Preventive Dispatch for Transmission De-icing

Fatemehalsadat Jafarishiadeh, *Student Member, IEEE*, Farshad Mohammadi, *Student Member, IEEE*
and Mostafa Sahraei-Ardakani, *Member, IEEE*

***Abstract*--This letter introduces a novel approach to prevent ice formation on transmission lines during ice storms. First, weather forecast is used to calculate minimum currents needed to raise the conductor temperature above the freezing point. Then, a preventive unit commitment model is developed to enforce those minimum limits. Simulation studies are conducted on the three-area RTS-96 system. The results confirm the effectiveness of the developed model in preventing ice formation, through adjustment of generation dispatch and slightly increasing the cost. Limitations of the work are also discussed.**

***Index Terms*—De-icing, power system reliability, power system resiliency, preventive unit commitment, thermal capacity, transmission system.**

I. INTRODUCTION

THE accretion of ice on transmission lines threatens the security of power systems and usually leads to high repair expenses. Temperatures between -10 °C to 0 °C accompanied by wind speed of up to 20 m/s, provide the conditions that would allow glaze to form around transmission lines [1]-[2]. The ice coat adds extra weight to the transmission lines, beyond the tolerance calculated for the infrastructure used in low altitude transmission systems. Currently, mechanical and electrical deicing approaches are implemented to resolve this issue [3]. The mechanical de-icing methods use high traction force to break the ice accumulated on the lines and the electrical solutions are based on the Joule effect to mitigate the consequences of ice storms [4] - [6]. These techniques are applied to lines that have already been iced over. A preventive de-icing method has been introduced in [7] that utilizes sequential line outages to increase the current on remaining lines and melt the ice. The voltage impacts, as well as the inherent power flow control capabilities of transmission switching may limit the applicability of this method.

This letter develops a preventive method that emphasizes the role of available weather forecast information in power dispatch calculations, before and during an ice storm. The developed method adds lower flow constraints to the operation model to prevent the drop of temperature in the immediate surrounding of the line below a specified level and avert the probability of ice formation. In the remainder of the letter, the conditions that results in ice formation on the lines is specified in section II. The lower boundary for the line flow is calculated in section III, and in section IV, the proposed methodology is applied to the IEEE three-area RTS-96 system.

II. ICE ACCRETION DEVELOPMENT

The ice accretion on power lines can be due to the precipitation icing or in-cloud icing. Precipitation icing occurs as glaze, wet snow or dry snow. Dry snow does not pose a threat as it occurs when wind speeds are sufficiently low, and its density is less than 100 kg/m^3, which results in a mass that is much lower than the power line's limit. On the other hand, the higher density of glaze (700 to 900 kg/m^3) and wet snow (400 to 600 kg/m^3) can cause damage. These phenomena occur when the temperature is between -10 ℃ and 0 ℃ for glaze and between 0 ℃ and 3 ℃ for wet snow. In-could icing most often develops near the top of exposed mountains and can manifest as soft or hard rimes depending on the size of the droplets, temperature and the wind speed. Soft rime and hard rime with density of 600 to 800 kg/m^3, and 200 to 600 kg/m^3 appear when the temperature is between -10 ℃ and 1 ℃ and -20 ℃ and 1 ℃, respectively [9]. It should be noted that the transmission infrastructure utilized in high altitudes are designed to better withstand the hard rime ice formation. In lower altitudes the hard rime formation probability is rather low and, thus, not a major concern in ice storms.

The defining parameters in precipitation icing are precipitation rate, surface air temperature, liquid water content of snowflakes, wind speed, wind direction, air temperature, relative humidity and visibility. As each icing event can be a mixture of different icing types, we focus on the situations that the possibility of glaze formation is higher. Strong adhesion quality of glaze creates a surface for the snow and ice to collect on, while isolating the line and preventing further heat transfer. The severity of these conditions also stems from their duration, typically lasting more than a day. These events put the transmission system at risk.

In all these events, our objective is to prevent water droplets from freezing on transmission lines, which is achieved by keeping the surface temperature of the lines above the freezing point. The temperature on the power lines is a function of the physical properties of the conductor, its current and the cumulative influence of the ambient temperature, wind speed, and the air's water content [8]. Thus, the low current carrying transmission lines are the lines that are vulnerable to glaze formation during freezing rain conditions. The proposed methodology is used to find the minimum heat that should be produced in the lines that

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Fatemeh Jafarishiadeh, Farshad Mohammadi, and Mostafa Sahraei-Ardakani are with the Department of Electrical and Computer Engineering, University of Utah, Salt Lake City, UT, USA (e-mails: Fatemeh.jafarishiadeh@utah.edu, farshad.mohammadi@utah.edu, mostafa.ardakani@utah.edu.)

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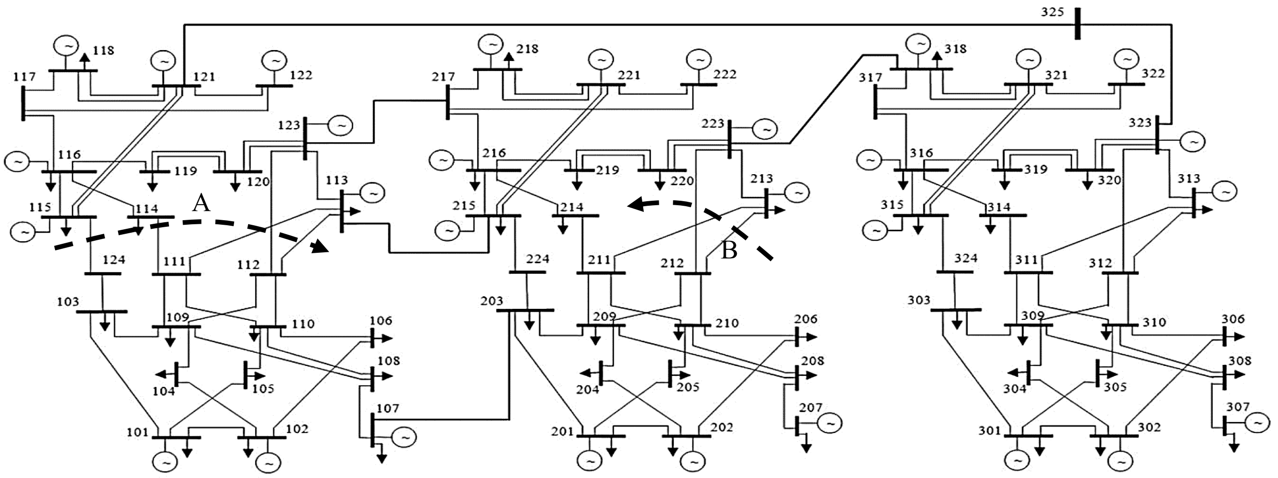

Fig. 1. Ice storm paths: A and B

are likely to be affected by the ice storm, to prevent the ice formation.

III. Methodology

The mechanism of ice forming on the transmission lines can be described as the insufficient heat exchange between the wire surface and the environment. Out of the factors that determine the surface temperature of the transmission lines, line current is the only feature that can be controlled. Accordingly, in the proposed method, the heat generated by the current is used to keep the line surface free of ice. The main idea is to control the line currents to keep the target lines from freezing through adjusting the generation dispatch.

A. Heat exchange formulation

The ice storm weather conditions typically last for a few hours to days. During the predicted hours, the severity of the conditions may change. Assuming the most critical combination of the temperature and wind speed is to last for the entire duration of the operation, the required heat is calculated using the steady-state heat balance formula discussed in [8]. In this formula, the heat is obtained by the line current (*I*) and solar energy (q_s) and transmitted to its surrounding air via the convection (q_c) and radiation (q_r).

$$q_c + q_r = I^2 \cdot R(T_{avg}) + q_s, \qquad (1)$$

In the ice storm conditions, there is no solar heat gain. Thus, the heat balance formula can be written as:

$$q_c + q_r = I^2 \cdot R(T_{avg}), \qquad (2)$$

where, T_{avg} is the average temperature of the aluminum strand layers in Celsius, $R(T_{avg})$ is the AC resistance of the conductor at temperature T_{avg}.

Convective heat loss in the windy environment is forced convection and is calculated using (3). The radiation heat loss is characterized in (4),

$$q_c = K_{angle} \cdot 0.754 \cdot N_{Re}^{0.6} \cdot k_f \cdot (T_s - T_a), \qquad (3)$$

$$q_r = 17.8 \cdot D_0 \cdot \varepsilon \cdot \left[\left(\frac{T_s + 273}{100}\right)^4 - \left(\frac{T_a + 273}{100}\right)^4\right], \qquad (4)$$

where the temperature on the surface of the wire and the ambient temperature are T_s and T_a, respectively. The average temperature of the boundary layer is denoted by $T_{film} = \frac{T_s + T_a}{2}$. The wind direction factor is K_{angle}, N_{Re} is Reynold's number and k_f is the thermal conductivity of air at temperature T_{film}. The radiated heat loss mainly depends on the difference between the temperature of the conductor and its environment. The emissivity of the conductor (ε) and its diameter (D_0) also impact the radiative heat transfer.

B. Lower power limit implementation

Based on the predicted weather forecast and using (2-4), the minimum power flow required to prevent ice formation on the transmission lines (f^{ICE}) is calculated. The subsequent minimum thermal capacity constraints can be added to the operation models. In practice, the method should be integrated in both day-ahead security-constrained unit commitment (SCUC) and real-time security-constrained economic dispatch (SCED). Day-ahead weather and load forecast would help SCUC to find a preventive day-ahead schedule. The real-time SCED would, then, use the updated weather and load forecast to adjust the dispatch if necessary. In this letter, to show the merits of the developed method, the altered constraints are only added to the day ahead SCUC, using the day-ahead weather and load forecast [10]-[11]. In the normal conditions, power flow is limited between zero and the line's maximum thermal capacity. The direction of power flowing in the lines is determined by the positive and negative signs allocated to the power flow values, derived from solving the unit commitment problem. Thus, the power flow limits are typically modeled as a constraint, bounding the flow between negative and positive thermal capacity of that line:

$$-f_{ij}^{max} \leq f_{ij} \leq f_{ij}^{max}. \qquad (4)$$

However, by adding the new lower power flow limit, the inequality is converted into two separate inequalities for the positive and negative power flows, respectively:

$$f_{ij}^{ICE} \leq f_{ij} \leq f_{ij}^{max}, \qquad (5)$$

$$-f_{ij}^{max} \leq f_{ij} \leq -f_{ij}^{ICE}. \qquad (6)$$

As either (5) or (6) should be satisfied, the modeling

TABLE I
AFFECTED LINES IN EACH PATH AND THEIR MINIMUM POWER FLOW

	From bus	To bus	Line	f^{ICE} (T_a =-16 °C, T_s = 2 °C, V_w = 10 m/s)	f^{ICE} (T_a =-8 °C, T_s = 2 °C, V_w = 16 m/s)
Path A	111	113	19	106.78	78.09
	111	114	20	93.83	68.56
	112	113	21	106.78	78.02
	112	123	22	216.79	158.40
	115	124	29	116.48	85.11
Path B	211	213	59	147.15	107.41
	212	213	61	148.17	108.15
	212	223	62	289.54	211.36

approach adds a non-convex and discontinuous constraint to the problem. One way of modeling this disjunctive constraint is through a mixed-integer formulation as shown in (7)-(8):

$$f_{ij}^{ICE} - (1-z)M \le f_{ij} \le f_{ij}^{max} + (1-z)M, \qquad (7)$$

$$-f_{ij}^{max} - zM \le f_{ij} \le -f_{ij}^{ICE} + zM, \qquad (8)$$

where, if the power flowing on the line is positive, z takes a value of 1, and for negative power flow, z takes 0. Additionally, M is a sufficiently large positive number that voids one of the constraints, depending on the value of z.

It should be noted that long transmission lines may span an extended geographical area. In such cases, different segments of the line may experience rather different weather conditions. For these lines, the minimum flow requirement should be calculated separately for each segment of the line [12]. The line's minimum flow requirement will, then, be the maximum of these minimum flow values. Additionally, to prevent thermal limit violations, if the line's minimum flow requirement is larger than the line's thermal capacity, and some of the line segments are not affected by the ice storm, the maximum thermal flow limit of the line should not be changed. In case the minimum flow requirement exceeds the line's thermal capacity, the presented method alone will not be able to prevent ice formation. The method may still be able to alleviate the problem, but other tools and techniques will be required to either prevent the ice formation or deice the system after the storm.

IV. SIMULATION STUDIES

The developed preventive de-icing method was applied to the IEEE three-area RTS-96 system and the simulation studies were performed using ECLIPSE IDE 4.13 and IBM CPLEX 12.8. Various ice storm conditions, considering different combinations of temperature and wind speed (V_w), were tested on the system, to explore the limitations of the developed method. Two main scenarios, depicting the role of changes in ambient temperature and wind speed on the lower power flow limit, were chosen. In the first scenario, the ambient temperature, the surface temperature, and wind speed are set to -16 °C, 2 °C, and 10 m/s, respectively. In the second scenario, the ambient temperature and wind speed are increased to -8 °C and 16 m/s and the surface temperature is kept at 2 °C. As ice storms often only affect a part of the system, in these scenarios, the number of transmission lines impacted by the ice storm is considered to be limited. Two separate areas were selected as the regions affected by the ice storm. These areas are labeled as A and B in the Fig. 1, consisting of 5 and 3 lines respectively. The minimum power flow for each specified line is shown in Table I, that would prevent ice formation.

TABLE II
COST ASSOCIATED WITH IMPOSING THE MINIMUM POWER FLOW LIMITS IN DIFFERENT SCENARIOS

Scenario	Cost ($ million/day)
Original	2.43
T_a =-16°C, T_s = 2°C, V_w = 10 m/s, Path A	2.69
T_a =-8°C, T_s = 2°C, V_w = 16 m/s, Path A	2.49
T_a =-16°C, T_s = 2°C, V_w = 10 m/s, Path B	2.73
T_a =-8°C, T_s = 2°C, V_w = 16 m/s, Path B	2.49

By imposing the added constraint, the power flow for the at-risk lines changes and would not drop below the calculated minimum limit. The altered power in lines generates sufficient heat that prevents the formation of ice on the lines. Fig. 2 presents the flows for path A in hour 1 of the unit commitment model. There are three bars for each line, from left to right representing the original power flow (without preventive dispatch), the lower thermal power limit, and the altered preventive power flow on the lines. In case of ice storm moving on path A, lines 19, 20, 21, 22 and 29 are the at-risk lines. For the ambient temperature of -16 °C and the wind speed of 10 m/s, in hour 1, the power flow for lines 19 and 21 are sufficient and more than the calculated lower limit. On the other hand, the power flow on lines 20, 22 and 29 is not enough to keep the lines from freezing over. Adding the lower flow limit constraints to the unit commitment model, alleviates the situation, and the power flow on all the at-risk lines is increased above the limits as shown in Fig. 2.

Altering power flow to avoid the repair costs, is achieved through changing the dispatch, which changes the overall system operating costs. Table II presents the operation costs, calculated for each scenario. The dispatch cost, ensuring that the surface temperature of lines in path A will remain over 2 °C for 24 hours, in the first scenario with ambient temperature of -16 °C and wind speed of 10 m/s, is $2.7 million/day, a %10 increase compared to the original unit commitment cost. Although the overall cost has increased, the tradeoff between the increased cost and the averted repair expenses should be considered. The economic loss of the 2008 ice storm in China was more than $20 billion dollars, which was triggered by the damages inflicted to the power system. This economic loss is clearly much larger than any added operation cost as a result of a preventive redispatch. Moreover, the reliability consequences of damaged transmission lines can be severe.

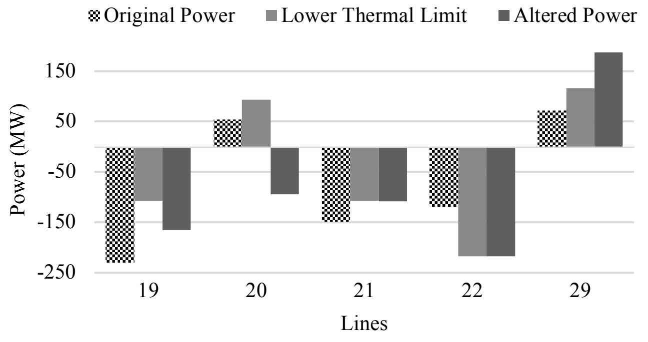

Fig. 2. Power flow on lines 19, 20, 21, 22 and 29 in path A, in hour 1 (T_a =-16 °C, T_s = 2 °C, V_w= 10 m/s)

V. Conclusions and Discussion

A preventive de-icing method for transmission lines based on the Joule effect was developed. The developed method calculates minimum flow limits for the lines in the ice storm region to prevent the formation of ice. The constraints are then added to the operation models through a mixed integer formulation. The simulation results presented in the letter show that the method may be effective during certain ice storms. There are, however, limitations to the application of the developed model. The nonconvex preventive flow limits, presented in the letter, may lead to infeasibility in the problem. This will become more likely if a large number of lines are affected or when the ambient conditions are harsh. In our simulation studies, the unit commitment problem was infeasible for ambient temperature of -16 °C and below combined with the wind speed of 16 m/s and above for both paths A and B. Further research is required to properly study the conditions, under which the developed method will show satisfactory performance.

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