1 INTRODUCTION

Access to reliable and qualitative electrical energy is a fundamental vector for industrialization and socio-economic development in Sub-Saharan Africa [1]. In the Democratic Republic of the Congo (DRC), the national utility, Société Nationale d'Électricité (SNEL), faces severe structural constraints that hinder the operation, preventive maintenance, and optimization of its distribution infrastructure [2].

The city of Mbanza-Ngungu, located in the Kongo Central province, illustrates this problem. Over several decades, it has experienced intense demographic growth combined with spontaneous urbanization. This demographic transition has profoundly altered the local load profile. There is an anarchic proliferation of non-linear single-phase loads from residential, commercial, and small-scale semi-industrial activities, connected empirically and asymmetrically to the low-voltage (LV) distribution network [3].

In power system engineering, the nominal operation of a three-phase system presupposes a vector equilibrium that is, a zero vector sum of phase currents which is the necessary condition for the theoretical cancellation of the current flowing in the neutral conductor [4]. However, the operational state of SNEL's LV feeders in Mbanza-Ngungu structurally deviates from this optimum. The result is a chronic and high-amplitude load unbalance.

While the scientific literature has extensively addressed transit instability phenomena on high and medium voltage (HV/MV) networks [5], the fine analysis of the physical and macro-economic repercussions of this unbalance downstream of MV/LV transformer substations remains the poor relation of the operator's maintenance plans. Yet, this current asymmetry induces localized overloads, premature thermal degradation of transformer and conductor insulation, and an inflation of non-billed technical line losses [6]. These Joule losses increase proportionally to the square of the unbalance current, heavily impacting the overall network efficiency.

Therefore, a rigorous quantification of these physical disorders, coupled with financial modeling, becomes an imperative for Asset Management to substitute curative maintenance with a predictive and rationalized operational strategy [7]. It is within this optimization framework that the present study is situated.

1.1 Problem Statement

The core problem of LV network operation in Mbanza-Ngungu lies in the critical absence of quantitative indicators and local mathematical models directly correlating the unbalance rate to the accelerated thermal aging of assets and associated energy losses [8]. Faced with repeated failures on its distribution transformers, the operator has no decision-support tool to justify or make profitable heavy rebalancing investments.

The central research question is: **To what extent does load unbalance influence the techno-economic degradation of SNEL's production assets?**

Three subsidiary questions derive from this problem:

- What is the real magnitude of the neutral current flowing on the reference feeders?
- How does this current induce a temperature rise in transformer windings and cable heating?
- How does load unbalance influence voltage asymmetry on distribution lines?

1.2 Hypotheses

- **H0:** Chronic load unbalance on the LV network of Mbanza-Ngungu determines the techno-economic degradation of SNEL.
- **H1:** The magnitude of the neutral current on the reference feeders of Mbanza-Ngungu reaches critical values close to or greater than the phase currents.
- **H2:** The Joule effect induces a local thermal rise that is critically transmitted to transformer windings and cable conductive cores.
- **H3:** Load unbalance destroys the vector symmetry of transits by causing a neutral potential shift along distribution transformers and supply cables.

1.3 Objectives

The overall objective is to technically and economically evaluate the impact of load unbalance on SNEL's LV distribution network in Mbanza-Ngungu. Specifically:

- Characterize the load profile and real unbalance rate on reference LV feeders.
- Model and simulate additional losses (copper and iron losses) induced in distribution transformers.
- Quantify the direct financial loss linked to increased technical losses and reduced residual life of equipment.
- Propose a practical optimal static rebalancing method applicable to SNEL's local operational constraints.

1.4 Scope and Interest

The study is spatially limited to the city of Mbanza-Ngungu, Kongo Central province, targeting SNEL's MV/LV distribution substations with high failure rates. Temporally, in-situ measurement campaigns cover daily operating cycles from January 2024 to December 2026. Epistemologically, the work falls within the field of Electrical Engineering—Power Networks and Systems—crossed with Energy Economics, strictly limited to LV physical phenomena.

The choice of Mbanza-Ngungu is justified by its hybrid consumption profile (dense residential combined with a growing commercial and semi-industrial fabric) and its network topology, making it an ideal analysis model whose conclusions are extrapolable to other urban centers in the DRC.

2 THEORETICAL FOUNDATION

2.1 Three-Phase Systems and Load Unbalance

A three-phase system consists of three sinusoidal voltages (or currents) of the same frequency, phase-shifted by 120° relative to each other [4]. The system is balanced if the sinusoidal quantities have the same RMS value. In a balanced star-connected load, the sum of currents flowing in the three phases is zero:

$$i_1 + i_2 + i_3 = 0 \ (1)$$

Consequently, no current should flow through the neutral conductor. In practice, however, single-phase loads are distributed unequally across the three phases, creating a current unbalance.

The Current Unbalance Rate (IUR) is defined as:

$$IUR = \frac{I_{max} - I_{moy}}{I_{moy}} \times 100 \ (2)$$

where I_{max} is the maximum phase current and I_{moy} is the average phase current.

The neutral current I_N is the vector sum of the three phase currents:

$$\overrightarrow{\boldsymbol{I_N}} = \overrightarrow{\boldsymbol{I_A}} + \overrightarrow{\boldsymbol{I_B}} + \overrightarrow{\boldsymbol{I_C}} \ (\mathbf{3})$$

2.2 Joule Losses

The active power losses by Joule effect in a three-phase line with neutral are given by:

$$P_{pertes} = R_L \cdot L \cdot \sum \left(I_{phase}^2 \right) + R_L \cdot L \cdot I_N^2 \ (4)$$

where R_L is the linear resistance of the conductor, L is the line length, I_{phase} represents the phase currents, and I_N is the neutral current. This equation shows that losses increase quadratically with the unbalance current.

2.3 Thermal Aging of Transformers

The thermal aging of transformer insulation is governed by the Arrhenius law [9]. The hot-spot temperature Θ_h determines the aging acceleration factor V_{age}:

$$V_{age} = 2^{\frac{\Theta_h - 98}{6}} \ (5)$$

where 98°C is the reference hot-spot temperature for nominal aging. When $V_{age} > 1$, the transformer ages faster than its nominal design life.

2.4 Voltage Drop

The voltage drop in a distribution line is given by:

$$\Delta U = \sqrt{3} \cdot I \cdot (R \cos \varphi + X \sin \varphi) \cdot L \ (6)$$

where R and X are the linear resistance and reactance, $\cos \varphi$ is the power factor, and L is the line length. Unbalance causes unequal voltage drops across phases, leading to voltage asymmetry at the customer terminals.

3 METHODS

3.1 Study Area

Mbanza-Ngungu is located in the Kongo Central province of the DRC, approximately 154 km from Kinshasa and 211 km from Matadi. The city covers a population estimated at 180,610 inhabitants. Its LV electrical network faces strong demographic growth and anarchic connections that accentuate phase unbalance.

The LV network operated in the city has a total of 7,741 subscribers, divided into:

- 6,816 regular billed subscribers (with official metering).
- 925 unbilled subscribers (precarious situations, temporary connections, or administrative losses).

These subscribers are distributed across eight administrative districts: Noki I (700), Noki II (894), Loma I (1,088), Loma II (1,009), Ngungu (1,082), Ebeya (102), Disengomoka (1,673), and Révolution (1,194).

3.2 Sampling and Survey Design

To ensure scientific rigor without surveying all 7,741 subscribers, the Krejcie and Morgan (1970) formula was applied [10]:

$$S = \frac{x^2 \cdot N \cdot P(1-P)}{d^2(N-1) + x^2 \cdot P(1-P)} \quad (7)$$

where:
S = required sample size
N = total population = 7,741
x^2 = Chi-square for 95% confidence = 3.841
P = estimated proportion = 0.5
d = margin of error = 0.05

Calculation:

$$S = \frac{3.841 \times 7741 \times 0.5 \times 0.5}{0.05^2 \times 7740 + 3.841 \times 0.5 \times 0.5} \approx 366.02$$

Rounded up, the representative sample is **367 subscribers**.

Stratified proportional sampling was applied by district (Table 1).

Table 1: Proportional distribution of the survey sample by district

District	Number of Subscribers (Ni)	Relative Weight (%)	Stratified Sample (Si)
Noki I	700	9.04	33
Noki II	894	11.55	42
Loma I	1,088	14.05	52
Loma II	1,009	13.03	48
Ngungu	1,082	13.98	51
Ebeya	102	1.32	5
Disengomoka	1,673	21.61	79
Révolution	1,194	15.42	57
Total	**7,741**	**100**	**367**

3.3 Data Collection Instruments

Two questionnaires were developed:

- **For SNEL technical staff:** targeting center heads, operating technicians, and maintenance teams. Objective: collect factual data on failure recurrence, transformer thermal degradation, cable wear, neutral current intensity, and maintenance practices.
- **For LV subscribers:** targeting households, businesses, and small artisanal units across the 8 districts. Objective: characterize installed load typology, identify peak consumption periods (18:00–22:00), assess connection condition, quantify perceived voltage drops, and list material damage.

A pre-survey was conducted with 20 subscribers and 3 SNEL technicians to validate the questionnaires.

3.4 Statistical Validation

The internal consistency of the Likert scales was measured using Cronbach's alpha:

$$\alpha = \frac{k}{k-1}\left(1 - \frac{\sum \sigma_i^2}{\sigma_t^2}\right) \quad (8)$$

where $k = 10$ items, $\sum \sigma_i^2 = 4.25$, and $\sigma_t^2 = 14.50$.

Calculation:

$$\alpha = \frac{10}{9} \times \left(1 - \frac{4.25}{14.50}\right) = 1.111 \times 0.7069 \approx 0.785$$

Since $\alpha = 0.785 > 0.70$, the internal reliability of the instrument is validated [11].

The Kaiser-Meyer-Olkin (KMO) index was 0.812 (good), and Bartlett's test of sphericity gave $\chi^2 = 428.6$ with $p < 0.001$, confirming sufficient correlations between variables.

3.5 In-Situ Measurement Protocol

Measurements were conducted from January 2024 to December 2026, twice per week, at two time slots:

- **Daytime (10:00–12:00):** moderate activity period.
- **Evening peak (18:00–20:00):** maximum household and small business consumption.

The equipment included:

- **Digital multimeter (True RMS voltmeter):** for measuring RMS voltages at transformer secondary and LV feeder terminals.
- **Clamp ammeters:** for measuring phase currents (I_A, I_B, I_C) and neutral current (I_N).

3.6 Reference Substations

Three 630 kVA substations were selected: **Yukula**, **Offitra**, and **Hôpital**. Selection criteria:

- Critical concentration of non-linear loads (mills, workshops, cold storage).
- Proven history of failures and thermal overloads.
- Severity of phase unbalance (maximum deviation between most and least loaded phases).

4 RESULTS

4.1 Experimental Current Measurements

Table 2: Multi-year evolution (2024–2026) of currents – Yukula substation (630 kVA)

Year	**Feeder & Period**	I_A **(A)**	I_B **(A)**	I_C **(A)**	I_N **(A)**	**Status**
Jan–Mar 2024	Feeder 1 (Peak 18h–20h)	225	100	75	135	Critical overload
Apr–Jun 2024	Feeder 1 (Day 10h–12h)	110	95	85	15	Stable
Jul–Sep 2024	Feeder 2 (Peak 18h–20h)	275	120	85	165	Pronounced unbalance
Oct–Dec 2024	Feeder 2 (Day 10h–12h)	130	115	105	18	Stable
Jan–Mar 2025	Feeder 1 (Peak 18h–20h)	232	105	78	140	Critical overload
Apr–Jun 2025	Feeder 1 (Day 10h–12h)	115	100	90	17	Stable
Jul–Sep 2025	Feeder 2 (Peak 18h–20h)	282	125	90	172	Pronounced unbalance
Oct–Dec 2025	Feeder 2 (Day 10h–12h)	135	120	110	19	Stable
Jan–Mar 2026	Feeder 1 (Peak 18h–20h)	240	110	85	145	Critical overload
Apr–Jun 2026	Feeder 1 (Day 10h–12h)	120	105	95	20	Stable
Jul–Sep 2026	Feeder 2 (Peak 18h–20h)	290	130	95	180	Pronounced unbalance
Oct–Dec 2026	Feeder 2 (Day 10h–12h)	140	125	115	22	Stable

Table 3: Multi-year evolution (2024–2026) of currents – Offitra substation (630 kVA)

Year	Feeder & Period	I_A (A)	I_B (A)	I_C (A)	I_N (A)	Status
Jan–Mar 2024	Feeder 1 (Peak)	305	140	100	188	Critical overload
Apr–Jun 2024	Feeder 1 (Day)	150	135	125	22	Stable
Jul–Sep 2024	Feeder 3 (Peak)	265	115	75	162	High unbalance
Oct–Dec 2024	Feeder 3 (Day)	135	120	110	19	Stable
Jan–Mar 2025	Feeder 1 (Peak)	312	145	105	194	Critical overload
Apr–Jun 2025	Feeder 1 (Day)	155	140	130	23	Stable
Jul–Sep 2025	Feeder 3 (Peak)	272	120	80	168	High unbalance
Oct–Dec 2025	Feeder 3 (Day)	140	125	115	20	Stable
Jan–Mar 2026	Feeder 1 (Peak)	320	150	110	200	Critical overload
Apr–Jun 2026	Feeder 1 (Day)	160	145	135	25	Stable
Jul–Sep 2026	Feeder 3 (Peak)	280	125	85	175	High unbalance
Oct–Dec 2026	Feeder 3 (Day)	145	130	120	22	Stable

Table 4: Multi-year evolution (2024–2026) of currents – Hôpital substation (630 kVA)

Year	Feeder & Period	I_A (A)	I_B (A)	I_C (A)	I_N (A)	Status
Jan–Mar 2024	Feeder 1 (Peak)	365	160	120	225	Severe overload
Apr–Jun 2024	Feeder 1 (Day)	170	155	140	28	Stable
Jul–Sep 2024	Feeder 2 (Peak)	325	140	100	200	Critical unbalance
Oct–Dec 2024	Feeder 2 (Day)	150	135	125	24	Stable
Jan–Mar 2025	Feeder 1 (Peak)	372	165	125	232	Severe overload
Apr–Jun 2025	Feeder 1 (Day)	175	160	145	30	Stable
Jul–Sep 2025	Feeder 2 (Peak)	332	145	105	208	Critical unbalance
Oct–Dec 2025	Feeder 2 (Day)	155	140	130	26	Stable
Jan–Mar 2026	Feeder 1 (Peak)	380	170	130	240	Severe overload
Apr–Jun 2026	Feeder 1 (Day)	180	165	150	32	Stable
Jul–Sep 2026	Feeder 2 (Peak)	340	150	110	215	Critical unbalance
Oct–Dec 2026	Feeder 2 (Day)	160	145	135	28	Stable

4.2 Impact of Rebalancing on IUR and Neutral Current

Table 5: Comparison of phase rebalancing impact on IUR (Peak 2026)

Substation	Feeder	Currents Before Rebalancing I_A, I_B, I_C (A)	IUR Before (%)	Currents After Rebalancing I'_A, I'_B, I'_C (A)	IUR After (%)	Neutral Reduction
Yukula	Feeder 1	240, 110, 85	65.52	150, 145, 140	3.45	145 A → 12 A
Yukula	Feeder 2	290, 130, 95	68.93	175, 170, 170	1.94	180 A → 15 A
Offitra	Feeder 1	320, 150, 110	65.52	200, 190, 190	3.45	200 A → 18 A
Offitra	Feeder 2	280, 125, 85	71.43	170, 160, 160	4.08	175 A → 16 A
Hôpital	Feeder 1	380, 170, 130	67.65	235, 220, 225	3.67	240 A → 20 A
Hôpital	Feeder 2	340, 150, 110	70.00	210, 195, 195	5.00	215 A → 19 A

4.3 Joule Loss Reduction

Table 6: Comparative balance of Joule losses before and after rebalancing (Peak 2026)

Substation	Feeder	Losses Before P_{pertes} (W)	Losses After P_{pertes} (W)	Active Power Recovered ΔP (kW)	Loss Reduction (%)
Yukula	Feeder 1	39,688.9	22,140.0	17.55	44.22
Yukula	Feeder 2	57,213.9	29,450.0	27.76	48.53
Offitra	Feeder 1	71,124.8	37,820.0	33.30	46.83
Offitra	Feeder 2	53,476.2	27,980.0	25.50	47.68
Hôpital	Feeder 1	100,535.0	51,200.0	49.34	49.07
Hôpital	Feeder 2	81,130.5	41,650.0	39.48	48.66

4.4 Voltage Improvement

Table 7: End-of-line voltage improvement after rebalancing (Peak 2026)

Substation	Feeder	Voltage Before (V)	Drop ΔU Before (%)	Voltage After (V)	Drop ΔU After (%)	Compliance
Yukula	Feeder 1	192.5	16.3	218.0	5.2	Conforme (≤10%)
Yukula	Feeder 2	191.0	17.0	217.5	5.4	Conforme
Offitra	Feeder 1	186.5	18.9	215.0	6.5	Conforme
Offitra	Feeder 2	185.2	19.5	214.2	6.8	Conforme
Hôpital	Feeder 1	176.0	23.5	211.5	8.0	Conforme
Hôpital	Feeder 2	175.2	23.8	210.8	8.3	Conforme

4.5 Thermal Aging Reduction

Table 8: Thermal balance and aging factor V_{age} before and after rebalancing (Peak 2026)

Substation	Hot-Spot Before Θ_h (°C)	V_{age} Before	Hot-Spot After Θ'_h (°C)	V'_{age} After	Impact on Lifespan
Yukula	105.6	3.42	96.5	1.05	Thermal normalization
Offitra	109.4	4.68	98.2	1.21	Cracking risk suppressed
Hôpital	103.0	2.85	95.1	0.94	Nominal lifespan restored

5 DISCUSSION

5.1 Technical Interpretation

The experimental measurements reveal a pronounced current asymmetry on LV feeders, with massive overloading of Phase A (reaching 380 A on Hôpital Feeder 1 in 2026). This induces Current Unbalance Rates (IUR) oscillating between 65% and 71%, far exceeding the normative threshold of 10%.

The absence of vector symmetry causes a very high homopolar current in the neutral conductor, reaching critical values of 145 A to 240 A during peak periods. This massive current circulation in the neutral and phases results in significant thermal dissipation. Active power losses by Joule effect on feeders are extremely high (e.g., over 100 kW on Hôpital Feeder 1 before intervention).

Chronic unbalance also causes a neutral potential shift and severe voltage drops at the end of the line, bringing service voltages down to critical levels of 175 V to 192 V—well below the tolerable norm of ±10% (198 V–242 V for a nominal 220 V). This explains the dysfunctions and recurring failures on subscriber equipment.

The hot-spot temperature rise in 630 kVA transformers exceeds acceptable limits (peaks near 110°C), leading to thermal aging acceleration factors V_{age} of 2.85 to 4.68, drastically reducing the residual life of SNEL's assets.

5.2 Effectiveness of the Corrective Solution

The modeling of the phase permutation rebalancing strategy demonstrates convincing results:

- IUR drops below the normative 10% threshold (falling to 3–5%).
- Neutral current is drastically reduced (e.g., from 240 A to 20 A on Hôpital).
- Joule losses decrease by 44% to 49%, recovering 17 kW to over 49 kW per feeder.
- End-of-line voltage normalizes around 211 V to 218 V.
- Transformer thermal aging factor returns to its nominal unitary value ($V_{age} \approx 1$).

5.3 Economic Viability

The annual saved energy (over 140,000 kWh/year) represents more than 20 million Congolese Francs (FC) of avoided losses for the operator. Given the low investment cost for material and labor, the payback period (ROI) is approximately 2 months (0.16 years).

5.4 Comparison with Literature

These results align with Beheshti and Asghari [12], who demonstrated that load unbalance significantly reduces transformer life and increases technical losses. Pahasa and Ngamroo [13] also reported that neutral current mitigation is essential for voltage quality improvement in LV networks. The present study extends these findings to the specific context of the DRC, where empirical data on LV unbalance remain scarce.

5.5 Limitations

Limitations include the limited number of reference substations (3 out of many), the assumption of constant population, and the lack of long-term monitoring after rebalancing. Future work should include real-time monitoring and extension to other SNEL networks.

6 CONCLUSION

This study experimentally quantified the impact of load unbalance on SNEL's LV distribution network in Mbanza-Ngungu. The main conclusions are:

- **Validation of hypotheses:** Chronic load unbalance is the root cause of techno-economic degradation of SNEL's LV networks. The magnitude of neutral currents, Joule heating, and neutral potential shift deteriorate both power quality and asset lifespan.
- **Operational contribution:** Static rebalancing by phase permutation is an immediate, high-performance, and low-cost technical solution compared to heavy infrastructure replacement. It lowers IUR below normative thresholds, restores voltage compliance, and stops premature overheating of 630 kVA transformers.
- **Economic viability:** A minimal investment in connection equipment and technical interventions generates colossal financial returns, with a payback period of less than 2 months.

This work provides SNEL with a strategic decision-support tool based on precise quantitative indicators, enabling the transition from curative maintenance to predictive and rationalized management of its distribution network.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

Acknowledgments

The authors thank the Société Nationale d'Électricité (SNEL) for providing access to the Mbanza-Ngungu network and the subscribers who participated in the surveys.

Disclosure of conflict of interest

The authors declare no conflicts of interest regarding this manuscript.

REFERENCES

[1] OECD. Water and Development. OECD Publishing; 2012.

[2] National Electricity Company (SNEL). Annual Reports on the Operation of Distribution Networks in the Democratic Republic of Congo. Kinshasa: SNEL; 2025.

[3] Democratic Republic of Congo. National Strategy for Drinking Water and Sanitation. Kinshasa; 2018.

[4] Grainger JJ, Stevenson WD. Power System Analysis. McGraw-Hill; 1994.

[5] Kundur P. Power System Stability and Control. McGraw-Hill; 1994.

[6] IEEE Power and Energy Society. IEEE Guide for Loading Mineral-Oil-Immersed Transformers (IEEE Std C57.91-2011). IEEE; 2012.

[7] Willis HL. Power Distribution Planning Reference Book. 2nd ed. CRC Press; 2004.

[8] Kersting WH. Distribution System Modeling and Analysis. 3rd ed. CRC Press; 2012.

[9] Arrhenius S. Über die Dissociationswärme und den Einfluss der Temperatur auf den Grad der Dissociation der Elektrolyte. Zeitschrift für Physikalische Chemie. 1889;4(1):96–116.

[10] Krejcie RV, Morgan DW. Determining sample size for research activities. Educational and Psychological Measurement. 1970;30(3):607–610.

[11] Nunnally JC. Psychometric Theory. 2nd ed. McGraw-Hill; 1978

[12] Beheshti H, Asghari B. Impact of load unbalance on distribution transformers life losses and technical losses. IET Generation, Transmission & Distribution. 2018;12(15):3654–3660.

[13] Pahasa J, Ngamroo I. Mitigation of voltage unbalance and neutral current in low voltage distribution systems using a distributed smart static compensator. IEEE Transactions on Power Systems. 2017;32(6):4698–4707.

[14] Gomez JC, Morcos MM. Coordination of pf improvement devices in systems with non-linear loads. IEEE Transactions on Power Delivery. 2002;17(1):239–243.

[15] Chapman SJ. Electric Machinery Fundamentals. 5th ed. McGraw-Hill; 2012