**Review on multiple short circuits accumulation effects on power transformers**

Abduvokhid Abdullaeva), Tulkin Jabborov, Feruza Nasretdinova, Feruza Khalilova

Fergana state technical university, Fergana, Uzbekistan

a) Corresponding author: [abdullevabduvokhid@gmail.com](mailto:abdullevabduvokhid@gmail.com)

**Abstract.** This paper aims to serve as a valuable resource for researchers and industry professionals, offering insights into mitigating the cumulative effects of short circuits and improving the reliability and lifespan of power transformers. This paper investigates the impact of multiple short-circuit events on power transformer windings, with an emphasis on their cumulative effects. A systematic review of research conducted over the past decade is presented, focusing on the influence of short circuits on transformer windings. The article analyzes simulation and experimental studies, discussing their key results and insights. The findings reveal that each short-circuit event contributes to the accumulation of facts such as heat, stress and electromagnetic forces, resulting in cumulative deformation of the transformer windings. This progressive deformation accelerates the transformer’s aging process, reduces its mechanical and electrical stability, and negatively affects its operational parameters. Over time, the cumulative impact significantly increases the likelihood of winding failures and transformer breakdowns, especially under subsequent short circuits or overloads. This article aims to serve as a valuable resource for researchers and engineers seeking to mitigate and evaluate the cumulative effects of short circuits on power transformers in future studies.

**INTRODUCTION**

Electricity is one of the main parts of all sectors, requiring the reliable and continuous operation of power systems to deliver stable and high-quality energy to consumers. At the heart of these systems, power transformers play a crucial role in transmitting and distributing electricity, ensuring the stability of the power network [1]. However, as one of the most critical and expensive components, power transformers are prone to failures, particularly those caused by short-circuit events [2], [3], [4]. Such failures disrupt system reliability and cause substantial financial losses for manufacturers and consumers alike [5], [6], [7].

Short-circuit failures remain a significant challenge in the energy sector [2], [3], [8], [9], [10], [11]. These events often lead to mechanical deformation of transformer windings. Multiple short circuits causing cumulative damage characterized by progressive deformation, reduced mechanical strength, and accelerated transformer aging [5], [6], [12], [13]. Transformers that have been in service for over 20 years show a marked decline in their resilience to short-circuit impacts due to aging insulation and mechanical support systems [2]. While international standards such as IEC and IEEE are in place to improve short-circuit tolerance, repeated short circuits continue to degrade transformer performance, shortening their operational lifespan [14]. Recent studies report that over 30% of transformer failures are due to insufficient short-circuit tolerance [3], [12], [13], [15]. The cumulative effects of short circuits are particularly problematic because they are often hidden and progressive. Each short-circuit event contributes to the accumulation of mechanical stress and thermal damage [16], which may not be immediately visible but significantly reduces the transformer's ability to withstand future faults. This makes it difficult for operators to predict when a transformer will fail, leading to unplanned outages and costly repairs. Furthermore, the impact of transformer failures extends beyond replacement costs, as they can disrupt the power supply to critical infrastructure, even leading to blackouts. For example, a single transformer failure can cost energy companies millions of dollars in repair and replacement expenses, not to mention the indirect losses associated with power outages. In 2011, a power outage incident caused an estimated $60 million in economic losses [17].

To better understand the effects of short-circuit faults, researchers have developed simulation models, such as finite element models [18], [19], [20] for analyzing transformer failure and equivalent circuit models for diagnosing winding behavior [21]. However, challenges persist in accurately calculating plastic deformation and predicting cumulative damage caused by repeated short-circuit events. These limitations underscore the need for further investigation into the cumulative effects of multiple short circuits on transformer windings.

This paper systematically reviews the cumulative impact of multiple short-circuit events on power transformer windings by synthesizing recent research findings, including simulation and experimental studies. The article identifies critical gaps in existing studies, particularly in assessing cumulative deformation, and provides insights into improving transformer diagnostics, durability, and lifespan. By addressing these challenges, this work aims to advance academic research while offering practical guidance for industry professionals to enhance power system reliability and reduce operational risks.

**LITERATURE REVIEW**

2.1 **Studies on Short-Circuit Tolerance.** Scientists and researchers have conducted studies in areas such as the cumulative deformation of power transformers, the thermal accumulation effect of short circuits, the determination of elastic modulus based on the degree of polymerization, analyze transient vibration signals under the influence of short circuits, simulation of the effect of short circuits on transformer windings. These studies have led to several important findings.

A team of researchers led by Shuhong Wang at Xi'an Jiao tong University developed a model to study plastic deformation in transformer windings using ANSYS and Maxwell software [2]. Their research revealed that short-circuit currents are particularly intense in the low-voltage windings of transformers, where the resulting dynamic electromagnetic forces initially reach their peak amplitude and then gradually diminish. The study notes that when plastic deformation occurs in the winding material, the hardening criterion adjusts the yield limit as plastic strain increases, enabling the calculation of cumulative deformation. This process depends on factors such as the total strain increment, the current stress state, and the specific properties of the yield function. Furthermore, it was found that plastic deformation only takes place when the maximum stress exceeds the yield stress level of the windings. Also, the model was further utilized to investigate the impact of pre-stress on winding deformation. The findings demonstrated that the maximum plastic cumulative deformation in the winding discs forms a "V" shape pattern relative to the applied pre-stress. And, the minimum total plastic deformation closely matches the pre-stress amplitude specified in the transformer's initial parameters. The study also observed rapid and significant strain variations in the winding when electromagnetic forces acted in radial and axial directions. The article misses key points: the effect of short circuits on elastic deformation, environmental impact, and insulation aging. Simulations lack comparison with experiments. Claims about superconducting transformers lack supporting details.

Scientists of China Electric Power Research Institute [12] studied cumulative plastic deformation of power transformer insulating paper due to short circuit under various conditions. The following results were obtained: The cumulative deformation of the insulating paper is positively related to the number and impact of short circuit. The aging process, polymerization degree, and elastic modulus decrease, while cumulative deformation increases. As the magnitude of the short-circuit force increases, cumulative deformation and elastic modulus increase. The impact of multiple short circuits on cumulative deformation is greater for long-interval than for short-interval. One 80 MPa short-circuit force impact to cumulative deformation of insulation paper is approximately equivalent to the six 50 MPa short-circuit force impacts. And one 120 MPa short-circuit force impact to cumulative deformation of insulation paper is approximately equivalent to the four 80 MPa short-circuit force impacts. The article is well-written but overlooks some details. Environmental factors like temperature, vibration, and operational conditions are ignored. Short-circuit force variations in transformers of different sizes are not explored. Testing 150 conditions is thorough but could benefit from more variables like temperature ranges and paper types.

Ming Hui Duan and other researchers [13] developed a two-wire vibration model to illustrate the relationship between forces and mechanisms. They emphasize that cumulative effect of power transformer divided two group: thermal accumulation and force accumulation. They also analyzed transient vibration signals under the influence of short circuits. Experiments revealed that 95% of the deformation in the insulating pressboard strain occurs during the first load, with only minor increases in deformation as the load continues. After 22 short-circuit impacts, there were no significant changes in short-circuit impedance. The authors emphasized that the damage to the winding under short-circuit stress is a cumulative process. When the winding deforms or experiences looseness faults, the vibration entropy and half-frequency ratio increase, while the dominant frequency ratio decreases. Gradually, slight deformation accumulates over time, eventually leading to complete damage to the winding. The drawbacks of article: the article covers the cumulative effect of short circuits but could expand to include electrical performance, environmental factors, and maintenance strategies. Research doesn’t explore temperature, humidity.

Zongxi ZHANG, Yun FENG, Rui LIU, Qiang OU, and Junwen REN proposed the obtaining radial buckling stress (ORBS) method to analyze the radial stability of transformer windings. This method is based on the non-equivalent force differences observed at various heights [14]. The actual stress in transformer windings was simulated using the finite element method in the COMSOL Multiphysics software. The simulation revealed that the magnetic field lines connect the upper and lower parts of the winding, and the radial component of the leakage flux increases, while the axial component decreases. The deformation stress intervals obtained by simulation showed a difference of 1.59% when compared with the deformation stress intervals obtained from the test method. Transformers experiments multiple short circuits were conducted by gradually increasing the short-circuit current. These experiments showed an increase in impedance, while the capacitance remained nearly unchanged. The article highlights that after multiple short circuits if the winding does not experience permanent deformation, it means that the maximum stress is lower than the critical stress. According to the authors, when analyzing radial stability, it is essential to focus on the critical force or steps of buckling deformation. When calculating the permissible voltage [22] the dimensions of the winding and the conductor must be considered. If only the radial width is excluded, the permissible voltage calculated according to the IEC standard shows a 42% higher value. The research article on the mechanical stability of power transformer windings identifies several drawbacks, including the notable challenge of determining the critical force boundary.

Electric Power Research Institute of State Grid Tianjin Electric Power Company’s researchers [23] studied how the degree of polymerization and the elastic modulus of insulation cardboard change with different levels of heat accumulation. The article highlights that during a short circuit, an adiabatic process occurs, leading to thermal accumulation in the transformer winding. This causes the degree of polymerization to decrease from 800 to 400, and even to 280, which can result in plastic deformation. Experiments conducted on insulation cardboard under cyclic loading demonstrated that the response of elastic deformation is rapid and plastic deformation is small. In experiments, it was observed that with an increase in heat accumulation time, the stress-strain cycle curve also increases. Additionally, as the heat accumulation time or the number of cycles increases, the maximum strain rises. The maximum strain values of insulation cardboard with different levels of thermal accumulation grow differently as the number of cycles increases. Furthermore, with increasing heat accumulation time, the elastic modulus of the insulation materials decreases. The article's limitations include limited focus on mechanical deformation and insulation wear due to electromechanical forces. Real-world factors like load fluctuations, ambient temperatures, and prolonged use are not fully addressed. The study assumes an adiabatic process for short circuits under 10 seconds, which may not reflect heat dissipation in longer or repeated cases. Findings are specific to oil-paper and cardboard insulation, limiting applicability to transformers with other insulation systems.

Conducting high short-circuit tests on large-capacity power transformers is both expensive and poses significant risks. To address this issue, a research team at Xi'an Jiao tong University evaluated the reliability of simulation calculations by comparing them with analytical calculations conducted on a real-type transformer [24]. The study utilized a 3D model of a 110 kV transformer in ANSYS software to carry out numerical simulations. The researchers examined the relationship between stress and deformation in transformer insulation and simulated the winding's mechanical behavior under short-circuit conditions. The results showed that as the short-circuit current passing through the winding increases, both the deformation and maximum equivalent stress also increase. Moreover, electromagnetic forces were found to concentrate in areas where plastic deformation had already occurred, further intensifying damage in those regions. After repeated short-circuit events, the winding was significantly damaged. Similarly, short-circuit tests on an operational transformer revealed that electromagnetic forces accumulate in deformed areas of the winding, heightening the risk of additional damage during future short-circuit incidents. The deformation width obtained as a result of the simulation showed an average difference of 11.1% compared to the deformation width obtained as a result of the experiment. The article details electromagnetic-mechanical coupling but is limited to a 110 kV transformer, lacks analysis of aging effects, does not focuses high and low-voltage behavior.

Yuxin Miao and his team investigated the magnetic force characteristics of windings with cumulative damage resulting from short circuits [25]. Their findings revealed that such damage typically manifests as radial warping, axial tilt, and axial displacement. A comparison of healthy and damaged windings showed the following: In axially descended windings, magnetic leakage at the top and bottom shifts radially, while the overall leakage flux distribution slightly moves upward. In radially warped windings, the outward-warped areas experience an increase in leakage flux, including a rise in the maximum leakage flux. Conversely, in inward-warped sections, leakage flux decreases but causes a rise in leakage flux in nearby windings. In windings with axial tilt, the leakage flux significantly increases near the wire closest to the main channel side. The study also demonstrated that the harmonic response of damaged windings in the 100-200 Hz frequency range shows higher vibration signal amplitudes than healthy windings. This difference is especially prominent in axially tilted windings, where a noticeable variation occurs at 300 Hz. Furthermore, axial descent in windings results in increased axial forces at the top, leading to a shift in stress distribution upward. In radially warped windings, stress tends to concentrate in neighboring coils. The cumulative damage effects of short circuits on windings are well-covered, but some gaps remain: the study is based on a specific prototype, a 40,000 kVA/110 kV transformer, which may not generalize well to other transformer designs, sizes, or configurations. It highlights specific damage modes, such as radial warping, axial tilt, and axial dislocation, but overlooks others and excludes external factors like aging, temperature, and humidity. The lack of experimental validation reduces practical reliability.

The cumulative impact of repeated short circuits leads to plastic deformation, aging, and deterioration of material properties. Simulation and experimental tests reveal that electromagnetic forces and heat accumulation are key contributing factors. However, certain gaps remain, such as the exclusion of environmental factors and insulation aging, which emphasizes the need for further improvements to enhance transformer reliability and protection.

**2.2** **Finite Element Models.** Finite Element Analysis (FEA) is a commonly used computational method to simulate and analyze the physical behavior of complex systems, including power transformer windings [26], [27]. Recently, it has become the preferred approach for studying transformer short-circuit characteristics [28]. By dividing the winding structure into smaller elements, FEA evaluates electromagnetic forces, mechanical stress, and deformation during short circuits with high precision.

In the context of short circuits, FEA plays a crucial role in evaluating:

* Electromagnetic forces from high fault currents causing mechanical stress on windings [29].
* **Mechanical stress and deformation** caused by these axial and radial forces [28], [30].
* Thermal effects like localized heat generation that accelerate insulation wear [26], [31].

FEA is often preferred over experimental methods for several reasons:

* Testing transformers before operation often leads to 30% failures, increasing expenses [29], [32].
* Obtaining transient process or core loss results experimentally is challenging [33].
* It ensures accurate results and insights often unachievable in experiments [29].

Studies confirm that FEM results closely match experimental outcomes, proving its reliability [32]. Additionally, several advanced software tools are commonly used for FEA in transformer studies:

* **ANSYS Maxwell**: examined the impact of electromagnetic forces on transformer performance [34], analyzed internal electromagnetic forces during both normal operation and short-circuit conditions [35]. Additionally, employed to model the current, magnetic flux density, and heat distribution in the coils It was used to model the current, magnetic flux density, and heat distribution in the coils [33], as well as ANSYS Workbench used to obtain the temperature profile of an oil-immersed distribution transformer [36].
* **COMSOL Multiphysics**: utilized to model the thermal characteristics and heat transfer of the porcelain bushing in both 2D and 3D models [37], to simulate winding damage caused by repeated short circuits by analyzing mechanical responses under various short-circuit loads [6]. Also, transient currents during short-circuit faults in transformers were examined, employing a 3-phase fault and an equivalent model to analyze electromagnetic forces [38]. Furthermore, applied to investigate the mechanical behavior of transformer windings during external short-circuit faults [39], analyze factors influencing transformer winding radial strength using a 2D axisymmetric magnetic-structure model [40], and study heat dissipation and ferrofluid effects inside a transformer [41]
* **OrCAD /** PSpice. The transformer winding model was created using OCAD and analyzed with PSpice to study the effects of axial shifting and radial deformation on its performance [42].

These tools enhance understanding of transformer behavior, improving design and testing.

FEA studies show the effect of short-circuit forces on transformer performance. It helps detect inter-turn faults by calculating leakage inductance, which is more accurate than traditional methods. Leakage inductance is higher in secondary windings due to more turns and lower current, impacting fault detection. FEA compares 2D and 3D models, with 3D providing more detail on magnetic energy and leakage inductance, especially at coil ends [27]. FEA also shows that radial forces are strongest in the middle of windings, while axial forces are strongest at the top and bottom [35]. It detects stress distribution in the windings, pointing out regions that may deform under electromagnetic forces. FEA results can also evaluate the winding's fatigue life, illustrating how repeated stress impacts the transformer's durability [43].

FEA offers several advantages in transformer studies. It provides accurate calculations of leakage inductance and magnetic flux during short-circuit conditions, which simplifies solving electromagnetic field problems [27], [35]. It also helps analyze mechanical stresses and deformations in transformer windings, identifying critical failure points. The FEM can be used to study winding deformations and other important parameters [44]. FEA simulates different short-circuit scenarios, helping engineers predict failures and design stronger transformers [43]. It shows where the highest stresses are in windings during short-circuits, improving transformer safety and reducing the risk of failures in electrical systems.

FEA is a key tool for studying transformer windings, helping to analyze leakage inductance, electromagnetic forces, and mechanical deformations. However, its accuracy depends on computational complexity, model assumptions, and validation. 3D FEA requires high computing power, while 2D models are faster but may not fully capture leakage flux and winding interactions. The accuracy of results relies on numerical methods and input parameters like core material properties, winding geometry, and nonlinear magnetic behavior. Simplified assumptions, such as ideal boundary conditions, can cause differences between simulations and real transformer performance [27], [35].

Modeling limitations impact the accuracy of FEA. The challenge of linking electromagnetic forces with mechanical stresses makes achieving precise results more difficult [43]. During faults, windings experience strong electromagnetic and mechanical stresses, making multi-physics simulations essential. These simulations require precise material definitions and validation with experimental data [45]. To ensure reliability, FEA results must be compared with experimental or analytical methods. Differences can arise due to simplifications in boundary conditions or material modeling. Hybrid approaches combining FEA with analytical techniques improve accuracy [27], [35]. Modeling limitations impact the accuracy of FEA. The challenge of linking electromagnetic forces with mechanical stresses makes achieving precise results more difficult [43]. During faults, windings experience strong electromagnetic and mechanical stresses, making multi-physics simulations essential. These simulations require precise material definitions and validation with experimental data [45]. To ensure reliability, FEA results must be compared with experimental or analytical methods. Differences can arise due to simplifications in boundary conditions or material modeling. Hybrid approaches combining FEA with analytical techniques improve accuracy [27], [35]. Additionally, FEM is time-consuming and difficult to build models for some complex structures, which further complicates the process of obtaining reliable results.

**Emerging trends in FEA improve transformer winding stress analysis through advanced simulations. Coupled electromagnetic-structural models enhance understanding of hoop and compressive stresses, while 3D Finite Element Modeling provides a precise view of radial and axial forces. Assessing electromagnetic force distribution and material stress along the winding structure helps identify critical zones and refine the design. These advancements enhance fault detection and mechanical stress evaluation, contributing to the design of stronger and more durable transformers** [43].

**2.3** **Experimental Analysis.** Experimental studies are essential for understanding how electrical and mechanical stresses affect transformers. Power transformers experience various stresses, such as short-circuit conditions and thermal fluctuations, which impact their windings, insulation systems, and overall performance. By analyzing these effects, researchers can develop better diagnostic techniques to detect failures before they lead to catastrophic faults, enhancing transformer reliability and longevity [37], [46].

Laboratory experiments provide a controlled environment to study transformer behavior, which is difficult to replicate in real-world conditions. These tests are crucial for evaluating the mechanical strength of transformer windings under short-circuit forces [47], tracking radial deformations and winding displacements caused by operational stresses [48], and validating computational models like FEA to predict electromagnetic and thermal effects [20]. Through controlled testing, researchers can refine simulation models and enhance transformer designs, ultimately improving performance and durability.

To assess transformer conditions, experimental studies focus on key parameters. Radial and axial deformations are identified using image processing and ultra-wideband transceivers [48], while short-circuit current response helps evaluate winding strength and reliability under fault conditions [47]. Additionally, frequency response analysis (FRA) detects internal faults and winding shifts by analyzing changes in impedance and resonance frequencies [42]. These measurements aid in developing more resilient transformers, ultimately enhancing power system stability and efficiency. If off-load tapping is used on the HV winding, the size and direction of the force along the Y-axis change compared to when no tapping is applied [32].

While experimental tests provide valuable real-world data and validate theoretical models, they also have limitations. Short-circuit tests generate strong electromagnetic forces that may damage transformer windings [46], [49], and these experiments can be costly and restricted by safety concerns [37].

To complement experimental studies, simulations offer a faster and safer way to analyze transformer behavior. They simplify data collection [37] and allow for testing scenarios that may not be feasible in real life [49]. Additionally, simulation results allow us to predict the progression of potential issues [50]. Moreover, simulations are cost-effective and enable rapid testing of various conditions. However, they rely on assumptions that may not always be accurate and cannot fully capture all real-world complexities. Therefore, combining both experimental and simulation approaches ensure a more comprehensive understanding of transformer performance.

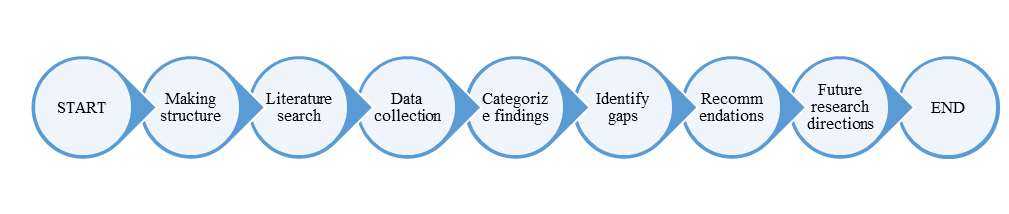
**2.4** **Cumulative Effects of Short Circuits.** After a short-circuit fault, the windings undergo hidden damage that builds up over time, so it is important to study how windings are affected by repeated short-circuits [23], [28]. Electromagnetic forces from these faults cause stress and deformation in the windings [2], [6]. A model that incorporates the electromagnetic and mechanical properties of transformer windings can aid in studying stress buildup and evaluating the coil's capacity to endure short circuits through simulation [2], [28].

Electromagnetic forces generated by multiple short circuits cause mechanical deformation of windings [2]. The failure of insulation spacers contributes by concentrating stress and causing uneven stress distribution in the nearby disks and conductors. Over time, these effects accumulate, resulting in significant winding deformation and structural damage after repeated short circuits [6]. The deformation expands over time and leads to irreversible damage [28].

The cumulative effect in transformers can manifest as both the accumulation of forces and thermal. Heat generated by repeated short circuits weakens the insulation, which in turn reduces its mechanical strength [23], [42]. Electromagnetic forces increase stress, especially in medium-voltage windings, making them more likely to deform [28]. Older transformers, especially those over 20 years old, lose their ability to resist short circuits due to material wear [2], [6]. The insulation spacers in these transformers wear out, causing further winding damage after several short-circuit events [6]. Understanding these effects is important for designing transformers that are more resistant to short circuits [2].

### **METHODOLOGY**

Figure 1 shows a flowchart of the article writing process. This diagram shows the main steps in writing an article and their sequence. The process begins with an introduction and ends with a list of references. Each step corresponds to a section of the article and helps to understand the structure of the research.



**FIGURE 1.** Flowchart of the article writing process.

A comprehensive literature search was conducted using scientific databases such as IEEE Xplore, Scopus, and ScienceDirect to gather relevant studies. Keywords such as power transformers, short circuit effects, cumulative damage, transformer windings, electromagnetic forces, and insulation aging were used to identify articles. The selection criteria included peer-reviewed articles, conference papers, and technical reports published between 2015 and 2024, with a focus on the cumulative damage effects of short circuits on transformer windings.

In the study was examined key parameters such as transformer type, short-circuit conditions, experimental setups, simulation models, and findings from selected research. The study placed special emphasis on examining mechanical deformation, thermal influences, and insulation aging caused by repeated short circuits. Both qualitative and quantitative approaches were used—qualitative analysis identified trends, common findings, and research gaps, while quantitative analysis focused on measuring deformation, stress distribution, and insulation degradation over multiple short-circuit events. The effects were categorized into mechanical deformation, thermal accumulation, and insulation aging for a clearer understanding. Additionally, real-world transformer failure cases were analyzed to compare theoretical and simulation-based results with practical observations. This validation process helped strengthen the reliability of the study’s conclusions, providing a solid foundation for further research on transformer short-circuit resistance.

The findings reveal that repeated short circuits significantly reduce the mechanical strength of transformer windings, leading to cumulative deformation and increased failure risks. To address this, recommendations include developing methods to predict how many short-circuit events a transformer can withstand, improving diagnostic tools to monitor winding health, and using advanced materials to enhance durability. A critical gap identified is the lack of accurate models to determine the number of short-circuit events a transformer can endure before failure. Future research should focus on creating fatigue analysis models that integrate mechanical, thermal, and electrical stress factors, as well as exploring new materials and designs to improve transformer resilience to repeated short circuits.

The cumulative impact of repeated short circuits leads to plastic deformation, aging, and deterioration of material properties. Simulation and experimental tests reveal that electromagnetic forces and heat accumulation are key contributing factors. However, certain gaps remain, such as the exclusion of environmental factors and insulation aging, which emphasizes the need for further improvements to enhance transformer reliability and protection.Currently, there are variants of DFIG brushless, multipole without gearbox, rotor 5-phase DFIG and others. But the issues of modeling and application of hybrid DFIG in wind farms have not been studied enough. The advantage of the hybrid shuttle is that its technical characteristics have higher indicators compared to other alternative options. In addition, the shape of the output voltage is considered very close to the sine wave.

### **ANALYSIS AND DISCUSSION**

**4.1 Impact of Short Circuits on Transformer Windings.** Short circuits impose significant thermal and electromagnetic stresses on transformer windings, leading to mechanical deformation and insulation degradation. Research highlights that repeated short-circuit incidents result in localized heating, which weakens insulation and accelerates material fatigue.

The interaction between short-circuit currents and leakage magnetic fields generates intense electrodynamic forces, leading to winding deformation [51]. These forces, combined with uneven temperature distribution, result in increased hot spot temperatures, which further elevate winding displacement, stress, and total deformation [52].

The radial deformations caused by short-circuit currents are proportional to the magnitude of the forces and their duration, with inward deformation observed in low-voltage windings and outward deformation in high-voltage windings. Additionally, axial displacement is most pronounced at the winding’s center, where force imbalances cause bending and potential misalignment [51]. These cumulative effects of heat and electromagnetic forces contribute to distinct deformation patterns, such as axial tilt and radial warping, which significantly impact transformer performance and longevity.

**4.2 Aging Process of Transformers.** Short-circuit events accelerate transformer aging by gradually degrading structural and thermal resilience. Repeated short-circuit forces lead to cumulative deformation and structural fatigue, increasing failure risks over time [51]. Additionally, repeated short-circuit forces and uneven temperature distribution cause axial conductor displacement and decrease the mechanical stability of windings [51], [52].

Experiments show that repeated short-circuit forces result in cumulative deformation, which weakens the structural integrity of transformer windings. This process, known as mechanical aging, increases the risk of failure over time [51]. The combination of electromagnetic forces and uneven temperature distribution further exacerbates axial conductor displacement, reducing the overall mechanical stability of the windings [51], [52].

Excessive heat generated during short-circuit events leads to insulation aging, winding damage, and deformation of structural components, ultimately compromising transformer performance and increasing the risk of failure [41], [52]. To mitigate these effects, advanced cooling techniques, such as ferrofluid-based insulation oil, have been developed. These techniques effectively reduce hotspot formation, thereby extending transformer lifespan [41].

**4.3** **Industrial and Practical Implications. Power transformer manufacturers and operators face significant challenges due to the cumulative effects of short circuits. Repeated short-circuit forces cause gradual winding displacement, leading to internal misalignments that compromise operational reliability** [51]. **Additionally, uneven temperature distribution exacerbates mechanical wear, accelerating the degradation of insulation materials and increasing the risk of failure** [52].

### **Several strategies can be used to extend the life of transformers. The use of advanced cooling systems, such as ferrofluid-based cooling, effectively reduces hot spot temperatures and extends transformer life** [41]. **Additionally, improved winding materials and the cylindrical transformer design for low-power applications offer advantages like reduced leakage flux, core loss, and volume, along with better heat dissipation and built-in winding protection, enhancing efficiency and minimizing size for compact, energy-efficient systems** [33]. **By implementing these improvements, manufacturers and operators can significantly improve transformer durability, ensuring greater reliability and reduce operational risks.**

### **OPEN ISSUES AND FUTURE DIRECTIONS**

**5.1 Unresolved Issues in Transformer Short-Circuit Studies.** Despite extensive research on transformer short-circuit behavior, several key challenges remain unresolved. One major issue is the cumulative mechanical degradation caused by multiple short-circuit events, which is difficult to predict and quantify accurately [51]. Existing models often fail to capture the long-term effects of repeated short circuits on winding displacement and insulation aging, leading to uncertainties in transformer lifespan estimation [52]. Additionally, the influence of uneven temperature distribution on transformer mechanical stability requires further investigation, as it significantly impacts insulation performance and structural integrity.

### **5.2 Future Research Directions.** Another critical challenge is the lack of accurate prediction methods for determining how many short-circuit events a transformer winding can endure before failure. Current methodologies mainly focus on assessing individual short-circuit impacts but fail to account for the cumulative effect over time. Developing reliable fatigue analysis models that integrate mechanical, thermal, and electrical stress factors is essential to enhance transformer design and operational reliability.

**CONCLUSIONS**

This review systematically examined the cumulative effects of multiple short-circuit events on power transformer windings, with a focus on understanding how repeated short circuits degrade mechanical strength and ultimately lead to transformer failure. The study revealed that short circuits impose significant electromagnetic and thermal stresses, causing progressive mechanical deformation, insulation degradation, and accelerated aging. Over time, these cumulative effects reduce the transformer’s ability to withstand further short-circuit events, leading to operational failures and substantial financial and operational losses.

A critical finding is the need to determine how many short-circuit events a transformer can endure before failure. Current methodologies often fail to account for the long-term cumulative damage caused by repeated short circuits, making it challenging to predict the remaining operational lifespan of transformers in service. Advanced simulation tools and experimental studies have provided valuable insights into stress distribution and deformation patterns, but further research is needed to develop accurate predictive models that integrate mechanical, thermal, and electrical stress factors.

This review is highly relevant for both researchers and industry professionals, as it highlights the importance of improving transformer design, diagnostics, and maintenance practices to enhance reliability and reduce risks. By addressing the identified gaps, such as the need for advanced fatigue analysis models and the incorporation of environmental factors, future research can contribute to the development of more resilient transformers. Additionally, the adoption of innovative cooling techniques, improved winding materials, and advanced simulation tools can significantly extend transformer lifespan and improve power system stability.

In conclusion, this review not only advances academic understanding of transformer short-circuit behavior but also provides practical recommendations for industry stakeholders. Future work should focus on developing comprehensive models that account for cumulative damage, integrating multi-physics simulations, and exploring new materials and designs to mitigate the effects of short circuits. By doing so, the energy sector can achieve greater reliability, efficiency, and sustainability in power transmission and distribution systems.

**REFERENCES**

1. X. Luo, Q. Xiao, Q. Wang, W. Gan, B. Deng, and Z. Sheng, “Research on Short-Circuit Force of Transformer Winding with Single-Phase Short-Circuit and Three-Phase Short-Circuit,” *2021 11th International Conference on Power and Energy Systems, ICPES 2021*, pp. 219–223, 2021, doi: 10.1109/ICPES53652.2021.9683798.
2. S. Wang, H. Zhang, S. Wang, H. Li, and D. Yuan, “Cumulative Deformation Analysis for Transformer Winding under Short-Circuit Fault Using Magnetic-Structural Coupling Model,” *IEEE Transactions on Applied Superconductivity*, vol. 26, no. 7, Oct. 2016, doi: 10.1109/TASC.2016.2584984.
3. A.A. Abdullaev, Z.Z. Tuychiev, T.K. Jabborov, M.Kh. Kobilov, Z.Z. Najmitdinov, and Z.M. Sharipov, “A review on power transformer failures: analysis of failure types and causative factors,” *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 38, no. 2, pp. 713–722, May 2025, doi: 10.11591/ijeecs.v38.i2.pp713-722.
4. A. Abdullaev, Z. Tuychiev, M. Kobilov, T. Jabborov, B. Boynazarov, and F. Nasretdinova, “Comprehensive review of power transformer damage: A fifty-year analytical study,” *AIP Conf Proc*, vol. 3331, no. 1, p. 030005, Nov. 2025, doi: 10.1063/5.0306120.
5. C. Yan, C. Xu, H. Liu, S. Kang, and B. Zhang, “Numerical and Experimental Investigations on Transformer Winding Damages Under Multiple Short-Circuit Faults,” *IEEE Transactions on Applied Superconductivity*, 2024, doi: 10.1109/TASC.2024.3463515.
6. C. Xu, C. Yan, S. Kang, H. Liu, and B. Zhang, “Study on the Damage to Transformer Windings Under Multiple Short-Circuit Faults,” *2023 IEEE International Conference on Applied Superconductivity and Electromagnetic Devices, ASEMD 2023*, 2023, doi: 10.1109/ASEMD59061.2023.10369700.
7. J. F. Araujo, E. G. Costa, F. L. M. Andrade, A. D. Germano, and T. V. Ferreira, “Methodology to evaluate the electromechanical effects of electromagnetic forces on conductive materials in transformer windings using the von mises and fatigue criteria,” *IEEE Transactions on Power Delivery*, vol. 31, no. 5, pp. 2206–2214, Oct. 2016, doi: 10.1109/TPWRD.2016.2579165.
8. P. Emini, D. Dimitrov, and N. Berisha, “Impact of Renewable Energy Integration on Short Circuit Levels in Power System: Wind Park,” *2024 International Conference on Renewable Energies and Smart Technologies, REST 2024*, 2024, doi: 10.1109/REST59987.2024.10645371.
9. S. N. Afifi and M. K. Darwish, “Impact of hybrid renewable energy systems on short circuit levels in distribution networks,” *Proceedings of the Universities Power Engineering Conference*, Oct. 2014, doi: 10.1109/UPEC.2014.6934697.
10. M. Dali, F. Charaabi, and J. Belhadj, “Short-circuit fault analysis and protection of stand-alone AC and DC microgrids,” *2022 IEEE International Conference on Electrical Sciences and Technologies in Maghreb, CISTEM 2022*, 2022, doi: 10.1109/CISTEM55808.2022.10043929.
11. H. Zahloul, H. Hamzehbahmani, A. Khaliq, and S. Veremieiev, “An Approach to Dynamic Behaviour of a Grid Connected PV System during Symmetrical Short Circuit Fault,” *2022 13th International Renewable Energy Congress, IREC 2022*, 2022, doi: 10.1109/IREC56325.2022.10002093.
12. H. Sui *et al.*, “Cumulative Effect Properties of Transformer Insulating Paper under Multiple Short-Circuit Impacts,” *IEEE Transactions on Dielectrics and Electrical Insulation*, 2024, doi: 10.1109/TDEI.2024.3495582.
13. X. Luo *et al.*, “Research on cumulative effect and diagnosis method of transformer short-circuit impulse,” *J Phys Conf Ser*, vol. 2477, no. 1, p. 012034, Apr. 2023, doi: 10.1088/1742-6596/2477/1/012034.
14. Z. ZHANG, Y. FENG, R. LIU, Q. OU, and J. REN, “Analysis and Short-circuit Test Investigation on Mechanical Stability of Power Transformer Winding,” Aug. 2024, doi: 10.21203/RS.3.RS-4756034/V1.
15. M. Kobilov, Z. Tuychiev, T. Jabborov, and A. Abdullaev, “Modelling of the non-contact automatic voltage regulation system on single phase distribution transformers,” *PRZEGLĄD ELEKTROTECHNICZNY*, vol. 12, no. 12, pp. 14–17, Dec. 2024, doi: 10.15199/48.2024.12.04.
16. I. A. Khudonogov, E. Y. Puzina, and A. G. Tuigunova, “Evaluation of short circuit currents effects on power transformers’ residual service life,” *2019 International Conference on Industrial Engineering, Applications and Manufacturing, ICIEAM 2019*, Mar. 2019, doi: 10.1109/ICIEAM.2019.8743069.
17. M. Shuai, W. Chengzhi, Y. Shiwen, G. Hao, Y. Jufang, and H. Hui, “Review on Economic Loss Assessment of Power Outages,” *Procedia Comput Sci*, vol. 130, pp. 1158–1163, Jan. 2018, doi: 10.1016/J.PROCS.2018.04.151.
18. Z. Zhao, X. Ma, and Q. Wu, “Simulation and Analysis of Dynamic Characteristics of Transformer Winding in Short-Circuit Fault by Finite Element Method,” *Proceedings of 2021 IEEE 4th International Electrical and Energy Conference, CIEEC 2021*, May 2021, doi: 10.1109/CIEEC50170.2021.9511065.
19. Z. Ye, C. Kreischer, and S. T. Kulig, “Analysis of transformer short circuit characteristics based on 3-D Finite Element Method,” *PEAM 2011 - Proceedings: 2011 IEEE Power Engineering and Automation Conference*, vol. 2, pp. 90–93, 2011, doi: 10.1109/PEAM.2011.6134915.
20. M. S. Chaouche, H. Houassine, S. Moulahoum, and I. Colak, “Finite element method to construct a lumped parameter ladder network of the transformer winding,” pp. 1092–1096, Dec. 2017, doi: 10.1109/ICRERA.2017.8191224.
21. Y. Chen, C. Zhang, Y. Li, Z. Zhang, W. Ying, and Q. Yang, “Comparison between Thermal-Circuit Model and Finite Element Model for Dry-Type Transformer,” *2019 22nd International Conference on Electrical Machines and Systems, ICEMS 2019*, Aug. 2019, doi: 10.1109/ICEMS.2019.8922410.
22. A. Bakshi, “Effect of Width of Axial Supporting Spacers on the Buckling Strength of Transformer Inner Winding,” *IEEE Transactions on Power Delivery*, vol. 34, no. 6, pp. 2278–2280, Dec. 2019, doi: 10.1109/TPWRD.2019.2914834.
23. M. Duan *et al.*, “Research on the Heat Accumulation Effect of Transformer Short Circuit,” in *2023 3rd International Conference on New Energy and Power Engineering, ICNEPE 2023*, 2023. doi: 10.1109/ICNEPE60694.2023.10429370.
24. C. Yan, C. Xu, H. Liu, S. Kang, and B. Zhang, “Numerical and Experimental Investigations on Transformer Winding Damages Under Multiple Short-Circuit Faults,” *IEEE Transactions on Applied Superconductivity*, 2024, doi: 10.1109/TASC.2024.3463515.
25. Y. Miao, Y. Li, X. Wang, Z. Yu, P. Li, and Z. Xu, “Study on Magnetic-Force Characteristics of Windings with Short-Circuit Cumulative Damage,” *2023 IEEE International Conference on Applied Superconductivity and Electromagnetic Devices, ASEMD 2023*, 2023, doi: 10.1109/ASEMD59061.2023.10368753.
26. H. Zhou, D. Wu, Y. Song, and Y. Ding, “Finite Element Analysis of the Effect of Load Current on the Winding Temperature in 110kV Oil-immersed Transformers,” *ITOEC 2023 - IEEE 7th Information Technology and Mechatronics Engineering Conference*, pp. 1437–1441, 2023, doi: 10.1109/ITOEC57671.2023.10291286.
27. A. Ehsanifar, M. Dehghani, and M. Allahbakhshi, “Calculating the leakage inductance for transformer inter-turn fault detection using finite element method,” *2017 25th Iranian Conference on Electrical Engineering, ICEE 2017*, pp. 1372–1377, Jul. 2017, doi: 10.1109/IRANIANCEE.2017.7985256.
28. X. Lin, J. Liu, F. Wang, W. Ai, Z. Li, and S. Chen, “Magnetic-Structural Coupled Simulation of Power Transformer Winding Cumulative Effect,” *Proceedings of 2022 IEEE 5th International Electrical and Energy Conference, CIEEC 2022*, pp. 2860–2865, 2022, doi: 10.1109/CIEEC54735.2022.9846838.
29. J. Y. Lee, H. M. Ahn, J. K. Kim, Y. H. Oh, and S. C. Hahn, “Finite element analysis of short circuit electromagnetic force in power transformer,” *Proceedings - The 12th International Conference on Electrical Machines and Systems, ICEMS 2009*, Nov. 2009, doi: 10.1109/ICEMS.2009.5382899.
30. S. Wang, S. Wang, T. Zhu, N. Zhang, H. Li, and H. Qiu, “Research on Dynamic Response of Power Transformer Windings under Short Circuit Condition,” *ICHVE 2018 - 2018 IEEE International Conference on High Voltage Engineering and Application*, Jul. 2018, doi: 10.1109/ICHVE.2018.8642176.
31. E. Mechkov, R. Tzeneva, V. Mateev, and I. Yatchev, “Thermal analysis using 3D FEM model of oil-immersed distribution transformer,” *2016 19th International Symposium on Electrical Apparatus and Technologies, SIELA 2016*, Aug. 2016, doi: 10.1109/SIELA.2016.7543027.
32. A. Sinha and S. Kaur, “Analysis of short circuit electromagnetic forces in transformer with asymmetrically placed windings using Finite Element Method,” *2nd IEEE International Conference on Innovative Applications of Computational Intelligence on Power, Energy and Controls with their Impact on Humanity, CIPECH 2016*, pp. 101–105, May 2017, doi: 10.1109/CIPECH.2016.7918746.
33. A. Gohari, A. Hekmati, A. Mosallanejadand, H. Torkaman, and E. Afjei, “Design and Comparative Finite Element and Thermal Analysis of 1-Phase Cylindrical Transformer for Low-Power Applications,” *2021 12th Power Electronics, Drive Systems, and Technologies Conference, PEDSTC 2021*, Feb. 2021, doi: 10.1109/PEDSTC52094.2021.9405861.
34. K. Dawood and G. Komurgoz, “Investigating effect of Electromagnetic Force on Sandwich Winding Transformer using Finite Element Analysis,” *2021 28th International Workshop on Electric Drives: Improving Reliability of Electric Drives, IWED 2021 - Proceedings*, Jan. 2021, doi: 10.1109/IWED52055.2021.9376371.
35. K. Dawood, G. Komurgoz, and F. Isik, “Computation of the Axial and Radial forces in the Windings of the Power Transformer,” *Proceedings - 2019 4th International Conference on Power Electronics and their Applications, ICPEA 2019*, Sep. 2019, doi: 10.1109/ICPEA1.2019.8911132.
36. E. G. P. Ediriweera, K. Wickramasinghe, K. R. I. Sithmini, E. A. A. G. Ekanayaka, R. Samarasinghe, and J. R. Lucas, “Localizing hotspot in an oil immersed distribution transformer using finite element analysis,” *2020 IEEE Electric Power and Energy Conference, EPEC 2020*, Nov. 2020, doi: 10.1109/EPEC48502.2020.9320046.
37. G. Deepanraj and L. Kalaivani, “Computational Model for Transformer Bushing using Advanced Finite Element Method,” *6th International Conference on Electronics, Communication and Aerospace Technology, ICECA 2022 - Proceedings*, pp. 364–368, 2022, doi: 10.1109/ICECA55336.2022.10009207.
38. S. Yadav and R. K. Mehta, “FEM Based Study of Short Circuit Forces on Power Transformer Windings,” *2019 3rd International Conference on Recent Developments in Control, Automation and Power Engineering, RDCAPE 2019*, pp. 540–544, Oct. 2019, doi: 10.1109/RDCAPE47089.2019.8979046.
39. D. Zhou, Z. Li, C. Ke, X. Yang, and Z. Hao, “Simulation of transformer windings mechanical characteristics during the external short-circuit fault,” *Proceedings of the 5th IEEE International Conference on Electric Utility Deregulation, Restructuring and Power Technologies, DRPT 2015*, pp. 1068–1073, Mar. 2016, doi: 10.1109/DRPT.2015.7432389.
40. L. Luo, X. Luo, X. Wen, and W. Qin, “Research on Radial Stability of Power Transformer Windings,” *2022 4th International Conference on Smart Power and Internet Energy Systems, SPIES 2022*, pp. 367–371, 2022, doi: 10.1109/SPIES55999.2022.10082567.
41. S. Nasser, E. Dine, X. Mininger, and C. Nore, “Heat Transfer in a Ferrofluid-Based Transformer: Multiphysics Modeling Using the Finite Element Method,” *IEEE J Multiscale Multiphys Comput Tech*, vol. 7, p. 207, 2022, doi: 10.1109/JMMCT.2022.3200019.
42. S. Pradhan and S. K. Nayak, “Winding Dislocation of a Power Transformer and its Analysis to Locate and Estimate the Deformation,” *2nd International Conference on Energy, Power and Environment: Towards Smart Technology, ICEPE 2018*, Jul. 2018, doi: 10.1109/EPETSG.2018.8659337.
43. R. G. Cornelius, B. Lenhard, H. Medeiros, V. C. Bender, T. B. Marchesan, and R. Carraro, “Electromagnetic Forces and Mechanical Stresses in Power Transformers: An Analysis Based on Computer Aided Engineering,” *2022 14th Seminar on Power Electronics and Control, SEPOC 2022*, 2022, doi: 10.1109/SEPOC54972.2022.9976413.
44. S. Pradhan and S. K. Nayak, “Deformation Study of a Transformer Winding using Frequency-Response Analysis and Finite-Element Analysis,” *2022 22nd National Power Systems Conference, NPSC 2022*, pp. 708–712, 2022, doi: 10.1109/NPSC57038.2022.10069362.
45. Z. Li, Z. Hao, C. Yan, Y. Dang, H. Xu, and B. Zhang, “Deformation simulation and analysis of power transformer windings,” *Asia-Pacific Power and Energy Engineering Conference, APPEEC*, vol. 2016-December, pp. 1445–1449, Dec. 2016, doi: 10.1109/APPEEC.2016.7779728.
46. C. E. Sclceanu, D. C. Ocoleanu, D. Iovan, M. Ionescu, S. Seitan, and C. Boltasu, “Experimental Study of the Behaviour of Distribution Transformers under Short-Circuit Conditions,” *2024 International Conference on Applied and Theoretical Electricity, ICATE 2024 - Proceedings*, 2024, doi: 10.1109/ICATE62934.2024.10749000.
47. Z. Bo and L. Yan, “Research on Radial Stability of Large Transformers Windings under Multiple Short-Circuit Conditions,” *IEEE Transactions on Applied Superconductivity*, vol. 26, no. 7, Oct. 2016, doi: 10.1109/TASC.2016.2594843.
48. S. Mortazavian, M. M. Shabestary, Y. A. R. I. Mohamed, and G. B. Gharehpetian, “Experimental studies on monitoring and metering of radial deformations on transformer HV winding using image processing and UWB transceivers,” *IEEE Trans Industr Inform*, vol. 11, no. 6, pp. 1334–1345, Dec. 2015, doi: 10.1109/TII.2015.2479582.
49. M. Gutten, R. Janura, and M. Brandt, “Analysis of Short-Circuit Effects on Transformer state by Frequency Method,” *Conference on Diagnostics in Electrical Engineering CDEE*, 2016.
50. C. Xiao, W. Zhang, W. Yu, J. Hou, L. Cong, and C. Liu, “Analysis of Transformers Windings Deformation Based on Axial Vibration,” *2021 IEEE 2nd China International Youth Conference on Electrical Engineering, CIYCEE 2021*, 2021, doi: 10.1109/CIYCEE53554.2021.9676921.
51. Y. Zhai, R. Zhu, Q. Li, X. Wang, Y. Gu, and S. Li, “Simulation Research on Electrodynamic Force and Deformation of Transformer Windings under Short-circuit Condition”, doi: 10.1109/ICHVE53725.2022.9961358.
52. Y. Li *et al.*, “Research on the Influence of Uneven Temperature Distribution of Transformer Windings on Short Circuit Strength,” *IEEE Transactions on Applied Superconductivity*, 2024, doi: 10.1109/TASC.2024.3420297.