Preventive Unit Commitment for Transmission Line De-icing in Changing Weather Conditions

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***Abstract*— This paper is centered on augmenting the power transmission system resiliency in changing ice storm weather conditions. This is facilitated by preventing glaze formation on transmission lines by keeping the surface temperature of lines above a pre-calculated level. The Joule effect is used to control the line surface temperature through power dispatch manipulation. The power flow in the transmission lines in the affected geographical area should be maintained above an hourly minimum limit to generate sufficient heat. The varying weather conditions necessitate the change in target transmission lines' lower flow limit. The proposed approach has been implemented on the IEEE 73 bus RTS-96 system, and the results confirm the effectiveness of the proposed method.**

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

I. Introduction

Ice storms are winter events that threaten the reliability of power transmission systems. These events occur when the temperature is below 0 °C and the wind speed is more than 1 m/s. These conditions usually last for more than a few hours. These circumstances lead to ice formation on transmission lines that further isolates the lines, creating an adhesive surface for the snow to accumulate on [1].

The research conducted on the ice formation on transmission lines shows that the adherence property of freezing rain and hard rime is high and can jeopardize the reliability of transmission systems in the ice storm conditions. In contrast, the adherence quality of wet snow and soft rime is negligible and as such rarely have harmful impacts on the overhead lines [2], [3]. The difference between hard rime and freezing rain is in the fact that occurrence of hard rime is due to in-cloud icing, but freezing rain happens as a result of precipitation icing. The in-cloud icing usually ensues in mountains and heights where the transmission infrastructure has been designed to withstand the inevitable formation of hard rime. Therefore, the probability of these events endangering transmission systems is low. On the other hand, the risk that the precipitation icing imposes on low altitude transmission lines is more significant as the added weight to the transmission lines is beyond the tolerance of the infrastructure [4].

Generally, this phenomenon is combated through mechanical or electrical de-icing methods which are implemented after the event. Warming up the transmission lines that have layers of ice over them through short circuit current, load current or direct current are among electrical de-icing methods [5], [6]. The electrical de-icing methods are based on the Joule effect, where the heat generated from the current is used to clear the lines and to mitigate the consequences of ice storms. In mechanical de-icing the traction force is used to break the ice and free the lines from the added weight [7], [8]. The after-event improved weather condition allows for these methods to be productive, in due course.

In [5], a strategy based on transmission switching is proposed to optimally de-ice high voltage lines. In this method, a sub-set of lines is chosen and the power flow is re-routed to the reduced set of lines to increase their power flow and melt the ice buildup over them. Dynamic programming is used to distinguish the sequential scenarios that results in minimum highest ice accretion instances after each time step. Accordingly, different scenarios for a 40-hour time window were created. In the base scenario, it is assumed that already there is an ice layer on the lines. The weather condition is described with 4.15 meters per second wind speed and temperature that sinusoidally oscillates between -8 ˚C and -2 ˚C. With 10 to 40 lines monitored, this method was successful in reducing the maximum thickness of ice layer in cases that have lower precipitation rates. However, in the remaining cases the time required to melt the ice buildup on the lines was up to 300 minutes which is more than time available and thus this strategy did not resolve the problem of de-icing the target lines. Note that generation dispatch was not adjusted in [5].

It should be noted that if the ice storm conditions are consistent over a few days, implementing the aforementioned de-icing methods may be too little too late. In these situations, the ice storm may have already inflicted severe damage to transmission lines and transmission towers. Similar incidents in Canada and China in 1998 and 2008, respectively, led to significant economic loss in the billions of dollars [9], [10]. As a result, waiting to de-ice the lines after the event, may prove to

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be very costly for power systems. To avoid such consequences, the impacts of ice storm on transmission system should be mitigated during the event. In [11], a preventive method is introduced that utilizes line outages to increase the current on remaining lines and as a result melt the ice. The selection of switched lines is based on the ranking AC contingencies. The method has been applied to a 23-bus system and one line has been chosen for switching. Since a small system has been selected, the consequences of outage of one line is more prominent. Thus, on the buses affected by increasing the power flow, voltage-drop is observed which may limit the applicability of method.

The process of ice formation on transmission lines can be associated with the relative heat exchange between the transmission lines and their surroundings. In winter, due to the reduced load in summer peaking systems, transmission lines often carry less power and generate less heat. The environmental conditions and the fact that these lines are more prone to glaze formation, due to reduced loading, become the propelling factor in ice storm events. In [12], a preventive de-icing method is implemented that emphasizes the role of available weather forecast information in power dispatch scheduling before an ice storm. The Joule effect was used to determine the heat required in the preventive de-icing where the wind speed and ambient temperature were assumed uniform through a 24-hour time window.

In this paper, a lower thermal rating constraint proportional to the actual hourly changing weather condition in an ice storm is added to the power flow constraints. The objective is to gauge the impact that extreme and changing temperature and wind speed have on the limits of this method; the number of lines that can be focused on to keep the temperature of the immediate surrounding of above a specified level and thus reduce the probability of ice formation on them. In section II, the mechanism of combating ice development on lines is explained in methodology. In section III, the lower boundary for the line's thermal capacity limit is calculated, and then the proposed methodology is applied to the IEEE 73 bus RTS 96 in section IV.

II. Methodology

In this paper, the main 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 [13]. Out of the factors that determine the surface temperature of the transmission lines, line current is the only feature that can be controlled.

The low current carrying transmission lines are the lines that are vulnerable to glaze formation during freezing rain conditions. 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 change the line current to keep the target lines from freezing by adjusting the generation dispatch. The proposed methodology is used to find the minimum heat that should be produced in the lines that are likely to be affected by the ice storm, to prevent the ice formation.

III. Heat Exchange Formulation

In normal operational conditions of power systems, unit commitment (UC) is used to determine the units that are to produce power and the production level of each of them for the forecasted demand. UC is an optimization problem with the objective of minimizing the total production cost subject to physical and operational constraints [14]. UC problem is solved for day-ahead market with an hourly resolution [15]. The cost function encompasses the cost of producing the power from generator g at the time t ($c_g(P_g(t))$), no-load cost, start-up cost and shut-down cost of generator g which are indicated by NL_g, SU_g and SD_g, respectively. Thus, the optimization problem can be written as:

$$Minimize \sum_t \sum_g c_g\left(P_g(t)\right) + u_g(t) \times NL_g + v_g(t) \times SU_g + w_g(t) \times SD_g \quad (1)$$

subject to:

$$u_g(t) \times P_g^{max}(t) \leq P_g(t) \leq P_g^{max} \times u_g(t) \quad (2)$$

$$-F_k^{max} \leq F_k(t) \leq F_k^{max} \quad (3)$$

$$F_k(t) = b_k \times (\theta_{k,to}(t) - \theta_{k,from}(t)) \quad (4)$$

$$\sum_{\forall k \in \delta(i)^+} F_k(t) - \sum_{\forall k \in \delta(i)^-} F_k(t) + \sum_{\forall g\ at\ bus\ i} P_g(t) = d_i(t) \quad (5)$$

$$u_{g,s} \geq u_g(t) - u_g(t-1), s \in \{t+1, \dots, t+UT_g - 1\} \quad (6)$$

$$1 - u_{g,s} \geq u_g(t-1) - u_g(t), s \in \{t+1, \dots, t + DT_g - 1\} \quad (7)$$

$$v_g(t) \geq u_g(t) - u_g(t-1) \quad (8)$$

$$0 \leq v_g(t) \leq 1 \quad (9)$$

$$w_g(t) \geq u_g(t-1) - u_g(t) \quad (10)$$

$$0 \leq w_g(t) \leq 1 \quad (11)$$

$$P_g(t) - P_g(t-1) \leq R_g^+ \times u_g(t-1) + R_g^{SU} \times \left(1 - u_g(t-1)\right), \quad (12)$$

$$P_g(t-1) - P_g(t) \leq R_g^- \times u_g(t) + R_g^{SD} \times \left(1 - u_g(t)\right), \quad (13)$$

where *d(t)* denotes the demand that is to be supplied, F_k stand for the flow in line k, while F_k^{max} is the maximum line flow rating. The set $\delta(i)^+$ consists of lines that are assumed to be transferring power to bus i and conversely, set $\delta(i)^-$ consists of lines that are to be transferring power from bus i. The set of generators at bus i is represented by $g(i)$. The susceptance of line is denoted by b. The maximum and minimum value for the capacity of generator g is expressed with P_g^{max} and P_g^{min}, respectively.

The thermal capacity of the lines is one of the transmission system constraints that are imposed. This constraint prevents over heating of lines and the subsequent damages that can ensue from overheating. To assure that the line temperature does not exceed its limits, (3) is enacted in UC for each line. As the power can be transferred in both directions, the formula limits power between the negative and positive maximum values.

The maximum current of the overhead transmission lines is limited by the temperature limit of the conductor. Assuming that the overhead transmission line is a uniform conductor, its temperature would follow the IEEE standard steady-state thermal balance equation [13]. A numerical method is introduced in this standard that connects the core and surface temperatures of a bare stranded overhead conductor to the current and weather conditions. It is assumed that there is no radial temperature variation in the lines and the lines have effective radial thermal conductivity.

In this formula, the heat is obtained by the line current (I) and solar energy (q_s) and transmitted to its surrounding air via convection (q_c) and radiation (q_r):

$$q_c + q_r = I^2 \times R(T_{avg}) + q_s, \tag{14}$$

Equation (14) can be used to determine the minimum flow in the line that can keep the surface temperature over the freezing point. There are changes that should be considered. In the ice storm conditions, there is no solar heat gain. Accordingly, the heat balance formula can be rewritten as:

$$q_c + q_r = I^2 \times R(T_{avg}), \tag{15}$$

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}. The resistance is calculated for the temperature over 0˚ C, but the change in the resistance for low temperature is very small and as such can be neglected.

There are two types of convective heat loss: natural convection and forced convection. In natural convection, the flow of power through the conductor heats up the conductor. Then, the cool air around the line absorbs the heat and rises and is replaced by cool air again. In case of forced convection, this process is sped up when blowing air carries the heated air away. It is obvious that the cooling power of natural convection is lower compared to forced convection. Convective heat loss in the ice storm condition is the forced convection and is calculated using (16).

$$q_c = K_{angle} \times 0.754 \times N_{Re}^{0.6} k_f \times (T_s - T_a), \tag{16}$$

Radiated heat loss happens when a bare overhead conductor is heated above the temperature of its surroundings. In this situation, the heat is transmitted by radiation to the atmosphere. The radiation heat loss is characterized in (17).

$$q_r = 17.8 \times D_0 \times \varepsilon \times \left[\left(\frac{T_s+273}{100}\right)^4 - \left(\frac{T_a+273}{100}\right)^4\right], \tag{17}$$

In (17), 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}. The wind direction factor is K_{angle}, where φ, is the angle between wind direction and the conductor's axis. N_{Re} is Reynold's number and k_f is the thermal conductivity of air at temperature T_{film}. Reynold's number is a dimensionless number that factors in the wind velocity (V_w), air density (ρ_f) and the kinematic viscosity of air (μ_f) in the temperature calculation. It is used to differentiate between laminar and turbulent flow and is calculated at the mean film temperature of the conductor's boundary layer. The air density is calculated based on the measurements at the elevation of conductor above sea level which is denoted by He.

$$N_{Re} = \frac{D_0 \times \rho_f \times V_w}{\mu_f}, \tag{18}$$

$$K_{angle} = 1.194 - \cos(\varphi) + 0.194 \times \cos(2\varphi) + 0.368 \times \sin(2\varphi), \tag{19}$$

$$k_f = 2.424 \times 10^{-2} + 7.447 \times 10^{-5} \times T_{film} - 4.407 \times 10^{-9} \times T_{film}^2, \tag{20}$$

$$\rho_f = \frac{1.293 - 1.525 \times 10^{-4} \times H_e}{1 + 0.00367 \times T_{film}} + \frac{6.379 \times 10^{-9} \times H_e^2}{1 + 0.00367 \times T_{film}}, \tag{21}$$

$$\mu_f = \frac{1.458 \times 10^{-6} (T_{film} + 273)^{1.5}}{T_{film} + 383.4}. \tag{22}$$

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.

As in the actual ice storms the wind speed and ambient temperature changes throughout the storm, the minimum power flow in the line required to prevent freezing would also change for each hour for the target lines. It should be noted, that in response to a sudden change in current or weather conditions, the conductor temperature will change in an approximately exponential manner, eventually reaching a new steady-state temperature if there is no further change. But in reality, the mentioned changes both in the environment and the line temperature does not happen suddenly and is gradual for the duration of the event.

IV. Lower Power Limit Implementation

Lower limit of power flow in lines ($fICE$) can be calculated using (14) through (22) based on the predicted weather. Equation (3) can be rewritten as:

$$fICE_k(t) \le F_k(t) \le F_k^{max}, \tag{23}$$

or

$$-F_k^{max} \leq F_k(t) \leq -fICE_k(t). \quad (24)$$

Equations (23) and (24) require the power flow in each direction to always be between the calculated lower flow limit and the thermal capacity of the lines. Implementing (23)-(24) as is in the optimization UC problem adds discontinuous constraint to the problem. The direction of the line's power flow is unknown pre-solution, but by allocating a new binary variable (z) to the direction of the flow, where it takes a value of 1 for the positive sign, and 0 for negative power flow, this modeling issue can be resolved. Additionally, M which is a sufficiently large positive number is added to (23)-(24) and its role is to cancel out one of the constraints, depending on the value of z. The resulting mixed-integer formulation is shown in (25)-(26):

$$fICE_k(t) - (1-z) \times M \leq F_k(t) \leq F_k^{max} + (1-z) \times M, \quad (25)$$

$$-F_k^{max} - z \times M \leq F_k(t) \leq -fICE_k(t) + z \times M. \quad (26)$$

It should be noted that although the severe cold weather conditions would allow the power flow in lines to surpass the thermal capacity for the duration of ice storm, the transmission lines usually span an extended geographical area and only one segment of the target lines may be in the cold environment. Therefore, the maximum thermal limit of the lines is not altered to avoid negatively affecting the other segments of the line [16]. There may be instances that the flow in lines should be greater or equal to the maximum power flow allowed on lines. In such cases, the power flow limit is fixed at the maximum flow.

V. Simulation Studies

The developed preventive de-icing method was applied to the IEEE 73 bus RTS-96 and the simulations were performed using the ECLIPS IDE 4.13 and IBM CPLEX 12.8. The temperature and wind speed of the impacted region in Quebec relating to January 4th of 1998 was used to test the effectiveness of the proposed method [17]. As the weather data is collected from different stations in the target area, 7 stations were chosen, and the data collected were interpolated to present the changes in the temperature and wind speed as is shown in Fig. 1.

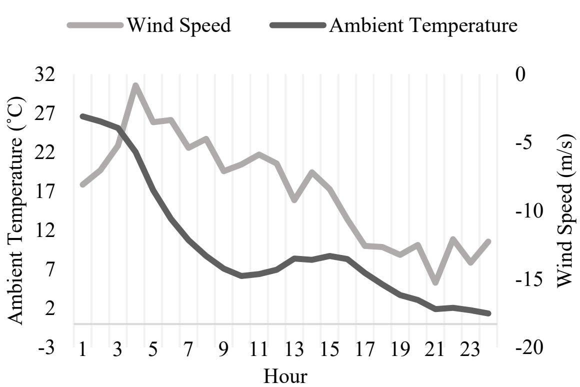

Fig. 1. Ambient temperature and wind speed for the 24 hours of January 4th of 1998 in Quebec.

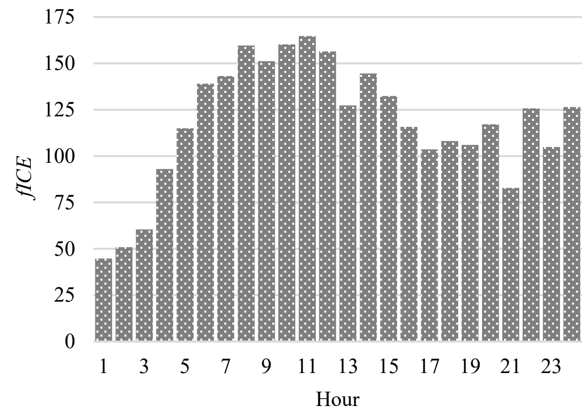

Fig. 2. The lower power flow limit for line 12 for the 24 hours of the ice storm day.

The temperature at the start of the ice snow events is -3˚C and towards midnight drops to -17.5˚C. On the other hand, the wind speed is 17.5 meters per second and peaks to 30 meters per second in three hours but from then on gradually decreases to 10 meters per second. This incongruous change in the wind and temperature is typical in ice snow events.

The lower power limit for the hours 9 through 16 shows a considerable increase compared to the early hours of the same day, which indicates that the wind speed more than 10 meters per second has a substantial impact on the power flow lower limit. The thermal capacity of this line is 175 MW, which *fICE* did not exceed for the duration of the day. Given the ambient temperature and wind speed trajectory, the lower power flow limit is calculated to keep the surface temperature from dropping below 2˚C. As ice storms often only affect part of the system, the number of transmission lines impacted by the ice storm is considered to be limited. Here line 12 has been selected as the target line and the minimum power flow that would prevent ice formation for line 12 is shown in Fig 2.

The calculated lower power flow limit is added to the UC problem and the power flow in line 12 is recorded. It is observed that by imposing the added constraint, the altered line flow generates enough heat that the surface line temperature does not drop below the target 2˚C. The flows for line 12 with and without the lower power flow limit is presented in Fig. 3 to showcase the changes in flow compared to the normal conditions. It can be clearly seen that not only the power flow value has changed for the line, but also the power flow direction has been impacted. The change in power flow allows for a higher temperature on the line as can be seen in Fig. 4. The temperature before imposing the lower power flow is calculated to fall below negative 10˚C. Although, there is power flowing in the line, the power is not enough to keep the line from freezing.

The altered power flow in one line to avoid the repair costs, would change the optimization problem. While the solution would maintain the temperature of the line over the freezing temperature, it would also add to the total operation cost of the system. The operation cost calculated for the UC problem with and without the lower power flow limit for line 12 is shown in

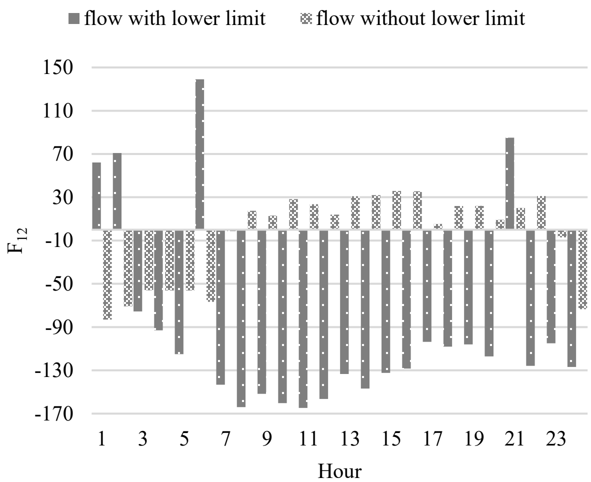

Fig. 3. The power flow on line 12 for the 24 hours of the day during the ice storm.

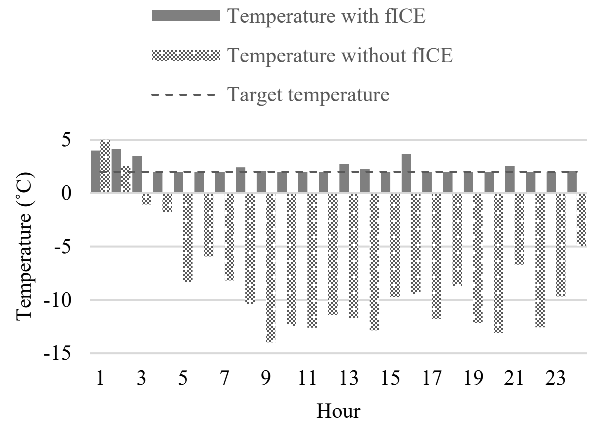

Fig. 4. The line surface temperature for the 24 hours of ice storm and the target temperature, with and without the lower power flow limit.

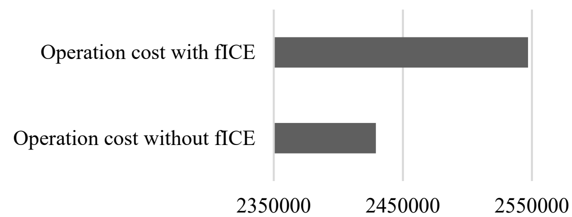

Fig. 5. Total operation cost with and without imposing the lower power flow limit on line 12 for the 24-hour ice storm.

Fig. 5. The dispatch cost has increased to $2.54 million/day, which is a 4.8% increase compared to the original unit commitment cost. Although the overall cost has increased, the increase is negligible compared to the averted repair costs. Repairing the damage that can be inflicted by ice storms on the transmission system and the economic loss to the area is significantly higher. Moreover, the reliability consequences of damaged transmission lines can be severe and rather costly for the power system for an extended duration of time.

VI. Conclusion

In this paper, a preventive de-icing method for transmission lines based on the Joule effect was developed that takes the changing weather conditions into account for the duration of the event. The minimum flow limits for the lines in the ice storm region is calculated using the developed method to prevent the formation of ice on lines. Then, the UC constraints are altered to set a limit for the lower power flow through a mixed integer formulation. The simulation results show that taking the changes in the weather conditions into account, is effective in keeping the line temperature over the desired value but the severe weather conditions, limits the proposed method rather significantly. These limitations lead to infeasibility in the problem when the number of lines considered is increased. In this study, the unit commitment problem was infeasible for the given ambient temperature and wind speed if more than one line was chosen and when the ambient conditions were harsh. With ambient temperature closer to zero and wind speed less than 10 meter per second, the lower power flow limit can be imposed on more lines. Therefore, the proposed method is more effective during certain ice storms that the weather is not as harsh, or when there are fewer transmission lines in the area that is impacted by the ice storm. Further research is required to properly study the conditions, under which the developed method will show satisfactory performance.

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