Temperature Fluctuations in Power conductors: Analysis and Overcurrent Relay Adaptation Strategies for Mitigation

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Abstract
In electrical networks, the efficient flow of energy faces constraints primarily associated with the conductor's temperature. By assessing transmission infrastructure, identifying critical geographical and climatic zones, one can compute the line's temperature. Focusing on the importance of maintaining optimal conductor temperature for efficient power transmission, this paper evaluates the critical role of conductor temperature in overhead transmission lines and explores its dynamic variations influenced by various ambient conditions. Emphasizing the significance of maintaining optimal conductor temperature, the study delves into mitigation strategies and adaptive protection mechanism, with a focus on overcurrent relays, with specific emphasis on the efficacy of current-time graphs. By addressing these factors, the research aims to enhance the reliability and efficiency of power transmission systems, ensuring sustained performance under diverse environmental scenarios. Overall, the paper contributes valuable insights to optimize the flow of energy in overhead transmission lines, thereby enhance the robustness also, improving the resilience and functionality of electrical networks.

Keywords: Thermal Rating, Transmission line, Adaptability, Annealing, Adaptive Relay, Reliability

1. INTRODUCTION

The power sector is undergoing a transformative shift towards sustainable and efficient energy transmission. Amidst this evolution, the impact on temperature variations on overhead transmission line has emerged as a pivotal factor influencing their operational integrity. As temperatures change, conductor resistance alters, effecting the efficiency of power transmission [1]. Bare overhead conductors play a pivotal role in overhead transmission lines, demonstrating significant importance in the face of temperature variations. The inherent design of bare conductors renders them particularly adept at navigating fluctuating temperatures. Their exposure allows for efficient dissipation of heat, minimizing thermal resistance and maintaining optimal operating conditions. This characteristic becomes crucial in regions experiencing diverse temperature ranges, as bare conductors exhibit superior thermal performance compared to insulated counterparts [2]. Temperature induced effects on electrical resistance are mitigated by the design of bare conductors, ensuring consistence and reliable power transmission. Additionally, these conductors experience reduced sag in high temperature, mitigating the risk of contact with surrounding objects and enhancing overall safety [3]. Moreover, the adaptability of bare conductors to temperature variations aligns with the dynamic nature of environmental conditions in transmission lines routes. By embracing these temperature induced challenges, bare overhead conductors emerge as a resilient and efficient solution for power transmission [4].

Engineers have been consistently intrigued by the prospect of enhancing the current carrying capability of bare overhead conductors. The temperature of overhead conductor is crucial in context of overhead transmission lines. Exploring the temperature dynamics of bare overhead conductors and the application of overcurrent relay to protect transmission lines from undesired temperature spikes is the focus of this study, elucidated through pertinent literature reviews. The paper [3] highlighted the variations in steady state thermal ratings by understanding how thermal performance fluctuates under different conditions and describes a probabilistic method to evaluate the thermal capacity of conductors in real time, considering dynamic changes and determining the permissible operating duration during transient conditions. In [4] the authors offer several recommendations to enhance surveillance of transmission lines and gather data on the thermal strain of overhead lines. In [5] the authors experimentally validate the calculations of conductor temperature derived from a weather model and ascertain the time required to reach thermal overload. In [6] the authors suggest the protection strategies to mitigate the impact of energy sources on interconnected distribution network. The authors in [7] provides a method employing probability to evaluate thermal capacity, grounded in risk assessment. In [8] the authors illustrated the impact of thermal limits on transmission lines and explores how these limits can be utilized for economic generation dispatch.

As ambient temperatures vary, the resistance of the conductors also changes, leading to fluctuations in line impedance. This affects the line's voltage drop, power losses, and overall efficiency. Additionally, temperature fluctuations can cause conductor sag, altering the mechanical characteristics of the line and potentially leading to clearance issues or even line faults during extreme conditions such as high wind or ice loading. These fluctuations also impact the thermal rating of the conductors, potentially reducing their current carrying capacity during peak demand periods.

To mitigate the effects of temperature fluctuations on transmission lines, various strategies are employed, including the use of overcurrent relays with specific characteristics such as inverse time, Inverse Definite Minimum Time (IDMT), very inverse, or extremely inverse settings. These relays are designed to respond differently to varying levels of fault currents and thus provide optimal protection against overcurrent conditions caused by temperature related fluctuations. By integrating these relay settings into the protection scheme, transmission line operators can effectively manage temperature related challenges and ensure the reliability and stability of the grid.

This paper deals with the temperature fluctuation of Aluminum Conductor Steel Reinforced (ACSR) conductors. ACSR bare overhead conductors and effective mitigation strategies through overcurrent relay under steady state thermal conditions, within the geographical context of Assam, India. In Assam, the utilization of ACSR bare overhead conductor is strategic and multifaceted, driven by the region’s climatic and operational considerations. ACSR conductors are well suited for Assam’s environmental conditions due to their capacity to withstand temperature variations [4]. Assam experiences a diverse climate, ranging from hot to humid to cool temperatures, and ACSR conductors exhibit superior thermal performance under such fluctuations.

The paper is organized as follows: Section 2 describes the theoretical foundation and the proposed methodology. While Section 3 presents the experimental results and discussion, and section 4 provides concluding remarks.

2. METHODOLOGY

A) Consequences of thermal overload

The assessment of the thermal rating of a conductor in overhead transmission lines, considering both static (thermal equilibrium) and transient conditions, involves using the heat balanced equation for the conductor [9].

$$Q_s + I^2R(T_c) = Q_c + Q_r + mC_p dT_c/dt \quad (1)$$

Where Q_s and $I^2R(T_c)$, representing heat gain from solar radiation and Joule heating due to current flow (with R being temperature dependent). Q_c and Q_r account for heat loss through convection and long-wave radiation, respectively. These heat terms are quantified in units of W/m. The term mC_p denotes the conductor's heat capacity in J/m ºC.

The determination of a conductor's ampacity, or its ability to carry current, involves assessing its steady state thermal (SST) rating under constant conditions. This entails assuming that the conductor has already reached a temperature equilibrium, signified by setting the derivative of the conductor temperature with respect to time (dT_c/dt) to zero. Given that heat loss rates due to radiation and convection are not linearly related to the conductor temperature, an iterative process is employed to solve the remaining equation for conductor temperature in terms of current and environmental factors. In scenarios where current or ambient conditions fluctuate, the conductor temperature undergoes calculation as a function of time following a step change in current, as denoted by equation (1). This equation is solved iteratively at each time step to ascertain the transient thermal rating within a specified time period. This iterative approach is crucial for accurately assessing the conductor's temperature under varying conditions and after changes in current, offering a comprehensive understanding of its transient thermal behavior.

Exceeding the maximum allowable conductor temperature, typically set at 75ºC, poses significant risks to the integrity and functionality of power lines. The selection of this temperature limit is a strategic measure aimed at minimizing undesirable consequences such as strength loss, sagging, and line losses [3].

When the flow on a power line surpasses the specified conductor temperature, detrimental outcomes may manifest. One immediate concern is the loss of clearance due to sag. In extreme scenarios, the power line may come into direct contact with objects below, leading to permanent faults. Such faults can have severe repercussions, including loss of life, property damage, and subsequent outages. In some instances, this may even escalate into cascading events, amplifying the impact on the power system.

Another consequence of exceeding the conductor temperature limit is the potential loss of strength due to annealing. Annealing is a gradual and irreversible process involving the recrystallization of metal. This phenomenon damages the grain matrix established through cold rolling, resulting in a notable reduction in strength. The compromised structural integrity of the power line poses further risks to its reliability and safety.

In essence, the careful consideration of conductor temperature limits is crucial for preventing the escalation of these hazards. By adhering to the specified temperature threshold, the detrimental effects of sag, strength loss, and potential cascading events can be mitigated, ensuring the sustained and secure operation of power lines in the long run.

The establishment of a safety clearance with ample specifications is a fundamental practice, ensuring that, under most circumstances, the likelihood of flashover occurrences remains exceedingly minimal.

Nevertheless, the potential for complications arises as a consequence of gradual processes like creep elongation, leading to an increase in both permanent sag and a reduction in conductor strength over time. Comprehensive awareness of the conductor temperature under various ambient conditions and current flows holds paramount importance. This knowledge serves a dual purpose, proving invaluable in both system planning and the day-to-day operation and maintenance of transmission lines. This careful consideration ensures that operational security and reliability are upheld without compromise.

Furthermore, a proactive approach involving the continuous monitoring of temperature in critical stretches of transmission lines becomes imperative. This proactive monitoring not only facilitates the anticipation of transmission capacity on an hourly basis but also enables the strategic utilization of favorable periods for economic dispatch. By harnessing this information, operators can optimize resource allocation and streamline energy distribution during periods of heightened efficiency, contributing to the overall effectiveness and sustainability of the transmission network. In essence, the integration of temperature insights into the operational framework is a key element in fostering a resilient and efficient transmission infrastructure.

B) Fluctuations in Steady State Thermal Rating

- Transmission line ratings are dynamic, subject to constant fluctuations based on ambient conditions. Periodically, the capacity of a transmission line surpasses its static rating, reflecting the variable nature of its performance. This variability underscores the need for real-time monitoring and assessment to ensure optimal utilization. The dynamic adjustments in line ratings highlight the intricacies of managing transmission infrastructure, necessitating a comprehensive approach that considers environmental factors, weather conditions, and other dynamic variables to maintain a reliable and efficient power transmission system [3].
- Steady state thermal rating in overhead transmission lines experiences variations influenced by diverse factors. Ambient temperature, wind speed, solar radiation, and conductor temperature collectively impact the line's thermal performance. Elevated ambient temperatures typically reduce the line's capacity, while increased wind speed aids cooling, potentially enhancing the rating. Solar radiation induces additional heating effects. The variability in these environmental elements necessitates continuous monitoring and adjustment of the steady state thermal rating to ensure optimal efficiency and prevent overloading. Managing these variations is crucial for maintaining the reliability and safety of the transmission infrastructure.
- The temperature of an ACSR Drake 26/7 bare overhead conductor in overhead transmission lines is influenced by ambient conditions, primarily ambient temperature and wind speed.
- Continuous current flow through the conductor generates heat due to resistive losses. The balance between heat generated and dissipated determines the steady-state temperature. It's crucial to consider these factors in the design and operation of overhead transmission lines to ensure efficient and reliable power transmission. Engineering calculations, such as the Conductor Ampacity, help assess the maximum current-carrying capacity under varying ambient conditions.

C) Adaptive overcurrent Relay protection for transmission lines

Overcurrent relays monitor and respond to variations in current flow, providing a proactive defence against potential issues like overloads and short circuits. Their adaptive nature allows for swift and precise actions to mitigate risks, ensuring the resilience of the transmission lines and overall reliability of the power grid.

The operation of an overcurrent relay involves setting current thresholds, known as pickup currents. When the current exceeds the preset value, the relay responds by activating the protective devices, such as circuit breakers, to isolate the faulty section of the power system. The time delay in relay operation is essential for coordination with other protection devices and preventing unnecessary tripping during transient conditions [6].

One critical aspect of overcurrent relay protection is coordination. Coordination ensures that the relays at different locations along the transmission line operate selectively, meaning that only the relay nearest to the fault should trip. This prevents unnecessary shutdowns of healthy sections of the power network, maintaining system reliability. Inverse-time overcurrent relays, including Inverse Definite Minimum Time (IDMT), very inverse, and extremely inverse types, are commonly used for protecting overhead transmission lines. These relays operate based on the principle that the time it takes for the relay to trip is inversely proportional to the magnitude of the fault current.

The time-current characteristics is expressed by a general formula [10].

$$t = \frac{K}{I^n - 1} \quad (2)$$

where, *t* represents the operating time of the relay or time delay. *K* is the relay time multiplier constant, and *I* denote the current magnitude or current during a fault. *n* is the time-current characteristic exponent As per British Standards, crucial attributes of overcurrent relays include the following characteristics [10].

Inverse Definite Minimum Time (IDMT):

$$t = \frac{0.14}{I^{0.02} - 1} \quad (3)$$

Very inverse:

$$t = \frac{13.5}{I - 1} \quad (4)$$

Extremely inverse:

$$t = \frac{80}{I^2 - 1} \quad (5)$$

For instance, IDMT relays offer a balance between speed and selectivity, while very and extremely inverse relays are more sensitive to lower magnitude faults, which could be crucial in detecting early signs of conductor degradation due to temperature stresses.

3. EXPERIMENTAL RESULTS AND DISCUSSION

In Assam, transmission lines utilizing ACSR conductors are engineered to safely carry a maximum static rating of 992A per conductor. This rating is determined based on calculations predicting that the conductor's temperature will reach 75°C under specific conditions. These conditions include an assumed wind speed 3.6 m/s, an ambient temperature of 27 ºC, and a solar radiation intensity of 1024 W/m^2.

Table 1: Conductor Temperature for ACSR Conductor with Steady State Thermal Rating

Ambient Temperature (°C)	Wind speed (m/s)	Conductor temperature (°C)
15	1.1	32.46
20	3.1	48.77
25	2.1	46.63

25	5.1	60.81
30	4.6	61.46
35	4.1	62.30
35	5.1	65.95
40	1.6	54.74
50	3.6	59.29
55	4.1	73.62
60	3.6	75.22
70	5.1	83.71
80	5.6	89.24
80	2.1	84.93

Table 1 shows that the ACSR conductor temperature under steady state thermal rating is lower at low ambient temperatures and higher at high ambient temperatures, with variations depending on wind speeds.

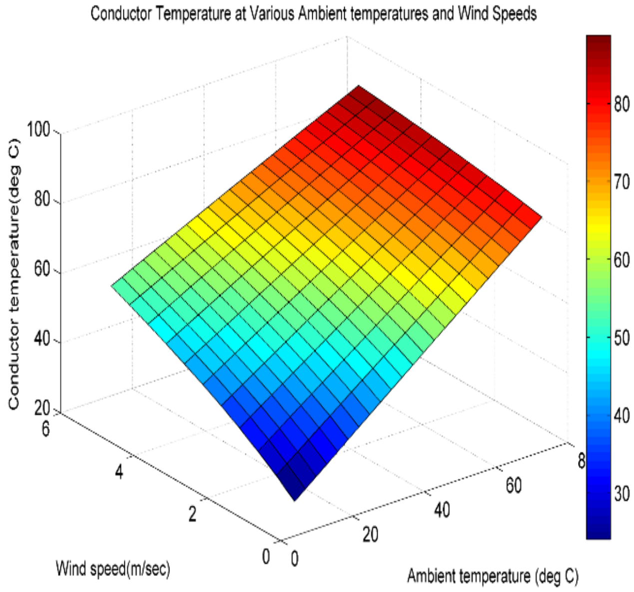

Fig. 1: Conductor temperature under varying ambient conditions for fixed static rating

The fig. 1 shows the temperature of the Drake 26/7 ACSR conductor changes from 24.07°C to 89.65°C under various ambient conditions when a continuous current of 992A passes through line. This indicates how the conductor's temperature fluctuates based on environment factors during steady state current flow.

To protect power transmission lines from overcurrent caused by factors like temperature variations in conductors, Inverse-time overcurrent relays can be employed. In ACSR conductors, as temperature increases, resistance also increases, leading to a decrease in current flow.

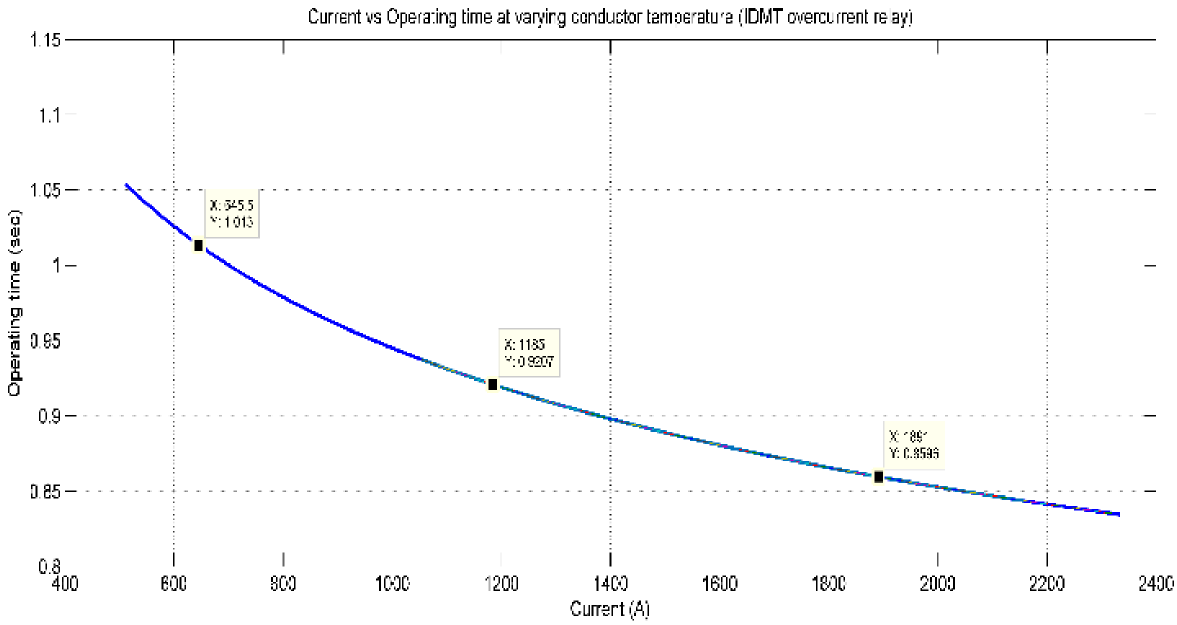

Fig. 2: Current Vs Operating time at varying conductor temperature for IDMT overcurrent relay
(Y axis- Operating time in seconds/X axis- Current in Ampere)

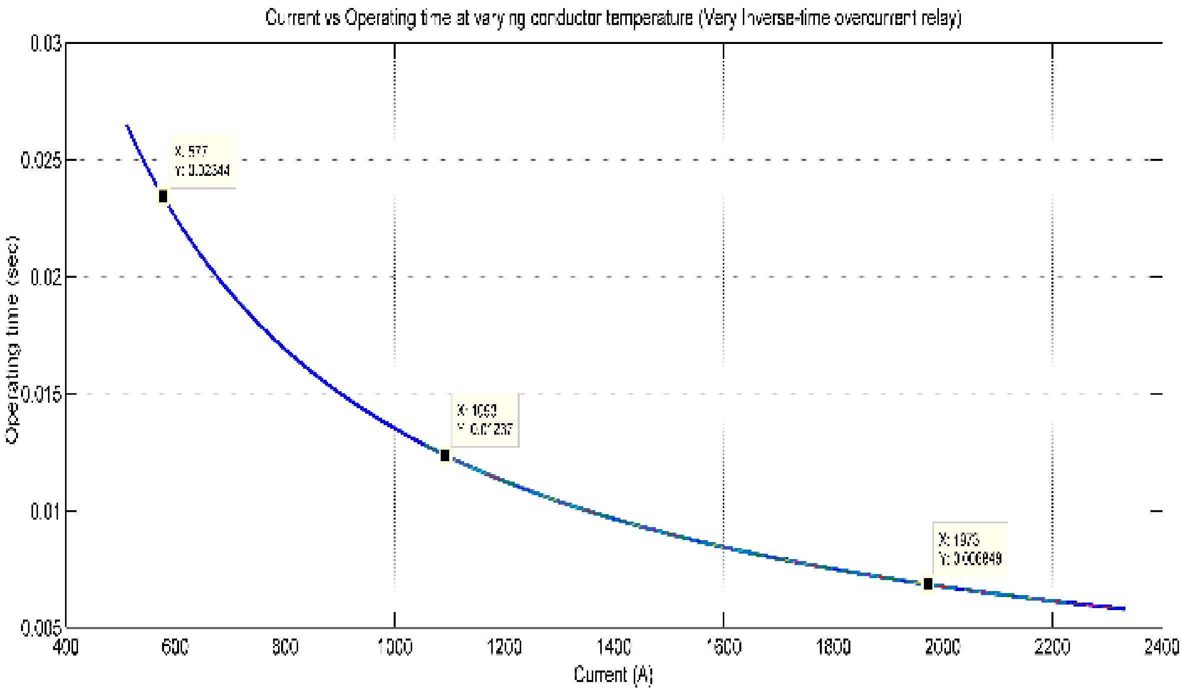

Fig.3: Current Vs Operating time at varying conductor temperature for Very inverse overcurrent relay
(Y axis- Operating time in seconds/X axis- Current in Ampere)

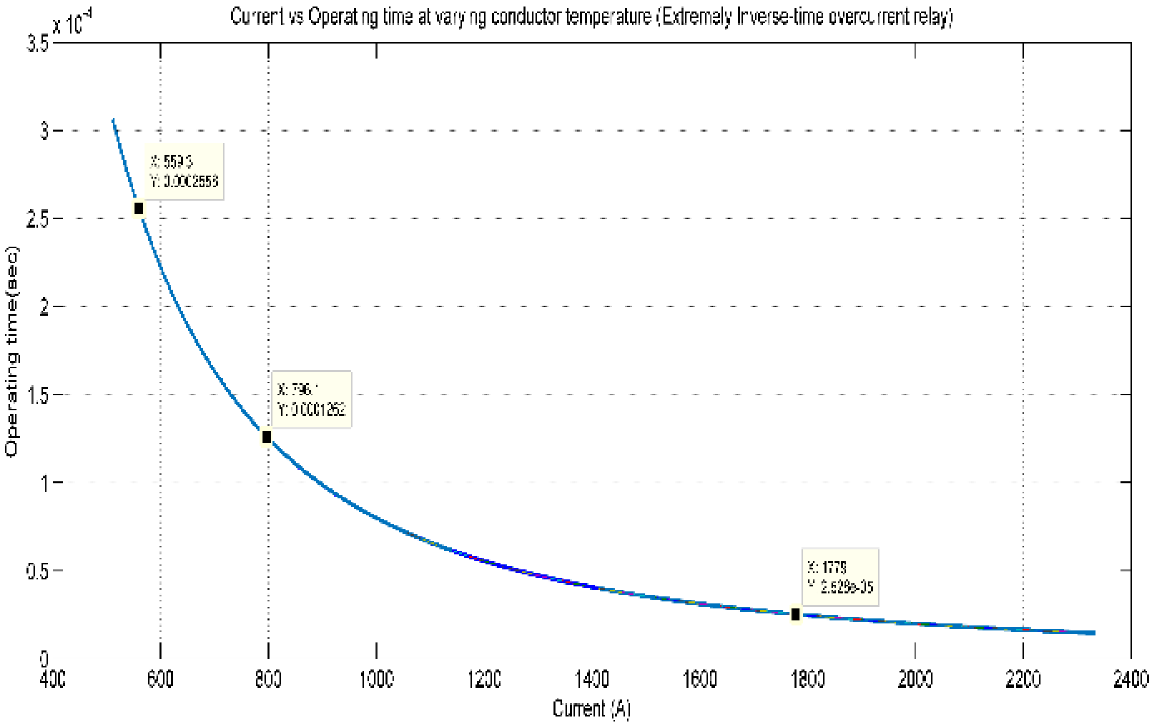

Fig. 4: Current Vs Operating time at varying conductor temperature for Extremely inverse overcurrent relay
(Y axis- Operating time in seconds/X axis- Current in Ampere)

Figures 2, 3, and 4 are depicted based on the results of temperature fluctuations of the ACSR conductor obtained from the preceding analysis. Fig. 2 illustrates that for higher current magnitudes, the relay operates faster. Conversely, a decrease in current flow leads to a slower response from the IDMT relay, providing a safety margin during temporary overcurrent conditions. In Fig.3, the operating time decreases more rapidly with increasing current magnitude, offering a quicker response time for higher current magnitude. Fig. 4, offers the most rapid response for higher current magnitudes, ensuring efficient protection against overcurrent conditions induced by temperature fluctuations.
These relays are crucial for protecting overhead transmission lines by quickly isolating faulty sections. To enhance adaptive protection, these relays can be integrated with temperature sensors on the conductors [11]. The relay settings can be adjusted based on the conductor temperature variations, ensuring optimal and timely response to faults while considering environmental condition.

4. CONCLUSION

The meticulous consideration of conductor temperature and its susceptibility to variations under diverse ambient conditions is paramount in ensuring the reliability and efficiency of overhead transmission lines. As ambient temperature rises, the conductor temperature also increases. For instance, at an ambient temperature of 30 ^oC, the conductor temperature measures 61.46 ^oC, while at 70 ^oC ambient temperature, the conductor temperature rises to 83.71 ^oC. Additionally, these temperatures are influenced by wind speed. The analysis has underscored the crucial need for effective mitigation strategies and adaptive protection measures, with a particular focus on overcurrent relays, including IDMT, very inverse, and extremely inverse types. By understanding and addressing the challenges posed by temperature

fluctuations, the power industry can enhance the overall stability and longevity of the electrical infrastructure, ensuring a robust and resilient electrical grid for the future.
The future scope could involve exploring advanced sensor technologies for real-time temperature monitoring of ACSR conductors, integrating machine learning algorithms to predict temperature variations, and developing smart grid solutions for adaptive protection using a combination of overcurrent relays, such as IDMT, very inverse, and extremely inverse relays. Additionally, investigating the integration of renewable energy sources into the overhead transmission lines and assessing their impact on temperature variations could be a valuable avenue for future research

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