# A review on power transformer failures: analysis of failure types and causative factors

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**ABSTRACT**

This article analyzes power transformers and their components, types of damage, factors causing them. The advantage of this review article is that it was initially conducted a theoretical analysis based on published articles on power transformer damage in recent years. Then a statistical analysis was carried out on damaged power transformers in real condition. In the theoretical analysis, the articles published in the databases in recent years were first identified by keywords, and then sorted according to their relevance to the topic. A statistical examination of the damaged power transformers was performed utilizing the theoretical approach. According to the results of the analysis, damage to power transformers in 6(10) kV networks occurs mainly in 100 kVA, 160 kVA and 250 kVA power transformers. One of the factors that cause the power transformer to fail is the irregular implementation of restrictions on the power supply to electrical consumers. And these failures mainly damage the windings of the power transformer. We hope that the materials in this analytical article will serve as a crucial resource.



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## 1. INTRODUCTION

Nowadays, the demand for electricity is increasing day by day. Fulfilling this requirement requires increasing the reliability of the energy system. Power transformers are one of the main electrical devices of the energy system, and these electrical devices are a crucial part of the energy system and one of the valuable components [1]–[3]. Power transformers are used in the transmission and distribution of electrical energy by changing the voltage and current from one value to another while maintaining constantly the frequency and power value.

Any transformer problem leads in both decreased power system reliability and financial losses [4]. Various international standards [5]–[11] have been developed about transformer failures and to improve of power transformer reliability. Monitoring, assessment, and corrective actions are included in the operational and maintenance measures for the power transformers of energy system [12]. According to research results, the short-circuit withstand of long-term serviced power transformers is lower than that of new transformers [13].

Through monitoring the condition of power transformers may be protect transformers from damage, while at the same time achieve to economic and energy efficiency gains for enterprises. By applying measures developed on the basis of monitoring and diagnostic results, it is possible to increase the operational reliability of power transformers [14]–[16]. This is important in ensuring the stability of the energy system.

According to [10], under normal conditions, the service life of power transformers is 40 years, after this period, it was found that the probability of failure of power transformers is very much. If the work is performed poorly during the service, the power transformer does not work under normal conditions and short circuits occur a lot, the service life of these power transformers will be shrunk. In order to improve service quality and reduce operating costs of aging transformers, various condition monitoring and investigation methods are currently used to diagnose various internal faults [17].

Several research studies have shown that transformer failure probability and other aspects of its working life depend on the main failure causes, such as electrical, thermal, mechanical, and chemical stresses [18], [19]. This, in turn, is a factor that accelerates the wear and tear of the power transformer. According to [13] the acceleration of ageing of the transformer is related to the decrease of its mechanical and dielectric strength due to long-term use of the transformer. To date, various types of tests have been developed to identify faults in power transformers [20], [21] and many diagnostic methods have been researched [22]–[25]. To prevent power transformers' failure in the future and prevent suffering significant financial losses as well as an increase in the dependability of the energy system, this article looks at the causes of power transformers' failure.

The rest of the article is as follows: The first of which is an introduction that covers background study and motivation. Section 2 contains the methods used in this research, while in 3rd section, an analytical study was conducted on the location of the elements of the causes that lead to damage to power transformers. A comprehensive analysis of the power transformer elements' operations, damage kinds, contributing factors and diagnostic techniques was carried out in section 4. Section 5 describes the analytical studies conducted on the analysis of power transformer damage statistics. General conclusions on the analysis of power transformer damage and the factors causing it are presented in section 6.

## 2. METHOD

Figure 1 shows the sequence of writing the article a review on power transformer failures: analysis of failure types and causative factors. At first, I asked the question "where can I get the information I need" and multiple research publications such as IEEE Xplore, Research Gate, Springer Link, Pro Quest, Elsevier and Google Scholar were chosen to construct the data in this analytical research work. Data was collected from databases using keywords such as "analysis", "power transformers failure", "fault", "damage", "failure causes", "power transformer component", "working life", and "diagnosing methods". Among these collected data, articles published in the last 25 years were selected. Among these articles, more than 200 articles were reviewed and more than 60 articles relevant to the topic were selected for use.

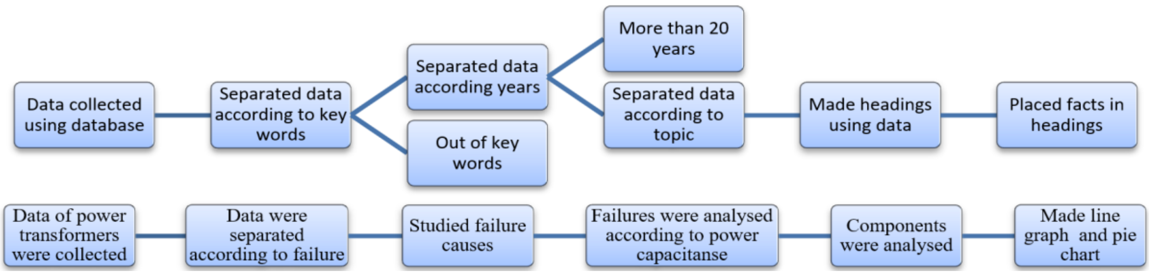



Figure 1. The sequence of writing the article topic on power transformer failures: analysis of failure types and causative factors

During the review of the selected articles, the headings of the manuscript were formed. Then, each article was studied in detail and the information corresponding to the article headings was placed. This strategy helps you avoid reviewing the article multiple times. The circumstances leading to the damage of the power transformer were determined and chart of failures of power transformers cause by various factors was constructed.

After the analysis of the power transformer and its components, the functions of these components, the types of failure and the causes of their occurrence were analyzed. The methods of diagnosing power transformers were studied, and the diagnostic methods that were found to have a high level of accuracy for identifying failure in each component were cited.

A statistical analysis was conducted on 6(10) kV power transformers in operation in the Fergana region. As an assist to the research, we used the IEEE Standard C57.125 "Guide for Failure Investigation, Documentation, and Analysis for Power Transformers and Shunt Reactors". This guide can be used to analysis all important factors of failure investigation of power transformer. The guide also includes extensive appendices on transformer construction, diagnostic testing, and sample failure investigation case studies.

Figure 2 shows the failed power transformers in the 6(10) kV power grids in Fergana region. A line graph depicting the relationship between electricity capacity and the number of failures was created for the years 2022-2023.

In this case, since most of the power transformers in power networks are in the range of 25 kVA to 4,000 kVA, power transformers in this power range were selected. The sum of 6 kV and 10 kV failed power transformers were taken. An analysis was conducted on the damage of the components of power transformers that failed. The elements of the main damaged power transformer expressed in percentage. Made chart of failure analysis of elements of damaged 6(10)/0.4 kV voltage power transformers in Fergana region by location was built Figure 2. Summarizing the results of the conducted research, the conclusions were presented.

Figure 2. Damaged power transformers detected during the experiment

## 3. ANALYSIS OF THE CAUSES OF FAILURES TO POWER TRANSFORMERS

The using of power transformers by the established standards allows them to be used effectively for a long time. This increases the reliability of the energy system. The probabilities of a transformer failures and other working life factors depend on the primary fault origins, such as electrical, dielectric, thermal, mechanical, physical chemical and unclassified stressors. The causes of power transformer failure were considered in the literature [2], [19], [22], [26]–[28], and the summarized situation is shown in Figure 3.

From an electrical standpoint, lightening and switching surges are more likely to cause breakdown of core and winding insulation. Additionally, mechanical stresses and winding deformations may impact cooling system and contribute to the fast temperature increase brought on by short circuit forces [29]. Moreover, if moisture particles are added due to any maintenance condition it may further lead towards the quick degradation of insulation system [2].

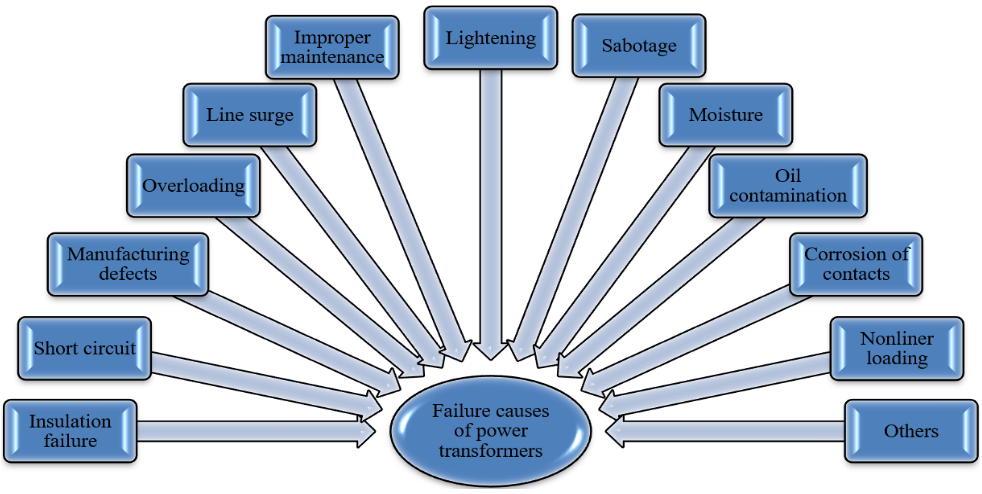



Figure 3. Failures of power transformers cause by various factors

Power transformers fail for a number of reasons. These include insulation damage, circuit damage, and overvoltage. According to [26], the main causes of power transformers' failure are insulation failure and line surge, which make up 46.5% of the factors that cause damage to transformers. According to the research conducted by [30], the main causes of the failures were overvoltage, winding faults, and insulation degradation.

## 4. POWER TRANSFORMER COMPONENTS AND CAUSES OF THEIR FAILURES

The elements that can cause damage in power transformers [26], [27]. According to the results of the analysis of the causes of failure of power transformers [22], the failure of electrical devices occurs due to the effect of long-term short-circuit currents that cause turn-to-turn short circuits, burning and explosions, geometrical changing of transformer winding. Damage to the following elements can cause the transformer to fail.

Table 1 shows the results of an analytical study on the damage to components of power transformers. The table shows the analysis of power transformer winding, OLTC, bushing, solid and oil insulations, cooling system, protection system and tank components. The function of these components, the conditions that cause damage, types of damage and diagnosis methods of it are considered.

Table 1. Functions, damage, causes and diagnostic methods of power transformer components

| Component | Function | Causes of failure | Types of failure | Diagnosing methods |
|---|---|---|---|---|
| Winding | Creating and changing magnetic field, changing the value of voltage and current | Manufacturing defects, transient overvoltage, short circuit, faulty connection, damage during shipping [1], [26], [27] | Insulation ageing, winding deformation, turn-to-turn and inter-disk short circuit, missing core ground, disk space variation, thermal losses [1], [26], [31]–[34] | Dissolved gas analysis (DGA) [26], Frequency response analysis (FRA) [35]–[38], Transfer function method and other [39] |
| Tap changer (OLTC) | Controls voltage by either increasing or decreasing the number of turns in the secondary transformer winding [1] | Poor maintenance, old capacitors or burned-out capacitor, regular use of the tap changer, over voltage or miss-use [1], [40] | Failures of mechanical system, defects in the current circuit, damages produced in the insulation system [40] | Acoustic methods [40], [41], DGA [42] |
| Core | Improves and conducts magnetic flux, giving it mechanical strength [28] | DC magnetization, excessive heating, displacement of the core steel [26], [28] | Displacement of core steel | DGA, OLCM, vibration signal analysis, vibroacoustic detection [28], [43]–[46] |
| Bushing | Makes a route for current to go through the tank wall [1], [12], [47] | SC, loosening of conductors, high voltages, ingress of water, extended periods of time between oil replacements, a lack of oil, earthquake, sabotage [48] | Cracks in the porcelain, bad gaskets, ingress of water inside insulation, deterioration of oil [47] | Periodic inspection and maintenance [28], DGA [47], power factor and capacitance [49], multi-source recording waves [50] |
| Insulation (Solid) | Stores electrical charge, dielectric to separate the various voltages of the transformer's components, mechanical purpose by supporting the winding | Transportation, SC, ageing of insulation, Oxidation, moisture, overloading, a lack of oil, forces generated during SC | Mechanical damage, hot spot | DGA [51], PD, insulation resistance test and polarization index [52], Grey correlation analysis [53], frequency dielectric spectroscopy [54], [55] |
| Insulation (Oil) | Insulation between the winding and the appropriate cooling of the transformer | Malfunction of the oil circulation, poor heat transfer to secondary cooling circuit, overheating of insulation, ageing of insulation, moisture and oxygen, SC [52] | Oil contamination, water in oil, high temperature, oil dirt, increased viscosity of the oil, too high temperature in the second cooling circuit, generation of conducting particles [52] | DGA [28], color examination [52], particles in oil due to ageing and over, chemical diagnosis, Raman methods [56]–[58] |
| Cooling system | Reduce the heat in the transformer by dissipating it to the environment through pipes | Corrosion, high humidity and sun radiation, poor maintenance, over use or motor wear-out, bad thermostats, more gas pressure [59] | Low heat exchange, faults in the cooling fans, cooling system to operate not in the way needed [1] | radiator temperature, infrared thermography, image processing method [46], [59] |
| Protection system | Identifying the issue and then quickly fix it. If the problem cannot be fixed, it is isolated so that the transformer won't be damaged [28] | Overheating of oil, a lack of oil, high voltage to pass to the winding, humidity and moisture | Exploding, dielectric faults | The Buchholz protection, pressure relief valve circuits, surge protection, and tap changer pressure relief and surge protection methods [1], [27], [28], [60] |
| Tank | A storage for the oil and support additional transformer-related equipment [28], [61] | Environmental stress, corrosion, high humidity and sun radiation, reduction in oil level | Mechanical damage, high gas pressure, corrosion, cracks, oil leakage [28], [62] | FRA [61], Vibration signal analysis [43], [63] |

In order to detect early damage to power transformers, various diagnostic works are carried out on them. Today, several diagnostic methods have been developed, and dissolved gas analysis (DGA) and frequency response analysis (FRA) methods stand out among other methods due to their high accuracy and wide application in detecting damage to the active part of the power transformer.

Using this Table 1, it is possible to obtain information about the functions performed by the power transformer components, the conditions that cause their damage, the types of component damage, and the methods of their diagnosis. Using diagnostic methods, it is possible to identify the damaged component of the power transformer. Also, knowing the damaged component in the power transformer, it is possible to predict its damage factor. Based on this condition, we may be able to create strategies to limit the damage to power transformers in the future.

## 5. FAILURE STATISTICS FOR POWER TRANSFORMERS

As a result of the growth of the world's population and the development and expansion of modern technologies, the demand for electricity is increasing day by day. It requires statistical analysis on these electrical devices which play an important role in the energy system. According to the results of research carried out in [26], [28], in the years 2010-2015, when the damaged power with a voltage of 10/0.4 kV is analyzed by the number of damaged of power transformers, the most damage corresponds to 100 kVA. The next places are occupied by 63 kVA and 25 kVA power transformers. It is noted in [6], oil immersed transformer lifespan is about to be 20,55 years.

In 10 kV networks, power transformers fail mainly due to damage to winding. Especially, one of the most common damages that cause failure of power transformers is the displacement of the winding in the axial direction due to the imbalance of forces in the axial direction. It is shown in Table 2 that, failure statistics and main types of damage affecting power transformers of 10/0.4 kV in the distribution grids of one the Russian power systems. 25% of all transformer failures were due to mechanical displacement of winding, 18% of transformer failures resulted from turn-to-turn short circuits [22].

In Figure 4 shows the dependence graph of power transformer damage on its elements [22], [64]. It claims that when components like winding, insulation, and core are damaged, the power transformer fails. The most damaged power transformer element is its winding and insulation damage, which accounts for 41% of the total damage. Bushing is next place with 14%.

Table 2. Failure statistics and main types of damage affecting power transformers of 10/0.4 kV in the distribution grids of one the Russian power systems

| Total number of transformers | Number of transformers with mechanical displacement of winding | Number of transformers with turn-to-turn SC | Number of transformers with other damage |
|---|---|---|---|
| 200 | 46 | 22 | 132 |
| 134 | 30 | 10 | 94 |
| 36 | 13 | 23 | 0 |
| 31 | 11 | 19 | 1 |
| 401 | 100 | 74 | 227 |

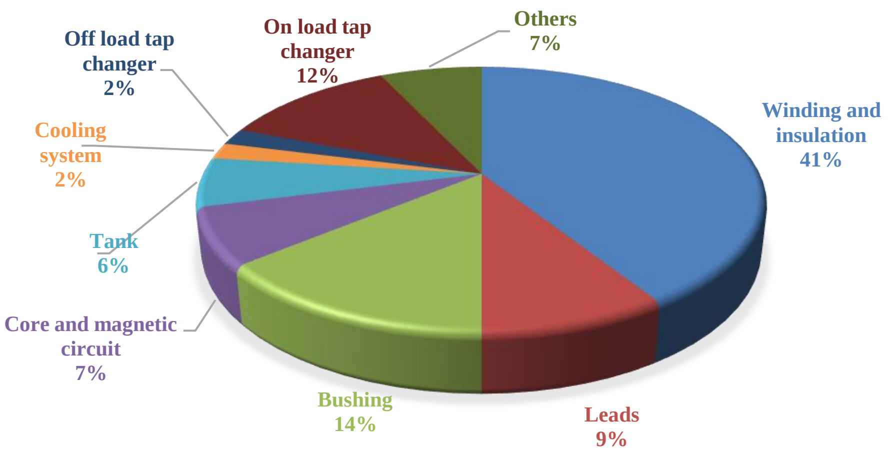
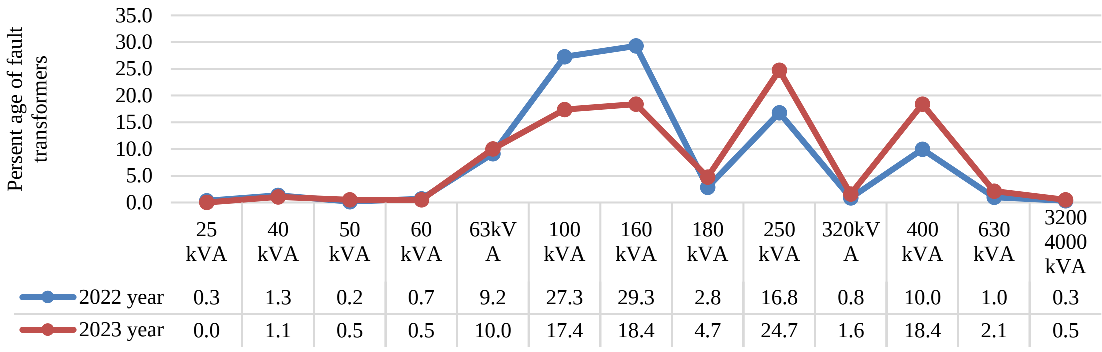



Figure 4. Failure statistics for power transformers

The failure of power transformers is directly related to the damage of its constructive active parts: winding and core. It is equally important in any voltage network that the active parts are damaged and the power transformers fail. The analysis of factual data on transformer failures at power system facilities in [22] reveals that defects in the active parts, specifically the winding, which make up 43% of 10/0.4 kV transformers and over 30% of 110 kV voltage class transformers with rated powers of 16–40 MVA, are one of the main causes of this state of events.

Figure 5 indicates that, a statistical analysis on the existing 9178 power transformers with a capacity of 25 kVA to 4000 kVA in the 6(10) kV power grids of Fergana region, their damage and the causes of damage in 2022-2023. According to the result of 2022 analysis, the most frequently damaged power transformers in this network are 160 kVA and 100 kVA power transformers, while the results of 2023 show the most damage to 250 kVA power transformers. The series of least damaged power transformers are led by 25 kVA and 50 kVA power transformers in 2022 and 2023, respectively.

Figure 6 shows the results of a statistical analytical study conducted in the Fergana region which is damage to power transformer elements by location is expressed in percentages. According to it, the highest rate was shown by winding damage with a rate of 53% and bushing failure with a rate of 28%. The least damage is the damage in the core with an indicator of 2%.




| | 25 kVA | 40 kVA | 50 kVA | 60 kVA | 63kVA | 100 kVA | 160 kVA | 180 kVA | 250 kVA | 320kVA | 400 kVA | 630 kVA | 3200 4000 kVA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2022 year | 0.3 | 1.3 | 0.2 | 0.7 | 9.2 | 27.3 | 29.3 | 2.8 | 16.8 | 0.8 | 10.0 | 1.0 | 0.3 |
| 2023 year | 0.0 | 1.1 | 0.5 | 0.5 | 10.0 | 17.4 | 18.4 | 4.7 | 24.7 | 1.6 | 18.4 | 2.1 | 0.5 |

Figure 5. Analysis of damaged power transformers in 6(10) kV networks in Fergana region in 2022-2023

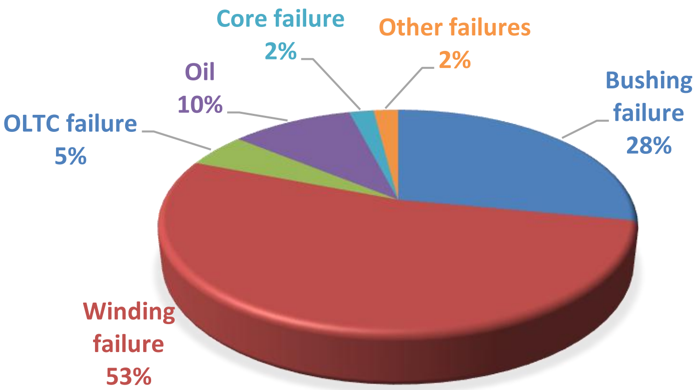



Figure 6. Failure analysis of elements of damaged 6(10)/0.4 kV voltage power transformers in Fergana region by location

The low percentage of damage in the OLTC device can be expressed by the low need for this device in 6(10) kV voltage networks. Based on Figure 6, we can understand that more attention should be paid to reducing damage in power transformer winding. Because, winding is one of crucial and expensive part of power transformers. Moreover, more than 1/3 of the total number of failures of power transformers are transformer failures due to damage to the winding.

## 6. RESULTS AND DISCUSSION

In [26], [27] studies investigated damage of power transformers and their components. Previous studies have not clearly shown the effect of restrictions imposed by the power supply company on the supply of electricity to consumers on power transformer failure. During the analysis of failed power transformers, we found that the restrictions placed by the power supply company on the delivery of electricity to consumers negative affect power transformers working life. Singh *et al.* [26] according to the results of the statistical analysis conducted by the authors, it is shown that power transformers with 25 kVA, 63 kVA, and 100 kVA are the most damaged in power networks with voltages of 10/0.4 kV. Our research shows that 100 kVA, 160 kVA and 250 kVA power transformers lead the most damaged power transformer list.

The results of the study in Fergana region show that the failure of power transformers increased in the winter season, it refutes results of the study of [26]. As one of the reasons for this, we can point to the restrictions imposed on the supply of electricity to consumers. For example, in the winter season, if there is a disconnection from the network due to the restriction of electricity in an area, the people living in this area do not disconnect the "electric heating device" from power network, but it remains on. If the rest of the electricity consumers do the same and leave the "electric heating devices" connected to the network, the limitation period will expire after a certain time. In this case, in order to provide consumers with electricity, connecting electrical devices under load, in particular, power transformers, to the electrical network, may cause their terminals to melt and their service life to decrease or fail. According to the results of research carried out in recent years, the components that have the most influence on the failure of the power transformer are protective devices [27] and insulation damage [26]. Based on the results of our research, we can say that this component is its winding.

In the course of the research, the breakdown of power transformers and its components was studied in connection with the damage of its components. The methods used in their diagnosis were considered. However, systematic analysis and improvement of the diagnostic methods used in the detection of damage to power transformer components may require additional and in-depth research. Our research shows that the failure of power transformers is directly related to the damage of its components, and in the future, research can be carried out to identify damage in power transformer coils and improve its diagnostic methods. Recent observations show that power transformer failures can be reduced by reducing constraints on the supply of electricity to consumers.

## 7. CONCLUSIONS

The objective of this study was to comprehensive investigation into power transformer failures: analysis of failure types and causative factors. The research determined that when eliminating power transformer failures in 6(10) kV power networks, it is necessary to pay more attention to 100 kVA, 160 kVA, and 250 kVA power transformers, which have the most failures. It is by reducing damage to power transformers of this capacity that we can reduce the number of total failures of power transformers. This has a positive effect on increasing the reliability of electric networks. The observations from this study suggests that there is a need to regulate the restrictions on the power supply to electricity consumers. In the implementation of scientific research work on the damage to power transformer parts, more emphasis should be placed on reducing the damage to the winding, which is the active part of the power transformer. This work has opened up several questions that need further investigation. Further work needs to be done to establish what should be the range of restrictions on the power supply to electrical consumers.

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