# Enhancing the Power System Resilience to Ice Storms

*Anahita Bahrami, Mingyu Yan, Mohammad Shahidehpour, Shikhar Pandey, Deepak Tiwari, and Honghao Zheng*

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***Abstract*—This paper proposes an improved resilience enhancement plan (REP) for power distribution and transmission networks against ice storms that would de-ice the ice-covered lines in a timely manner and maintain the infrastructure reliability and security. REP is a comprehensive solution which is adaptable for both transmission and distribution networks as each encounters its own unique constraints during ice storms. Depending on the voltage level, the REP for power transmission lines includes fixed DC de-icing devices (FDID) and mobile DC de-icing devices (MDID). The power distribution REP presents the optimal coordination of power system schedules with the preposition and routing of mobile DC de-icing vehicles (MDIV) and portable DC de-icing devices (PDID) to reduce ice related outages. The proposed REP framework coordinates de-icing schedule (DIS), power system flows on congested lines, and transportation flows on congested roads to maximize the power system resilience in an ice storm.**

***Index Terms*—Ice storm, power distribution system, transmission grid resilience, mobile de-icing vehicle, portable de-icing devices**

## I. Introduction

The threat of ice storms has consistently compromised the security of the power grid as well as the lives of individuals affected by these extreme weather events in the past few decades [1]. Many transmission and distribution networks remain overhead across the United States leaving these networks vulnerable to severe weather effects including ice storms [2]. Heavy ice accretions covering transmission and distribution lines could cause major damage to power system infrastructure and potentially result in blackouts [3]-[4]. Just 6-7 millimeters of ice accumulation can add hundreds of pounds of weight per line span and easily bend and damage power system infrastructure as shown in Fig. 1.

To enhance the power system resilience against ice storms, it is essential to pre-position necessary resources and adjust the power system operation quickly in order to mitigate damages caused by rapid ice collections on transmission and distribution networks. De-icing the ice-covered lines, which can save transmission and distribution grid in ice storms, is one of the most efficient ways of enhancing the power system resilience in such cases [5]. In general, there are two types of de-icing methods for power lines: mechanical and thermal.

Mechanical methods refer to all methods utilized to physically break the ice to remove the accumulated ice on power lines. Mechanical methods are generally based on two approaches, the first one directly breaks the ice accretion by scraping the ice, and the second approach utilizes the energy released by shock waves, vibrations, or twisting of the line. Manual scrapers are one of the most common mechanical methods used in the industry for transmission lines. Transmission de-icing techniques include blade-based and heat-based de-icing. The blade-based technique provided by the Hydro-Quebec's Research Institute uses the teleoperated trolley equipped with blades to de-ice ice-covered lines [6]-[7]. This trolley can generate a high traction force to shear the ice by blades. The accuracy of this device, which is exposed to a mixture of water and ice at extremely low temperatures, could be impacted by extreme working conditions, resulting in permanent damages to transmission lines.

Fig. 1. Damaged tower during an ice storm

Mechanical distribution network de-icing methods including electromagnetic pulse de-icing, sliding shovel scraping, artificial de-icing, dithering, tapping, and impacting. In these methods, contact with an insulated pole disturbs the icing balance and breaks the physical structure of the accumulated ice on the conductors, and the conductor is then able to shake the ice off after several attempts. In addition to being labor-intensive, these methods have high material damage risks [8]-[9]. Though mechanical method is labor-intensive, it is preferred for de-icing critical short sections of power networks that need to be de-iced quickly. However, many electric utilities recommend and prefer thermal de-icing methods due to their ability to de-ice longer lines. Some of these methods are suitable for overhead power lines, while others are suitable for ground wires (GW).

The Joule heating effect, short-circuit de-icing, DC de-icing, and on-load de-icing are some of the thermal de-icing

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techniques. Thermal methods require around 100 times more energy than mechanical methods. These methods have drawbacks ranging from large reactive power requirements, service interruptions, and investment in expensive de-icing devices. Among all, DC de-icing method is currently the most economic and reliable method to be applied in the real world. DC de-icing is suitable for both transmission and distribution networks but requires specific equipment for each. DC de-icing method generates heat by providing a large DC current and has the following advantages:

- *Easy to control the generated heat accurately.* The most important issue in de-icing is to control the generated heat accurately. If the generated heat is insufficient, the ice cannot be removed. If the generated heat is excessive, the heat could damage the line. However, it is feasible to control the heat accurately by using the DC de-icing method since we control the DC current by electronic converters, which is easy to achieve in practice.
- *Cheap.* The de-icing device only requires power electronic converters to convert AC power into DC current. Therefore, this device can use some cheap and mature power electronic converters.
- *Scalable.* The device can easily adjust the current value for power lines with different voltage levels. Therefore, one device can be used for different voltage levels (e.g., 30 kV–110 kV).
- *Mobile.* The DC de-icing device is small and can be mounted on trucks. One truck can be routed to de-ice different lines, which saves on the investment cost for de-icing devices.

On the other hand, the line is on outage while being de-iced in this method which can create some challenges and require planning on the operation side. These method's drawbacks are:

- *Low energy efficiency.* The generated heat by DC current covers the entire line. However, the ice only sticks to the line surface. The heat generated in the center of the line cannot be directly used to melt the ice and is partly wasted.
- *Outage.* The line is on outage while being de-iced, which could result in the power interruption.

This paper presents one of the most effective and safe thermal de-icing methods for both transmission and distribution networks as well as a resilience enhancement plan (REP) to ensure the security of the distribution power lines in ice storms.

## II. Power Transmission System DC De-Icing

The DC deicer-based method can adjust DC currents to de-ice different types of transmission lines. These devices are categorized into fixed de-icing devices (FDID) [10] and mobile DC de-icing devices (MDIDs) for transmission lines [11]-[12]. Different from fixed de-icing devices, which are installed on certain lines, MDIDs are considered a versatile option which can be routed in real time to de-ice various transmission lines in critical geographic locations.

### A. Fixed De-Icing for Extra -High Voltage Line

The conventional DC de-icing devices utilize three-phase thyristor rectifier, which could generate large harmonics and damage expensive transformers. Accordingly, large filters were added to de-icing devices, which would require additional space and increase the cost of de-icing. Here, Fig. 2 presents the proposed de-icing rectifier with 12 pulse DC de-icing transformers, the harmonic magnetic potential internal offset is utilized in the rectifier transformer, which can reduce the harmonic by 95%. Furthermore, a continuous coil winding method with multi-conductor pairs is provided, which can reduce the heat generated by the transformer by 30%. The proposed rectifier meets the GB/T14549 standards. Using this method, the required space and the investment cost are reduced significantly. By paralleling the proposed two rectifiers, the fixed de-icing device for the extra-high voltage (i.e., 500 kV) line is obtained.

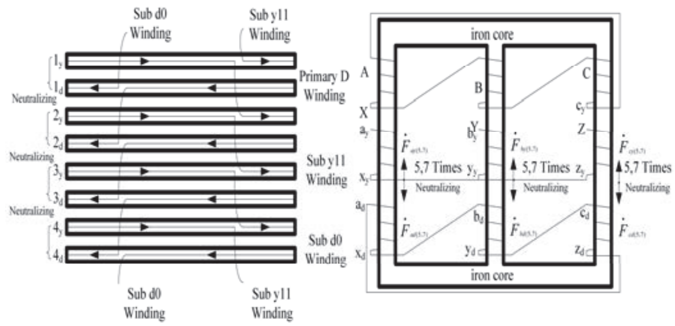


Fig. 2. Rectifier Transformer with 12-pulse

### B. Mobile De-Icing Device (MDID)

The fixed de-icing device shown in Fig. 2 is permanently installed on a transmission line which cannot be routed to de-ice other ice-covered lines. This strategy is deemed expensive, which is utilized for critical extra-high voltage transmission lines. MDID, which can be routed to de-ice several lines, would guarantee the power transmission network security and economics simultaneously. The MDID topology in Fig. 3 consists of a mobile grounding system, mobile de-icing system, and mobile transportation system.

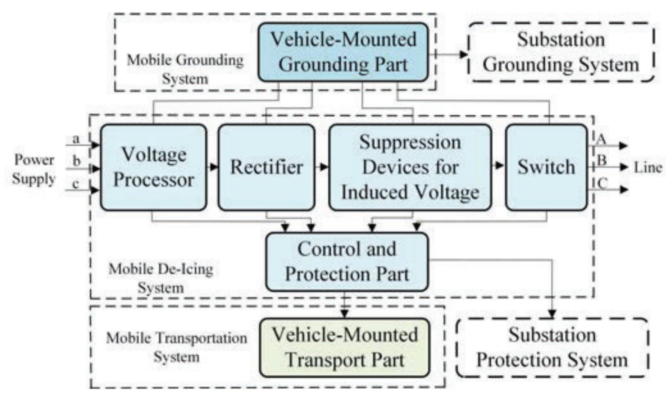


Fig. 3. Topology of MDID

The topology of rectifier is the same as that in the fixed de-icing device. MDID should be first delivered to the corresponding de-icing depot or substation, where the local transformer provides the power to MDID. Once the vehicle-mounted grounding and the control-protection elements of MDID are connected to the respective substation grounding and protection systems, the MDID generates the DC current for de-icing of power transmission line.

## III. Power Distribution System DC De-Icing

The distribution lines suffering from the ice storm can remain in service while covered with ice accretion. However, the lines

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could be damaged if the thickness of ice exceeds a designed threshold. De-icing removes the ice accretion and thus enhances the grid security. However, a line will be on outage during the de-icing period [13]. Not all de-icing methods are suitable for power distribution networks. However, thermal de-icing is favored due to the provision of less invasive solutions for a power distribution network with a large number of branches. Thermal de-icing in a power distribution network is divided into AC and DC de-icing methods. In transmission lines, the reactance is larger than the resistance and AC de-icing techniques are deemed more advantageous. Whereas DC ice-melting is ideal for distribution lines. Thermal de-icing devices are designed as mobile and portable based on distribution network voltage characteristics. Mobile thermal de-icing devices would require a mobile generator which could limit the melting flexibility and efficiency. However, the efficiency can be improved by using the DC de-icing method. A portable DC thermal de-icing device with its small size and flexibility, which could also be mounted on mobile systems, is more suitable for hard-to-access regions in power distribution network.

### A. *Mobile De-Icing Vehicle (MDIV)*

Since power distribution lines are shorter in length, a mobile device is used to perform the de-icing function. A mobile de-icing vehicle (MDIV) is a truck-mounted converter, shown in Fig. 4, which is employed around the world and can be routed to de-ice several lines before and during ice storms.

Fig. 4. Mobile de-icing vehicle (MDIV)

The DC de-icing process of MDIV is carried out by converting the AC power to DC current to perform the de-icing process when the distribution voltage is relatively low, and the ice-melting distance is relatively short. Therefore, the heat-based DC de-icing device rectifies the power generated by the mobile power supply for de-icing of the power distribution network. Then the rectified DC voltage is applied to the three-phase circuit by grounding the three phases at the end of the line. The ice-melting current can be adjusted using the voltage of the vehicle-mounted power supply. MDIV can often melt the ice on 3-mile-long lines and is ideal for partial and complete de-icing of distribution network lines. Because the branch line is separated from the main line by a switch, the main line can keep the power supply and reduce the blackout range when melting the ice.

The difference between transmission and distribution MDIV is that the transmission version consumes a large sum of de-icing power, which requires de-icing depots equipped with transformers to be stationed at the substation for MDIV. In contrast, the distribution network MDIV uses smaller components which are more portable. The distribution network MDIV is equipped with a mobile generator which would not require de-icing transformers. MDIV is used for the transmission network (i.e., 220kV lines) and the distribution network (i.e., 110kV and lower voltage lines).

### B. *Portable De-Icing Devices (PDID)*

A portable DC de-icing device (PDID), shown in Fig. 5, is a small, lightweight de-icing device that can be easily moved around and used in areas of distribution system which are not easily accessible by MDIV. PDID's rectifier transforms the AC voltage generated by the portable generator into a DC current to melt the accumulated ice on the line. The only drawback of this compact PDID is its short ice-melting distance. Statistically, there is a higher chance of a pole collapse or a line breakage during an ice storm in the power distribution network. The economic loss caused by power outages resulting from a pole collapse or a line breakage during an ice storm and the emergency repair and recovery are considerable. However, the investment cost of a distribution network de-icing system to mitigate possible disruptions caused by ice storms is much less in comparison. The portable de-icing system has significant economic and social benefits and can ensure the distribution network resilience in winter.

Fig. 5. Portable de-icing device (PDID)

## IV. Resilience Enhancement Plan (REP)

Ice storm forecast and monitoring which can be done through long-, mid-, and short-term ice storm forecasts, and real time ice-thickness monitoring are instrumental in the operation planning of power systems. Furthermore, ensuring the resilience of the power system during an ice storm necessitates a real-time operation planning strategy to minimize the effects of the storm on the transmission and distribution systems. The resilience enhancement plan (REP) considered in this article, and depicted in Fig. 6, includes four components, i.e., de-icing schedule (DIS), MDIV routing for power distribution system, transportation system operation, and distribution system operation. Each element of REP strategy will be discussed in the following.

When the ice thickness exceeds a given threshold, the distribution system outage probability will increase, and its

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reliability will decrease. De-icing scheduling (DIS) determines the de-icing period to restrict the ice thickness accumulated on power lines during an ice storm and is the practice of placing MDIVs in proper de-icing depots. De-icing an ice-covered line is comprised of multiple steps from removing the line out of service, installing the MDIV and shorting stub, de-icing the power line, uninstalling the MDIV and shorting stub, and finally switching the line into service and each step takes considerable amount of time that needs to be taken into account during DIS.

MDIV routing is the process of routing mobile devices to proper de-icing locations for removing the ice from power distribution lines before the ice thickness reaches the threshold level. This threshold is determined by power system operators and the REP involves employing one of the de-icing techniques mentioned in the previous section. REP is one of the components of a de-icing strategy proposed by [14] and illustrated in Fig. 7.

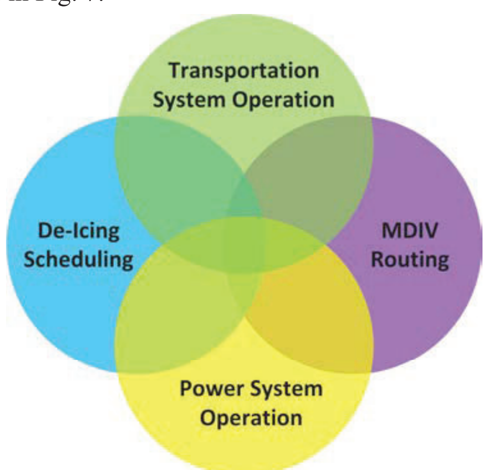


Fig. 6. Resilience Enhancement Plan (REP) Framework

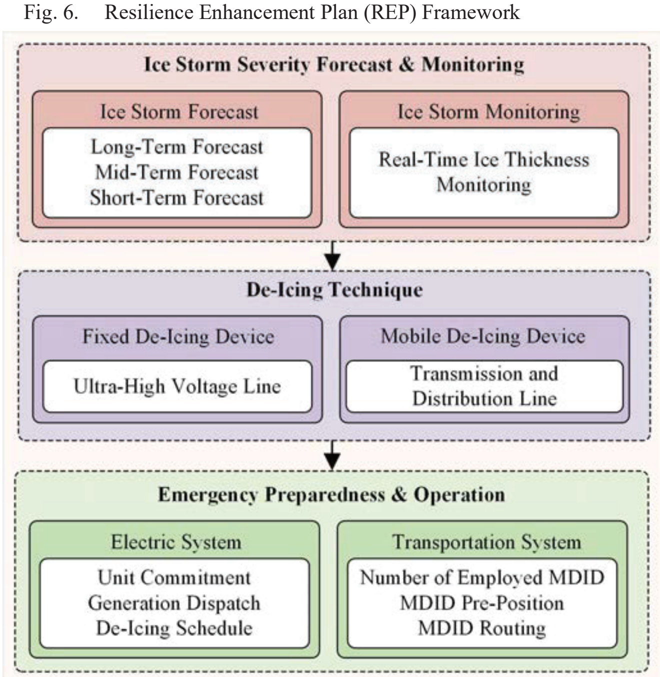


Fig. 7. Proposed de-icing method for resilience enhancement strategy

Coordinating DIS, MDIV routing, and transportation systems which are components of the proposed REP strategy for distribution lines ensure the power network security during ice storms. Transportation system plays an important role as the majority of the de-icing of the ice-covered power network is done through utilizing MDIVs for distribution lines. Fig. 8 illustrates the REP during an ice storm, where the de-icing process will only take a fraction of the DIS time. Most of the DIS time is spend on commuting to the de-icing location and setting up the de-icing device. Therefore, it is crucial to incorporate transportation systems in the REP strategy especially for de-icing power distribution network lines during an ice storm.

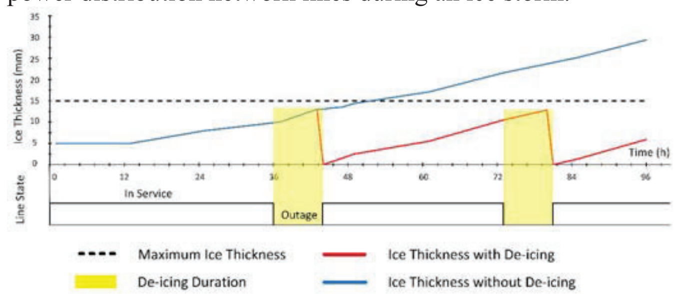


Fig. 8. Power line with and without de-icing during an ice storm

The REP for a power distribution network is often more time-consuming and complicated than that of a transmission system due to the vast number of overhead lines in a power distribution network. Therefore, the power distribution resilience before, during, and after ice storms can be enhanced by the MDIV scheduling and routing on local roads. The resilience enhancement framework for power distribution systems consists of a coordinated model of MDIV placement in a depot and routing on a transportation network when an ice storm strikes. Accordingly, transportation congestion and capacity would need to be considered when applying DIS to a power distribution system.

To reduce the MDIV's commuting time on congested roads, we apply the following considerations and requirements:

1. Apply a REP model that coordinates MDIV placement and routing with an urban transportation network to maintain the power distribution network resilience during ice storms. The urban transportation network operation optimizes the MDIV routing by considering road congestion and transportation flow distribution. The power system operations consist of the distribution network reconfiguration and distributed energy resource (DER) dispatch.
2. MDIV is considered an emergency vehicle and all other vehicles would yield the right-of-way to reduce MDIV's commuting time. The coordination of the MDIV routing with transportation system operation is considered in REP for enhancing the resilience of a power distribution system.
3. Power distribution and transportation networks are prone to damages caused by ice storms. The forecasting of uncertainties pertaining to weather changes and infrastructural limitations should be considered in the REP calculations to minimize their impacts on the resilience of the coordinated power distribution and transportation systems.

Fig. 9 illustrates the MDIV routing from a depot to a de-icing location. When the MDIV reaches the de-icing location, equipment operators remove the designated distribution line out of service, install MDIV to de-ice the distribution line, uninstall MDIV or PDID once the job is done, switch the de-iced line back into service, and drive MDIV or PDID to the next de-icing location. The de-icing process will take approximately 4 hours, which depends on the ice thickness and the de-icing current.

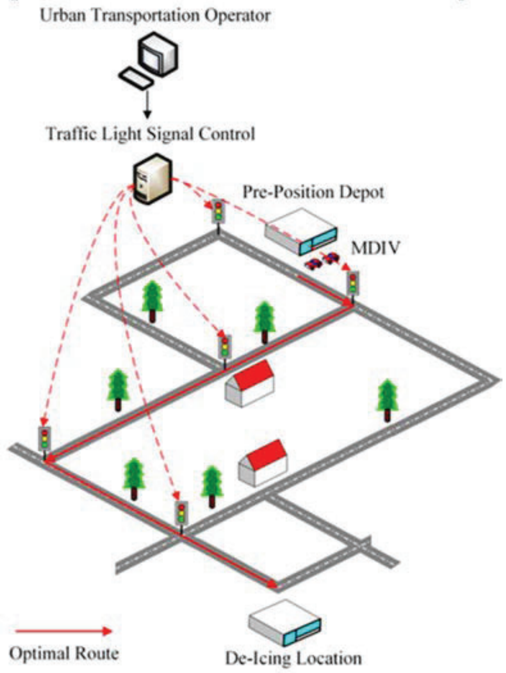


Fig. 9. Optimal traffic control for managing the flow of MDIDs during an ice storm

In practice, when the ice thickness exceeds a given threshold, the distribution system outage probability will increase, which could have a major impact on the grid reliability. DIS determines the de-icing period to restrict the ice thickness accumulated on power distribution lines during an ice storm and places MDIVs in proper de-icing depots. Accordingly, MDIVs will be routed through congested roads to remove the ice from power distribution lines before the ice thickness reaches the threshold. The de-icing technique employed for REP depends on the size and the location of the designated power line and the weather condition in an ice storm. Once the de-icing is completed in a de-icing depot, an MDIV is routed to other de-icing locations using local congested roads in the transportation system. The exclusion of transportation system constraints might result in an infeasible REP schedule. In other words, MDIV might not reach the designated de-icing locations on time if the transportation congestion is ignored in the REP scheduling. This is because ice storms could result in severe traffic congestion in a transportation system, which could also increase the MDIV commuting time significantly.

## V. Conclusion

The use of de-icing devices can enhance the security, resiliency, and reliability of power distribution networks against ice storms. This paper introduces a REP strategy for power system operations in ice storms by routing MDIDs in coordination with transportation networks to reinforce the power network operation in ice storms. The REP coordinates DIS, MDIV routing, power distribution and transportation networks to schedule the MDIV pre-positioning and dispatch in real time. It is demonstrated that REP decreases energy supply interruptions and offers the power system a chance to absorb, adapt, and recover from ice storms while considering all infrastructure dependencies of power and transportation networks. It is envisioned that REP supports social welfare by sustaining the power grid credibility and security and supplying customer loads during extreme weather conditions. Future work will focus on the outage prediction and planning and operation strategies for power systems under ice storms.

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