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Health Index Evaluation of Power Transformers Based on Electrical and Insulation Diagnostic Parameters

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Abstract

Power transformers are essential components of electrical power transmission systems, where insulation deterioration and operational aging can compromise reliability and increase the risk of failure. Comprehensive condition assessment is therefore necessary to support effective maintenance planning and enhance transformer asset management. This study aims to assess the condition of power transformers using a Health Index (HI) approach that integrates electrical and insulation diagnostic parameters. The study was conducted on 14 power transformers installed at 150-kV transmission substations. The assessment incorporated several diagnostic parameters, including dissolved gas analysis (DGA), moisture content, acidity, interfacial tension, breakdown voltage, insulation resistance, dielectric dissipation factor (tan δ), winding resistance, and sweep frequency response analysis (SFRA). These parameters were integrated into five assessment factors: internal fault indicators, paper insulation condition, insulating oil quality, electrical insulation condition, and winding condition. The results indicated that four transformers were classified as Very Good, four as Good, three as Fair, and three as Poor. Furthermore, the analysis revealed a negative relationship between transformer service age and HI values, with a coefficient of determination (R^2) of 0.7793, suggesting a strong association between aging and transformer condition. Field verification confirmed that the HI classifications were consistent with the transformers' actual operating conditions and diagnostic findings. This study demonstrates that the proposed HI method provides a comprehensive and practical framework for assessing transformer condition, supporting more effective condition monitoring, preventive maintenance planning, and informed decision-making in power system asset management.

INTRODUCTION

Power transformers are among the most critical assets in modern electrical power transmission networks because they are essential for voltage transformation, power transfer, and maintaining the continuity of electricity supply (Bindi et al., 2023; Mharakurwa, 2022; Olajuyin & Olubakinde, 2022; Rahman, 2023). The increasing demand for reliable electricity infrastructure has intensified the need for effective transformer asset management, particularly because unexpected transformer failures can cause widespread power outages, increased maintenance costs, and reduced power system reliability. Transformer outages may also compromise the stability of interconnected transmission networks, especially under high-load conditions when system flexibility is limited. Therefore, maintaining the operational reliability of power transformers has become a significant challenge for electric utilities worldwide (Azmi et al., 2022; Ma et al., 2026; Mharakurwa, 2022; Rahman, 2023; Vita et al., 2023).

The reliability of power transformers is strongly influenced by the condition of their insulation systems, which gradually deteriorate due to continuous exposure to thermal, electrical, mechanical, and environmental stresses. Long-term operation may accelerate insulation aging through elevated operating temperatures, excessive loading, insulating oil oxidation, moisture contamination, and mechanical stresses affecting transformer components. Insulation degradation is considered a major contributor to transformer failure because deterioration processes can progress into severe internal faults if they are not detected and addressed at an early stage. Consequently, accurate condition assessment methods are required to identify degradation trends and support preventive maintenance strategies before catastrophic failures occur.

Transformer condition assessment has become increasingly important as many transmission assets continue operating beyond their original design life. Conventional maintenance strategies based solely on fixed schedules may not accurately reflect the actual condition of individual transformers because each unit experiences different operational stresses, loading profiles, environmental conditions, and maintenance histories. Diagnostic techniques such as dissolved gas analysis (DGA), insulation resistance measurement, dielectric dissipation factor (tan δ) testing, moisture analysis, and dielectric breakdown voltage testing have been widely applied to evaluate transformer conditions. However, assessing transformers using a single diagnostic parameter often provides limited information and cannot fully characterize the overall condition of complex transformer systems.

Recent studies have demonstrated the importance of integrating multiple diagnostic parameters into a comprehensive assessment framework. The Health Index (HI) method has been widely adopted as an approach that combines various electrical and insulation condition indicators into a single quantitative value representing the overall condition of a transformer. Zeinoddini-Meymand and Vahidi (2016) developed a transformer HI calculation method using condition-monitoring parameters, demonstrating that multiple diagnostic indicators can provide a more representative assessment than individual parameters. Similarly, Tang et al. (2012) proposed a simplified transformer HI model for reliability assessment by integrating condition-related parameters into a unified evaluation framework.

Previous research has also investigated transformer aging through indicators of insulation degradation. Studies have demonstrated that diagnostic parameters such as dissolved gas concentrations, insulating oil quality characteristics, dielectric properties, and winding conditions provide valuable information about transformer deterioration mechanisms. Recent investigations have employed advanced diagnostic techniques, including artificial intelligence (AI)-based approaches and predictive maintenance models, to enhance transformer condition monitoring. However, many existing studies have focused on specific diagnostic aspects, particularly oil-based parameters, without comprehensively integrating electrical and insulation characteristics into a single evaluation framework.

The limitations of previous approaches highlight a research gap in the development of a comprehensive HI evaluation model that simultaneously incorporates multiple electrical and insulation diagnostic parameters across transformer populations. Although individual diagnostic techniques provide valuable information, their isolated application may not adequately capture the combined effects of insulation degradation, declining electrical performance, insulating oil deterioration, and mechanical condition changes. Furthermore,

relatively few studies have examined how individual diagnostic factors contribute to overall HI classifications and how these classifications correspond to actual transformer operating conditions.

Addressing this research gap is important because accurate transformer condition assessment directly supports condition-based maintenance and strategic asset management decisions. Inaccurate assessments of transformer condition may lead to unnecessary maintenance activities, inefficient resource allocation, or delayed corrective actions that increase the risk of failure. Therefore, electric utilities require an assessment framework capable of integrating diverse diagnostic data into a reliable indicator that reflects actual transformer conditions. The HI approach offers potential advantages by enabling condition classification and supporting the prioritization of maintenance activities based on transformer health status.

The novelty of this research lies in the application of a multiparameter HI evaluation framework that integrates electrical and insulation diagnostic parameters across a population of operating power transformers. Unlike approaches that primarily rely on a limited set of insulating oil diagnostic indicators, this study incorporates DGA, moisture content, acidity, interfacial tension, dielectric breakdown voltage, insulation resistance, dielectric dissipation factor (tan δ), winding resistance, and sweep frequency response analysis (SFRA). These parameters are organized into five assessment factors: internal fault indicators, paper insulation condition, insulating oil quality, electrical insulation condition, and winding condition. This integration provides a more comprehensive representation of transformer health.

This study aims to assess the condition of 14 power transformers installed at 150-kV transmission substations using an integrated HI approach based on electrical and insulation diagnostic parameters. Specifically, the study examines transformer condition categories, identifies the dominant diagnostic factors contributing to HI values, evaluates the relationship between transformer service age and health condition, and verifies the consistency between calculated HI classifications and actual field observations. Through this approach, the study seeks to provide empirical evidence regarding the applicability of multiparameter HI assessment to transformer condition evaluation.

The primary contribution of this research is the development of a practical assessment framework that can assist electric utilities in implementing condition monitoring, preventive maintenance planning, and transformer asset management. By providing a comprehensive assessment based on multiple diagnostic indicators, the proposed approach can improve the understanding of transformer degradation mechanisms and support more informed maintenance decisions. The findings are expected to contribute to advances in transformer reliability management by demonstrating the applicability of the HI method as a practical tool for assessing the condition of operating power transformers.

METHOD

The study examined 14 power transformers installed at 150-kV transmission substations, with rated capacities ranging from 30 to 60 MVA and varying service ages and loading conditions. Diagnostic data were obtained from routine testing and condition-monitoring activities conducted as part of transformer maintenance programs. These data reflected the electrical and insulation conditions of the transformers during operation.

Diagnostic Parameters

Transformers condition evaluation was performed using several electrical and insulation diagnostic parameters commonly adopted in transformer condition assessment practices. The evaluated parameters include dissolved gas analysis (DGA), moisture content, acidity, interfacial tension (IFT), colour, breakdown voltage (BDV), insulation resistance, tan delta, winding resistance, and sweep frequency response analysis (SFRA). These parameters were selected because they are capable of representing transformer internal fault indications, insulation degradation characteristics, dielectric performance, insulating oil quality, and winding mechanical conditions (Kurniawan & Sudiarto, 2025; Vatsa & Hati, 2024). The diagnostic parameters and corresponding standards adopted in this study are summarized in Table I.

Table 1. Diagnostic Parameters And Test Standards

Parameter	Standard
DGA	IEC 60599
Moisture	IEC 60422
Acidity	IEC 62021
IFT	ASTM D971
Colour	ASTM D1500
BDV	IEC 60156
Insulation Resistance	IEEE STD 43
Tan Delta	IEC 60247
Winding Resistance	IEC 60076
SFRA	IEC 60076-18

Source: Author's own work based on IEC and IEEE standards.

Fig. 1 shows the Health Index framework used in this research. The diagnostic criteria were grouped into different evaluation groups based on oil quality, electrical insulation condition, paper insulation condition, internal fault indication, and winding condition.

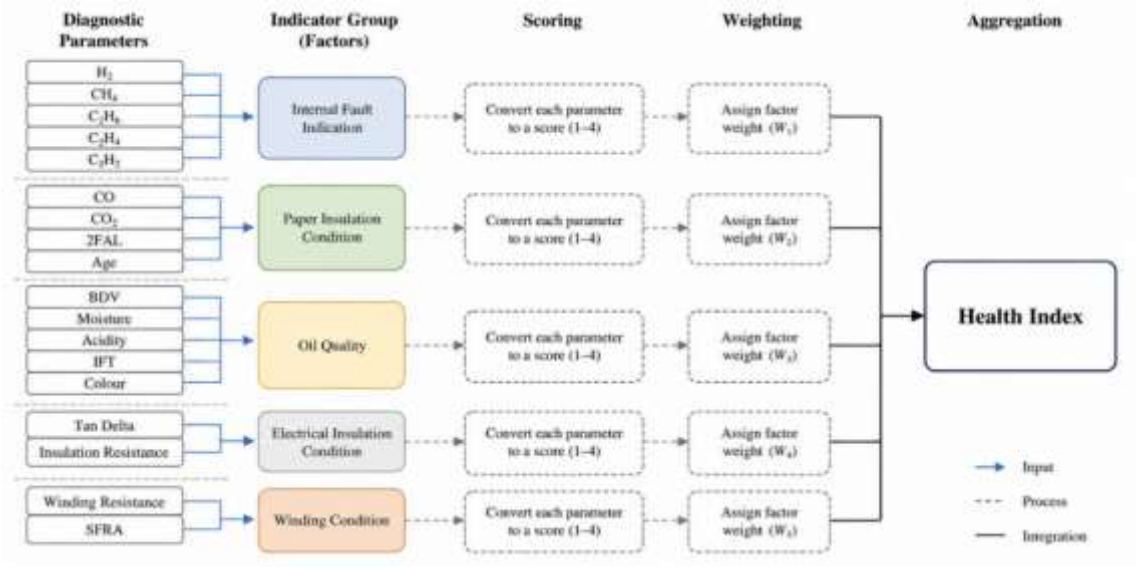


Figure 1. Health Index Framework

Source: Author's own work based on the Health Index evaluation framework.

Each parameter was given a weighting factor based on its contribution to the evaluation of the transformer's state and turned into a score value. Following that, the weighted scores from each evaluation group were combined to arrive at the overall transformer Health Index value

(Abu-Elanien & Salama, 2010). The equation for calculating HI expressed in (1) (Tang et al., 2012).

$$HI = \frac{\sum_{i=1}^{n} W_i S_i}{\sum_{i=1}^{n} W_i} \times 100\% \quad (1)$$

The symbols description for Wi denotes the weighting factor of parameter i , Si denotes the score of parameter i , n denotes the total number of diagnostic parameters.

Diagnostic Classification

The calculated Health Index values were categorized into several transformer condition levels to facilitate interpretation of transformer health conditions. The classification adopted in this study is presented in Table II (Tang et al., 2012).

Table 2. Health Index classification

Health Index	Condition Category
85 ≥	Very Good
85-70	Good
50-70	Fair
30-50	Poor
≤ 30	Very Poor

Source: Adapted from Tang et al. (2012).

Transformers classified within the good category indicate satisfactory electrical and insulation conditions, whereas transformers categorized as poor or very poor indicate substantial insulation deterioration and require further technical evaluation.

Data Analysis

The obtained Health Index values were further analysed to evaluate the overall condition of the transformer population and to identify dominant diagnostic parameters contributing to transformer degradation. Comparative analysis was also conducted to investigate the relationship between transformer operational age and Health Index values. Furthermore, the distribution of transformer condition categories was evaluated to provide a comprehensive representation of transformer health characteristics within the investigated transformer population.

RESULT AND DISCUSSION

The results of transformer Health Index evaluation using electrical and insulation diagnostic factors are discussed in this section. The acquired Health Index values were analysed to assess transformer condition, pinpoint key diagnostic elements that cause transformer degradation, and investigate the connection between operational age and transformer health status. In addition, the Health Index values that were computed were used to analyse the overall state features of the transformer group that was studied.

Health Index Evaluation Results

The Health Index values of the studied transformers were calculated by integrating several electrical and insulation diagnostic parameters into several assessment groups, including internal fault indication (IF), paper insulation condition (PI), oil quality (OQ), electrical insulation condition (EI), and winding condition (WC). Table III presents the weighted contribution values of each assessment factor and the resulting Health Index values for the investigated transformers.

Table 3. Health Index Evaluation Results

Transformer	IF	PI	OQ	EI	WC	HI	Condition
T1	0.834	1.047	0.519	0.496	0.304	80.00	Good
T2	0.556	0.349	0.346	0.124	0.304	41.13	Poor
T3	1.112	1.396	0.519	0.496	0.076	89.98	Very Good
T4	0.556	0.349	0.173	0.124	0.304	37.65	Poor
T5	1.112	1.396	0.692	0.496	0.304	100.00	Very Good
T6	0.556	1.047	0.173	0.124	0.076	49.40	Poor
T7	1.112	0.698	0.346	0.124	0.304	64.60	Fair
T8	1.112	1.396	0.519	0.372	0.304	92.58	Very Good
T9	1.112	1.396	0.519	0.496	0.304	95.68	Very Good
T10	0.556	1.396	0.519	0.496	0.304	81.78	Good
T11	0.834	1.047	0.519	0.248	0.304	73.80	Good
T12	0.556	1.047	0.519	0.248	0.304	66.85	Fair
T13	1.112	0.698	0.346	0.496	0.076	68.20	Fair
T14	0.834	1.396	0.519	0.248	0.304	82.53	Good

Source: Author's own work based on transformer diagnostic data analysis.

Analysis of Diagnostic Factors

The data shown in Table III demonstrate that the examined transformers have varying Health Index scores depending on the significance of each evaluation element. Paper insulation, oil quality, and electrical insulation are often higher in transformers that are classified as being in excellent condition, suggesting adequate dielectric and insulation characteristics. On the other hand, transformers classified in poor condition tend to exhibit lower contribution values in several assessment factors, particularly oil quality and electrical insulation.

Oil quality was identified as one of the dominant factors affecting transformer Health Index values. Lower oil quality contributions generally indicate deterioration of insulating oil characteristics associated with increased moisture content, oxidation products, and reduced dielectric strength. Degradation of insulating oil may accelerate insulation aging and reduce transformer operational reliability (ASTM International, 2016; Gupta et al., 2025).

The electrical insulation factor also significantly influences transformer condition assessment. Lower electrical insulation contributions indicate deterioration of dielectric characteristics caused by thermal stress, contamination, and moisture ingress. These conditions may increase dielectric losses and reduce insulation performance during transformer operation (Ekanayake et al., 2016). In addition, the paper insulation factor contributes significantly to the overall transformer condition. Higher paper insulation contributions indicate relatively good cellulose insulation condition, whereas lower values may indicate degradation of paper insulation caused by thermal aging and long-term operational stress (Vatsa & Hati, 2024).

The internal fault factor derived from dissolved gas analysis (DGA) results also contributes to transformer Health Index values. Abnormal gas generation patterns may indicate thermal faults, partial discharge activity, or electrical discharge phenomena occurring within transformer insulation systems (Institute of Electrical and Electronics Engineers [IEEE], 2019). Meanwhile, the winding condition factor obtained from winding resistance and SFRA measurements reflects the mechanical and electrical integrity of transformer windings during operation (Duanaputri et al., 2024).

The obtained results demonstrate that the Health Index values are influenced by combined effects of oil degradation, insulation deterioration, thermal stress, and long-term operational conditions. Integration of these diagnostic factors enables a more comprehensive evaluation of transformer condition using the Health Index approach.

Relationship of Age and Health Index

Transformer operational age is one of the factors influencing Health Index values due to continuous exposure to thermal, electrical, and environmental stresses during service operation. In general, transformers with longer operational periods tend to exhibit lower Health Index values compared to units with relatively shorter service ages. This condition reflects gradual degradation of transformer insulation systems caused by aging mechanisms and long-term operational stresses (Vatsa & Hati, 2024). The correlation between the Health Index values and the transformer's operating age is shown in Fig. 2.

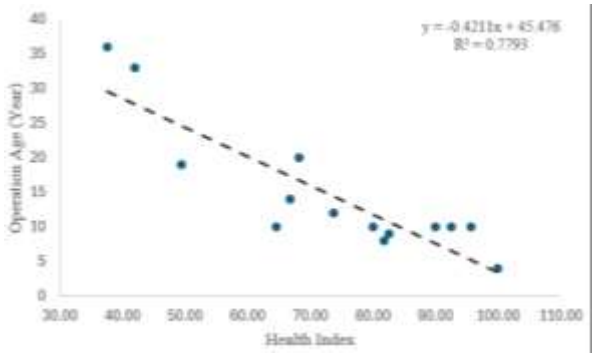


Figure 2. Relationship between operational age and transformer Health Index values.
Source: Author's own work based on correlation analysis results.

Fig. 2 indicates a negative correlation between transformer operational age and Health Index values with an R^2 value of 0.7793, suggesting that transformer aging has a considerable impact on overall transformer condition. The observed trend shows that increasing operational age is generally accompanied by decreasing Health Index values due to deterioration in oil quality, paper insulation, and electrical insulation characteristics. Several transformers with relatively long operational periods exhibit lower Health Index values as a result of insulation degradation caused by continuous thermal stress and prolonged operating conditions. Thermal aging may accelerate cellulose deterioration, increase moisture formation, and reduce dielectric strength of transformer insulation systems (Jongen et al., 2015). However, transformers that are used for similar durations may have different Health Index values. This finding indicates that transformer condition is not determined solely by service age but is also influenced by loading characteristics, maintenance quality, environmental conditions, and operational stresses (Abu-Elanien et al., 2012). Transformers operating under heavier loading conditions tend to experience faster insulation deterioration compared to transformers operating under normal operating conditions. Furthermore, transformers with proper maintenance practices and effective oil treatment histories generally maintain better Health Index values despite having relatively long service periods. These findings demonstrate that maintenance management and operational practices play important roles in preserving transformer reliability and insulation performance throughout transformer operation.

The evaluation results confirm that transformer operational age has a significant relationship with Health Index values, although transformer condition is also affected by operational and maintenance characteristics. Therefore, transformer condition assessment should not rely exclusively on operational age but should also incorporate comprehensive diagnostic evaluation based on multiple electrical and insulation parameters.

Classification of Transformer Condition

The assessment results indicate that the investigated transformers exhibit varying condition levels based on the calculated Health Index values. A significant portion of the transformer population is classified in very good and good categories, indicating that most units still maintain acceptable insulation performance and operational reliability. These transformers generally demonstrate stable oil characteristics, satisfactory dielectric performance, and minimal indications of internal fault activity. Nevertheless, several transformers are categorized in fair and poor conditions due to lower contributions from oil quality, paper insulation, and electrical insulation factors. Reduced values in these assessment factors indicate degradation of transformer insulation systems associated with thermal aging, moisture ingress, oxidation processes, and prolonged operational stresses (Paul & Goswami, 2024). The distribution of transformer condition categories based on Health Index values is presented in Fig. 3.

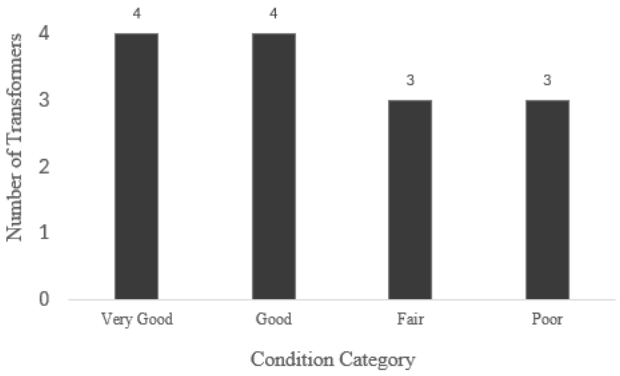


Figure 3. Distribution of transformer condition categories based on Health Index values.
Source: Author's own work based on Health Index classification results.

As illustrated in Fig. 3, four transformers are classified in very good condition and four transformers are categorized in good condition, indicating that the majority of the investigated units are still operating under satisfactory conditions. In contrast, three transformers fall within the fair category and three transformers are classified in poor condition, indicating deterioration in insulation and dielectric characteristics in several transformer units. Transformers categorized in poor condition generally exhibit lower insulation reliability and degraded oil quality characteristics compared to transformers operating in good and very good conditions. These conditions may increase the probability of insulation failure and reduce transformer operational reliability if proper maintenance and continuous monitoring activities are not implemented (Badawi et al., 2022).

Verification of Health Index Results Based on Actual Field Conditions

In addition to the quantitative assessment based on diagnostic parameters, verification was conducted by comparing the obtained Health Index classifications with the actual

conditions observed in the field. This verification process aims to evaluate the capability of the Health Index method in representing the real operating condition of transformers. The comparison was performed using inspection findings, diagnostic test records, maintenance history, and operational observations. By comparing the calculated Health Index values with actual transformer conditions, the effectiveness of the proposed assessment approach can be further evaluated (Tang et al., 2012; Zeinoddini-Meymand & Vahidi, 2016).

Table 4. Comparison Of Health Index Classification And Actual Field Conditions

Category	Transformer	Actual Field Condition
Very Good	T3, T5, T8, T9	No significant abnormalities observed during inspection and diagnostic testing. The transformers maintain satisfactory insulation performance and operational reliability.
Good	T1, T10, T11, T14	Operating normally with acceptable diagnostic test results and requiring routine maintenance activities to preserve transformer reliability.
Fair	T7, T12, T13	Minor indications of insulation and oil degradation were identified, requiring periodic monitoring and preventive maintenance to prevent further deterioration.
Poor	T2, T4, T6	Inspection and diagnostic results revealed several abnormalities, including elevated combustible gas concentrations (C_2H_2, C_2H_6, and CO), increased moisture and acidity levels, oil leakage, physical corrosion, low insulation resistance, hotspot indications, abnormal tan delta values, and winding resistance deviations. These conditions indicate significant deterioration of the insulation system and may adversely affect transformer reliability if corrective actions are not implemented.

Source: Author's own work based on field verification results.

Table IV shows that the Health Index classifications are generally consistent with the actual field conditions of the investigated transformers. Transformers in the Very Good and Good categories exhibited satisfactory operating performance without significant abnormalities. Transformers classified as Fair remained suitable for operation but require periodic monitoring. Meanwhile, transformers categorized as Poor showed various indications of insulation degradation, oil quality deterioration, and operational abnormalities. These results demonstrate that the Health Index method can effectively represent transformer condition and support maintenance decision-making (Badawi et al., 2022; El-Rashidy et al., 2025; Gupta et al., 2025).

CONCLUSION

This study demonstrated the applicability of the Health Index (HI) approach for assessing power transformer conditions by integrating multiple electrical and insulation diagnostic parameters, including dissolved gas analysis (DGA), moisture content, acidity, interfacial tension, dielectric breakdown voltage, insulation resistance, dielectric dissipation factor (tan δ), winding resistance, and sweep frequency response analysis (SFRA). Integrating these parameters into a single assessment indicator provided a more comprehensive representation of transformer condition than assessments based on individual diagnostic parameters. The assessment of 14 power transformers installed at 150-kV transmission substations identified four transformers classified as Very Good, four as Good, three as Fair, and three as Poor. Lower HI values were associated with insulation degradation, deteriorating insulating oil quality, abnormal dissolved gas concentrations, and declining electrical

performance. Furthermore, the analysis revealed a negative relationship between transformer service age and HI values, with a coefficient of determination (R^2) of 0.7793, indicating a strong association between aging and transformer condition deterioration. However, transformer condition was also influenced by operating conditions, maintenance practices, and environmental factors. Field verification indicated that the HI classifications were consistent with observed transformer conditions, supporting the potential application of this approach as a practical tool for condition monitoring and maintenance planning.

Future research should expand the proposed HI evaluation framework by incorporating a larger population of transformers operating at different voltage levels and under diverse environmental and loading conditions to improve the model's generalizability. Further studies could also incorporate advanced analytical techniques, including machine learning, predictive modeling, and adaptive weighting methods, to enhance transformer condition prediction and remaining useful life estimation. Integrating real-time monitoring data into the HI framework could further support continuous condition assessment and facilitate more proactive maintenance strategies in power system asset management.

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