



Analysis of Distribution Transformers with Variable Load Conditions

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Abstract: Transformers are critical components in the electrical distribution system that function to increase or decrease the electrical voltage as needed. Variable load transformer analysis is an important study to understand the performance and efficiency of transformers under a wide range of operational conditions. Variable loads can affect the efficiency, voltage regulation, operating temperature, and life of the transformer.

The efficiency of a transformer is affected by power losses consisting of copper loss (related to load current) and core loss (related to voltage). Efficiency is usually higher at full load and decreases at low load due to the significant contribution of core loss. In addition, load fluctuations can cause voltage variations on the secondary side, which requires adjustment through a tap changer to maintain voltage stability.

Temperature management is also an important aspect because temperature increases due to high loads can accelerate insulation degradation and reduce the life of transformers. Efficient cooling systems, such as oil or air cooling, are often used to solve this problem. Real-time condition monitoring and preventive maintenance can help in detecting and addressing problems before they become serious.

With a comprehensive analysis involving load studies and operational simulations to predict the performance of transformers under various conditions. This helps in designing better transformers and determining optimal operating strategies to improve the efficiency and reliability of transformers.

Keywords: Transformer, Loss of power, Voltage regulation, Transformation ratio, Transformer optimization, Load power, Electrical distribution system, Load variation.

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I. Introduction

Transformers are essential components in the electricity distribution system that function to change the electrical voltage from one level to another to support the efficient delivery of electrical energy from the plant to the consumer. As the demand for electrical energy evolves, transformers must be able to operate efficiently and reliably in a variety of dynamically variable load conditions.

Variable load on a transformer is a condition in which the load current handled by the transformer fluctuates due to variations in electrical demand. This change in load can be caused by various factors such as electricity usage patterns by consumers, operational hours (e.g. peak and non-peak), and intermittent integration of renewable energy sources. Analysis of transformers with variable loads is important to ensure that the transformer can operate efficiently, maintain voltage stability, and have a long operating life.

The efficiency of the transformer is greatly affected by the power losses that occur, whether it is the loss of copper dependent

on the load current or the loss of the core that depends on the voltage. This loss of power contributes to the heating of the transformer, which in the long run can accelerate the degradation of the insulating material and reduce the life of the transformer. Therefore, effective temperature management and cooling systems are crucial aspects in the operation of transformers with variable loads.

In addition, voltage regulation is also a challenge when the load changes. The transformer must be able to adjust the transformation ratio through the tap changer mechanism to keep the output voltage within the desired limit. This is important to ensure that the quality of power received by consumers remains stable and reliable.

Real-time monitoring of transformer conditions as well as the implementation of preventive maintenance strategies can help in identifying and addressing potential problems before more severe damage occurs. Through comprehensive analysis, including load studies and operational simulations, transformer performance can be predicted more accurately, allowing for better transformer design and optimal operational strategy.

Thus, the analysis of transformers with variable loads is an important step in ensuring the reliability and efficiency of the power distribution system, which ultimately contributes to improving service quality and customer satisfaction.

II. Literature Review

This literature review reviews the literature and previous research related to the analysis of variable load transformers. Transformers are a vital component in power distribution systems, and a deep understanding of their performance under fluctuating load conditions is essential to ensure operational efficiency and reliability.

2.1. Basic Principles of Transformers

According to Harlow (2012), transformers operate on the principle of electromagnetic induction to convert electrical voltage from one level to another. The efficiency of a transformer is affected by two main types of power losses: copper losses that occur in the winding and core losses that occur in the core material.

2.2. Efficiency and Power Loss

Research by Gupta and Singh (2017) shows that the efficiency of transformers fluctuates with load variations. At full load, the efficiency is usually higher because the copper loss is greater, but it is proportional to the power transferred. At low loads, core loss becomes more dominant, which can reduce overall efficiency. This study emphasizes the importance of transformer designs that are able to optimize efficiency at various load levels.

2.3. Voltage Regulation

Research by El-Hawary (2018) discusses the importance of voltage regulation in transformers. Load variations can cause voltage fluctuations on the secondary side, which can affect power quality. Transformers with tap changer mechanisms allow adjustment of the transformation ratio to keep the output voltage within the desired limits.

2.4. Temperature Management and Refrigeration Systems

A study by Pennacchi et al. (2016) investigated the impact of operating temperature on transformer lifespan. Temperature increases due to high loads can accelerate the degradation of insulation materials and other components. Efficient cooling systems, such as oil or air cooling, are necessary to manage temperature rise and extend the life of the transformer.

2.5. Condition Monitoring and Preventive Maintenance

Research by Khan and Khan (2020) highlights the importance of real-time monitoring of transformer conditions. Modern sensor technology allows the collection of operational data such as temperature, current, and voltage, which can be analyzed to detect potential problems before serious damage occurs. Preventive maintenance based on an analysis of operational conditions can improve reliability and reduce repair costs.

2.6. Performance Simulation and Prediction

According to Zhang et al. (2019), simulations and predictive models are important tools in the analysis of transformers with variable loads. Simulation allows prediction of transformer

performance under various load conditions, aiding in better transformer design and determination of optimal operational strategies.

2.7. The Effect of Variable Loads in the Distribution System

A study by Mohammadi and Abapour (2021) shows that load variations in the electricity distribution system can affect the stability and efficiency of the overall grid. Transformers that are able to adapt to variable loads contribute to the stability of the network and the quality of power received by consumers.

The research conducted shows that the analysis of transformers with variable loads is a complex and multifaceted research field. An understanding of the basic principles of transformer operation, efficiency, voltage regulation, temperature management, condition monitoring, and performance simulation is essential for improving transformer design and operation. Further research is needed to develop transformers that are more efficient and reliable in the face of the challenges of changing loads.

III. Methodology

This methodology describes the steps and approaches used in the analysis of transformers with variable loads. The main objective of this study is to understand the performance of transformers under various load conditions and identify the factors that affect the efficiency, voltage stability, and operational life of transformers.

3.1. Data Collection

The first step in this analysis is the collection of transformer operational data from the electricity distribution system. The required data includes:

- Current and voltage on the primary and secondary sides.
- Power factor.
- Daily load and load fluctuations over a period of time.
- Transformer operating temperature.
- Loss of power (copper and core).

This data can be obtained through a real-time monitoring system equipped with relevant sensors.

3.2. Power Loss Analysis

Power loss analysis is performed to understand how load changes affect the efficiency of the transformer. The steps include:

- Calculate copper losses based on load current using the I^2R equation, where I is the load current and R is the winding resistance.
- Calculate core losses that tend to be constant and dependent on voltage using factory data or direct measurements.
- Determine the total power loss and efficiency of the transformer at various load levels.

3.3. Load Simulation

Load simulations are carried out to model the performance of transformers under various operational conditions. Simulation

software such as MATLAB or PSCAD can be used to create transformer models. The steps in the simulation include:

- Create a mathematical model of the transformer that includes electrical and thermal parameters.
- Run simulations with varying load data inputs to see the transformer response.
- Analyze simulation results to understand voltage fluctuations, power loss, and temperature rise under various load conditions.

3.4. Temperature Measurement and Thermal Management

Thermal management analysis involves measuring the temperature of the transformer and evaluating the cooling system. The steps include:

- Using a temperature sensor to monitor temperature rise in the transformer winding and core.
- Evaluate the effectiveness of the cooling system used (e.g. oil or air cooling).
- Analyze the relationship between temperature rise, load, and transformer life.

3.5. Voltage Regulation

Voltage regulation analysis is performed to ensure the transformer can keep the output voltage within the desired limit even if the load changes. The steps include:

- Measures the voltage on the secondary side of the transformer at various load levels.
- Use a tap changer to adjust the transformation ratio and maintain voltage stability.
- Analyzing voltage data to determine the effectiveness of voltage regulation and its impact on power quality.

3.6. Transformer Life Evaluation

Transformer life evaluation involves analyzing the degradation of insulating materials and other components due to variable loads. The steps include:

- Using a thermal aging model to estimate insulation life based on operating temperature.
- Analyze load and temperature data to determine degradation patterns.
- Determine preventive maintenance strategies to extend the life of transformers.

3.7. Development of Recommendations

Based on the results of analysis and simulation, recommendations are developed to improve the performance and reliability of the transformer. Recommendations may include:

- Optimize transformer design for efficiency under a wide range of load conditions.
- Implementation of a more effective cooling system.

- Implementation of preventive maintenance strategies based on real-time condition monitoring.

3.8. Result Validation

Validation of results is carried out by comparing the results of analysis and simulation with actual operational data. The steps include:

- Collect operational data after the implementation of recommendations.
- Compare transformer performance before and after implementation.
- Refine models and recommendations based on validation findings.

IV. Discussion

The analysis of transformers with variable loads can be carried out comprehensively, allowing for the identification of problems and the development of effective solutions to improve the efficiency and reliability of transformers.

4.1. Case model

City X has a Diesel Power Plant (PLTD) that supplies electricity to about 50,000 residents. The main transformer in PLTD has a capacity of 5 MVA with a primary voltage of 20 kV and a secondary voltage of 0.4 kV. In recent years, PLTD has experienced significant load fluctuations mainly due to increased electricity consumption during peak hours and the integration of renewable energy systems such as solar panels that affect load stability.

4.2. Benefits of Case Studies

The benefit of this case study is to analyze the performance of the transformer in PLTD Kota X in the face of variable loads and to provide recommendations that can improve the efficiency and operational reliability of the transformer.

4.3. Data Collection

Transformer operational data was collected over a three-month period which included:

- **Current and Voltage:** Current and voltage data on the primary and secondary sides on an hourly basis.
- **Power Factor:** Power factor data during various load conditions.
- **Daily Load:** A daily load pattern that shows the fluctuation of load between peak and non-peak hours.
- **Operating Temperature:** Temperature data on the core and winding of the transformer.
- **Power Loss:** Copper and core loss data measured during the observation period.

4.4. Power Loss Analysis

Power loss analysis is performed using the current and voltage data collected. The calculation is carried out to determine copper losses and core losses. The results of the calculation show that:

- **Copper loss** increases significantly during peak hours with higher currents.
- **Core loss** remains constant and is lower than copper loss during peak load.

4.5. Temperature Measurement and Thermal Management

Temperature measurements are made using temperature sensors placed on the core and winding of the transformer. The analysis shows that:

- **Temperature Rise:** A significant increase in temperature occurs during peak loads.
- **Effectiveness of the Cooling System:** The oil cooling used is effective in keeping the temperature within safe limits, although there is a need to increase the cooling capacity during peak loads.

4.6. Voltage Regulation

Voltage regulation is analyzed by monitoring the stress on the secondary side during the observation period. Tap changers are used to adjust the transformation ratio and maintain the output voltage. The results of the analysis show that:

- **Voltage Fluctuations:** Voltage fluctuations occur that can affect the quality of power received by consumers.
- **Tap Changer Effectiveness:** Tap changers are effective in adjusting the transformation ratio, but there is a need for more frequent adjustments during rapid load changes.

4.7. Transformer Life Evaluation

The life evaluation of the transformer was carried out by analyzing temperature data and insulation degradation patterns. Thermal aging models are used to estimate the life of the insulation. The results of the evaluation showed that:

- **Insulation Degradation:** Accelerated insulation degradation occurs during periods of high load.
- **Transformer Life:** Can be affected by the frequency and duration of peak loads.

4.8. Recommendations

Based on the results of the analysis, several recommendations are put forward to improve the efficiency and reliability of transformers:

- **Cooling System Optimization:** Increases the capacity of the cooling system to manage temperature rises during peak loads.
- **Real-time Monitoring:** Implementation of a real-time condition monitoring system to detect and address potential problems before damage occurs.
- **Tap Changer Adjustment:** Fine-tune the tap changer adjustment strategy to deal with voltage fluctuations more effectively.
- **Preventive Maintenance:** Perform preventive maintenance based on operational condition data to extend the life of the transformer.

Using case studies will be able to show that transformer analysis with variable loads provides valuable insights into the operational performance of transformers under dynamic load conditions. The implementation of the proposed recommendations can improve the efficiency, voltage stability, and operational life of the transformer in the City X PLTD, thereby ensuring a reliable and quality electricity supply for consumers.

Basic calculations to understand the efficiency of transformers with variable loads:

Example of Efficiency Calculation

Suppose a transformer has the following specifications:

- Capacity: 100 kVA
- Primary Voltage: 10 kV
- Secondary Voltage: 400 V
- Copper Loss: 2 kW at full load
- Core Loss: 1 kW

At Full Load (100 kVA):

- **Output Power:** 100 kW (assume power factor 1 for simplicity)
- **Total Loss:** 2 kW (copper) + 1 kW (core) = 3 kW
- **Input Power:** 100 kW + 3 kW = 103 kW
- **Efficiency:** $(100 \text{ kW} / 103 \text{ kW}) * 100\% \approx 97.09\%$

At Half Load (50 kVA):

- **Output Power:** 50 kW
- **Copper Loss:** $(2 \text{ kW} / 4) = 0.5 \text{ kW}$ (because copper loss is directly proportional to the square of the current)
- **Total loss:** 0.5 kW (copper) + 1 kW (core) = 1.5 kW
- **Input Power:** 50 kW + 1.5 kW = 51.5 kW
- **Efficiency:** $(50 \text{ kW} / 51.5 \text{ kW}) * 100\% \approx 97.09\%$

At Low Load (10 kVA):

- **Output Power:** 10 kW
- **Copper Loss:** $(2 \text{ kW} / 100) = 0.2 \text{ kW}$
- **Total loss:** 0.2 kW (copper) + 1 kW (core) = 1.2 kW
- **Input Power:** 10 kW + 1.2 kW = 11.2 kW
- **Efficiency:** $(10 \text{ kW} / 11.2 \text{ kW}) * 100\% \approx 89.29\%$

From the above example, it can be seen that the efficiency of the transformer changes with the variation of the load, and at very low loads, the efficiency tends to decrease due to the significant influence of core loss.

V. Conclusion

From the analysis of transformers with variable loads is an important aspect in ensuring the reliability and efficiency of the power distribution system. From the various studies and case studies that have been conducted, several key conclusions can be drawn:

5.1. Transformer Efficiency

The efficiency of the transformer is greatly affected by the variation in load. At full load, efficiency tends to be higher because the proportion of copper loss to total transferred power is lower. However, at low loads, efficiency decreases as constant core loss becomes more dominant. Therefore, the transformer design must be optimized to maintain good efficiency at various load levels.

5.2. Voltage Regulation

Loads can cause voltage variations on the secondary side of the transformer. In order to maintain voltage stability and power quality, the tap changer mechanism is very important. Real-time adjustment of the transformation ratio allows the output voltage to remain stable even when the load fluctuates.

5.3. Thermal Management

Temperature rises caused by high loads can accelerate the degradation of insulation materials and reduce the operational life of transformers. Efficient cooling systems, such as oil or air cooling, are essential for managing temperature rises and keeping transformers in safe operating conditions. The use of real-time temperature monitoring technology can be helpful in identifying potential thermal problems before they become serious.

5.4. Preventive Maintenance

Real-time monitoring of the condition of the transformer using modern sensor technology allows for early detection of potential problems. The operational data collected can be used for trend analysis and the development of effective preventive maintenance strategies. This approach not only improves the reliability of the transformer but also reduces repair costs and extends the operational life.

5.5. Upgrade Recommendations

Based on the results of the analysis, several recommendations that can be implemented to improve transformer performance include optimization of the cooling system, improvement of transformer efficiency, adjustment of tap changer strategy, and implementation of data-based preventive maintenance. The implementation of these recommendations can improve the efficiency, voltage stability, and operational life of transformers, as well as ensure a reliable and quality power supply for consumers.

Therefore, the analysis of transformers with variable loads provides valuable insights to overcome operational challenges in power distribution systems. By understanding how various factors such as efficiency, voltage regulation, thermal management, and maintenance affect the performance of transformers, the right steps can be taken to improve the reliability and efficiency of the electrical system. Continuous research and innovation in this field is essential to face the increasingly complex and dynamic demands of electrical energy in the future.

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