Literature Survey on Power System Resilience Against Ice Storms

Rawand Badawi, Thomas Overbye
Department of Electrical and Computer Engineering
Texas A&M University
College Station, TX
rawand_badawi@tamu.edu, overbye@tamu.edu

***Abstract*—Ice accumulation on power lines during an ice storm can result in permanent damage and widespread power outages if left unaddressed. This paper presents a literature survey on the resilience of power systems against ice storms, focusing on three pillars of resilience: modelling, situational awareness, and response. Physical and data driven approaches for modelling ice formation around power lines are examined. Situational awareness as achieved through various methods for tracking spatiotemporal changes in ice storms, fragility modelling of power system components, and the assessment of power system resilience in different studies is also discussed. Finally, mitigation strategies are explored, including mechanical techniques that rely on force to break ice off a power line and electrical methods that use heat from power flow to melt it.**

Keywords—resilience, ice storms, modelling, situational awareness, response.

I. Introduction

Power system resilience characterizes the ability of the system to anticipate, absorb, and recover from an external disturbance, particularly high-impact, low-frequency (HILF) events that have a low probability of occurring and the potential to cause significant damage [1], [2], [3]. HILF events include natural disasters such as ice storms, earthquakes, hurricanes, floods, tsunamis, etc. Severe weather events resulted in 80% of major electric outages in the US from 2000 to 2023 and winter storms specifically were responsible for 23% of these outages [4]. According to the National Severe Storms Laboratory, ice storms are a type of winter storms that accumulate at least ~ 6.5 mm of ice on exposed surfaces [5]. Overhead transmission and distribution power lines are most vulnerable in ice storms as the mechanical load of accumulated ice can down power lines and collapse electric poles and towers. Strong winds can further exacerbate conditions and result in conductor galloping, contact with vegetation and flying debris, and short circuits between power lines [6].

There are multiple instances where ice storms severely disrupted the delivery of electricity in North America. In 1998, an ice storm covered the northeastern region and brought more than 75 mm of ice accumulation. Thousands of power system components were damaged including power lines, poles, and towers and millions of customers were left without electricity [7]. A severe ice storm occurred in Oklahoma in 2020. Ice accumulation was measured to be ~ 40 mm [8]. At least 4200 poles and 9000 cross arms were destroyed as well as many power lines, transformers and other power system components. Additionally, more than 350,000 consumers lost access to electricity [9], [10]. Multiple winter storms hit Texas on February 11-20, 2021. Ice accumulation of at least 12 mm was recorded [11]. As a result, power lines snapped from the weight of ice and snow accumulation and generation infrastructure - including natural gas, nuclear, wind, and coal plants - froze and failed to supply electricity due to the severity of the storm. In total, approximately 4.5 million people were disconnected from electricity service and economic losses were estimated at $300 billion [12].

Events such as these have highlighted the need to improve power system resilience against ice storms. The winter storms in Texas exemplified the inadequacy of existing reliability metrics and the importance of accounting for HILF events [13]. The Extreme Cold Weather Preparedness and Operation, EOP-012-2 Reliability Standard has recently been approved by the Federal Energy Regulatory Commission (FERC) to address some of the shortcomings in reliability standards [14]. Moreover, research on power systems is becoming increasingly resilience-oriented to ensure a baseline level of resilience is maintained in their management and operation [15].

Planning tools are also being improved to account for the impact of severe weather events on power systems. Weather information is being explicitly integrated into related tools such as optimal power flow and contingency analysis [16]. According to the Energy Systems Integration Group, the necessary attributes of time series weather datasets for power system planning applications are: 1) the inclusion of necessary variables at sufficient resolution, 2) the coverage of multiple decades with ongoing extension, 3) coincidence and physically consistency, 4) to be validated, 5) documented, 6) physically refreshed, and 7) available and accessible [17]. An approach for modelling weather and environmental inputs in planning tools is presented in [18]. Additional models, referred to as Power Flow Weather/Whatever models (PFW), are created to represent the impact of weather on power flow component models. The adequacy of ENI representation across the electric grid footprint is ensured with spatial-temporal models of environmental inputs presented in a single PoWer Weather (PWW) file format. The complexity of each of these models depends on an application's requirements.

The pillars of power system resilience are modelling, situational awareness, and response [3]. In the context of power system resilience against ice storms, modelling refers to the estimation of ice accumulation on power system components.

Situational awareness involves monitoring the temporal and spatial aspects of ice storms and the risk posed to power systems so that models be updated accordingly. This information can be obtained from meteorological and geographic data, phasor measurement units, etc. Response strategies to ice storms can include preventative measures that aim to prevent the accretion of ice and mitigation measures that de-ice power system components once ice formation begins.

Power system resilience can also be described by a 4-stage framework proposed in [19]. Stage 1 before an event includes preparations that improve the grid's ability to absorb damage. Stage 2 involves management of the grid as the event is occurring and measures taken in real-time to ameliorate consequences. Stage 3 is related to the recovery of the grid after the event has concluded. These stages are incident focused. The last stage includes post-incident analysis so that failures be identified and better managed in future events.

This paper extends the works in [20], [21] and further surveys the existing literature on power system resilience against ice storms. The remainder of the paper is structured around the three pillars of resilience: Section II focuses on modeling ice storms, Section III discusses situational awareness, and Section IV examines response strategies. Conclusions are provided in the final section.

II. Modelling

Ice can accumulate around power lines in different forms. Precipitation can cause ice to accumulate around power lines in the form of glaze with a density of 700 – 900 kg/m^3 or wet snow with a density of 400-600 kg/m^3. Glaze appears on power lines when temperature inversion conditions for freezing rain persist for an extended period of time. That is, when the temperature of the power line and ambient layer of air is lower than $0°C$ and that of the layer of air further away from the power line is higher. These conditions create a path for rain droplets to drop in temperature as they go through the cooler layer of air and freeze upon contact with power lines. Glaze forms when temperatures are below $0°C$ and wet snow accumulates when the temperature is below $3°C$. Ice can also form as rime around power lines under foggy conditions. Power lines at high altitudes are particularly susceptible to this type of ice formation. The rime coating can be soft with a density of 200 – 600 kg/m^3 when temperatures are between $-20°C$ and $1°C$ or hard with a density of 600-800 kg/m^3 when temperatures are between $-10°C$ and $1°C$. Whether soft or hard rime accumulates depends on the size of the rain droplets, temperature, and wind speed [22], [23], [24].

Ice accretion on power lines can be calculated using physical models [25], [26], [27], [28] or data-driven, machine learning models [29], [30], [31]. Ice accretion is modelled rather than directly measured as severe ice storm conditions can limit accessibility to power system infrastructure. Physical models factor meteorological and geographic parameters into their calculations. While these models provide a straightforward method by which ice accretion can be calculated, obtaining accurate measurements of input values may be challenging [32]. In contrast, data-driven, machine learning models rely on statistical methods applied to historical data to learn recurring patterns and predict ice accretion. Although these models provide better estimations, they are more demanding computationally and are therefore of limited utility for real-time applications [33].

The physical model in [25] provides a simple formula for conservative estimations of ice accretion on a power line based on the precipitation rate of freezing rain and wind speed and independent of the radius of the line. The numerical, time-dependent model in [26] simulates ice-growth around a power line dynamically as meteorological input data changes during the storm. In [27] icing is calculated based on heat transfer between the line and its surrounding environment. However, since icing depends on additional factors, this model can deviate from actual values under certain conditions. The model in [28] assumes a dry growth mechanism where all freezing rain droplets that fall on a power line contribute to radial ice formation.

Two support vector machine-based learning algorithms that predict ice accretion based on temporal and weather changes in ice storms are presented in [29]. The first algorithm uses meteorological data to learn the system upon which ice accumulates according to the physical model in [25] and the second algorithm uses the data to learn and forecast ice accretion without an explicitly defined model. The prediction method in [30] accounts for icing thickness and duration and is based on a particle swarm optimization backpropagation neural network. In [31], an intelligent, short-term icing model for transmission lines is proposed. Fast independent component analysis is applied to meteorological data to improve the signal to noise ratio and empirical mode decomposition is applied to generate mode functions. The total icing is the summation of forecasts for each of these functions which are predicted by a support vector machine model. The work in [32] presents an empirical probabilistic model that is based on fitting regression curves created using the correlation between icing of a power line and meteorological factors.

III. Situational Awareness

The temporal and spatial aspects of an ice storm must be accounted for when impact on a power network is modelled. In [34], deterministic ice-storm scenarios are assumed for distribution networks. Each is characterized with ice thickness, wind speed, and wind direction. As distribution networks cover a small geographic area, the same conditions are assumed to hold throughout the system. The failure of individual components, particularly power lines and poles, is quantified by fragility models that consider failure from ice accumulation, wind speed, and falling trees. The overall resilience of the system is quantified by a connectivity-based approach that estimates the number of customers that continued to benefit from electricity services during the storm. In contrast, the work in [35] partitions transmission networks, which span a much larger area in comparison to distribution networks, into smaller cells and assumes that weather conditions are the same for the area of each cell . The stochastic nature of ice storms and spatial and temporal variations are accounted for by this cell partition as well as Sequential Monte Carlo simulations. The failure of individual transmission lines is modelled as a function of weather intensity and ice thickness as calculated in [25]. In like manner to the previous study, resilience of the system is measured by the level of load that remained connected throughout the storm.

In [36], ice accretion on power lines is calculated according to the method in [25] as well. Additionally, the wind load on each power line is considered. The failure of a power line is modelled as a probability that increases exponentially after a specific mechanical threshold is exceeded and a certainty after a higher threshold is passed. In this study, an ice storm event is divided into three stages: pre-failure, during, and post-failure stages. The resilience of power lines is quantified in each stage with individual resilience indices. That of the system includes in its calculation the probability of failure of each component and the expected impact of high-order failure scenarios where multiple lines fail at once. In [37], the probability distribution functions of translational speed, central pressure difference, wind speed and direction, and ice accumulation rate are calculated and integrated into a stochastic spatiotemporal model that simulates the propagation of ice storms. Ice thickness is the main factor that is accounted for in the calculation of the probability of failure of system components. The system's resilience is computed by the probability of occurrence of an ice storm and the expected energy not served as a result.

Resilience of the distribution network overseen by Oklahoma Electric Cooperative was evaluated in [38] through a statistical analysis of data from the 2020 ice storm. The metrics used to quantify performance of the system during the storm are the duration of a disruption, average failure and restoration rates, and maximum drop in performance. A resilience curve that illustrates the deterioration and improvement in resilience measured by the loss and restoration of network load, respectively, is presented. This curve is proposed as an alternative to the trapezoid curve which does not take into consideration restorative action during a disaster. The work in [39] presents statistical models that predict electric power outages as a result of hurricanes and ice storms in 3 km × 3 km grid cells spanned by a distribution network. Historical data from past weather events were compiled using a Geographic Information System to retrieve relevant information. The models are based on a spatial generalized linear mixed modeling (GLMM) approach that accounts for spatial correlation between outage locations and incorporates covariates such as wind speed, ice thickness, and the density of protective devices. The models are fitted using a composite likelihood method to reduce computational power.

Two models that describe the impact of meteorological factors and ice accretion on the occurrence of electric faults and insulator flashover are proposed in [40]. Additionally, these models are used in a multi-variable, multi-timescale dynamic simulation of the interaction between meteorological factors and power systems. In [41], ice storms affecting transmission networks are mainly characterized by ice accretion, wind speed, and geographic location. The failure of power system components is modelled with respect to a threshold for ice and wind load. Resilience curves are generated for the periods before, during, and after an ice storm to assess a power network's ability to avoid, withstand, and recover from damage.

IV. Response

Power lines can be de-iced by mechanical or electrical methods. Substantially less energy is required to implement mechanical methods as electrical techniques may rely on excessive amounts of reactive power as well as service interruptions. Nonetheless, electrical methods are more reliable as severe weather conditions may interfere in the operation of mechanical devices and hinder personnel access to power lines. Moreover, electrical techniques are more efficient at de-icing longer power lines and are generally less labor-intensive [42].

Mechanical methods exert physical force to remove icing from power lines. This can be achieved manually using hand-held tools to scrape off the ice, non-metal sticks to strike the ice, and ice rollers that are dragged along a power line [20]. Robots are also being deployed to perform these tasks. The HQ LineROVer is a remotely operated vehicle equipped with blades that can shear ice from power lines using traction force [43]. The De-icer Actuated by Cartridge (DAC) is a portable cylinder-piston system with a revolver barrel that stocks blank cartridges and breaks ice by generating shock waves along a power line [44]. Icing can also be shed from a power line by installing the Automatic Ice Control (AIC), an electromagnetic vibrator.

Additional measures can slow ice formation. Counterweights, inter-phase spacers, and spacer dampers can be connected to a power line to limit its rotation and hinder ice growth [45]. Snow resistance rings can be spaced along a power line to prevent ice from sliding and disrupt the formation of a continuous layer [46]. Hydrophobic coatings of low ice adhesion properties can be applied to power lines [47]. Furthermore, the conductor itself can also be made of anti-icing micro- or nano-structure hydrophobic material and better improve power system performance during an ice storm [48], [49].

Electrical methods rely on heat generated from current flow through power lines. Three phase, two-phase, or single-phase short circuit faults can be triggered so that high fault current melts the ice around a power line. The fault level that is required for this task will depend on the voltage level and the characteristics of the line [20], [45], [50]. There are de-icing devices that can be installed on power lines to convert AC power from the grid into DC currents. This method requires lines be taken out of service to be implemented. The absence of reactive power losses with DC current makes these a particularly attractive option for long lines with large cross-sections [42]. High frequency AC currents are also capable of melting ice. This technique leverages high frequency properties to uniformly heat a power line. Key among these are the lossy dielectric characteristic of ice at high frequencies and the skin effect, where current concentrates closer to the surface of a conductor [51].

Ice accretion can be prevented if the temperature of the power line is kept at $1.5° - 2°C$ or higher. This can be accomplished by increasing the flow of current through a power line so that resistive losses generate heat and increase the temperature of the line. This technique can also be used to de-ice a power line when ice does accumulate. The minimum current required to do so will depend on the parameters of a power line (diameter, resistance, etc.) and the thermodynamics between the power line and its surroundings [52]. Maintaining these current flows may be challenging because demand varies throughout the day and is minimum at nighttime when temperatures are lowest. Moreover, lines that carry the least amount of current are likely to be the most susceptible to icing which can make the additional current too large to meet without changes in the network's topology [53].

The works in [22], [54], [55], [56] factor ice storm conditions into dispatch optimization models in order to prevent the formation of ice around power lines. The work in [54] uses the formulas presented in [57] to calculate the current required to prevent icing and demonstrates how generation can be redispatched to ensure that the value of current required to prevent icing flows through power lines that are susceptible to icing. In [22], the minimum current required to keep the temperature of conductors above freezing point is calculated using the steady-state heat balance formula in the IEEE Standard for Calculating the Current Temperature Relationship of Bare Overhead Conductors [58]. The minimum and maximum current constraints are expressed as a mixed-integer formulation and are enforced in day ahead and real-time security-constrained unit commitment models that adjust generation dispatch to meet these current limits. The work in [55] extends the work in [22] to update calculations of minimum currents according to changes in weather conditions (temperature, wind speed, etc). In [56], the relationship between glaze icing from freezing rain and power transmission losses is described by an analytical glaze icing model that is created based on heat balance theory. This model is linearized and integrated in a preventative scheduling model that coordinates active power dispatch, demand response, and reactive power optimization to optimally distribute line losses for the purpose of de-icing transmission lines. For a more computationally efficient algorithm, the icing model is further linearized and a Lagrangian relaxation method is implemented to identify a practical solution.

In order to achieve the level of current flow required to prevent and/or de-ice a power line, the works in [33], [59], [60], [61] take out lines in the network to redistribute power flow through the remaining lines. The work in [59] calculates the current flow required using the formulas in [57]. A tracing-based method is proposed to determine which power lines to take out to increase the current flow on lines susceptible to icing during an ice storm. Selected lines are taken out sequentially according to the sensitivity of line flow on power lines at risk of icing to the outage of a selected line. In the event where the power flow does not converge or a voltage collapse occurs, the procedure is halted. Tracing procedures and contingency selection are completed offline so that the most proper sequence be followed. In [60], a risk-based model of transmission line de-icing scheduling during an ice storm is proposed. Dynamic outage rates of lines are calculated prior to the ice storm by a load-strength interference model where ice accretion is calculated from forecast data using the formulas in [25]. The optimization model is formulated as a dynamic integer programming problem with the objective of minimizing risk to the system and is solved using a genetic algorithm. The work in [61] introduces an ice thickness prediction model that is based on that proposed in [25] and a time varying forced outage rate model. This paper also presents a multi-objective de-icing outage optimization problem to minimize the maximum ice accretion on power lines and the expected energy not supplied of the system. A non-dominated sorting genetic algorithm-II optimization approach is used to determine the Pareto optimal solutions and a decision-making method is utilized to choose the final de-icing scheme. Multiple scenarios of ice accretion on power lines are simulated in [33] while considering heat from current flow and changes in weather and the state of the network. In each scenario, lines in a specific portion of the network are removed to overload other lines in the same portion so that ice be melted. A dynamic-programming based-method is applied to determine the optimal sequence of scenarios and the duration of the application of each scenario that would minimize the maximum ice accretion over all lines in the system during an ice storm.

The work in [62] presents an algorithm for the redispatch of generation so that current be increased on lines at risk of icing. If the required current levels cannot be achieved with a given network topology, an area-based forced outage scenario for power lines is implemented. In the case where these strategies are not sufficient, a stochastic contingency constrained generation dispatch model may take out additional lines including those susceptible to icing. The overall objective is to keep as many loads connected to the grid during the ice storm. The work in [53] proposes a security-constrained redispatching optimization model that includes limits on the minimum current flow required to prevent icing around power lines and N-1 security constraints. The problem was solved by a successive mixed integer linear programming algorithm. Weather prediction models are used to update the model with the icing condition of power lines, load and generation levels, and the minimum current values that are required.

V. Conclusion

Ice storms can result in significant damage to power systems and severely disrupt their operation. Overhead power lines are particularly susceptible as the mechanical load from ice accumulation can cause them to break and take down power towers they are connected to. This paper presents literature review on the resilience of power systems against ice storms, organized according to the pillars of power system resilience: modelling, situational awareness, and response. In the context of ice storms, modelling includes the estimation of ice accumulation on power system components. Situational awareness involves monitoring the temporal and spatial aspects of ice storms and the risk posed to power systems so that models be updated accordingly. Finally, response strategies to ice storms can be preventative and mitigating measures that aim to prevent the accretion of ice and de-ice power system components once ice formation begins.

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