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SURVEY

Enhancing Power Grid Resilience Against Ice Storms: State-of-the-Art, Challenges, Needs, and Opportunities

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ABSTRACT Ice storms have significantly impacted power systems in many ways over the past decades, causing serious damage to power generation, transmission, and distribution assets. Such storms have led to massive and extended power blackouts that have disrupted the lives of many communities, thus raising concerns from several electricity sector stakeholders. This paper aims to provide power grid operators, engineers, researchers, and regulators a comprehensive overview and comparison of the existing short- and long-term planning and operational methods to enhance the resilience of power grids against ice storms. Moreover, the paper also discusses several challenges, needs, and opportunities for future research and development, with a special focus on planning and operation mechanisms for power transmission and distribution network operators.

INDEX TERMS Ice storms, power blackouts, reliability, renewable energy source (RES), resilience.

I. INTRODUCTION

A. MOTIVATION AND BACKGROUND

Ensuring power system resilience against natural disasters and weather-related extreme events has been a priority for many regions and countries in recent years. This is primarily motivated by the increased reliance on electricity to meet essential needs and emerging concerns on the impact of climate change events on the power sector.

Among such extreme weather events, ice storms can be particularly dangerous and incredibly damaging to the transportation, communication, and the electric power industries in regions with subzero temperatures or where icing occurs seasonally. Ice storms have drastic effects on power systems infrastructure including power generation, transmission, and distribution assets.

Overhead transmission and distribution lines are typically the most affected power system components during ice storms. Some of the major impacts of ice storms on power lines include line overweighting, galloping, and ice flashover, which may lead to serious short-circuit conditions, the collapse of transmission and distribution towers, poles and/or lines, thus leading to extended power outages [1], [2]. Furthermore, ice accumulation on wind turbines and solar panels can reduce wind and solar power generation, respectively. It can cause major disruptions, especially in power systems with high penetration of renewable energy sources (RESs), which are more exposed to the weather [3]. Such disruptions may cause households to be left without power in extremely low temperatures. Table 1 summarizes the potential impacts of ice storms on power generation, transmission, and distribution systems [4].

B. RECENT ICE STORMS THAT IMPACTED POWER SYSTEMS

Several ice storms with major impacts on power systems have been reported in recent decades. In early 2008, a massive ice storm with successive waves of freezing rain struck southern

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TABLE 1. Impacts of ice storms on power generation, transmission and distribution [4].

Generation	• Fuel shortages during an ice storm can result in power generation reduction in thermal power plants. • Ice accumulation on solar photovoltaic panels may reduce the solar power generation. • Ice accumulation on wind turbine blades may reduce wind power generation.
Transmission	• Weight added to the power line may result in physical damage. • Power lines undergoing heavy tensile pressure may stretch, resulting in lower total capacity.
Distribution	• Physical damage to overhead power line infrastructure (e.g., power cables, insulators, poles, and transformers.)

(a) Downed power distribution line.

(b) Downed power transmission line.

FIGURE 1. The impact of the Quebec ice storm on (a) power distribution and (b) power transmission lines. Source: Hydro-Québec [10].

and central China, causing severe damage to power systems in various regions, especially the provinces of Guizhou, Hunan, Jiangxi, and Guangdong. In the Jiangxi province, more than 250 transmission lines were destroyed, leaving millions of customers without power for several days [5]. This ice storm resulted in more than $50 billion in economic losses and damaged thousands of power lines and towers [6].

Other significant ice storms that affected power systems in recent decades include the 1990 Iowa storm, which damaged several power transmission structures [7], the 1998 ice storm in southern Quebec and northern New York, and the 2013 North American ice storm that also affected Canada and Northeastern United States (US) and caused extended outages and significant economic losses [8]. In particular, the 1998 ice storm in Canada caused about $3 billion in damage and left millions of customers without power — some for several weeks [9]. Fig. 1 shows the impact of the 1998 ice storm on power distribution and transmission lines in Quebec, Canada. According to Hydro-Québec [10], more than 110,000 power system components including transmission towers, distribution poles, transformers, and insulators were replaced after that ice storm, as shown in Table 2.

TABLE 2. The Quebec ice storm in numbers [10].

Number of affected households	1.4 million
Number of affected people	> 3 million
Transmission and distribution lines rebuild	3,000 km
Transmission towers replaced	1,500
Transformers replaced	4,500
Insulators replaced	88,000

More recently, in November of 2020, Oklahoma was impacted by a severe ice storm that lasted two days, causing several power outages, lefting more than 500,000 without power, and an estimated $27 million in financial losses [11]. In February of 2021, the state of Oregon was affected by an ice storm that caused significant damages to power system infrastructure, especially in the Portland metro area. In the same month and year, the state of Texas was struck by the devastating winter storm Uri which, among other things, caused icing damage to power generation, transmission, and distribution assets, and massive rolling blackouts throughout the state [12]. On February 15th of 2021, nearly 2000 MW of wind power went offline due to low winds, frozen substation equipment, and ice formation on wind turbine blades [13]. The damages of this storm are estimated to be nearly $130 billion in Texas and $155 billion in the US [14]. Ice storms are predicted to happen more often or become more intense in the face of climate change, which reinforces the need for enhancing grid resilience.

C. CONTRIBUTIONS AND ORGANIZATION

With the increasing concerns over the impact of climate changes events on the electricity sector and the need for greater power system resilience in many regions, there is an immediate need for studies focused on methods aimed at increasing power system resilience against extreme-weather related events, including ice storms.

The existing reviews and surveys relating ice storms and power system have primarily focused on hydrophobic and anti-icing coatings materials for power lines [15], [16], [17], [18] and physical technologies and techniques for power transmission line anti-icing/de-icing [4], [19], [20], [21]. However, none of them discussed important short- and long-term planning strategies, including resilience assessment, preventative dispatch, and power grid upgrade planning, which can be essential to increase the resilience of power systems against ice storms. To the best of the author's knowledge, no previous work comprehensively classified and discussed existing power system planning and operation approaches to enhance power system resilience against ice storms nor discussed the related challenges, needs, and opportunities.

TABLE 3. A comparison of this work with existing literature.

Topics	References					
	[4]	[15]-[18]	[19]	[20]	[21]	This work
Long-term planning mechanisms	✓	✓		✓	✓	✓
Short-term planning mechanisms						✓
Operation mechanisms	✓		✓	✓	✓	✓
Both transmission and distribution lines						✓
Challenges, needs, and opportunities						✓

This paper aims to bridge the existing knowledge gap on this topic and provide power grid operators, engineers, researchers, and regulators with a comprehensive review and framework of the state-of-the-art planning and operation approaches along with opportunities for future research and development. The contributions of this paper are summarized as follows:

1) It provides a comprehensive overview and classification framework of the state-of-the-art planning and operation mechanisms to increase the resilience of power systems against ice storms, with applications to transmission and distribution lines.
2) It discusses select challenges, needs, and opportunities for further research and development related to this increasingly important topic.

A comparison of this work with the existing literature on power system planning and operation mechanisms against ice storms is provided in Table 3.

The remainder parts of this paper are organized as follows. Section II provides a brief overview of the power line icing formation process. Section III reviews the existing literature on long-term planning, short-term planning, and operation mechanisms to enhance power system resilience against ice storms. Section IV discusses select challenges, needs, and future research directions. Finally, relevant conclusions are presented in Section V.

II. A BRIEF OVERVIEW OF ICE STORMS AND IMPLICATIONS TO POWER SYSTEM RESILIENCE

Icing formation and accumulation on power system infrastructure is not a simple process as it results from the combination of thermodynamic equilibrium mechanisms, fluid dynamics mechanisms, and various environmental conditions [1]. Icing formation tends to occur when precipitation falls during an inversion phenomenon (i.e., when there is a positive difference of temperature between the upper air and the land surface temperature). Ice crystals are formed at high altitudes where the air temperature is very low. Then,

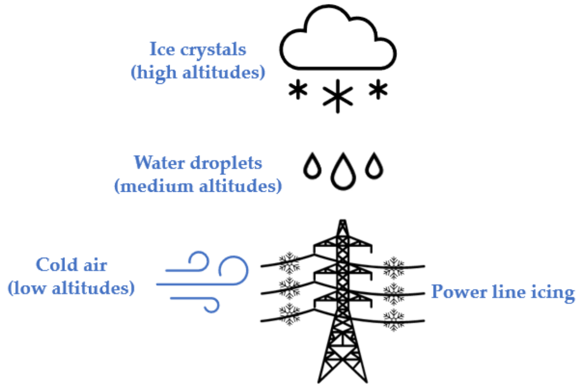

FIGURE 2. The icing formation process on overhead power lines.

after reaching medium altitudes with higher air temperatures, the ice crystals melt down and convert into water droplets. Finally, after touching the power equipment under very low temperatures, the water droplets condense into solid ice and accumulate in various ways, depending on the wind speed and air humidity levels. This process is illustrated in Fig. 2 for an overhead power line. In general, if the temperature of the air above the power lines is too low, the precipitation will freeze in the air and no ice will be accumulated on the line [2]. However, depending on the shape of the conductor, even non-sticky ice crystals may be occasionally accumulated on the line.

Some of the necessary conditions for ice formation include: 1) conductor temperature should be between -3°C and +2°C; 2) air humidity should be at least 85%; and 3) wind speed should be at least 1m/s [1]. If the ice accumulation persists for a long period, the ice will thicken, and the power line and the associated towers and poles can collapse if the total weight exceeds the maximum mechanical threshold. Just half an inch of ice can add up to 500 pounds of extra weight to a power line [22]. This in turn may result in extended power blackouts and costly repairs, which may even exceed the original cost of the line [2].

Conductor icing forms can be divided into glaze, rime, and mixed freeze as described below [1], [23].

a) ***Glaze:*** is the most dangerous form of conductor icing form due to its high density (i.e., typically between 0.6 and 0.9 g/cm^3) and strong adhesion force.
b) ***Rime:*** is a less severe form of icing form that is divided into granular rime (i.e., density between 0.1 and 0.3 g/cm^3) and crystalline rime (i.e., density between 0.01 and 0.08 g/cm^3). Both types of rime are typically brittle and have weak adhesion.
c) ***Mixed freeze:*** This type of ice formation can be divided into wet snow (i.e., density between 0.1 and 0.7 g/cm^3 with weak adhesion) and mixed snow (i.e., density between 0.2 and 0.6 g/cm^3 with stronger adhesion).

According to [24] and [25], the ice thickness R_H (mm) at altitude H(m) can be calculated as a function of the ice density ρ_i (g/cm^3), the freezing precipitation density (g/cm^3), the precipitation rate r(mm/h), the precipitation duration t (h), the

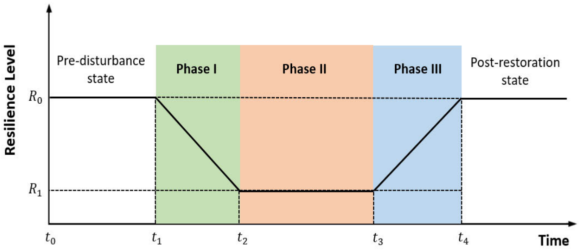

FIGURE 3. The resilience trapezoid [15].

altitude of the reference point H_0(m), the liquid water content in the air ê (g/cm^3), and the wind speed ω (m/s) as follows:

$$R_H = \frac{1}{\rho_i \pi}\left(\frac{H}{H_0}\right)^b \sqrt{(r\rho_r)^2 + t^2(3.6\omega\kappa)^2} \tag{1}$$

where b is the ice thickness adjustment index, which relates ice weight and altitude, typically between 0.2 to 0.45 [25].

The 2008 ice storm in the Chinese province of Jiangxi, for example, resulted in ice coverings with thicknesses between 10-30 mm on most transmission lines. However, in some mountain areas subject to colder winds with higher speeds, the ice thickness ranged from 80-90 mm, thus causing significant damage to several transmission lines [4].

The International Electrotechnical Commission (IEC) Standard 60826:2003 [26] presents a method to estimate the combined static wind and ice loads on overhead transmission lines. The authors in [27] proposed a complementary method based on dynamic ice and wind load modeling. This method considers potential low frequency and large amplitude oscillations of transmission line conductors during ice storms. Other ice accretion models for overhead transmission lines based on empirical analysis are presented in [28] and [29].

The Federal Energy Regulatory Commission (FERC) has defined resilience as "the ability to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capability to anticipate, absorb, adapt to, and/or rapidly recover from such event" [22]. The typical resilience trapezoid associated with an extreme event is illustrated in Fig. 3. Preventive measures are deployed during time period (t_0, t_1) in the pre-disturbance resilience state where the system has its original resilience level R_0. Phase I is where the disturbance is in progress during time period (t_1, t_2) and corrective actions take place. In Phase II, the system resilience level is significantly reduced to R_1, thus requiring effective emergency coordination during time period (t_2, t_3). In Phase III, the system resilience level is gradually restored until achieving the post-restoration state R_0 at time t_4 [13]. In the case of ice storms, anticipation, which includes prediction and preparedness in the pre-disturbance resilient state, plays an important role in mitigating negative impacts and facilitating timely power system restoration.

III. STATE-OF-THE-ART ON POWER SYSTEM RESILIENCE ENHANCEMENT AGAINST ICE STORMS

The existing literature on power system resilience against ice storms can be divided into long- and short-term planning strategies and operation mechanisms as illustrated in Fig. 4 Long-term planning strategies generally comprise the use of assessment, preventive, and/or mitigation techniques that may take several months or years to be deployed. Alternatively, short-term planning strategies can be generally deployed by utilities and system operators within days or hours when an ice storm is forecasted. Operation mechanisms, on the other hand, are put in place during the course of an ice storm to prevent system disruption or facilitate system restoration following a disruption. These planning and operation mechanisms are discussed in Sections III-A, III-B, and III.C, respectively.

A. PLANNING MECHANISMS

This section reviews the existing literature on planning mechanisms to enhance power system resilience against ice storms. It is divided into long- and short-term planning mechanisms as follows:

1) LONG-TERM PLANNING

Several long-term planning mechanisms have been designed to assess the resilience level of a power system against ice storms or to prevent/mitigate the impacts of ice storms before they are even formed. Such mechanisms may take months or years to be fully employed in power transmission and distribution systems, depending on their complexity. It is important to note that the use of anti-icing materials, such as hydrophobic or icephobic coatings can be considered a long-term planning solution to mitigate the impacts of ice storms. The works in [15], [16], [17], and [18] already provided comprehensive reviews of existing mechanisms and applications of functional coatings for overhead power lines and insulators, which is outside the scope of this paper. The long-term planning mechanisms considered in this paper are classified as follows:

a: RESILIENCE ASSESSMENT

Assessing and quantifying the potential impacts of ice storms on power systems is an essential step that should be considered before decisions on different resilience enhancement strategies are made [30]. Resilience assessment can be divided into resistance capability assessment and restoration assessment. Resistance capability assessment considering ice storms was studied in [31], [32], and [33]. The work in [31] proposed a framework to assess the resilience level of transmission systems against ice storms. Such a framework considers different ice storm spatiotemporal scenarios which are generated using weather data and are used in the fragility model of transmission towers and corridors. According to [31], the failure rate, λ_T, of a transmission tower subjected to ice storms can be calculated as follows:

$$\lambda_T = \begin{cases} 0, R_i^T < R_o^T \\ e^{\left(\frac{0.6931\left(R_i^T - R_o^T\right)}{4R_o^T}\right)} - 1, R_0 < R_i^T \leq 5R_o^T (2) \\ 1, R_i^T > 5R_o^T \end{cases} \tag{2}$$

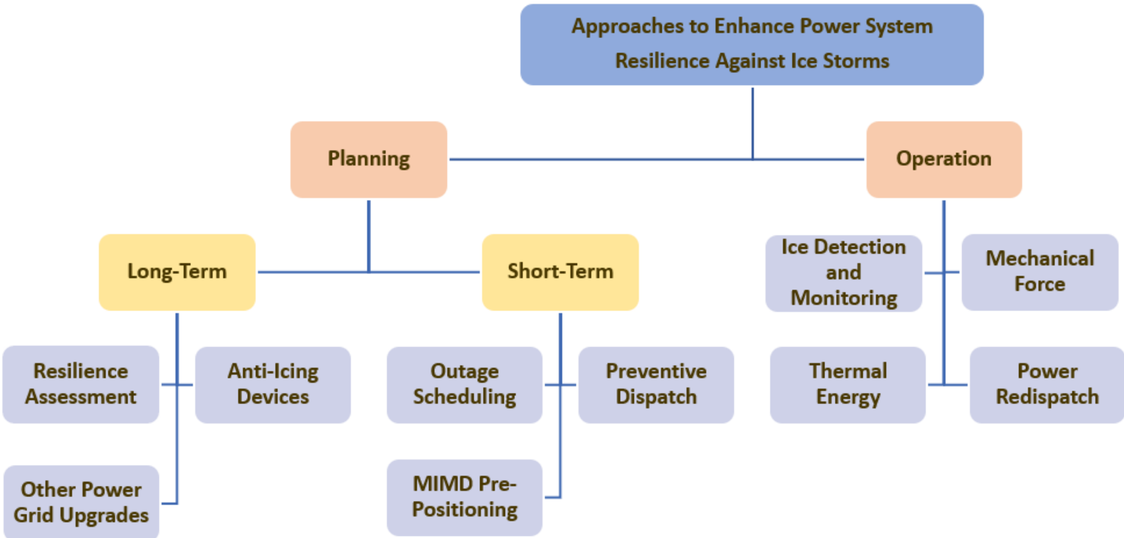

FIGURE 4. Classification of existing approaches to enhance power system resilience against ice storms.

where R_i^T is the ice thickness (mm) on the tower and R_o^T is the threshold ice thickness design (mm) of the tower. The failure rate, λ_L, of a transmission line segment subjected to ice storms can be calculated as follows:

$$\lambda_L = e^{\left(11\frac{R_i^L}{R_o^L}-18\right)}\Delta l \tag{3}$$

where R_i^L is the ice thickness (mm) at the midpoint of the line segment, R_o^L is the threshold design ice thickness (mm) of the line segment, and Δl is the length (mm) of the line segment. Eq. (2) and (3) were used in [31] in order to calculate the total amount of load curtailment and the respective probability of occurrence for different ice storm scenarios. Probabilistic models to estimate the ice accretion and physical damage to transmission towers to guide long-term investment decisions were developed in [32] and [33].

Studies that focused on restoration assessment considering ice storms were presented in [34] and [35]. The work in [34] proposed accelerated failure time models to estimate outage durations and restoration times for hurricanes and ice storms. In [35], the authors proposed a Monte Carlo simulation-based approach to estimate restoration times considering a moving ice storm with continuous severity levels.

Two recent works [36], [37] focused on both resistance capability assessment and restoration assessment. Hou et al. [36] proposed a comprehensive resilience assessment framework applied to distribution networks. It investigates different component failure modes and the effect of wind attack angle during ice storms. It also evaluates the cost-effectiveness of resilience enhancement strategies, such as vegetation management and distribution pole upgrades, and proposes a probabilistic framework to model restoration resources and repair times. In [37], the authors explored the quantification of operational resilience of distribution networks in Oklahoma using network data from the 2020 ice storm provided by Oklahoma Electric Cooperative. This work showed that conventional reliability indices, such as system average interruption frequency index (SAIFI), system average interruption duration index (SAIDI), and customer average interruption duration index (CAIDI) are not suitable to properly quantify the resistance and restoration capability of distribution networks against ice storms as they tend to obscure temporal characteristics of ice storms.

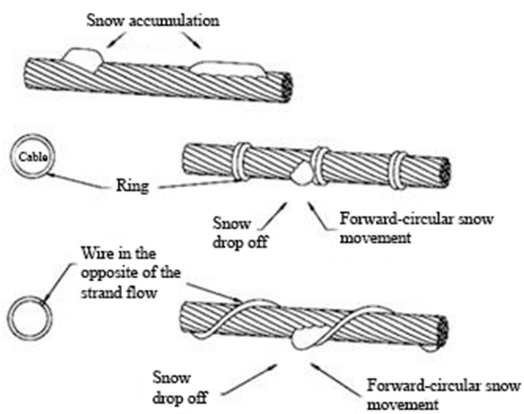

FIGURE 5. Rings perpendicular to the span of the line and opposite to the strand flow of the line [38].

b: ANTI-ICING DEVICES

Several devices have been developed to prevent ice accumulation on a permanent basis. Small rings made of rubber or plastic, for example, can be wrapped either perpendicularly to the span of the line as individual rings or wrapped opposite to the strand flow of the line. These two configurations are illustrated in Fig. 5 [38]. Generally, water and snow follow the strands of power lines. These rings, in turn, are designed to intersect the water flow, thus causing gravitational force to pull the water off the line and prevent ice formation by

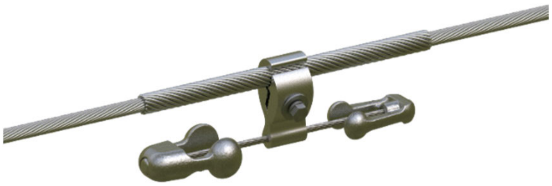

FIGURE 6. Counterweight (VORTX^{TM}) on a power line [39].

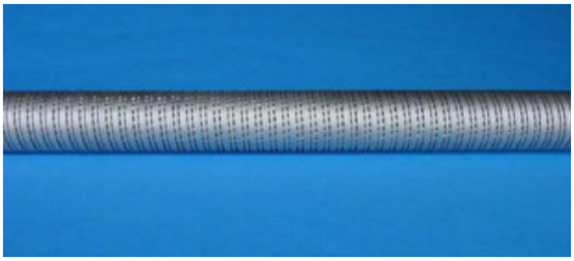

FIGURE 7. LC-Spiral rods wrapped around a power line [41].

limiting the time of contact of water with the line in a passive way (i.e., not requiring any active component or human labor to remove water or ice from the lines) [39].

Counterweights are another type of passive device installed along the span of power lines to prevent ice accumulation. They specifically prevent the formation of cylindrical ice deposits, which generally shed harder than noncylindrical deposits. They are designed to increase the torsional stiffness of conductor spans, and thus by limiting the rotation of conductor spans, lead to the formation of noncylindrical ice deposits. Fig. 6 illustrates a counterweight installed on a power line. In general, counterweights are more effective during wet snow than freezing rain events [4]. According to Farzaneh in [40], counterweights reduce the effect of snow and ice accumulation on power lines by only around 20% due to the length of the cylindrical ice accretion. In addition, counterweights can be used in conjunction with plastic rings to leverage the benefits of both passive devices. Low-Curie (LC) Spiral Rods are another passive device to prevent ice accumulation on power lines. They were designed in Japan and have been used in the last 30 years in several locations [41]. LC-Spiral Rods consist of ferromagnetic rods that are wrapped around the power line, as illustrated in Fig. 7. They are designed to generate heat by the effect of eddy currents and hysteresis on the ferromagnetic material [42]. Favorably, LC-Spiral Rods generate less heat during summer due to low Curie properties at higher ambient temperatures. However, they add extra weight to conductors and cannot be used on shielded conductors. In addition, they are less effective in preventing ice accumulation on power lines during ice storms with high wind gusts due to inconsistent and insufficient heat generation [41].

Some other devices can be installed in advance on power lines to remove ice, assuming that ice accumulation cannot be prevented. One example is the Automatic Ice Control (AIC) which vibrates over the span of the power line to remove ice accumulation. The AIC is powered by the line where it is mounted and is comprised of ice detection sensors and an electromagnetic vibrator [43]. A similar device, called Ice Shedder, is used to perform the same task, but using a motor to move an unbalanced weight that causes the device to vibrate [40]. They are illustrated in Fig. 8. The vibration created by such devices, however, can damage the structure of power lines over time [43].

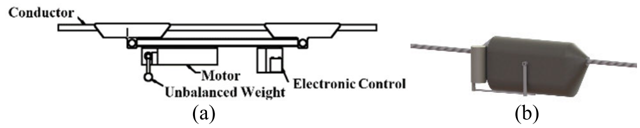

FIGURE 8. (a) Ice Shedder schematic, (b) An AIC attached to a power line [43].

c: OTHER POWER GRID UPGRADES

The works under this category proposed long-term power grid expansion and upgrade planning models considering the potential risk of ice storms. In [44], a two-stage stochastic optimization model was proposed to improve the resilience of transmission networks subjected to ice storms. The first-stage decisions include the deployment of new lines, generators, and flexible alternating current transmission system (FACTS) devices such as series compensators and phase-shifting transformers. In the second stage, the performance of the transmission network is evaluated based on different ice storm damage scenarios. In [45], a reliability-based distributed generation (DG) planning model was developed to improve the resilience of distribution systems in ice storm areas. The proposed nonlinear model optimally allocates DG units in distribution networks considering the failure rate and repair time of overhead distribution lines during ice storms. A modified genetic algorithm was used to solve the proposed problem based on input data from utilities in China. Case studies showed an overall economic loss reduction of 2.8 million Yuan (China's currency) for a 33-node distribution network. The work in [46] proposed a multi-stage defender-attacker-defender (DAD) model for distribution system resilience enhancement against ice storms. The proposed DAD model included long-term decisions on the line hardening and operational decisions on ice-melting dispatch, and routing of mobile ice-melting devices (MIMDs), mobile emergency generators (MEGs), and mobile energy storage systems (MESSs) in the first level. In the second level, ice storm attacks on both distribution and transportation networks are modeled. Case studies showed that the hardened distribution lines were those in the vicinity of upstream substation nodes to ensure the power supply from the bulk transmission system. Furthermore, it showed that MIMDs were able to delay line damages and facilitate system restoration. Also, MEGs and MESSs were able to supply power to microgrids and reduce the overall load shedding.

Another alternative for upgrading power grids and protecting wires from ice-storm is to bury overhead power lines. The Author in [47] summarizes past studies and analyzes historical performance data of underground and overhead power lines to assess the advantages and disadvantages of placing overhead electric distribution infrastructure underground. It is concluded that underground power systems, compared to overhead ones, may have fewer power outages, but the duration of outages may be much longer, and they are very expensive to be implemented. The study also proposes innovative programs that communities and local governments can leverage to overcome the high cost associated with undergrounding power lines.

2) SHORT-TERM PLANNING

Short-term planning mechanisms are designed to prevent or mitigate the impacts of ice storms on power systems, when an ice storm can be forecasted accurately, and reduce the system restoration time [34]. They include decisions that can take place hours or a few days before the ice storm hits a power system. They are classified and described as follows:

a: OUTAGE SCHEDULING

The first short-term planning models for power systems affected by ice storms reported in the literature fall under the *Outage Scheduling* category. The idea is to obtain an accurate outage rate based on short-term weather forecast data (i.e., ambient temperature and wind speeds). In [48], a tracing procedure was proposed to identify transmission lines to be taken out of service to increase current flow on at-risk lines during ice storms. The proposed procedure can prevent ice accumulation on at-risk lines at the cost of not meeting voltage reliability standards in all buses of the system. The work in [49] introduced a load-strength interference model to calculate the dynamic outage rates of transmission lines and proposed a de-icing outage scheduling model aimed at ensuring a certain level of power adequacy and minimizing the system risk during de-icing periods. This model was extended in [50] into a multi-objective de-icing outage scheduling problem to minimize both the ice thickness peak value and the energy not supplied during de-icing periods. The proposed nonlinear multi-objective model was solved using the non-dominated sorting genetic algorithm II (NSGA II) and validated on the IEEE 24-bus RTS system to generate a set of Pareto optimal solutions. Other similar short-term decision models for outage scheduling during ice storms were presented in [51] and [52].

b: PREVENTIVE DISPATCH

These approaches aim to prevent ice formation on power lines through the Joule effect (i.e., by raising the current flowing through the conductor, and consequently its temperature above the freezing point) based on short-term weather forecast. The current I needed to prevent icing can be obtained through Clem's classic formula as follows [2], [53]:

$$I^2 = \frac{\theta\sqrt{dv}}{8.4R}x10^4 \tag{4}$$

where θ is the temperature rise (^{o}C) needed, R is the conductor resistance (Ω/mile) at 20^{o}C, d is the conductor diameter (in), and v is the wind speed (mi/h). Eq. (2) is only valid for $v > 2$.

In [54], a unit commitment model was proposed to enforce minimum conductor temperature limits by adjusting generation dispatch. Limitations of this model include infeasible solutions for large number of affected lines and harsh ambient conditions (i.e., ambient temperature below -16^{o}C and wind speeds above 16 m/s) when tested on the IEEE three-area RTS-96 system. This work was extended in [55] to capture the changing weather conditions (i.e., ambient temperature and wind speeds) during an ice storm event. Huang et al. [56] proposed a preventive scheduling model to reduce the impact of ice glazing on transmission lines by optimizing the distribution of power losses. Such a model co-optimizes active and reactive power dispatch, and demand response to facilitate de-icing of transmission lines. The proposed model was validated on an IEEE 79-bus reliability test system (RTS) and the results showed that the integration of demand response and reactive power optimization provides better de-icing effects compared with the case with active power dispatch alone. However, when multiple lines are subject to ice formation, the icing cannot be completely eliminated on all lines.

c: MIMD PRE-POSITIONING

MIMDs or mobile de-icing devices (MDIDs) are typically truck-mounted converters that can generate and adjust DC currents in order to facilitate de-icing of power lines through the Joule Effect. They are considered a flexible and versatile de-icing option since they can be routed to critical geographic locations in real-time [57]. Their operation is described in detail in Section III-B, which covers de-icing operation mechanisms. Before MIMDs are routed in real-time, pre-positioning decisions should made in order to ensure an effective coordination with day-ahead unit commitment mechanisms. Yan et al. [58] proposed a two-stage robust optimization model for optimal coordination of power system schedule and pre-positioning of MIMDs. The first-stage decisions include the day-ahead unit commitment and pre-positioning of MIMDs. The second-stage decisions include the real-time power system dispatch, and MIMD routing and de-icing decisions. The proposed model was solved using the nested column-and-constraint generation algorithm and was validated on a real power-transportation integrated network system in Hunan Province, China. This model, however, did not consider the impact of traffic congestion on MIMD pre-positioning and routing decisions.

B. OPERATION MECHANISMS

The power system operation mechanisms against ice storms are deployed during or after an ice storm impacts a power line. They are divided in this paper into ice detection and motoring, mechanical force, thermal energy, and power redispatch which are described as follows:

FIGURE 9. Ice removal via roller by Manitoba Hydro [66].

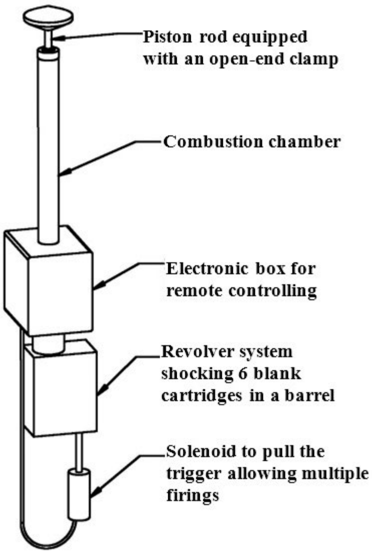

FIGURE 10. Schematic of a DAC [67].

a: ICE DETECTION AND MONITORING

Before de-icing mechanisms are employed in real-time, ice formation and accretion should be properly detected and monitored. This can be made by visual inspection or through automatic and less labor-intensive mechanisms, such as weight sensors [59], digital cameras [60], [61], Unmanned Aerial Vehicle (UAV) [62], patch antenna sensors [63], travelling wave location equipment [64], and radar sensing technologies [65], which are generally installed on power lines or transmission towers. Minullin et al. [65] compared the radar equipment readings and weight sensor measurements during an ice storm in Russia. It showed that radar sensing can monitor the real-time icing and ice-melting dynamics more effectively for the entire span of the transmission line. Such ice detection and monitoring devices, however, are typically costly and require frequent maintenance.

b: MECHANICAL FORCE

Several methods have been proposed to use mechanical force for power line ice removal purposes. The simplest one requires a 6-foot stick that is manually operated by a lineman elevated from the ground to break the ice by impact [66]. Manual ice removal by impact can also be performed through a roller attached to a vehicle by an insulated pole. As the vehicle is driven parallel to the line, the ice is scrapped off by the roller as shown in Fig. 9. Although very simple, such methods require considerable amount of manual labor and free access to road networks that may be icy during such storms. Hydro-Quebec developed another manual method to remove ice from power lines. The De-Icer Actuated by Cartridge (DAC), shown in Fig. 10, is a portable device that is operated by remote control. It is comprised of a cylinder-and-piston system that is raised to the power line by a mechanical or pneumatic line thrower and is fired through an electronic trigger. Once attached to the line, the piston can be fired through the remote control, thus generating a mechanical impulse that propagates through the span of the power line. As a result, the ice is broken instantaneously [67]. However, the impacting can potentially damage the mechanical structure of the power line over time [23]. Hydro-Quebec also uses a Robot Operated Vehicle (ROV) to mechanically remove ice from power lines. The ROV, as shown in Fig. 11, is equipped with steel blades, and is placed on the line manually. As it moves on the line, the ice is removed by the blades. Compared with the other manual mechanisms described above, ROV is the one that requires less manual labor. However, its operational range is limited to around 1 km [23].

c: THERMAL ENERGY

Methods that utilize thermal energy, either from internal or external heating sources, are widely used for ice removal from power lines. Internal heating solutions use the power line to generate heat by the Joule Effect and dissipate ice. Heat can be generated through various ways, such as a short circuit, high-frequency excitation, or a ground direct current (DC) [68]. The first method requires a controlled single-phase, two-phase, or three-phase short-circuit to be applied at one end of the power line. This process increases the temperature throughout the span of the line, thus melting the ice on the line [69]. The generated heat Q depends on the current I and the resistivity of the conductor ρ_T at temperature T, as expressed in (5) [68]. This method has a relatively low cost and easy operation. It was extensively used during the 2008 ice storm in China and was proved to be effective. However, it requires power lines to be out of service during de-icing operations.

$$Q = I^2 \rho_T \tag{5}$$

High-frequency (8-20 kHz) AC currents can also be used to generate heat and, aided by the skin effect, de-ice the surface of power conductors. In general, this method is very efficient and allows the power lines to remain in service while being de-iced. The drawbacks of this method include its high cost, poor scalability, lack of mobility, and difficulty to control the generated heat accurately [57], [70]. The work in [71] showed that by leveraging both the skin effect and dielectric losses, it is possible to produce even heating and,

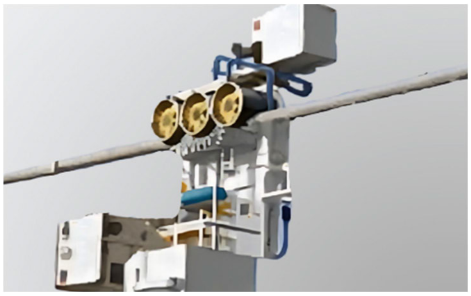

FIGURE 11. ROV breaking ice on a power line [49]. Concept art generated by A.I.

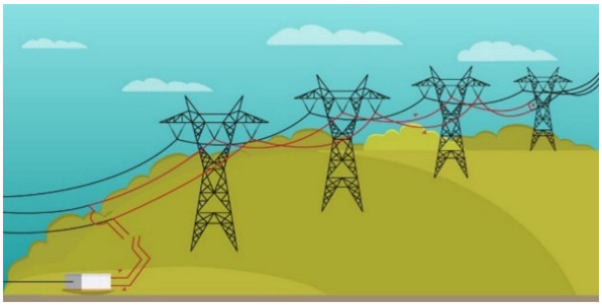

FIGURE 12. Illustration of the DC current method [40].

thus, increase the de-icing efficiency. Other AC-based thermal energy de-icing mechanisms include injection of reactive current from capacitor and inductor banks [72], [73], circulating currents from phase-shifting transformers [19], and on-load tap changing transformers [74]. In the case of extra high-voltage transmission lines, ice-melting current flow can be increased by reconfiguring parallel bundled conductors to series connections through switchgears installed at both ends of the line [75].

Another Joule Effect-based method, known as the DC current method, is widely used for de-icing power lines through fixed, mobile, or portable de-icing devices (PDIDs) [76]. It uses an external DC converter connected to the iced power lines in a closed-loop configuration, as illustrated in Fig. 12 [20], to apply a rectified DC voltage that can be adjusted by the external power supply [57]. The works in [77] and [78] introduced fixed DC-based de-icing devices comprised of a power rectifier with high voltage thyristors that can be installed at the substation to inject high currents and increase the temperature of transmission lines to be de-iced. When not used for de-icing purposes, such devices can work as a Static Var Compensator (SVC) to perform voltage regulation.

Alternatively, the deployment of MIMDs and PDIDs relies on the existence and availability of transportation networks close to the iced lines. A real-time routing model for MIMDs was presented in [79]. This model coordinates de-icing scheduling and MIMD routing while considering transportation network congestion and power distribution system operation, including the dispatch of distributed energy resources (DERs) (e.g., DG and energy storage systems) and network reconfiguration. It also showed that transportation

FIGURE 13. Illustration of an ice-melting drone in operation [81].

network congestion significantly impacts the MIMD routing decisions. Different than MIMDs, PDIDs are typically small and lightweight converters that can be used in areas that cannot be easily accessible by MIMDs. The main limitation of PDIDs is their shorter ice-melting distance. MIMDs and PDIDs are mostly used to de-ice short distribution networks at relatively low voltages. Their use for high-voltage transmission networks, however, requires large capacity and high-cost power electronics converters, thus limiting their cost-effectiveness in many regions [57].

Although less common, external heating sources not directly connected to power lines can also be used for power line de-icing. An electric utility in Southwest China has used a spitfire ice-melting drone, as shown in Fig. 13, that is able to melt up to 2.3-inch-thick ice within 10 minutes. This solution can be used in conjunction with a manual roller to facilitate manual thick ice removal in lines that are hard to reach [80], [81]. Another potential solution uses a surface slow-wave antenna to generate electromagnetic waves and heat the surface of the line, which remains in service during de-icing operations [82].

d: POWER REDISPATCH

This approach aims to prevent and/or reduce ice accumulation on power lines on a very short-term basis without applying short-circuits or using external power sources. It is based on re-dispatching power generation units in order to increase the power flow, and consequently the temperature of the lines exposed to ice and snowstorms in real time. In [83], a multi-step re-dispatch algorithm was proposed for transmission lines. Initially, power generation units are re-dispatched to increase the temperature of the conductors of the at-risk lines. If the temperature increase is not sufficient to prevent ice formation, some transmission lines are de-energized to increase the power flow in at-risk lines. If still not sufficient, a contingency-constrained AC power flow is performed to select priority lines for anti-icing temperature increase and minimize load shedding. The proposed approach was validated on an IEEE 118-bus system. Ciapessoni et al. [84] proposed a security-constrained generation re-dispatch model run on hourly basis to ensure a minimum anti-icing current to keep a minimum conductor temperature of critical transmission lines at 1.5 ^{o}C. This approach, however, was proven to be more effective dur-

TABLE 4. Advantages and disadvantages of existing approaches.

Classification			Methodology	Advantages	Disadvantages
Planning	Long-Term	Resilience Assessment	Resistance capability assessment [31]-[33]	Help guide better investment decisions	Require long-term ice storm forecasts
			Restoration assessment [34, 35]		
			Comprehensive resilience assessment [36, 37]		
		Anti-Icing Devices	Rubber and plastic rings [38, 39]	Simple and low cost	Partial ice removal
			Counterweights [40]	Simple and low cost	Partial ice removal
			LC spiral rods [41, 42]	Complete ice removal	Uncontrolled heat generation
			AIC [43]	Simple and low cost	May cause structural damage
		Other Power Grid Upgrades	Two-stage stochastic optimization considering FACTS devices [44]	Flexibility and adaptability to other natural disasters hazard risks	High cost and long deployment time
			Reliability-based DG planning [45]		
			Multi-stage DAD [46]		
			Bury overhead lines [47]	Improved aesthetics Fewer power outages	High cost Longer outage duration
	Short-Term	Outage Scheduling	Outage-line identification [48]	Do not require external de-icing devices or mechanisms	Inevitable load shedding
			Dynamic outage rate [49]		
			Multi-objective de-icing outage scheduling [50]		
			Dynamic programming for load current channeling [51]		
			Net-ability de-icing [52]		
		Preventive Dispatch	Unit commitment with minimum conductor temperature [54]	Do not require external de-icing devices or mechanisms	Increased power losses
			Unit commitment with changing weather conditions [55]		
			Power loss distribution optimization [56]		
		MIMD Pre-Positioning	Two-stage robust optimization [58]	High cost	Rely on transportation network availability
Operation		Ice Detection and Monitoring	Weight sensors [59]	Help guide better operation decisions	High cost and maintenance
			Digital cameras [60, 61]		
			UAV [62]		
			Patch antenna sensors [63]		
			Travelling wave location equipment [64]		
			Radar sensing technologies [65]		
		Mechanical Force	Manual impact [66]	Complete ice removal	Labor intensive
			Scrapping roller [66]	Complete ice removal	Rely on transportation network availability
			DAC [67]	Complete ice removal	May cause structural damage
			ROV [23]	Portable	May cause structural damage
		Thermal Energy	De-icing short-circuits [68, 69]	Complete ice removal	Labor intensive
			High-frequency currents [70]	Lines remain in service during de-icing	High cost, uneven heating
			High-frequency currents and dielectric losses [71]	Lines remain in service during de-icing, even heating	High cost
			Reactive current injection [72, 73]	Minimal labor	High cost, voltage regulation issues
			Phase-shifting transformers [19]		
			On-load tap changing transformers [74]		
			Conductor bundled reconfiguration [75]	Flexibility	Only applicable to extra-high voltage transmission lines
			DC current injection [57, 77, 78]	Complete ice removal	High cost
			MIMD routing [79]	Flexibility	Rely on transportation network availability
			Ice-melting drones [80, 81]	Independent from power line and transportation network	Limited range, partial de-icing
			Slow-wave antenna [82]	Portability	Limited range, partial de-icing
		Power Redispatch	Multi-step redispatch [83]	Do not require external de-icing devices or mechanisms	Inevitable load shedding, increase power losses

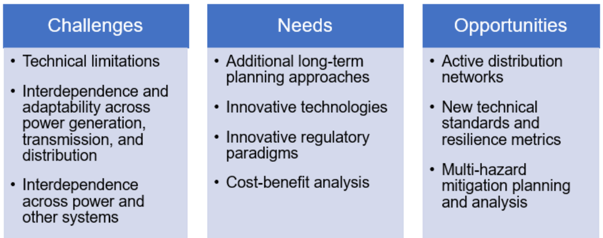

FIGURE 14. Summary of the existing challenges, needs, and opportunities.

ing moderate wet snow events (i.e., low wind speeds and precipitation rates) based on simulations for the Italian extra-high voltage level transmission grid.

Table 4 summarizes all the planning and operation mechanisms against ice storms discussed in this paper. It also presents the main advantages and disadvantages of each approach.

IV. CHALLENGES, NEEDS, AND OPPORTUNITIES

The main challenges, needs, and opportunities for future research and development associated with power system resilience enhancement against ice storms are summarized in Fig. 14 and discussed as follows.

A. CHALLENGES

a: TECHNICAL LIMITATIONS

Several technical limitations are yet to be addressed in both planning and operation mechanisms for power grids subjected to ice storm risks. The main existing technical challenges on the planning side include the need for long-term weather and ice storm forecasts for resilient assessment as well as the high investment costs and long deployment time of several anti-icing solutions. On the operation side, limited range, high cost and labor intensiveness, structural damage risks, dependence on transportation networks, and the need to deenergize power lines for many de-icing procedures remain open challenges to be addressed.

b: INTERDEPENDENCE AND ADAPTABILITY ACROSS GENERATION, TRANSMISSION, AND DISTRIBUTION SYSTEMS

Electricity consumers at the grid edge rely on the availability of all upstream components (i.e., generation, transmission, and distribution systems). Power transmission disruptions during ice storms, for example, will limit supply to both transmission and distribution systems. Most of the existing works on power system resilience enhancement against ice storms, however, have focused on approaches applied to either transmission or distribution systems separately. However, understanding the interdependence across power generation, transmission, and distribution is essential to develop system-wide solutions that are able to minimize the impacts of ice storms to end users. Resilience assessment tools, in particular, should also consider the impacts of ice storms on fuel supply disruptions. In this regard, the impact of ice storms on renewable power generation assets (e.g., solar panels and wind turbines) should also be considered. Moreover, new anti-icing/de-icing planning and operation approaches should be adaptable across different systems considering their regional, technical, and regulatory differences and interdependencies.

c: INTERDEPENDENCE ACROSS POWER AND OTHER SYSTEMS

Ice storms can significantly impact multiple interdependent systems simultaneously, including water, natural gas, power, transportation, and communication infrastructures. During the 2021 Texas winter storm, for example, a shortage of natural gas impacted many thermal power plants, which contributed to power shortages and multiple outages across the state. Understanding the interdependences across multiple infrastructures is paramount to unleash synergetic potentials in infrastructure resilience enhancement. Long-term resilience assessment tools as well as short-term planning and operation anti-icing/de-icing mechanisms for transmission and distribution networks, for example, should consider the respective impacts of ice storms on fuel disruption as well as the prioritization of critical loads for essential services such as water supply, transportation, and emergency communication services. In particular, the deployment of portable and mobile de-icing vehicles should consider the availability as well as the real-time conditions (e.g., traffic congestion and ice accumulation levels) of transportation networks, which may be unavailable or present hazardous conditions during severe ice storms.

B. NEEDS

a: ADDITIONAL LONG-TERM PLANNING APPROACHES

The majority of the approaches discussed in this paper fall under the *Operation* category, as shown in Table 4. Short-term planning and operation mechanisms are definitely important to ensure the resilience of power systems when an ice storm can be accurately predicted. However, short-term actions are more dependent on the availability of existing human and material resources (e.g., human labor and de-icing equipment), which may not be available depending on the severity and extent of the ice storm. Operation mechanisms, in particular, are considered remedial actions that can facilitate power system restoration. In many cases, the resilience level of the system is already degraded (i.e., outages are already in place – see Phase II in Fig. 3) when operation mechanisms are employed. Long-term planning mechanisms, on the other hand, may take several months or years to be fully employed in power systems, depending on their complexity. However, effective long-term planning mechanisms may help utilities and power system operators avoid undesired operational burdens and minimize power outages during ice storms. Moreover, new resilience assessment approaches are needed to quantify and analyze the power system recovery capability during ice storms. In this regard, dynamic-Bayesian-network-based degradation and maintenance [85] approaches and self-healing evaluation mechanisms [86], [87], [88] applied to ice storm disasters could be investigated.

b: INNOVATIVE TECHNOLOGIES

On the planning side, one of the main challenges is to find long-term and cost-effective solutions and technologies that can be used during normal and extreme system conditions to justify high investment costs. Anti-icing devices and materials, for example, have none or limited application during business-as-usual conditions. On the other hand, DERs can be leveraged during normal and extreme conditions. Furthermore, short-term planning models should be developed to investigate the optimal pre-positioning of mobile power generation and energy storage systems along with power grid reconfiguration strategies to increase the resilience of the system during ice storms. On the operation side, new de-icing technologies are needed to reduce human labor and the reliance on transportation networks in remote areas and hard-to-reach power lines. The use of ice-melting drones is an important step in this direction.

c: INNOVATIVE REGULATORY PARADIGMS

Addressing the technical challenges discussed above will require regulatory reforms across different jurisdictions. On the planning side, this includes policies and incentives aimed to ensure increased resilience across power generation, transmission, and distribution while justifying infrastructure planning and upgrading investments. Such regulatory mechanisms, however, should work in coordination with existing local and global decarbonization goals, strategic plans of utilities and system operators, and power capacity markets. Moreover, they should consider key geographical, social, and economic factors and their impacts during various ice storm scenarios and other extreme events. On the operation side, new regulatory mechanisms are needed to ensure increased power system flexibility and decentralization. In the event of an ice storm, demand response and DERs could be used to support de-icing of hard-to-reach power lines and facilitate system restoration. However, resilience-oriented market mechanisms are needed to properly compensate DER owners for grid services during extreme events. Therefore, innovative regulatory mechanisms should be designed to meet regional needs as well as to support multi-regional goals. This process, however, requires concerted efforts and coordination among different stakeholders.

d: COST-BENEFIT ANALYSIS

The majority of the works discussed in this paper focused solely on the technical aspects of the planning and operation mechanisms against ice storm risks. However, understanding the viability and the cost-effectiveness of each solution is paramount to inform better decisions in the short and long term. This is particularly important for long-term planning models, where capital investment costs in specific technologies may be too high for some system operators with limited resources, especially in rural areas. Cost-benefit analysis should also be conducted while proposing new planning or operation strategies. Economic factors such as capital investment costs, operation costs, and labor costs should be properly considered in the analysis.

C. OPPORTUNITIES

a: ACTIVE DISTRIBUTION NETWORKS

With the increasing grid integration of DERs, including DG, energy storage systems, and electric vehicles, there are many opportunities to use these resources for resilient enhancement of distribution networks against ice storms and other severe weather events. Opportunities in this area include the development of resilience assessment models for active distribution networks with multiple DERs, analysis on the performance of microgrids and virtual power plants to reduce load shedding and facilitate service restoration during ice storms, investments in power distribution sensing, monitoring, and control technologies, and the use of DERs and demand response mechanisms, in place of new and costly infrastructure upgrades.

b: NEW TECHNICAL STANDARDS AND RESILIENCE METRICS

With the increasing research on the impacts of ice storms on power system infrastructure, there are opportunities for new technical standards focused on power system resilience assessment, planning, and operation considering the various impacts of ice storms. The works in [27], [28], and [29] recently proposed complementary methods to IEC 60826:2003 for estimating combined wind and ice loads on overhead transmission lines considering multiple attributes. In February of 2023, FERC approved two new reliability standards filed by the North American Electric Reliability Corporation (NREC) for extreme cold weather to implement recommendations following the winter storm Uri in Texas. However, they focus on emergency operations (EOP-011-3) [89] and preparedness (EOP-012-1) [90] with a main emphasis on fuel supply and generation issues, without providing specific recommendations for mitigating the impacts of ice storms on power lines. Additionally, there has been a growing interest in the development of quantitative resilience metrics that can capture all phases of the resilience trapezoid in Fig. 3. Recent efforts in this direction were proposed in [3] and [91] and [92], which did not consider the specific impacts of ice storms. Therefore, future works can be conducted to analyze and develop power system resilience metrics applied to ice storms.

c: MULTI-HAZARD MITIGATION PLANNING AND ANALYSIS

Power systems in many regions are subjected to multi-hazard risks.

The Pacific Northwest region in North America, for example, has experienced severe ice storm events during the winter and severe wildfires during the summer. However, the majority of the existing resilience-oriented planning and operation mechanisms in power systems have focused solely on one type of severe weather event. Opportunities in this area include leveraging existing approaches that considered the impacts of wildfires, windstorms, heat waves, etc. for resilience enhancement against ice storms, and the development of multi-hazard mitigation planning and operation approaches. This is particularly important to justify long-term planning approaches that require high investment costs but provide multiple benefits.

V. CONCLUSION

Ice storms have posed several challenges to the resilient planning and operation of power systems in recent years. This paper comprehensively overviewed and classified the existing literature on power system resilience enhancement against ice storms, focusing on planning and operation mechanisms for utilities and power grid operators. Based on the existing literature, select challenges, needs, and opportunities for future research and development were presented and discussed. The main challenges identified in this paper include technical limitations in existing anti-icing and de-icing solutions and interdependencies within power systems and across other systems. The main needs include new long-term planning mechanisms, innovative technologies, regulatory paradigms, and cost-benefit analysis of existing approaches. Future opportunities include studies on active distribution networks for ice storm mitigation as well as new technical standards, resilience metrics, and multi-hazard approaches.

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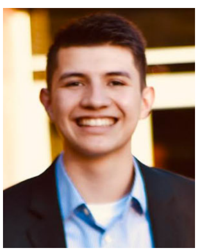

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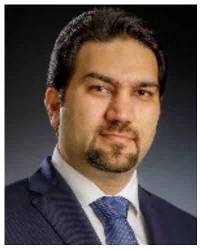

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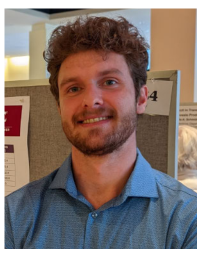

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