ANALYZING POWER CONDUCTOR TEMPERATURE VARIATIONS AND FORECASTING DYNAMIC THERMAL RATINGS USING FUZZY LOGIC FOR OVERHEAD LINES

A Project Report is Submitted in Partial Fulfilment of the Requirement for the Degree of

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DECLARATION

I hereby certify that the project entitled "**ANALYZING POWER CONDUCTOR TEMPERATURE VARIATIONS AND FORECASTING DYNAMIC THERMAL RATINGS USING FUZZY LOGIC FOR OVERHEAD LINES**" has been carried out and presented by me, under the guidance and supervision of professors **Dr. Purobi Patowary** and **Dhritika Saikia** in a manner satisfactory to warrant its acceptance as a prerequisite for the award of the Degree of Master in Electrical Engineering with specialization in Power System Engineering , Department of Assam Engineering College, Jalukbari under Assam Science and Technology University. All the data represented in this report is true and correct to the best of my knowledge and belief.

Further, the report has not been submitted/ reproduced in any form for the award of any other degree/diploma.

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ABSTRACT

In recent times, there has been a significant rise in the need for electricity, a trend expected to continue. This surge in demand has resulted in transmission lines operating at much higher capacities, which in turn exposes them to increased thermal and mechanical stress, ultimately impacting the reliability of the transmission network.

This project explores the efficient flow of energy in overhead transmission lines, with a focus on the critical role of the conductor temperature in a diverse climatic region like Assam. By assessing transmission infrastructure and considering geographical and climatic constraints, the study evaluates the dynamic variations of conductor temperature influenced by ambient conditions. Through an analysis of Static Thermal Rating (STR) and Dynamic Thermal Rating (DTR) for the region Assam, the research assesses the real-time capacity of power lines under changing environmental scenarios. Additionally, a novel approach utilizing fuzzy logic is introduced to model the Dynamic thermal rating, enhancing the accuracy of predicting thermal performance based on factors such as ambient temperature, wind speed, solar radiation.

The study further includes a comprehensive evaluation of summer and winter real time dynamic thermal and fuzzy dynamic thermal ratings, providing insights into seasonal variations. The importance of maintaining optimal conductor temperature for efficient power transmission is emphasized, along with proposed mitigation strategies and adaptive protection mechanisms such as overcurrent relays with special emphasis on current-time graphs. Overall, this research contributes valuable insights to optimize energy flow, enhance the reliability and efficiency of power transmission systems, and facilitate efficient energy management in diverse climate zones, thus advancing smart grid technology.

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I would also like to express my heartiest thanks to our respected head of the Department Dr. Runumi Sarma, for valuable advice and help during the entire course of the project.

I express my pleasure in submitting this project work on **"Analyzing Power Conductor Temperature Variations and Forecasting Dynamic Thermal Ratings Using Fuzzy Logic for Overhead Lines."** in partial fulfilment of the requirement for awarding of the Master of Engineering in Electrical Engineering (Power System Engineering) under the Assam science and Technology University.

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Abbreviation	**Description**
DTR	Dynamic Thermal Rating
STR	Static Thermal Rating
FDTR	Fuzzy Dynamic Thermal Rating
ACSR	Aluminum Conductor Steel Reinforced
OCR	Over Current Relay
SST	Steady State Thermal
IDMT	Inverse Definite Minimum Time
FIS	Fuzzy Inference System

CHAPTER 1
INTRODUCTION

The global demand for electricity has been steadily increasing, necessitating the development and enhancement of power transmission systems to efficiently deliver electrical energy across vast distances. Overhead transmission lines, a fundamental component of these systems, play a pivotal role in ensuring the reliable and uninterrupted supply of electricity. However, their performance can be significantly influenced by environmental factors, especially temperature variations. In the state of Assam, situated in the northeastern region of India, where climatic conditions can vary considerably throughout the year, understanding the temperature variations of Aluminum Conductor Steel Reinforced (ACSR) conductors becomes imperative for ensuring reliable and efficient power transmission.

This study aims to investigate the temperature fluctuations experienced by ACSR conductors in overhead transmission lines in Assam. Additionally, it seeks to propose mitigation strategies to address any potential issues arising from these temperature variations. The mitigation strategies will primarily focus on the implementation of Overcurrent Relays (OCRs), which are crucial components in protecting the transmission lines from overloads and short circuits.

Furthermore, the study aims to determine both static and dynamic thermal ratings for the overhead transmission lines in Assam. Static thermal ratings provide an estimate of the maximum current-carrying capacity of the conductors under steady-state conditions, while dynamic thermal ratings account for transient conditions such as wind and solar radiation. Additionally, a fuzzy dynamic thermal rating (FDTR) model will be developed to account for uncertainties inherent in environmental conditions and load variations.

By conducting this comprehensive analysis, this study aims to contribute to the enhancement of the reliability and efficiency of power transmission in Assam. The findings and recommendations derived from this research will be valuable for stakeholders involved in the planning, operation, and maintenance of the overhead transmission infrastructure in the region. Ultimately, the goal is to ensure the uninterrupted supply of electricity to meet the growing demands of Assam's populace while optimizing the utilization of existing transmission assets.

1.1 ACSR Conductors:

Aluminum Conductor Steel Reinforced (ACSR) conductors are commonly used in overhead transmission lines[1]. These conductors consist of a central core made of steel wires surrounded by one or more layers of aluminum wires. The steel core provides mechanical strength, while the aluminum strands offer low resistance for efficient transmission of electricity.

1.2 Temperature Variations:

It Refers to changes in temperature along the transmission lines. Temperature variations can occur due to seasonal changes, diurnal variations, or other environmental factors[2]. These changes can affect the performance and longevity of the cables, as extreme temperatures can lead to expansion, contraction, and even damage to the materials.

1.3 Overcurrent Relay (OCR):

An essential component of protective relay systems used in electrical networks [3]. OCRs detect abnormal currents in the transmission lines, such as overloads or short circuits, and initiate protective actions, such as tripping circuit breakers, to prevent damage to the equipment and ensure the safety of the system.

1.4 Static Thermal Rating (STR):

The maximum current-carrying capacity of the ACSR conductors under steady-state conditions [3]. It is determined based on factors such as conductor material, size, ambient temperature, and installation conditions. It's a critical factor in determining the safe operating limits of the transmission lines.

1.5 Dynamic Thermal Rating (DTR):

It Refers to the current-carrying capacity of the ACSR conductors under dynamic or transient conditions, such as changes in wind speed, solar radiation, and ambient temperature[4]. Dynamic thermal ratings provide a more accurate representation of the conductor's capacity during varying operating conditions.

1.6 Fuzzy Logic:

A mathematical approach used to handle uncertainty and imprecision in decision-making processes. In the context of this project, fuzzy logic will be applied to develop a dynamic thermal rating model that can account for uncertainties in environmental conditions and load variations, providing a more robust assessment of the conductor's capacity [6

1.7 Background and Motivation:

Assam, located in the northeastern region of India, experiences diverse climatic conditions, including high humidity, rainfall, and temperature fluctuations throughout the year. These environmental factors can impact the performance of overhead transmission lines, particularly the ACSR conductors used in the infrastructure. Temperature variations along the transmission lines can lead to thermal stress, affecting the conductors' mechanical integrity and electrical conductivity. As a result, there is a pressing need to understand these temperature dynamics and develop strategies to mitigate their adverse effects on the power transmission system.

Motivation:

<u>Reliability of Power Supply:</u> Ensuring uninterrupted electricity supply is crucial for supporting economic growth, industrial development, and the well-being of residents in Assam [4]. By addressing issues related to temperature variations and conductor performance, this project aims to enhance the reliability of the power transmission network, minimizing downtime and disruptions in electricity supply.

<u>Efficiency and Optimization</u>: Optimizing the performance of transmission lines can lead to more efficient energy distribution and utilization of existing infrastructure. By determining static and dynamic thermal ratings, as well as implementing mitigation[4]. strategies such as overcurrent relays, the project seeks to improve the overall efficiency of power transmission in Assam, reducing energy losses and enhancing system capacity.

<u>Resilience to Climate Change:</u> With climate change leading to increased frequency and intensity of extreme weather events, building resilience in the power infrastructure is paramount. By understanding and addressing the impact of temperature variations on transmission lines, the project contributes to building a more resilient energy system capable of withstanding environmental challenges in the long term.

Cost-Effectiveness and Sustainability: By optimizing the utilization of existing transmission assets and reducing the risk of equipment failures, the project aims to achieve cost savings for utilities and consumers alike [4]. Additionally, ensuring the sustainability of the power transmission network aligns with broader environmental goals, including reducing carbon emissions and promoting renewable energy integration.

1.8 Scope and Objectives:

The scope of this project encompasses a comprehensive study on the temperature variations experienced by Aluminum Conductor Steel Reinforced (ACSR) conductors in overhead transmission lines within the region of Assam, India. The investigation will include:

- Analysis of historical temperature data and climatic conditions specific to Assam to understand the range and variability of temperature fluctuations.
- Examination of the thermal characteristics and performance of ACSR conductors under varying temperature conditions.
- Proposal of mitigation strategies, focusing on the implementation of Overcurrent Relays (OCRs), to address potential issues arising from temperature variations.
- Determination of both static and dynamic thermal ratings for the overhead transmission lines in Assam to assess their current-carrying capacity under different operating conditions.
- Development of a fuzzy logic-based model to calculate dynamic thermal ratings, considering uncertainties in environmental factors and load variations.

The main objectives of this project is to enhance the reliability, efficiency, and resilience of the power transmission infrastructure in Assam, ultimately contributing to the sustainable and uninterrupted supply of electricity to the region.

1.9 Structure:

The report is structured as follows: Chapter 2 delves into the literature relevant to the study, Chapter 3 outlines the methodology employed, Chapter 4 gives the Fuzzy model for dynamic thermal ratings. Chapter 5 presents the findings and analysis, and Chapter 6 concludes the study with recommendations and future research directions.

CHAPTER 2
LITERATURE REVIEW

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 and determining static thermal ratings and dynamic thermal ratings (both real time fuzzy logic) is the focus of this study, elucidated through pertinent literature reviews.

- **P. Patowary and N. Goyal (2014)** in their paper "*Dynamic thermal rating and allowable operating time under transient conditions,"* 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 the paper, a significant aspect highlighted is the variation in steady-state thermal ratings. This observation underscores the importance of understanding how thermal performance fluctuates under different conditions. The analysis of these variations provides valuable insights into the robustness and efficiency of the system, offering essential information for optimizing its thermal management. Examining the impact of ambient conditions on ascertaining the accurate SST and STE ratings offers substantial advantages. This analysis not only result in enhanced line ampacity but also provides valuable insights into the associated risks and their duration, enabling a more informed trade-off between benefits and costs within the competitive electricity environment.

- **Wan et al. (1999)**, in their work provide a method employing probability to evaluate thermal capacity, grounded in risk assessment. **Moreira et al. (2006)** delves into illustrating the impact of thermal limits on transmission lines and explores how these limits can be utilized for economic generation dispatch

- **Rahim, Abidin et al. (2009)** authors experimentally validated the calculations of conductor temperature derived from a weather model and ascertain the time required to reach thermal overload. In this paper, it is elucidated that precision in calculations significantly improves when a conductor bears a modest current in contrast to a high current load. Remarkably, the error percentage remains consistent at 7%, regardless of whether the load is typical or elevated. Potential errors may arise from the measurement of variables such as wind speed, wind direction, ambient temperature, and solar radiation.

- **H. Shaker et al. (2012),** the paper proposes a fuzzy theory-based model for dynamic thermal rating (DTR) calculations in transmission line systems. It addresses uncertainties arising from limited sampling points and measurement errors due to varying weather conditions. The model utilizes fuzzy computation to predict future environmental phenomena, demonstrating validation and efficiency through numerical simulations with real database inputs.

- **J. Teh et al. (2018)**, the authors explore the limitations of traditional transmission line ratings and advocates for the implementations of dynamic thermal ratings systems to enhance capability and reliability in power networks. It compares DTR with static line ratings, reviews monitoring technologies, assesses reliability impacts, and investigates integration with renewable energy sources like wind power, offering insights into improving power system reliability and efficiency.

- **D. A. Douglass et al. (2019),** the paper explores the management of power flow on overhead transmission lines to maintain conductor temperatures below specified limits, crucial for preventing sag and aging. It contrasts static line ratings, calculated for conservative weather conditions, with dynamic line ratings that adjust in real time.

- **Usama et al. (2021)** , the authors suggest the protection strategies to mitigate the impact of energy sources on interconnected distribution network. The basic features of relays, reviews of established techniques to overcome the protection failure, advantages, and associated shortcomings have been explored. Generally, two strategies can be utilized to overcome the protection failure in the integrated network; either to maintain the existing protection system using grid standards and control techniques or to modify the settings to achieve proper relay coordination.

- **O. A Lawal et al. (2022),** the author suggested that forecasting is crucial for implementing Distributed Temperature regulation in smart grids. Various methods including ensemble forecasting, RNN, CNN and QR were evaluated, with 50^{th} percentile QR percentile QR performing the best.

- **Y. Yaqoob et al. (2022)**, in the paper proposes a fuzzy thermal aging model for transmission lines, incorporating a dynamic thermal rating system based on IEEE 738 standard. It focused on monitoring conductor temperature to assess transmission network reliability and aging, offering insights for maintenance and asset management under varying operational conditions.

Understanding and mitigating the temperature behaviour and real time assessment of thermal rating of overhead transmission lines is crucial for ensuring the resilience and efficiency of power systems. Ongoing research and development of innovative technologies continue to contribute to the enhancement of transmission line performance in diverse environmental conditions.

CHAPTER 3
METHODOLOGY

3.1 Consequences of Thermal Overload

Thermal overload in overhead transmission lines occurs when the current flowing through the conductor exceeds its capacity, leading to an increase in temperature. This can result from high power demand or inadequate cooling. Prolonged thermal overload may cause damage to the conductor, insulation or supporting structures, impacting the line's reliability and safety. Monitoring and managing heat dissipation are crucial to prevent such issues in transmission system.

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 [3].

$$Q_s + I^2R(T_c) = Q_c + Q_r + mC_p\, dT_c \,/\, dt \quad (3.1)$$

The equation incorporates factors such as Qs and $I^2R(Tc)$, representing heat gain from solar radiation and Joule heating due to current flow (with R being temperature-dependent). Qc and Qr account for heat loss through convection and long-wave radiation, respectively. These heat terms are quantified in units of W/m. The term mCp 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 (dTc/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 (3.1). 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 [1].
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.[2] 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.

3.2 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 [5]. 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 [6]. 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.

3.3 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 [5].

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].

$$t = \frac{K}{I^n - 1} \tag{3.2}$$

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):

$$t = \frac{0.14}{I^{0.02} - 1} \tag{3.3}$$

Very inverse:

$$t = \frac{13.5}{I - 1} \tag{3.4}$$

Extremely inverse:

$$t = \frac{80}{I^2 - 1} \tag{3.5}$$

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.

3.4 Theory of Dynamic Thermal Rating Systems

The steady-state dynamic thermal rating of exposed overhead conductors is determined according to the IEEE 738 standard, which considers meteorological factors. Key variables influencing DTR include solar heat absorption, convective heat dissipation to the surrounding air, radiative heat exchange with the environment, and the current flowing through the conductor. When environmental conditions are stable, the conductor's current-carrying capacity is dictated by the equilibrium between heat gained and lost.

The steady-state heat balance equation for the conductor as follow:

$$Q_c\,(T_c,T_a,V_w,\varphi) + Q_r(T_a,T_c) - Q_s(\,\omega) - I^2R(T_c) = 0 \quad (3.6)$$

Where, Q_c stands for the loss of heat via convection, while Q_r indicates heat loss through radiation. Conversely, Q_s represents the gain of heat through radiation, and $I^2R(T_c)$ illustrates the heat generated by the flow of current within a conductor, with I representing the maximum permissible current, equal to the line rating. These thermal factors are contingent upon several meteorological variables, such as ambient temperature (T_a), solar radiation angle (ω), wind speed (V_w), and incident wind angle (φ) relative to the line. Additionally, the temperature of the conductor (T_c) and its resistance (R), which varies based on temperature, play pivotal roles in determining these thermal influences [3].

Thus, the maximum current capacity permissible for the conductor amidst prevailing weather conditions can be determined from the Equation (3.6). The acceptable temperature range for the conductor may vary between steady-state and dynamic conditions. Consequently, different permissible currents are derived for each condition.

3.5 Assessment of Heat Loss Rate

The convective heat loss rate of a conductor depends on various factors such as wind speed and direction, air and conductor temperature, dynamic viscosity, density of the air, and the conductor's diameter. These factors influence the estimation of the maximum heat loss rate applicable in different wind conditions. Additionally, the radiated heat loss rate is determined by the conductor's diameter, ambient and conductor temperatures, and a parameter denoted as α. The darkness of the conductor's surface affects its ability to absorb heat, thus impacting the radiated heat loss [21]. The parameter α typically falls within the range of 0.23 to 0.91, depending on the condition of the conductor surface.

3.6 Assessment of solar heat Gain Rate

Solar heat intensity experiences variations across seasons and different times of the day, making its energy dependent on factors such as the projected area of the conductor (A_r), latitude (Lat), and solar absorptivity (α). It's noteworthy that α is considered equivalent to emissivity (ε). The latitude (Lat) typically spans from -90 to +90 degrees, while solar declination ranges from 0 to 90 degrees. Key determinants affecting heat flux density include solar altitude (H_c), hourly angle (ω), and atmospheric clarity [17].

3.7 Fuzzy dynamic Thermal Rating Evaluation of Overhead Transmission Lines

When uncertainty is considered, ranges of values can be derived, which are referred to as fuzzy numbers. In this section, the fuzzy approach is applied to the dynamic thermal rating system (DTR).

3.7.1 Fuzzy numbers:

An important aspect of fuzzy analyses is their computational efficiency, which can be obtained by formulating the membership functions into interval calculations [17]. The α-cut is the composition of each fuzzy interval, and fuzzy α-cut arithmetic is applied to calculate the results associated with the α-cut. Triangular fuzzy number A and the α-cut of this fuzzy number illustrated in Figure 3.1 are described as the follows:

$$\mu_A(x) = \begin{cases} 0 & x \leq a \\ \dfrac{x-a}{b-a} & a \leq x \leq b \\ \dfrac{c-x}{c-b} & b \leq x \leq c \\ 0 & x \geq c \end{cases} \tag{3.7}$$

$\forall \alpha \in [0,1]$: ${}^{\alpha}A = \{x \mid \mu_A(x) \geq \alpha\} = [\,{}^{\alpha}A_1,\ {}^{\alpha}A_2] = [\,{}^{\alpha}A_{\min},\ {}^{\alpha}A_{\max}\,]$,

where $\mu_A(x)$ denotes the triangular membership function of fuzzy number A. To utilize the fuzzy outcomes constructively, various defuzzification methods are employed to convert the fuzzy results into crisp numbers, such as distance, magnitude, and centroid point . The centroid point method is described as follows:

$$\bar{x}(A) = \frac{\int_{a_1}^{a_2} x \cdot \mu_A(x)dx}{\int_{a_1}^{a_2} \mu_A(x)dx} \tag{3.8}$$

where a_1 and a_2 are the constraints for all fuzzy numbers with a nonzero membership grade.

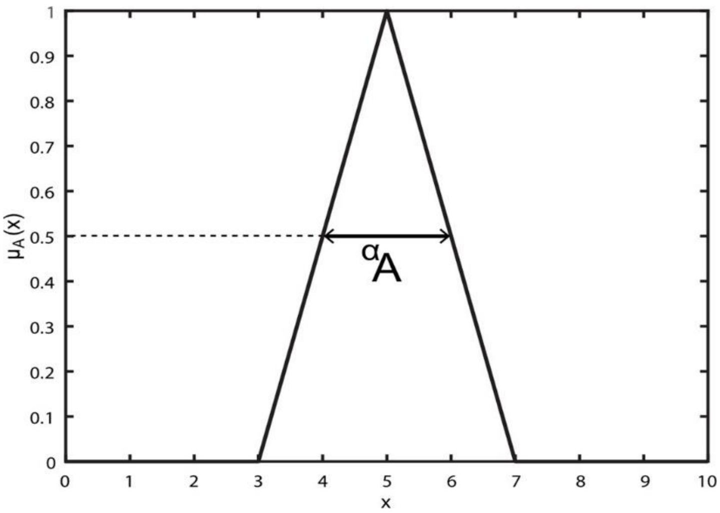

Figure 3.1: Fuzzy numbers and their α-cut

3.7.2 Fuzzy DTR

The transmission line heat balance Equation (3.6) incorporates several meteorological data inputs, whose uncertainties are addressed by fuzzy numbers. The calculations are therefore initiated by fuzzifying the input parameters.

Weather variables such as ambient temperature (T_a), wind speed (V_w), and wind angle (φ) surrounding the transmission line are uncertain due to the change in time and span. In addition, uncertainties are inherent in the respective measuring instruments [17].

All of these inputs were thus modeled using fuzzy numbers with their membership functions, such as $\mu_{V_w}(V_w), \mu_\varphi(\varphi)$, and $\mu_{T_a}(T_a)$.

3.7.3 Fuzzy Model of Convective Heat Loss Rate, $^{\alpha}Q_c$

The fuzzy model of convection heat loss rate, $(\,^{\alpha}Q_c)$, is as follows [17]:

$$^{\alpha}Q_c = [\,^{\alpha}Q_{c_1},\,^{\alpha}Q_{c_2}] = \begin{bmatrix} \max(\,^{\alpha}Q_{cH_1},\,^{\alpha}Q_{cL_1},\,^{\alpha}Q_{cN_1}), \\ \max(\,^{\alpha}Q_{cH_2},\,^{\alpha}Q_{cL_2},\,^{\alpha}Q_{cN_2}) \end{bmatrix} \tag{3.9}$$

where

$$ {}^{\alpha}Q_{cH} = \left[{}^{\alpha}Q_{cH_1}, {}^{\alpha}Q_{cH_2} \right] = \begin{Bmatrix} [1.01 + 1.35({}^{\alpha}\gamma_1)^{0.52}] \cdot {}^{\alpha}\lambda_1, \\ [1.01 + 1.35({}^{\alpha}\gamma_2)^{0.52}] \cdot {}^{\alpha}\lambda_2 \end{Bmatrix}, \tag{3.10} $$

$$ {}^{\alpha}Q_{cL} = \left[{}^{\alpha}Q_{cL_1}, {}^{\alpha}Q_{cL_2} \right] = \begin{Bmatrix} [0.754({}^{\alpha}\gamma_1)^{0.6}] \cdot {}^{\alpha}\lambda_1 \\ [0.754({}^{\alpha}\gamma_2)^{0.6}] \cdot {}^{\alpha}\lambda_2 \end{Bmatrix}, \tag{3.11} $$

$$ {}^{\alpha}Q_{cN} = \left[{}^{\alpha}Q_{cN_1}, {}^{\alpha}Q_{cN_2} \right] = \begin{Bmatrix} \left[3.645D^{0.75} + \left({}^{\alpha}\rho_{f_1}\right)^{0.5}\left(T_c - {}^{\alpha}T_{a_2}\right)^{1.25}\right], \\ \left[3.645D^{0.75} + \left({}^{\alpha}\rho_{f_2}\right)^{0.5}\left(T_c - {}^{\alpha}T_{a_1}\right)^{1.25}\right] \end{Bmatrix} \tag{3.12} $$

such that

$$ {}^{\alpha}\gamma = [{}^{\alpha}\gamma_1, {}^{\alpha}\gamma_2] = \left[D\,\frac{{}^{\alpha}\rho_{f_1}\,{}^{\alpha}V_{w_1}}{{}^{\alpha}\mu_{f_2}}, D\,\frac{{}^{\alpha}\rho_{f_2}\,{}^{\alpha}V_{w_2}}{{}^{\alpha}\mu_{f_1}} \right], \tag{3.13} $$

$$ {}^{\alpha}\lambda = [{}^{\alpha}\lambda_1, {}^{\alpha}\lambda_2] = \begin{bmatrix} \left({}^{\alpha}k_{\text{angle}} \cdot {}^{\alpha}k_{f_1}\right) \cdot \left(T_c - {}^{\alpha}T_{a_2}\right), \\ \left({}^{\alpha}k_{\text{angle}\,_2} \cdot {}^{\alpha}k_{f_2}\right) \cdot \left(T_c - {}^{\alpha}T_{a_1}\right) \end{bmatrix} \tag{3.14} $$

3.7.4 Fuzzy Model of Radiation Heat Loss Rate, ${}^{\alpha}Q_r$

The fuzzy radiation heat loss rate (${}^{\alpha}Q_r$) is as follows:

$$ {}^{\alpha}Q_r = \left[{}^{\alpha}Q_{r_1}, {}^{\alpha}Q_{r_2} \right] = \begin{Bmatrix} 17.8D\varepsilon \left[\left(\frac{T_c + 273}{100}\right)^4 - \left(\frac{{}^{\alpha}T_{\alpha_2} + 273}{100}\right)^4 \right], \\ 17.8D\varepsilon \left[\left(\frac{T_c + 273}{100}\right)^4 - \left(\frac{{}^{\alpha}T_1 + 273}{100}\right)^4 \right] \end{Bmatrix} \tag{3.15} $$

3.7.5 Fuzzy Model of Solar Heat Gain Rate, Q_s

The calculation of solar heat gain rate, (Q_S), begins as follows[17]:

$$ H_c = \arcsin[\cos(\text{ Lat }) \cdot \cos(\delta) \cdot \cos(\omega) + \sin(\text{ Lat }) \cdot \sin(\delta)], \tag{3.16} $$

$$ \delta = 23.46 \cdot \sin\left[\frac{284 + N}{365} \cdot 360\right], \tag{3.17} $$

$$ \mathrm{Z}_c = C + \arctan(\chi), \tag{3.18} $$

such that

$$\chi = \frac{\sin(\omega)}{\sin(\text{ Lat }) \cdot \cos(\omega) - \cos(\text{ Lat }) \cdot \tan(\delta)}, \tag{3.19}$$

where the solar azimuth constant C is a function of the fuzzy solar hour angle, ω, and solar azimuth χ, which can be estimated from the table shown in the IEEE 738 standard[3].

The following is also considered:

$$\theta = \arccos(H_c) \cdot \cos(Z_c - Z_l) \tag{3.20}$$

The solar heat intensity at the earth's surface is corrected for altitude by the following:

$$Q_{se} = k_{\text{solar}}\, q_s \tag{3.21}$$

such that

$$q_s = \begin{bmatrix} u_1 + u_2(H_c) + u_3(H_c)^2 + u_4(H_c)^3 \\ +u_5(H_c)^4 + u_6(H_c)^5 + u_7(H_c)^6 \end{bmatrix} \tag{3.22}$$

where $u_1, u_2, \dots u_7$ are the constants available in the IEEE standard 738 [3].

The following are also considered:

where

$$k_{\text{solar}} = s_1 + s_2 H_e + s_3 (H_e)^2 \tag{3.23}$$

and finally,

$$Q_s = \Psi \cdot Q_{se} \cdot \sin(\theta) \cdot A_r \tag{3.24}$$

3.8 Data Collection:

- From IEEE standard 738 model
- From Government meteorological department website
    - https://mausam.imd.gov.in
    - https://cdsp.imdpune.gov.in

CHAPTER 4

FUZZY DYNAMIC THERMAL RATING

Fuzzy logic can be a powerful tool for estimating dynamic thermal ratings in power systems. By incorporating linguistic variables and expert knowledge into the modeling process, fuzzy logic can handle the uncertainty and imprecision inherent in thermal rating estimation, especially in dynamic conditions where parameters are changing rapidly. Fuzzy logic controllers can adjust system parameters in real-time based on inputs such as ambient temperature, wind speed, and load conditions to ensure accurate and safe thermal ratings for power equipment [13].

In the realm of electrical engineering, optimizing the operation of power transmission systems is paramount for efficiency and reliability, particularly in regions with diverse and challenging climatic conditions. Assam, situated in Northeast India, exemplifies such a region, characterized by varying temperatures, humidity levels, and seasonal weather patterns. In this context, accurately estimating the dynamic thermal rating of transmission lines, particularly those utilizing Aluminum Conductor Steel Reinforced (ACSR) conductors, becomes a critical endeavor. Dynamic thermal rating refers to the real-time capacity of a transmission line, which fluctuates based on environmental factors such as ambient temperature, wind speed, solar radiation, and humidity [16].

Traditionally, static thermal ratings have been employed, providing conservative estimates of transmission line capacity under fixed environmental conditions. However, in regions like Assam, where climatic variables are dynamic and unpredictable, static ratings may result in underutilization of transmission infrastructure or, conversely, lead to overheating and potential outages during periods of high demand or adverse weather conditions.

To address this challenge, the application of fuzzy logic emerges as a promising approach. Fuzzy logic offers a framework for modeling the complex and uncertain relationships between environmental parameters and dynamic thermal ratings. By defining fuzzy sets and rules that capture the nuances of Assam's climatic variability, fuzzy logic systems can effectively estimate the real-time thermal performance of transmission lines, thus enabling more efficient and reliable operation of the power grid [17].

To create a fuzzy logic-based DTR estimation system, firstly identify relevant input variables, such as ambient temperature, wind speed, solar radiation, and load conditions, and define linguistic terms to describe their states. Next, a set of fuzzy logic rules is formulated based on expert knowledge and empirical data, specifying how the inputs should be mapped to the desired output (i.e., the estimated thermal rating). These rules often take the form of "if-then" statements that describe how the system should respond to different combinations of input variables.

Once the linguistic variables and rules have been defined, a fuzzy inference system (FIS) is used to process the input data and generate a crisp output value representing the estimated thermal rating. The FIS applies fuzzy logic operations, such as fuzzification, rule evaluation, and defuzzification, to transform the linguistic input variables into a numerical output value that reflects the current thermal rating of the power equipment [17].

One of the key advantages of fuzzy logic-based DTR estimation is its ability to adapt to changing operating conditions in real-time. By continuously monitoring input parameters and adjusting the fuzzy logic rules accordingly, the system can dynamically update its estimations to reflect the evolving state of the power system. This adaptive capability is particularly valuable in scenarios where environmental conditions are highly variable, such as during extreme weather events or sudden changes in load demand.

4.1 Types of fuzzy inference system

Fuzzy inference systems (FIS) are the core components of fuzzy logic-based systems, responsible for transforming fuzzy input data into crisp output values through a process of inference. There are several types of fuzzy inference systems, each with its own characteristics and applications:

- <u>Mamdani FIS</u>:

  Named after its creator, Ebrahim Mamdani, this is one of the most widely used types of fuzzy inference systems. It employs fuzzy logic rules expressed in the form of "if-then" statements to map fuzzy input variables to fuzzy output variables [22]. The output fuzzy sets are then combined using fuzzy inference methods such as max-min or max-product composition to obtain a fuzzy output set. Defuzzification is applied to convert the fuzzy output set into a crisp output value.

- Sugeno FIS:

  Proposed by Takagi and Sugeno, this type of fuzzy inference system differs from the Mamdani FIS in that it generates a crisp output directly from the fuzzy input. Instead of fuzzy output sets, Sugeno FIS outputs are represented as mathematical functions of the input variables [22]. Each rule in a Sugeno FIS typically defines a linear or constant function relating the input variables to the output. The final output is obtained by aggregating the outputs of all the rules, often using weighted averaging or centroid defuzzification.

Here, in this project Mamdani-type fuzzy interference system is used. The Mamdani inference system is well-suited for diverse climatic conditions like those found in Assam due to its ability to incorporate linguistic variables, expert knowledge, and robustness to uncertainty, making it a reliable tool for estimating dynamic thermal ratings in power systems operating in such regions.

4.2 Types of Learning in fuzzy models:

Several types of learning can be integrated into fuzzy models to improve their performance and adaptability, Here I discussed mainly two types of learning.

a) Supervised Learning:

   In supervised learning, the fuzzy model is trained using labeled input-output pairs. This approach is commonly used to fine-tune fuzzy logic controllers or optimize fuzzy inference systems by adjusting parameters such as membership functions or rule bases to minimize errors between predicted and actual outputs [22].

b) Unsupervised Learning:

   Unsupervised learning involves discovering patterns and structures in unlabeled data. Fuzzy clustering algorithms, such as Fuzzy C-Means (FCM), can be integrated into fuzzy models to partition input data into fuzzy clusters, which can then be used to identify trends, patterns, or anomalies in the data.

By integrating these learning techniques into fuzzy models, they can become more adaptive, robust, and effective in modeling complex systems and handling diverse data sources, making them valuable tools for a wide range of applications, including control systems, pattern recognition, optimization, and decision support [22]. Here, Supervised learning is more suitable for training a fuzzy model to estimate dynamic thermal ratings, as it allows the model to learned from labelled examples and make predictions on new, unseen instances based on learned patterns.

4.3 Type of membership function used in fuzzy logic:

a) Triangular Membership Function:

The triangular membership function is characterized by a triangular shape with three parameters: the left foot, the peak (or center), and the right foot.
It is defined mathematically as [22]:

$$\mu(x) = \max(\min((x - a) / (b - a), (c - x) / (c - b)), 0) \quad (4.1)$$

where a, b, and c are the parameters defining the left foot, peak, and right foot of the triangle, respectively.
Triangular membership functions are simple to implement and interpret, making them widely used in fuzzy logic systems.

b) Gaussian Membership Function:

The Gaussian membership function is bell-shaped and symmetric around its mean. It is defined mathematically as:

$$\mu(x) = e^{(-((x - c) / \sigma)2\ )} \quad (4.2)$$

where c is the mean and σ is the standard deviation.
Gaussian membership functions are useful for modeling uncertainty and are often used when the distribution of the data is known or assumed to be Gaussian.

c) Trapezoidal Membership Function:

The trapezoidal membership function is similar to the triangular membership function but has a flat top. It is defined mathematically using four parameters: the left foot, the left shoulder, the right shoulder, and the right foot [22].

Trapezoidal membership functions provide more flexibility than triangular functions for modeling asymmetric fuzzy sets.

Here, Triangular memberships functions are often preferred for DTR forecasting due to their simplicity and ease of interpretation [17]. In context of DTR forecasting, where the relationships between variables may not be highly complex, the simplicity of triangular membership functions can be advantageous.

4.4 Input and output variables for fuzzy model:

- Input Variables for Fuzzy model-
  - Wind Speed
  - Wind Angle
  - Ambient Temperature
  - Solar Angle
  - Transmission line height

- Output Variable for Fuzzy model-
  - Dynamic thermal rating

4.5 Ranges of variables

- Wind Speed (0 m/s to 5 m/s)
- Wind Angle (0^0 to 90^0)
- Ambient Temperature (10^0 to 60^0)
- Solar Angle (15^0 to 30^0)
- Transmission line height (0 m to 55 m)

4.6 Fuzzy model:

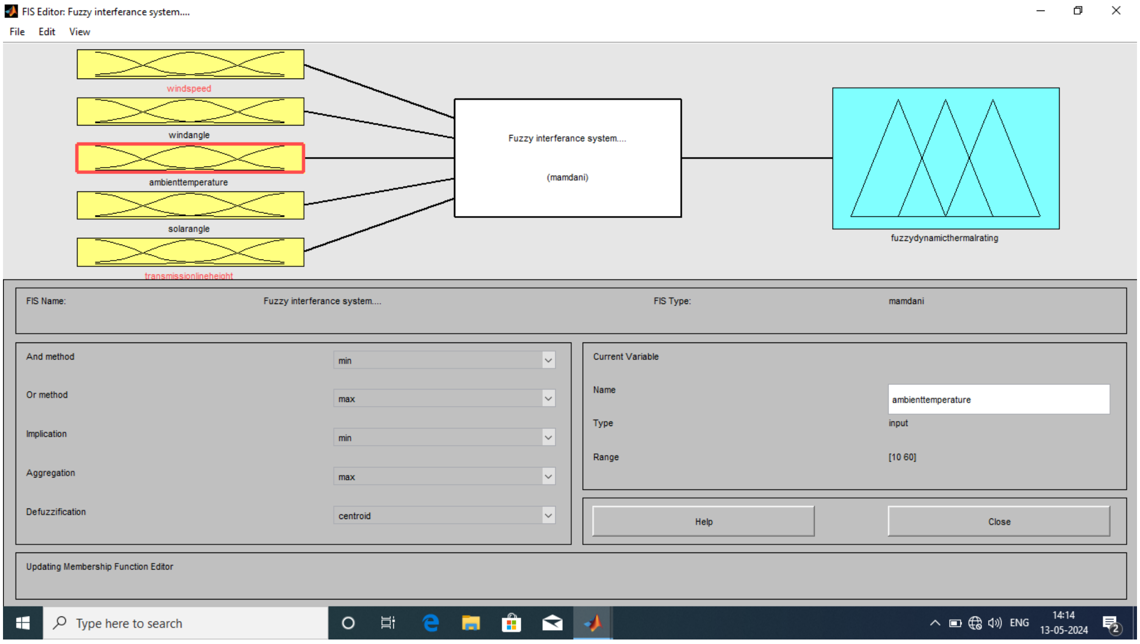

Figure 4.1 : Fuzzy model for estimating dynamic thermal rating

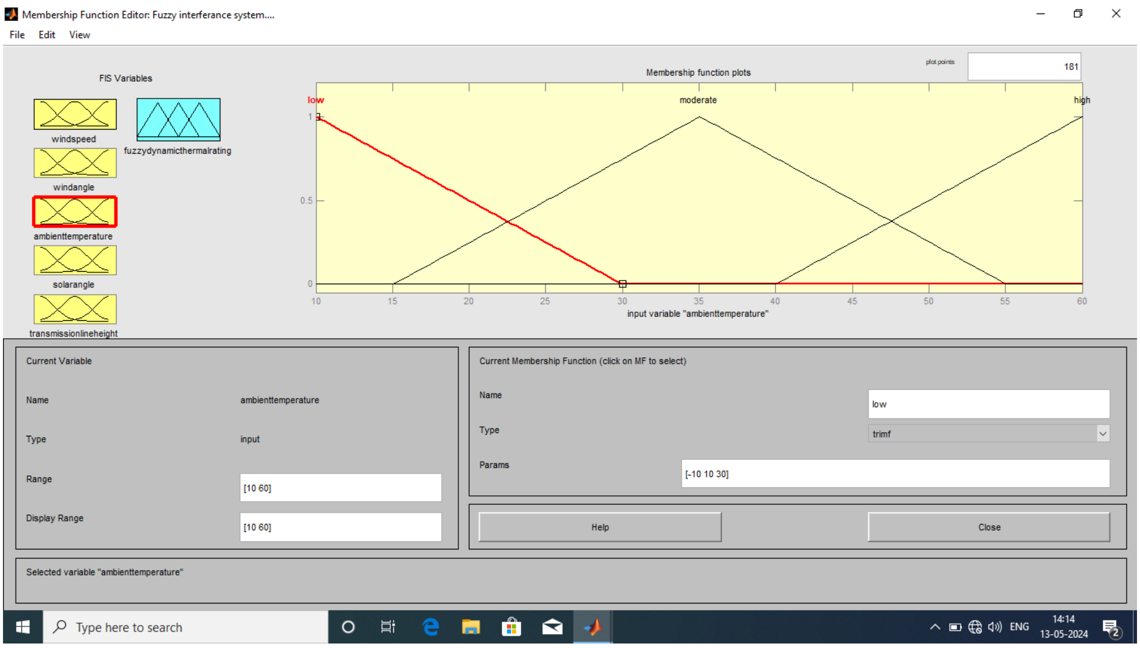

Figure 4.2 : Membership function for fuzzy dynamic thermal rating

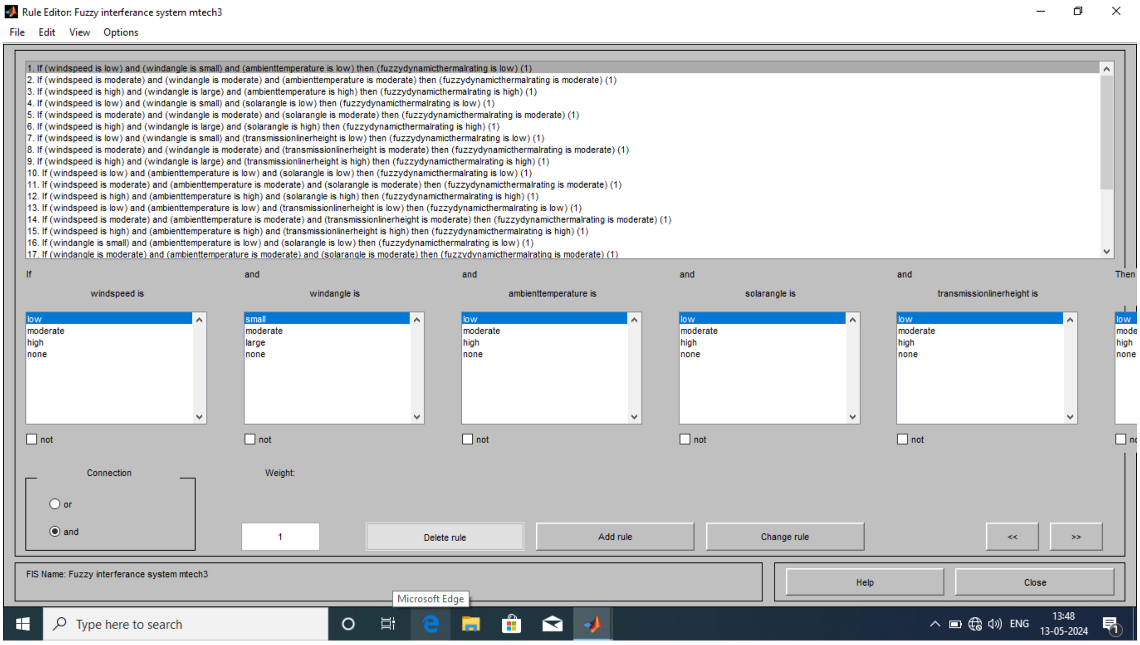

Figure 4.3 : Rules for fuzzy dynamic thermal rating

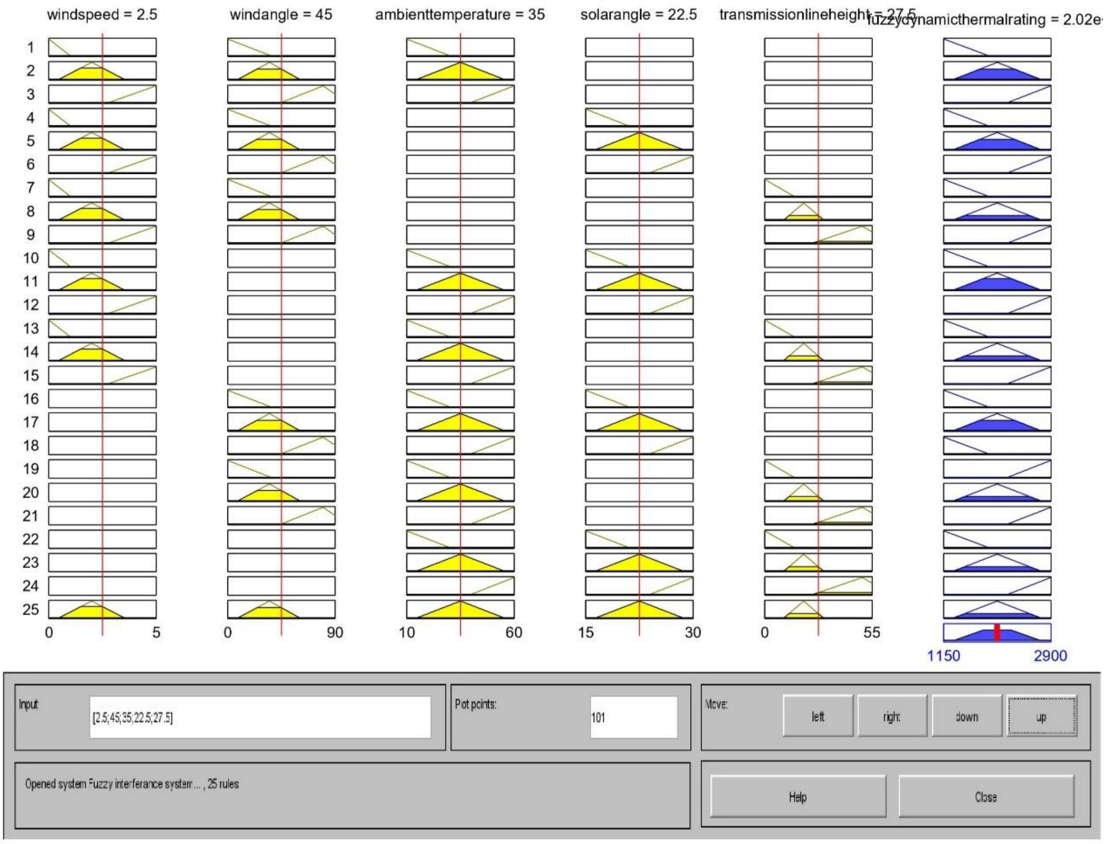

Figure 4.4 : Fuzzy dynamic thermal rating forecasting

CHAPTER 5
RESULTS AND ANALYSIS

In Assam, transmission lines equipped with ACSR conductors are designed to support a maximum static rating of 992A each conductor. This rating is established through calculations that anticipate the conductor's temperature reaching 75 ^{o}C under predefined circumstances. These circumstances encompass an assumed wind speed of 3.6m/s, an ambient temperature of 27 ^{o}C, and a solar radiation intensity of 1024 W/m^2.

Table 5.1: 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.

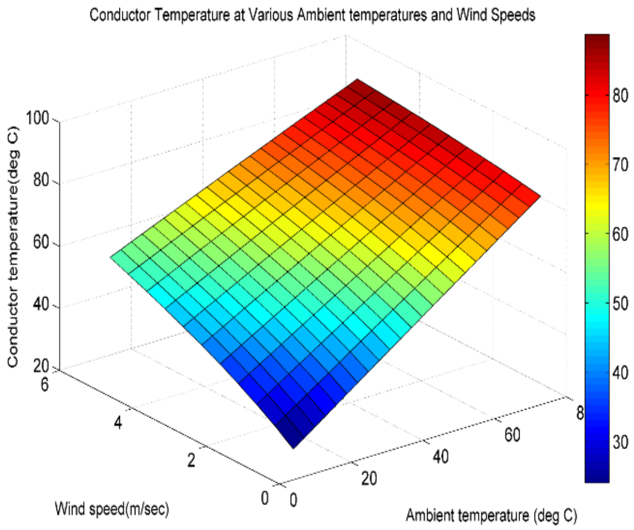

Figure 5.1: Conductor temperature under varying ambient conditions for fixed static rating

The Figure 5.1 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.

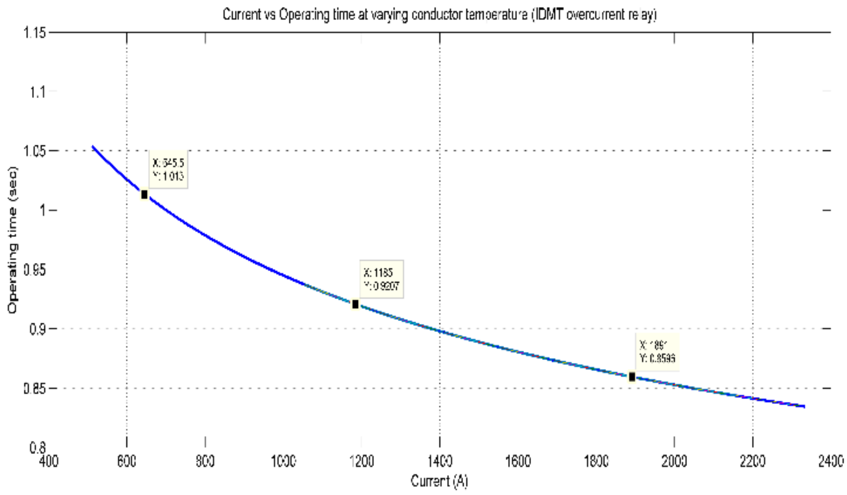

Fig. 5.2: Current Vs Operating time at varying conductor temperature for IDMT overcurrent relay

(Y axis- Operating time in seconds/X axis- Current in Ampere)

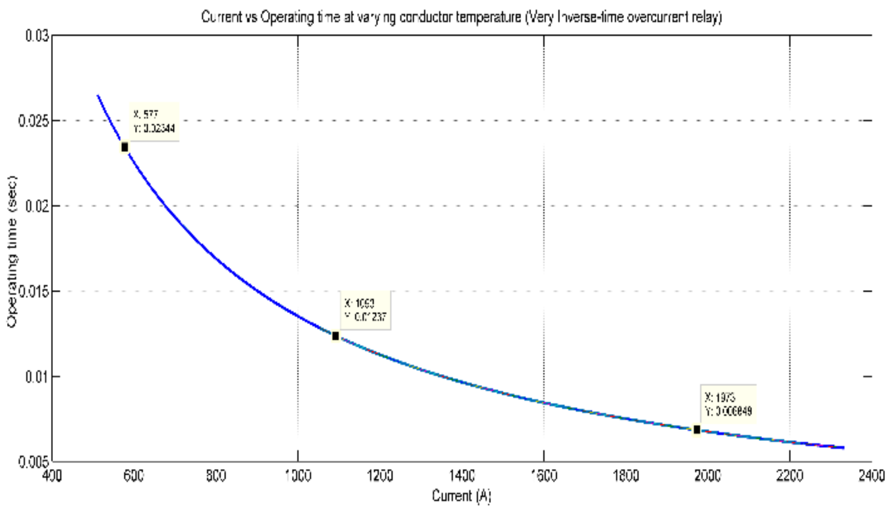

Figure 5.3: Current Vs Operating time at varying conductor temperature for Very inverse overcurrent relay

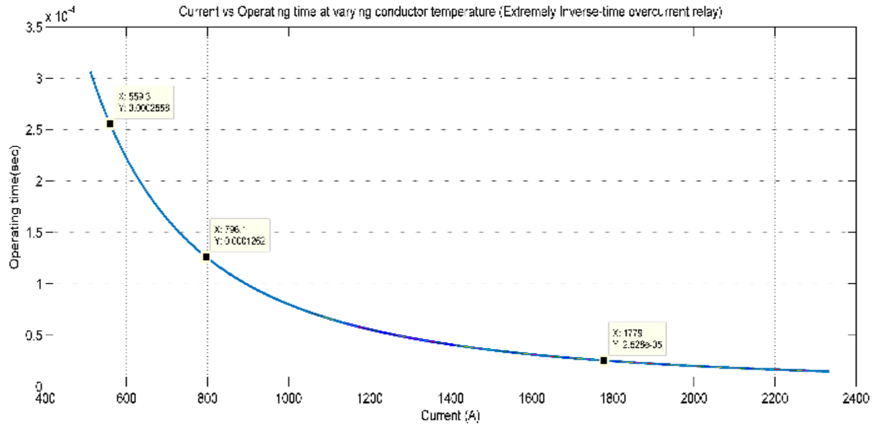

Figure 5.4: Current Vs Operating time at varying conductor temperature for Extremely inverse overcurrent relay

(Y axis- Operating time in seconds/X axis- Current in Ampere)

Figures 5.2, 5.3, and 5.4 are depicted based on the results of temperature fluctuations of the ACSR conductor obtained from the preceding analysis. Figure 5.2 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 Figure 5.3, the operating time decreases more rapidly with increasing current magnitude, offering a quicker response time for higher current magnitude. Figure 5.4, offers the most rapid response for higher current magnitudes, ensuring efficient protection against overcurrent conditions induced by temperature fluctuations.

To demonstrate the practical use of thermal rating forecasting, let's examine a 100km segment of a power transmission line in Assam, India, which experiences varied climatic conditions. The conductor considered is a Drake ACSR conductor, and parameter such as windspeed, wind angle, ambient temperature, solar angle are selected based on climatic conditions of the Assam region. The maximum line loading is set at 3000A, with an additional transmission capacity reserve of 10%

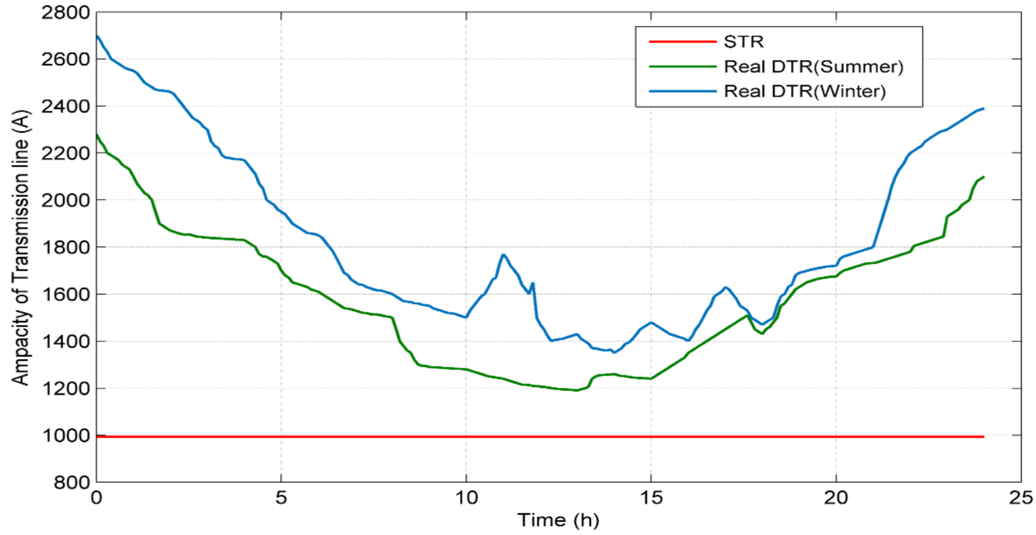

Figure 5.5 : Comparison of Real Time Dynamic Thermal Ratings for 24 h in Summer and Winter

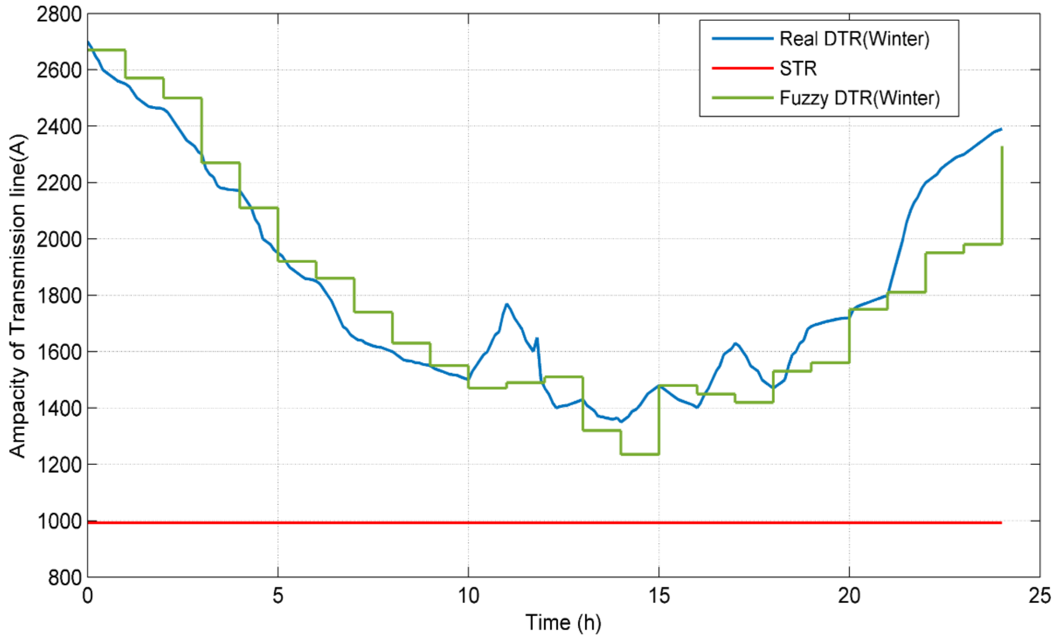

Figure 5.6: Dynamic Thermal Ratings of line for 24 h in Winter

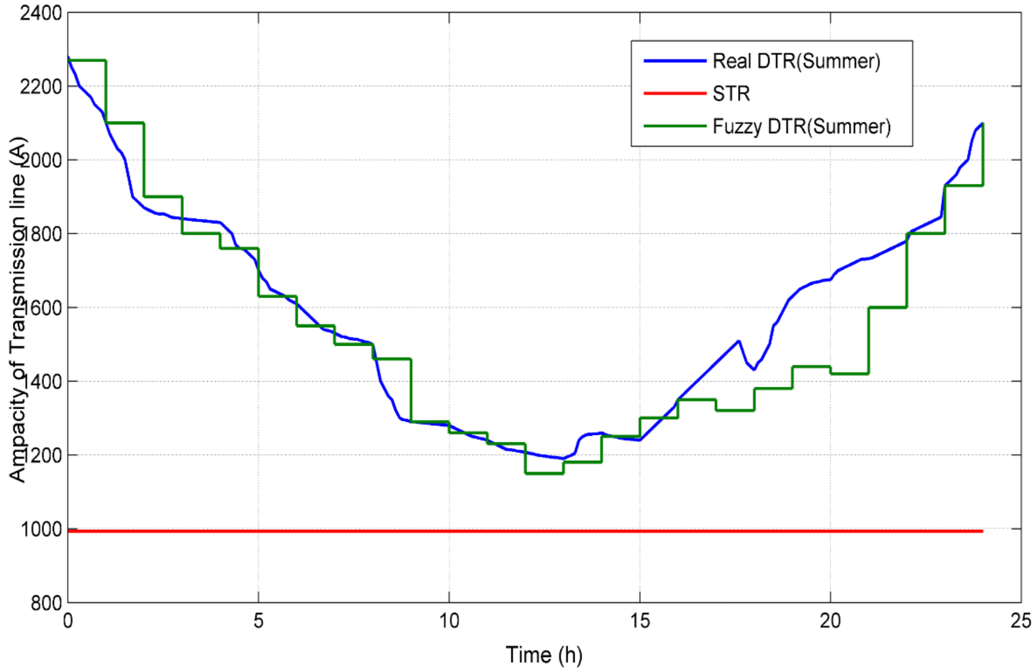

Figure 5.7: Dynamic Thermal Ratings of line for 24 h in Summer

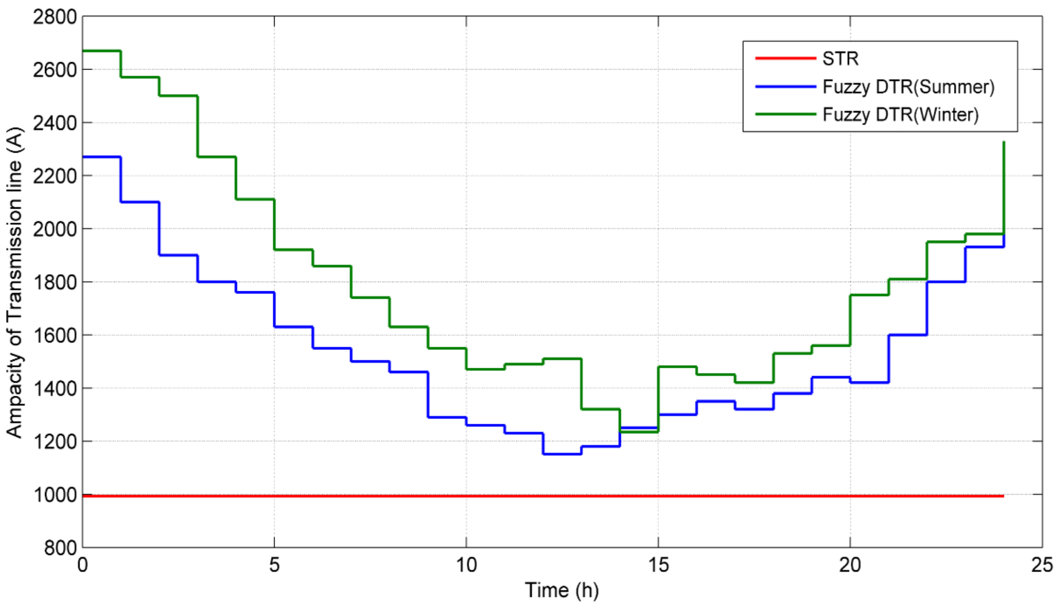

Figure 5.8 : Comparison of Fuzzy Dynamic Thermal Ratings for 24 h in Summer and Winter

Figure 5.5 displays the comparison of dynamic thermal ratings for summer and winter, highlighting their variance from static thermal rating. Also it indicates that the Dynamic thermal rating for winter season is higher compared to that for summer. To address the uncertainty surrounding dynamic thermal rating, fuzzy dynamic thermal rating is utilized. Figure 5.6 illustrates the comparison between fuzzy dynamic thermal rating, real-time dynamic thermal rating, and static thermal rating during the winter season. Figure 5.7 depicts a comparison between fuzzy dynamic thermal rating, real-time dynamic thermal rating, and static thermal rating during the summer season. Figure 5.8 shows the variation of fuzzy dynamic thermal rating throughout the winter and summer seasons

In Figure 5.5, the dynamic thermal ratings gradually decrease up to 10 hours in both summer and winter seasons. However, at 11 hours, there is a significant contrast between winter and summer dynamic thermal ratings, with winter's Real DTR at 1770A and summer's at 1240A. After 16 hours, the dynamic thermal ratings start increasing. The contrast between winter and summer dynamic thermal ratings at 11 hours could be due to variations in temperature and load conditions. Winter temperatures are typically lower, resulting in higher dynamic thermal ratings due to improved cooling efficiency. Additionally, load patterns may differ between seasons, affecting the overall stress on the transmission lines. In Figure 5.6, for the winter season, at 14 hours, the fuzzy dynamic thermal rating shows 1235A, while the real DTR is 1350A. This change may be occurring due to various factors such as fluctuating environmental conditions, changes in power consumption patterns or adjustments in the fuzzy logic control system. In Figure 5.7, the lowest dynamic thermal rating reaches 1190A at 13 hours. Figure 5.8, the curves of fuzzy dynamic thermal rating converge at 14 hours in both winter and summer seasons. This may occur due to consistent environmental conditions, balanced power demand, or adjustments made in the fuzzy logic control system to optimize thermal performance.

CHAPTER 6
CONCLUSION AND FUTURE SCOPE

6.1 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. 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.

Also in this project, evaluated the steady-state thermal rating and dynamic thermal rating over a 24-hour period, considering both summer and winter seasons. By comparing these ratings across seasons, the study provided valuable insights into the thermal behavior of the system under diverse climatic conditions, such as those found in regions like Assam. Furthermore, recognizing the inherent uncertainties associated with dynamic thermal rating, the research proposed a novel approach: fuzzy dynamic thermal rating. This methodology offers a robust framework to address uncertainties, accommodating the variability of climatic conditions and their impact on thermal ratings. By integrating fuzzy logic principles, the fuzzy dynamic thermal rating accounts for the complex interplay of factors influencing thermal performance, providing a more nuanced understanding of system behavior. The findings of this study contribute to the advancement of thermal rating methodologies, particularly in regions with diverse and challenging climatic environments like Assam, ultimately enhancing the reliability and efficiency of power infrastructure in such areas.

6.2 Future Scope

The future scope could involves integrating renewable energy sources, utilizing smart grid technologies, implementing machine learning algorithms for predictive analysis, developing optimization techniques, conducting field trials, examining policy implications, exploring resilience strategies, and assessing environmental impacts. These areas collectively aim to advance the understanding and implementation of dynamic thermal ratings, especially in regions with diverse climatic conditions.

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LIST OF PAPERS BASED ON THE REPORT

- "**Temperature Fluctuations in Power Conductors: Analysis and Overcurrent Relay Adaptation Strategies for Mitigation**" at International Journal for Multidisciplinary Research.

- "**Fuzzy Logic-Based Dynamic Thermal Rating Assessment for Adaptive Grid Operations"** at International Journal for Research in Applied Science & Engineering Technology.