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Thermal Impact Assessment on Power Transmission Capacity and Grid Reliability

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Abstract: Rising ambient temperatures and intensifying heatwaves, driven by climate change, exert significant thermal stresses on power transmission systems by simultaneously increasing electricity demand for cooling and degrading the thermal performance of overhead conductors, transformers, and associated infrastructure. Higher temperatures elevate conductor resistance, accelerate joule heating, and reduce convective and radiative cooling margins, leading to elevated conductor core temperatures, increased sag, and mandatory derating of line ampacity to maintain safe ground clearances and prevent annealing or mechanical failure. Empirical studies indicate that heatwaves can reduce effective transmission capacity by 1.9–5.8% on average by mid-century under various RCP scenarios, with regional variations (e.g., larger impacts in inland areas like MISO). Concurrent demand surges of 30–50% or more tighten reserve margins, while increased line losses (resistance rises ~0.4% per °C for aluminum) and accelerated aging of transformers further compromise reliability. Data from China show heatwaves increase outage frequency by 3.9–4.0% and duration by 7.9–8.3%, with each additional degree of temperature rise contributing ~0.1% more outages and each extra heatwave day adding ~0.5%. This paper provides a comprehensive thermal impact assessment, detailing physical mechanisms, quantitative effects on ampacity and losses, implications for grid reliability metrics.

Introduction

Power transmission systems are engineered to transport bulk electricity efficiently over long distances while maintaining thermal, voltage, and stability limits. Thermal limits often dominate for shorter lines, where the maximum allowable conductor temperature (typically 80–90°C or higher for specialized conductors) constrains ampacity to prevent excessive sag, loss of tensile strength, or clearance violations. Under normal conditions, static line ratings (SLR) provide conservative estimates based on worst-case assumptions (high ambient temperature, low wind, high solar radiation), ensuring safety but frequently underutilizing actual capacity. Climate change disrupts this balance: anthropogenic warming increases the frequency, intensity, and duration of heatwaves, creating coupled stresses where demand spikes coincide with reduced infrastructure performance.

During heatwaves, air-conditioning loads drive sharp peaks, often shifting maximum net load to late afternoon or evening. Simultaneously, transmission lines experience compounded heating from ambient temperature, solar absorption, and higher currents needed to meet demand. This elevates conductor temperature T_c, increases electrical resistance, inflates I^2R losses (which average ~5% system-wide but rise under peak conditions), and causes thermal expansion leading to sag. Sagging lines risk contacting vegetation or structures, triggering faults, wildfires, or forced outages. Transformers and underground cables face analogous thermal aging acceleration, with insulation degradation rates roughly doubling every 6–8°C above design hotspots. Generation assets, including gas-fired plants critical for peaking, also derate due to cooling limitations, amplifying the supply shortfall.

Projections indicate mid-century summertime transmission capacity reductions of 1.9–5.8% on average relative to historical baselines, with greater impacts in regions experiencing larger temperature rises (e.g., inland U.S. markets). Empirical evidence links heatwaves to increased outage frequency and duration, with heterogeneity across socio-demographic groups. Without intervention, these thermal impacts threaten reliability, elevate wholesale prices, increase curtailment of renewables, and heighten public health risks when outages coincide with extreme heat. This assessment examines the underlying physics, quantifies capacity and reliability effects, reviews real-world and projected cases, and discusses mitigation pathways, emphasizing the transition from static to dynamic, climate-adaptive operations.

Quantitative Impacts on Transmission Capacity

Capacity impacts are well-documented. A 2016 study estimated mid-century (2040–2060) summertime ampacity reductions of 1.9–5.8% on average across U.S. planning areas under different RCP scenarios, with larger effects in regions like MISO experiencing 2–5°C temperature rises. Australian analyses of transmission assets projected theoretical maximum summer ratings declining 2.3% (low emissions) to 5.1% (high emissions) by 2078. Regional heterogeneity is pronounced: coastal areas benefit from moderating effects, while inland corridors face steeper deratings.

During actual heatwaves, operators often apply conservative deratings or ambient-adjusted limits, reducing transfer capability precisely when imports or internal redispatch are most needed. Increased losses compound the issue, requiring even more generation to deliver the same net power to loads. For renewable energy zones (REZs), shifting from static to dynamic ratings can increase hosting capacity substantially (e.g., >50% in modeled cases) by better matching ratings to actual cooling conditions, often improved by afternoon winds during solar-driven peaks.

High-temperature conductors and reconductoring with HTLS or advanced composite cores offer long-term capacity uplift by allowing higher operating temperatures with reduced sag. However, widespread adoption requires investment and updated planning standards.

Effects on Grid Reliability and Operational Resilience

Thermal deratings degrade reliability through multiple channels. Reduced transmission capacity limits resource sharing during regional peaks, tightens reserve margins, and increases congestion. When combined with generation deratings (thermal plants lose efficiency; solar output drops ~0.3–0.5% per °C panel temperature rise) and demand surges, the probability of insufficient supply rises. Chinese outage data (2019–2021) show heatwaves increase frequency by 3.9–4.0% and duration by 7.9–8.3%, with each degree adding ~0.1% and each extra heatwave day ~0.5%. Projections under RCP pathways indicate 5–20% outage increases by 2050 without adaptation.

U.S. multi-year analyses cluster outages by weather drivers, revealing compound effects: heat + wind in California (vegetation contact from sag), heat + precipitation in Texas. Voltage sags and transformer failures rise during extremes, as seen in 2025 heat events with notable upticks in sustained voltage deviations. Cascading risks escalate when overloaded, sagging lines fault or when N-k contingencies bind under derated conditions.

Socio-demographic heterogeneity amplifies consequences: vulnerable populations in urban heat islands face higher indoor temperature risks during outages, with studies linking blackouts to elevated heat-related morbidity and mortality. Reliability metrics such as loss of load expectation (LOLE) or expected unserved energy worsen under unmodeled thermal dependencies, challenging traditional resource adequacy assumptions.

Mitigation Strategies and Adaptive Measures

Key mitigations include:

- **Dynamic Line Ratings (DLR)**: Real-time monitoring (sensors for temperature, tension, sag, or weather-based forecasting) allows operators to utilize latent capacity safely, improving situational awareness and deferring infrastructure upgrades. DLR often outperforms static or even seasonal ratings, with studies showing significant hosting capacity gains in REZs.
- **Grid-Enhancing Technologies (GETs)**: Advanced conductors (HTLS, ACCC with low-sag composite cores), series compensators, and power flow controllers increase effective capacity and redirect flows away from constrained corridors.
- **Operational Adaptations**: Temperature-aware optimal power flow, proactive demand response (pre-cooling, thermostat adjustments), energy storage coordination, and interregional coordination buffer stresses. Coupled power-gas modeling accounts for interdependencies during gas-fired peaking.
- **Planning and Infrastructure**: Climate-informed transmission expansion planning incorporates downscaled ensembles for derating factors and stress testing. Reconductoring, new corridors, and microgrids in vulnerable areas enhance resilience. Vegetation management reduces sag-related faults.
- **Modeling Enhancements**: Integrate conductor heat balance into security-constrained economic dispatch and unit commitment, using piecewise linear approximations or ML surrogates for tractability. Robust or stochastic optimization hedges against forecast uncertainty.

Empirical deployments (e.g., NYPA, various U.S. and international pilots) confirm DLR provides additional capacity most hours while maintaining reliability criteria.

Case Studies and Projections

Real-world events illustrate impacts. During U.S. heat domes, operators issue alerts, activate demand response, and manage deratings amid record gas burns. California and Texas show distinct patterns: heat + wind vs. heat + rain driving outages. European and Australian cases similarly link heat to capacity reductions and reliability strains. Projections under warming scenarios consistently forecast rising outage risks and capacity pressures, with greater effects under higher emissions pathways. Cooperative planning and GETs mitigate but do not eliminate risks, particularly during widespread events.

Challenges and Future Directions

Challenges include uneven sensor deployment for true DLR, regulatory hurdles for adopting dynamic ratings (liability concerns), data integration across weather and grid models, and equitable resilience (protecting vulnerable loads). Computational demands for large-scale thermal-aware optimization and updating standards for climate non-stationarity persist.

Future directions encompass widespread DLR/AAR adoption with real-time digital twins, hybrid physics-ML forecasting for conductor states and risks, multi-energy system co-optimization, and standardized climate stress testing in planning. Advances in HTLS conductors and non-wires alternatives will complement new builds. Policy support—performance-based incentives for GETs, updated NERC/FERC guidelines, and data-sharing platforms—is critical.

Conclusion

Thermal impacts from rising temperatures and heatwaves significantly constrain power transmission capacity through derated ampacity, increased losses, and sag risks, while degrading overall grid reliability via tighter margins, higher outage probabilities, and cascading potential. Quantitative assessments reveal capacity reductions of several percent on average by mid-century, with outage increases of 5–20% projected under various scenarios, underscoring the need for urgent adaptation. Transitioning to dynamic line ratings, deploying grid-enhancing technologies, and embedding temperature dependencies into operational and planning models offer proven pathways to unlock latent capacity, enhance resilience, and mitigate reliability risks. As climate extremes intensify alongside electrification and renewable growth, proactive thermal impact assessment and mitigation will be indispensable for maintaining a reliable, efficient, and equitable power system capable of withstanding future stresses.

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