Impact Assessment of Heat Waves on Resilience of Power System Components

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***Abstract*—Heat waves is a significant climatic phenomenon exerting profound effects on society, agriculture, the environment, and crucially, the power sector. This study aims to assess the impact of heat waves on power system components, particularly transmission lines and generators. A normal distribution model is employed to synthesize the historical heat wave data for a period of 10 years and applied to the IEEE 57-bus transmission test system. The resilience of the system components is determined in terms of impact of heat wave on the capacity of transmission lines and power generation output which are temperature-dependent. The resilience is also investigated for base case loading and overloading conditions during heat waves. The other key parameters such as Available Transfer Capability (ATC), system losses, remaining generator capacity, and generation cost are also evaluated to provide an insight into the power system's component resilience under heat wave conditions.**

Keywords—Extreme Weather Events, Generator, Heat Wave, Power System Components, Resilience, Transmission Line.

I. Introduction

In modern power systems, the paramount focus has traditionally been on ensuring a dependable, cost-effective, adaptable, and efficient electricity supply to consumers [1]. However, this priority has often overlooked the consequences of climate phenomena. In recent years, there has been a notable increase in the evaluation and enhancement of power system resilience, due to the concerns arising from high-impact, low-frequency events [2]. These events have swift and devastating effects, leading to extensive damage across various components and vast geographical areas [3]. The dynamic climatic conditions may lead to the vulnerability of the power grid to natural calamities, particularly heatwaves [5]. These extreme temperature events, exert significant pressure on ecosystems and societies alike [6]. Their impact extends beyond mere discomfort, often leading to profound disruptions in daily life and critical services. A heat wave typically refers to a prolonged period of unusually hot weather, often accompanied by high humidity levels. Definitions of heat waves are region-specific, tailored to the typical climate of the area and relative to seasonal norms. According to the World Meteorological Organization (WMO), a heat wave is characterized by five or more consecutive days of intense heat, with daily maximum temperatures surpassing the average maximum temperature by 5 °C (9 °F) or more [7].

The literature review examined methodologies and approaches to enhance power systems' resilience against extreme weather events, particularly heat waves. A modeling and optimization framework proposed in [8] using modified mixed integer linear programming (MILP) to optimize power system investment decisions, considering the impacts of extreme heat waves and droughts. This study stressed the importance of assessing system resilience and flexibility in the face of climate change, advocating for multi-regional planning and probabilistic frameworks. In [9], a reliability-centered methodology is introduced for identifying renovation actions to enhance resilience against heat waves in power distribution grids, focusing on critical network segments requiring renovation actions. A methodology is developed in [10] to assess the impacts of droughts and heat waves on thermoelectric power plants in the United States, integrating regression models, thermodynamic analyses, and climate models to predict power plant vulnerability. A screening-level analysis conducted by [11] evaluated the impacts of climate change on electricity transmission and distribution infrastructure in the United States, assessing changes in infrastructure performance, longevity, and associated economic costs. In [12], a critical risk determination method is proposed for urban electric power systems under extreme heat wave impact, utilizing energy-flow network analysis to identify primary risks in power system components. The impact of conductor temperature variations on power system operation, emphasizing accurate spatial distribution modelling is given in [13]. In [14], the impacts of rising air temperatures on electric transmission ampacity and peak per-capita electricity load in the United States is estimated, highlighting the importance of considering climate change in infrastructure planning. In [15], a non-steady state electro-thermally coupled weather-dependent power flow technique is proposed for improving overhead-line capacity, aiming to optimize line loading under dynamic weather conditions and enhance network reliability. These studies collectively contributed to understanding the impacts of heat waves on power systems and provided valuable insights into strategies for enhancing system resilience and reliability in the face of changing climatic conditions.

The literature review discussed various methodologies and approaches to enhance power systems' resilience against heat waves. However, some limitations exist within these studies. Firstly, while [8] proposed a comprehensive modeling framework, it may not fully account for the complex interactions and uncertainties associated with extreme weather events. Similarly, [9] focused on a specific distribution grid, limiting the generalizability of their findings to other regions. In ref. [10] relied on historical data, which may not fully represent future weather patterns and plant operations, introducing uncertainties in their assessments. In [11] conducted a screening-level analysis, which may overlook nuanced impacts and regional variations. In ref. [12] focused on a specific case study, potentially limiting the applicability of their findings to broader contexts. Additionally, [13] emphasized the importance of accurate spatial distribution

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modeling but did not fully integrate dynamic thermal rating into their analyses. In [14] relied on downscaled climate model projections, which may have inherent uncertainties. In [15], proposed a novel technique but highlighted the need for validation through field measurements.

Assessing the impacts of heat waves on power systems is necessary for several reasons. Firstly, heat waves can significantly strain power infrastructure, leading to increased demand for electricity and potential supply disruptions. By understanding these impacts, policymakers and stakeholders can develop proactive measures to enhance system resilience and reliability, ensuring uninterrupted power supply during extreme weather events. Additionally, as climate change continues to aggravate heat waves' frequency and intensity, assessing their impacts becomes increasingly critical for long-term infrastructure planning and adaptation strategies.

This paper focuses on modeling heat waves and assessing their effect on power system components, particularly transmission lines and generators. It aims to evaluate the operational resilience of the system by analyzing key indicators such as *Available Transfer Capability (ATC)* for transmission lines and remaining generation capacity for generators. Additionally, the study investigates the system's resilience under overloading conditions. The evaluation includes an assessment of total system losses and generation costs across various scenarios. By examining these parameters, the paper aims to provide insights into the impact of heat waves on power system performance and resilience, contributing to better understanding of the overall impact of extreme weather events on the power system.

II. PROPOSED METHODOLOGY

A. Modelling of the Heat Wave

In this study, the impact of heat waves is assessed through a comprehensive modelling approach. The heat wave phenomenon is simulated over a period of 10 years utilizing a normal distribution function as expressed by Eq.(1), which accurately captures the statistical characteristics of temperature fluctuations over time. This simulation enables us to predict and analyze the potential ramifications of prolonged periods of extreme heat on various aspects of the environment and human society.

$$f(t|\mu_T, \mathbb{T}^2) = \frac{1}{\mathbb{T}}\,\varphi\left(\frac{t-\mu_T}{\mathbb{T}}\right) \tag{1}$$

where t is the temperature, μ_T is the mean value and $\mathbb{T}$ is the standard deviation.

B. Modelling of Heat Wave Impact on Resilience of Power System Components

In the study, temperature-dependent functions are introduced to accommodate fluctuations in maximum power output and resistance of transmission lines across varying temperature conditions. These functions play a crucial role in precisely modelling the influence of heat waves on the power grid's performance.

a) Impact on Generator Capacity

The maximum power output (P_G^{max}) of steam turbines as function of temperature is evaluated by Eq.(2)

$$P_G^{max}(T) = P_G^{max}(T_0)\left(1 + k_p(T - T_0)\right) \tag{2}$$

where, T_0 is the reference temperature (in Celsius) ; k_p is the coefficient for the temperature dependence of maximum power output at T_0 and $P_G^{max}(T_0)$ is the maximum power output .Eq.(2) assesses the impact of the heat wave on the maximum power output.

b) Impact on Transmission Line Resistance

The resistance of transmission lines is modeled as a function of temperature using Eq.(3) to get the modified resistance:

$$R_L(T) = R_L(T_0)\big(1 + k_R(T - T_0)\big) \tag{3}$$

where, k_R is the temperature coefficient of the resistance, $R_L(T_0)$ is the resistance at reference temperature. Eq. (3) accounts for the increase in resistance with temperature, which affects the thermal performance of transmission lines.

c) Impact on Thermal Limit of Transmission Line

To assess the impact of heat waves on transmission lines, we utilize the temperature-dependent resistance function described above. For each transmission line in the power grid, the modified thermal limit ($P_L^{thermal}$) under heat wave condition are determined as follows:

$$P_L^{thermal} = \frac{V^2{}_L}{R_L(T)} \tag{4}$$

where, R_0 is the reference resistance of the transmission line, T is the temperature during the heat wave and V_L is per unit voltage of the transmission line.

d) Impact on Available Transfer Capability (ATC):

Available Transfer Capability, is the maximum amount of power that can be safely moved from one area to another during a heat wave, considering all the factors that could affect the power grid's performance and stability [16].

$$ATC = TTC - \sum(TRM\,, ETU) \tag{5}$$

where *TTC* is total transfer capability of transmission line, *TRM* is the total reliability margin and *ETU* is the existing transmission uses.

Fig. 1 illustrates the flowchart of the proposed methodology for analyzing the impact of a heat wave on a power system. The algorithm steps are as follows:

(1) Set the initial system parameters under normal conditions.

(2) Perform power flow analysis and calculate line losses, *ATC* and generation cost before heat wave occurs.

(3) Generate heat wave data using (1) to obtain data related to the heat wave conditions.

(4) Determine the effect of heat wave on system parameter using (2)-(5) indicating the temperature-dependent functions for resistance, thermal limits and the maximum power output of generators. Update system parameters based on the impact of the heat wave.

(5) Perform power flow analysis and calculate line losses, *ATC* and generation cost under the heat wave scenario.

(6) Repeat the above steps for 5% Overloading Conditions.

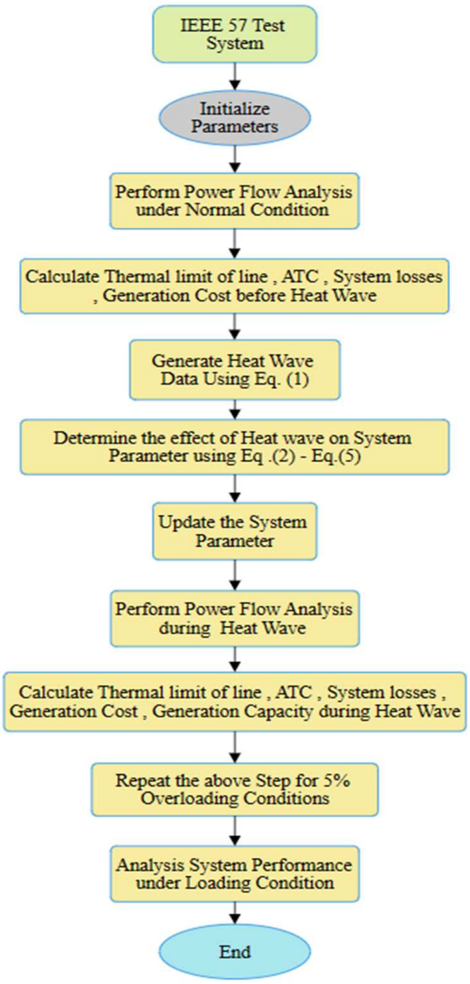

Fig. 1. Flow Chart of Proposed Methodology

III. Simulation and Results

A. Test System

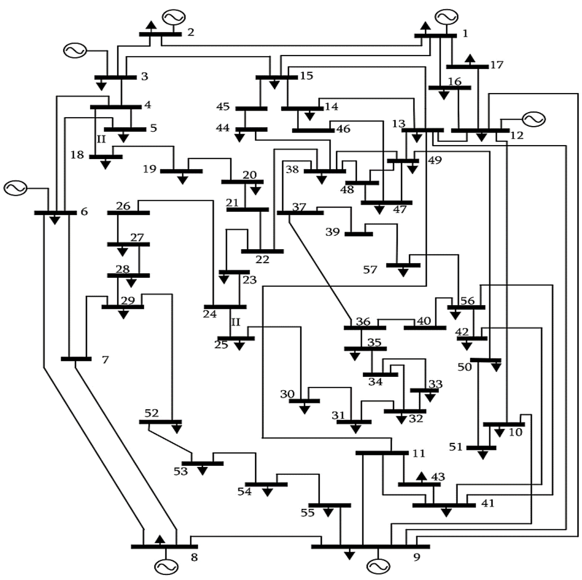

Fig. 2. IEEE 57 Bus Transmission System

The proposed simulation model is illustrated using an IEEE 57- bus transmission network. This network comprises 80 transmission lines, 57 buses, 42 loads, and 7 generators [17] as shown in Fig. 2. The system has total generation capacity of 1278.7 MW and total load demand of 1250.8 MW.

B. Heat Wave Data Generation

To simulate the impact of weather variations, particularly heat waves, the IEEE 57-bus transmission network is subjected to heat wave conditions. Heat wave modeling is facilitated through Equation (1), enabling the generation of a realistic heat wave profile. For this study, a 10-year heat wave profile is synthesized, with a focus on summer conditions, given their prominence in affecting power system components' performance. The synthesized heat wave profile, depicted in Fig. 3, captures the temperature variations over the 10-year period, providing insight into the intensity and duration of heat wave events experienced by the power grid. This profile serves as a crucial input for analyzing the impact of heat waves on transmission lines and generators within the IEEE 57-bus system.

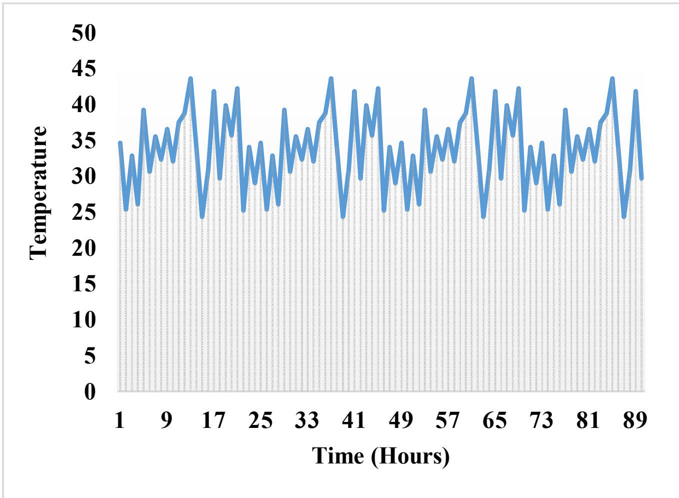

Fig. 3. Heat Wave

C. Results at Base Case

The analysis focuses on the impact of a heat wave on the transmission lines and generators within the power grid, using default system load conditions. The data presented in Fig.4 and Fig.5 demonstrates a reduction in the capacity of transmission lines during the heat wave, indicating a decrease in the maximum power that these lines can reliably transmit. This reduction in capacity suggests that the elevated temperatures associated with the heat wave may impose constraints or limitations on the transmission infrastructure, affecting its ability to efficiently transport electrical power.

Similarly, the analysis reveals a corresponding decrease in the output of power generators during the heat wave. This reduction in generator output signifies the operational adjustments made in response to the heat wave conditions, as generators adapt to the increased demand and potential stress on the grid caused by the extreme weather event.

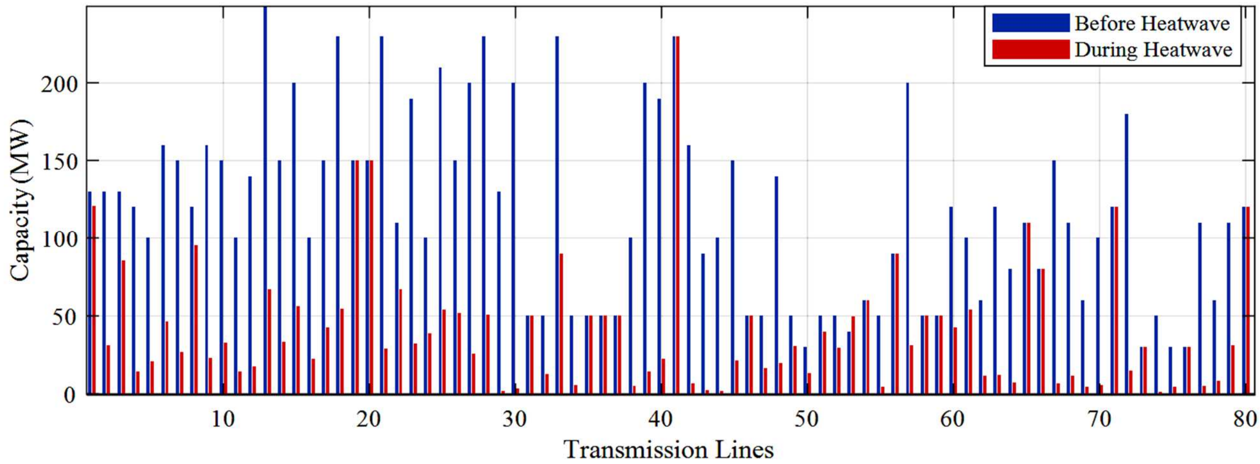

Fig. 4. Comparison of transmission line capacities before and during the heat wave (Base case)

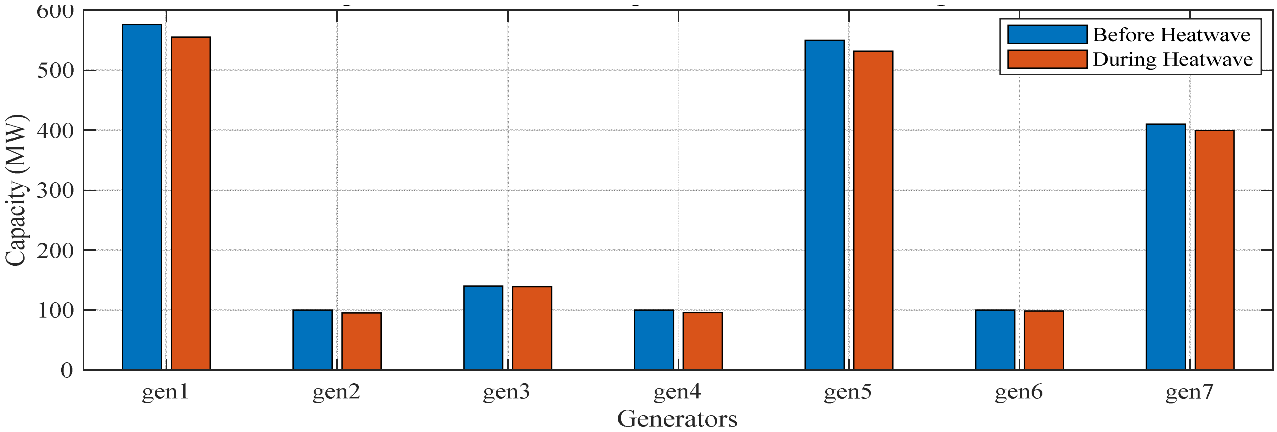

Fig. 5. Comparison of Generator capacities before and during the heat wave (Base case)

D. Results at 5% Overloading Case

In this scenario, the power system is subjected to a 5% overloading condition, and the impact of the heat wave on transmission and generation capacities is analyzed. The data presented in Fig. 6 and Fig. 7 indicates that under the 5% overloading condition, the overall capacity of transmission lines further decreases compared to the base case. Specifically, three lines (1-2), (8-9), and (14-46) become overloaded, potentially leading to congestion in power flow. However, it is noteworthy that despite the increased loading, there is no observable effect on the power output of generators. The generator outputs remain consistent with their values in the base case, suggesting that the generators are capable of meeting the increase demand imposed by the overloading condition.

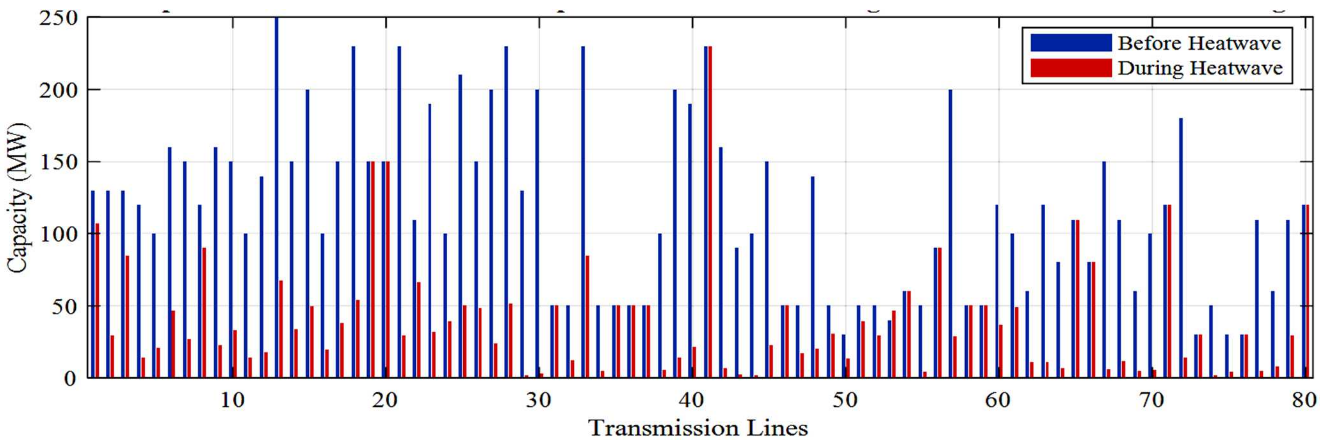

Fig. 6. Comparison of transmission line capacities before and during the heat wave (5% Overloading)

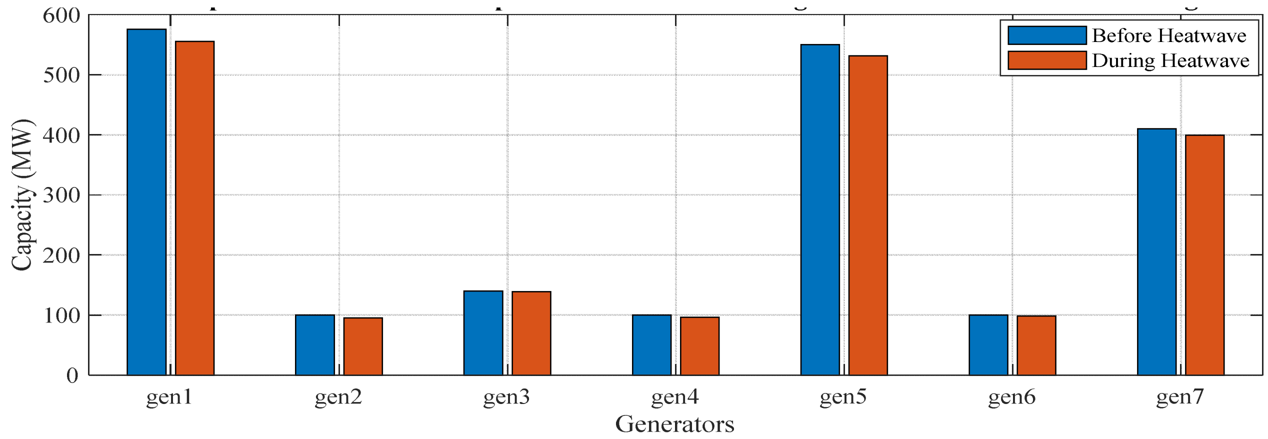

Fig. 7. Comparison of Generator capacities before and during the heat wave (5% Overloading)

E. Results of Impact on Available Transfer Capability ATC)

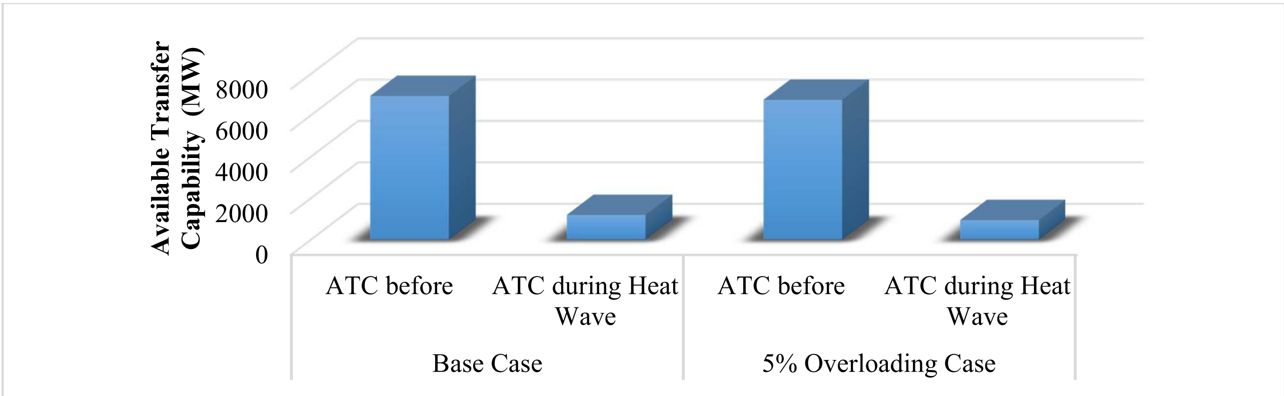

Fig. 8. Available Transfer Capability before and during the heat wave

As depicted in Figure 8, the Available Transfer Capability (*ATC*) undergoes notable variations under different operational conditions. Initially, before the onset of the heat wave, the *ATC* stands at 6928.08 MW, signifying the system's robust capacity to transfer power between areas while ensuring operational stability. However, during the heat wave, a significant decline is observed, with the *ATC* plummeting to 1187.56 MW. The significant decrease in *ATC* during the heat wave underscores the substantial impact of the extreme weather event on the power grid. Moreover, in a scenario featuring a 5% overloading condition, the *ATC* registers a slightly lower value of 6743.37 MW before the heat wave, indicating that the power system is already operating near its capacity limit due to increased load demands. During the heat wave within this overloaded context, the *ATC* further diminishes to 936.73 MW, illustrating the compounded effects of both overloading and heat wave-induced stress on the power grid's transfer capability. This additional decline highlights the challenges faced by the system in maintaining reliable power transfer under such challenging operational circumstances.

F. Comparison of Impact on different Parameters for Resilience Assessment

The comparison in Table 1 highlights the response of key parameters under different operational scenarios. Firstly, system losses remain consistent before and during the heat wave, indicating that temperature fluctuations did not notably affect the system's heat dissipation efficiency. However, the remaining generator capacity declines during the heat wave, particularly in the 5% overloading case, suggesting increased utilization of generator resources to meet heightened demand. This implies that generators are operating closer to their maximum capacity during the heat wave, especially in overloaded scenarios. Notably, the generation cost remains constant across base case scenarios and slightly increase in overdoing conditions. This suggests that any additional expenses incurred due to increased demand or system stress are balanced by other factors, such as fuel prices or operational efficiencies. Overall, these findings emphasize the resilience of the power grid to withstand challenges posed by heat waves and overloading conditions.

TABLE I. COMPARISON OF DIFFERENT PARAMETERS IN BASE CASE AND 5% OVERLOADING CASE (BEFORE AND DURING THE HEAT WAVE)

Parameters	**Base Case**		**5% Overloading Case**	
	Before	**During Heat Wave**	**Before**	**During Heat Wave**
Total System Losses (MW)	28.57	28.57	46.23	46.23
Remaining Generator Capacity (MW)	697.22	636.64	628.53	567.96
Generation Cost (Rs.)	51348.21	51348.21	58188.72	58188.72

IV. Conclusions

The study highlights the substantial impact of heat waves on power system components, notably transmission lines and generators. Significant reductions in transmission and generator capacities are observed during heat wave conditions, increasing the risk of congestion and potential supply disruptions. The evaluation of a 5% overload condition further emphasizes these challenges, revealing compounded effects on available transfer capability (*ATC*) and system losses. This research provides valuable insights into the dynamic responses of power systems to varying operational conditions, offering avenues for enhancing resilience and efficiency in the face of escalating extreme weather events.

References

[1] N. Bhusal, M. Abdelmalak, M. Kamruzzaman, and M. Benidris, 'Power System Resilience: Current Practices, Challenges, and Future Directions', *IEEE Access*, vol. 8, pp. 18064–18086, 2020, doi: 10.1109/ACCESS.2020.2968586.

[2] A. K. Gupta and K. Verma, 'Assessment of Infrastructural and Operational Resilience of Transmission Lines During Dynamic Meteorological Hazard', 2023.

[3] F. Mujjuni, T. R. Betts, and R. E. Blanchard, 'Evaluation of Power Systems Resilience to Extreme Weather Events: A Review of Methods and Assumptions', *IEEE Access*, vol. 11, pp. 87279–87296, 2023, doi: 10.1109/ACCESS.2023.3304643.

[4] A. K. Gupta and K. Verma, 'A Probabilistic Approach to Assess Quantitative Resilience of Transmission Line During Cyclone', in *2022 IEEE 10th Power India International Conference (PIICON)*, New Delhi, India: IEEE, Nov. 2022, pp. 1–6. doi: 10.1109/PIICON56320.2022.10045228.

[5] N. Freychet, S. Tett, J. Wang, and G. Hegerl, 'Summer heat waves over Eastern China: dynamical processes and trend attribution', *Environ. Res. Lett.*, vol. 12, no. 2, p. 024015, Feb. 2017, doi: 10.1088/1748-9326/aa5ba3.

[6] X. Chen, N. Li, J. Liu, Z. Zhang, and Y. Liu, 'Global Heat Wave Hazard Considering Humidity Effects during the 21st Century', *Int. J. Environ. Res. Public. Health*, vol. 16, no. 9, p. 1513, Apr. 2019, doi: 10.3390/ijerph16091513.

[7] W. Marx, R. Haunschild, and L. Bornmann, 'Heat waves: a hot topic in climate change research', *Theor. Appl. Climatol.*, vol. 146, no. 1–2, pp. 781–800, Oct. 2021, doi: 10.1007/s00704-021-03758-y.

[8] A. F. Abdin, Y.-P. Fang, and E. Zio, 'A modeling and optimization framework for power systems design with operational flexibility and resilience against extreme heat waves and drought events', *Renew. Sustain. Energy Rev.*, vol. 112, pp. 706–719, Sep. 2019, doi: 10.1016/j.rser.2019.06.006.

[9] L. Bellani *et al.*, 'A reliability-centered methodology for identifying renovation actions for improving resilience against heat waves in power distribution grids', *Int. J. Electr. Power Energy Syst.*, vol. 137, p. 107813, May 2022, doi: 10.1016/j.ijepes.2021.107813.

[10] M. A. Cook, C. W. King, F. T. Davidson, and M. E. Webber, 'Assessing the impacts of droughts and heat waves at thermoelectric power plants in the United States using integrated regression, thermodynamic, and climate models', *Energy Rep.*, vol. 1, pp. 193–203, Nov. 2015, doi: 10.1016/j.egyr.2015.10.002.

[11] C. Fant *et al.*, 'Climate change impacts and costs to U.S. electricity transmission and distribution infrastructure', *Energy*, vol. 195, p. 116899, Mar. 2020, doi: 10.1016/j.energy.2020.116899.

[12] C. Shen, W. Zhu, and L. Xu, 'Critical risk determination method of energy-flow network for urban electricity system under extreme heat wave impact', *Environ. Res.*, vol. 191, p. 110143, Dec. 2020, doi: 10.1016/j.envres.2020.110143.

[13] Y. Wang, Y. Mo, M. Wang, X. Zhou, L. Liang, and P. Zhang, 'Impact of Conductor Temperature Time–Space Variation on the Power System Operational State', *Energies*, vol. 11, no. 4, p. 760, Mar. 2018, doi: 10.3390/en11040760.

[14] M. Bartos *et al.*, 'Impacts of rising air temperatures on electric transmission ampacity and peak electricity load in the United States', *Environ. Res. Lett.*, vol. 11, no. 11, p. 114008, Nov. 2016, doi: 10.1088/1748-9326/11/11/114008.

[15] S. Talpur, T. T. Lie, and R. Zamora, 'Non-steady state electro-thermally coupled weather-dependent power flow technique for a geographically-traversed overhead-line capacity improvement', *Electr. Power Syst. Res.*, vol. 177, p. 106017, Dec. 2019, doi: 10.1016/j.epsr.2019.106017.

[16] H. Farahmand, M. Rashidinejad, A. Mousavi, A. A. Gharaveisi, M. R. Irving, and G. A. Taylor, 'Hybrid Mutation Particle Swarm Optimisation method for Available Transfer Capability enhancement', *Int. J. Electr. Power Energy Syst.*, vol. 42, no. 1, pp. 240–249, Nov. 2012, doi: 10.1016/j.ijepes.2012.04.020.

[17] A. Barzegar, A. Sadollah, L. Rajabpour, and R. Su, 'Optimal power flow solution using water cycle algorithm', in *2016 14th International Conference on Control, Automation, Robotics and Vision (ICARCV)*, Phuket, Thailand: IEEE, Nov. 2016, pp. 1–4. doi: 10.1109/ICARCV.2016.7838690.