Research on the Enhancement of the Resilience of Transmission Grid under Ice Storms Disaster

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***Abstract*— In recent years, infrastructure resilience research has become a hot topic in today's society. And the power grid, as the basis for the normal operation of other infrastructures, is of great significance to ensure its normal operation. It is crucial to improve the resilience of the power grid under natural disasters. This paper provides a resilience perspective on investment planning for transmission grid facilities to minimize grid system losses while taking into account investor investment efficiency issues. Through the establishment of a designer-attacker-defender three-layer mathematical model, comprehensive consideration of the grid resilience of the absorptive and adaptive enhancement of the grid, the selection of the grid line sub-level protection and the addition of DC ice melting equipment as an investment strategy to minimize the negative impacts of the rain, snow and ice, to achieve a differentiated and dynamic protection of the power grid system. The three-layer optimization model studied in this paper is solved by the designed two-layer C&CG algorithm, and the reasonableness of the comprehensive consideration of the grid investment problem from the resilience perspective is verified by analyzing the results of the arithmetic example of Yunnan Qujing Power Grid.**

Keywords—grid investment planning, the resilience of power grids, protector-attacker-designer models.

I. Introduction

Infrastructural facilities such as power grids, water grids and transportation networks play an increasingly important role in the normal functioning of society [1]. Extreme natural disasters such as typhoons, earthquakes, floods and ice storms may cause great damage to the power system, which in turn triggers widespread power outages, seriously affecting China's national production and causing incalculable economic losses. Therefore, it is more and more urgent to improve the resistance of power grids to ice and snow disasters [2].

Measures for power transmission lines to cope with snow and ice disasters can be divided into three categories: pre-disaster design, disaster ice prevention and de-icing [3]. In recent years, the frequency of snow and ice disasters has increased dramatically, and the post-disaster restoration work needs to be based on the actual situation of the first elimination of hazards, and the actual progress is difficult to estimate. In such a situation, it should be changed from focusing on post-disaster rescue to focusing on prevention, so this paper does not study the resilience for the time being. As to how to improve the resilience of the power grid, China has put forward a variety of methods and measures to prevent and control the power grid to cope with ice and snow disasters. DC ice melting devices and ice melting practices play an important role in guaranteeing the safe operation of power grids against ice and snow disasters, and its for ice-covered overhead conductors has become one of the most direct, effective, and reliable ways to melt ice [4].

Ref. 5 extends the attacker-defender (AD) model to a designer-attacker-defender (DAD) model, which increases the protection of the designer compared to the AD model, and significantly reduces the investment cost of the defense plan developed by the DAD model compared to the AD model [5]. Ref. 6 considers the impact of high-penetration distributed power access on the distribution network, and proposes a data-driven robust planning method that takes into account the resilience of the distribution network to accomplish the optimal allocation of distributed power location and capacity [6]. Ref. 7 introduces the temporal and spatial uncertainty of disaster occurrence into the robust optimization model and proposes a resilient network distribution planning for facility reinforcement and distributed power sources, which reveals that distributed generation is essential to improve the resilience of distributed networks under natural disasters [7]. In the above articles, these models focus on pre-disaster reinforcement design, less on grid resilience improvement, and the attack intensity and defense level considered are monolithic in nature. Therefore, this paper takes the toughness perspective to comprehensively consider the enhancement of the system's

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ability to resist ice and snow disasters from the perspectives of both absorptive power and adaptive power, and takes the hierarchical reinforcement of the lines as the main measure to enhance the absorptive power of the system, and the addition of the DC ice melting equipment as the main measure to enhance the adaptive power of the system in order to realize the dynamic protection of the grid system. In addition, there is little literature focusing on grid resilience enhancement and investment optimization under snow and ice disasters, and the research in this paper will fill this gap [8].

II. DESCRIPTION AND PARAMETERISATION

A. Modelling resilience enhancement under ice and snow disasters

NAN divides the power grid system into three layers according to the control level, the controlled system layer, the operation control system layer and the man-made scheduling layer. According to the above three layers of the grid system structure, this paper will be ice and snow disaster background grid toughness enhancement measures as follows [9].

(1) Subject to control system layer. Usually overhead line is the most serious damage under the snow and ice disaster grid equipment, this paper mainly for transmission network toughness to improve the study, for transmission network ice and ice protection measures are: the use of expanding diameter conductor ice technology; improve the conductor surface electric field strength of the ice technology; increase the conductor discharge tension to inhibit the torsion of the anti-ice technology and so on.

(2) operation and control system layer. The main measures are the construction of transmission line ice monitoring system, timely monitoring of ice-covered transmission lines in the ice-covered area of the ice-covered situation, and timely release of early warning.

(3) human scheduling layer. The main measures include: strengthening staff skills training, strengthening emergency drills, reviewing and summarizing the dispatching work in time after the disaster or drill, as well as improving the emergency response system and standardizing the emergency management.

The grid resilience planning model used in this paper is mainly aimed at optimizing the grid subject to control system layer, and since the ice melting time is much smaller than the repair time of the line after the actual damage, this paper assumes that the ice melting time is negligible, and the damage considered by the model is the independent damage of the disaster in the same period.

B. Related parameters, sets, variable definitions

TABLE I. RELATED PARAMETERS, SETS AND VARIABLE DEFINITIONS

M	A sufficiently large positive number
n	Grid network nodes
N	The set of nodes of the grid network
e	Transmission lines in the grid network
E	Collection of transmission lines in the grid network
C_e^l	Transmission lines e Protection costs for resistance to low-level ice damage
C_e^h	Cost of protection of transmission lines e against high level ice damage
C_n^b	Cost of equipping substation n with DC ice-melting equipment
N^d	Aggregation of demand-side nodes in the grid network
N^s	The set of generation-side nodes in the grid network
D_n	Active power required at demand-side node n,n$\in N^d$
S_n	Upper limit value of active power of generating unit at node n, $n \in N^s$
$C_{\max 0}$	Maximum amount of investment initially available
$\theta_{n\max}$	Maximum phase angle of the grid network node n
U_e	Maximum active power flow that can be allowed to pass through transmission line e
R_e	Resistance of transmission line e
Q_l	Maximum number of transmission lines that can be damaged by low-level ice damage
Q_h	Maximum number of transmission lines that can be damaged by high-level ice damage
$o(e), d(e)$	Start and end points of transmission line e
ω_n	Weighting factor for user n
σ_e^h	Whether or not transmission line e is protected against low-level ice damage Enhanced protection against low-level ice damage, 1 yes, otherwise, 0
σ_e^l	Whether transmission line e is given enhanced protection against high levels of ice damage, 1 yes, otherwise, 0
σ_n	Whether DC ice melting equipment is established at substation n, 1 yes, 0 no
x_e^l	Whether transmission line e is subject to low-level damage, 1 yes, otherwise, 0
x_e^h	Whether transmission line e is subject to high-level damage, 1 yes, otherwise 0
$\sigma_e^{l,n}$	Substation n that is equipped with DC ice melting equipment, whether or not the point e perform a low-level ice melting operation, 1 yes, otherwise, 0
$\sigma_e^{h,n}$	Substation n equipped with DC ice melting equipment, whether a high-level ice melting operation is performed for point e perform a high-level ice melting operation, 1 yes, otherwise, 0
f_e	Active power flow through transmission line e
θ_n	Phase angle at node n of the grid network
s_n	Active power of generating units at node n
LS_n	Amount of load shedding at node n on the demand side

III. GRID RESILIENCE PLANNING MODELLING

A. Basic description of the model

The problem of planning for grid resilience enhancement under ice and snow disasters can be described as a designer-attacker-defender game model [10], in which the designer deploys a design plan for grid resistance to ice disasters in the first stage of the whole successive game process. In the second stage of the game, the enemy of the grid system, the snow and ice disaster, destroys the transmission lines by covering the transmission lines with ice, such as broken lines, fallen poles, fallen towers, etc., to achieve the maximum damage to the grid system. Finally, as the defender selects a reasonable dynamic ice melting strategy to mitigate the impact of the disaster based on the actual damage and adjusts the power flow on the remaining transmission network to react to the ice disaster to minimize the damage.

B. Model building

With the above description, the grid resilience planning model is established as follows:

Objective function:

$$\max_{\sigma_e^l,\sigma_e^h,\omega_n} \min_{x_e^l,x_e^h} \min_{\sigma_e^{h,n},\sigma_e^{l,n},f_e,\theta_n,LS_n,s_n} (\sum_{n\in N^d} \omega_n LS_n) \tag{1}$$

Investment design protection phase:

$$\sum_{e\in E} C_e^l \sigma_e^l + \sum_{e\in E} C_e^h \sigma_e^h + \sum_{e\in E} C_n \omega_n \le C_{\max 0} \tag{2}$$

$$\omega_n \in \{0,1\} \forall n \in N \setminus N^s \tag{3}$$

$$\sigma_e^l \in \{0,1\} \forall e \in E \tag{4}$$

$$\sigma_e^h \in \{0,1\} \forall e \in E \tag{5}$$

Destruction phase:

$$\sum_{e\in E} x_e^l \le Q_l \tag{6}$$

$$\sum_{e\in E} x_e^h \le Q_h \tag{7}$$

$$x_e^h + x_e^l \le 1 \forall e \in E \tag{8}$$

$$x_e^l \in \{0,1\} \forall e \in E \tag{9}$$

$$x_e^h \in \{0,1\} \forall e \in E \tag{10}$$

Ice melt scheduling phase:

$$s_n + \sum_{(e\in E|d(e)=n)} f_e - \sum_{(e\in E|o(e)=n)} f_e + LS_n = D_n$$

$$\forall n \in N \tag{11}$$

$$\sigma_e^{l,n} \in \{0,1\} \forall e \in E, n \in N \setminus N^s$$

$$\sigma_e^{h,n} \in \{0,1\} \forall e \in E, n \in N \setminus N^s$$

$$0 \le LS_n \le D_n \forall n \in N^d \tag{12}$$

$$0 \le s_n \le S_n \forall n \in N^d \tag{13}$$

$$-U_e \le f_e \le U_e \forall e \in E \tag{14}$$

$$-\theta_{n\max} \le \theta_n \le \theta_{n\max} \forall n \in N \tag{15}$$

$$\frac{1}{6}\sum_{e\in E} \sigma_{e|o(e)=n}^{l,n} + \frac{1}{4}\sum_{e\in E} \sigma_{e|o(e)=n}^{h,n} \le \omega_n + (1-\omega_n) * M \tag{16}$$

$$\forall n \in N \setminus N^s$$

$$\sigma_{e|o(e)=n,d(e)=n'}^{h,n} \le \omega_n + \omega_{n'} \forall n, n' \in N \setminus N^s \tag{17}$$

$$\sigma_{e|o(e)=n,d(e)=n'}^{l,n} \le \omega_n + \omega_{n'} \forall n, n' \in N \setminus N^s \tag{18}$$

$$\sigma_e^l + \sigma_e^h + \sigma_e^{l,n} + \sigma_e^{h,n} \le 2 - x_e^l \tag{19}$$

$$\sigma_e^h + \sigma_e^{h,n} \le 2 - x_e^h \tag{20}$$

$$\forall e \in E, n \in N \setminus N^s \tag{21}$$

$$f_e - \left[1 - x_e^l + (\sigma_e^l + \sigma_e^h + \sigma_e^{l,n} + \sigma_e^{h,n}) * x_e^l\right]$$

$$* \left[1 - x_e^h + (\sigma_e^h + \sigma_e^{h,n}) * x_e^h\right](\theta_{o(e)} - \theta_{d(e)}) = 0 \tag{22}$$

$$\forall \in E, n \in N \setminus N^s$$

$$\sigma_e^{l,n} \in \{0,1\} \forall e \in E, n \in N \setminus N^s \tag{23}$$

$$\sigma_e^{h,n} \in \{0,1\} \forall e \in E, n \in N \setminus N^s \tag{24}$$

In the objective function (1), the investor aims to minimize the sum of the minimum dump loads with weights in the grid system. In this model, the toughness is measured by the satisfaction of the customer's demand, which is not available due to the damage of the grid system by snow and ice, ω_n reflecting the importance of different types of customers.

The first level of the investment design protection phase reflects constraints regarding investment:(2) denotes the investment cost constraint, whose total investment cost should be less than the total investment budget. (3)-(5) denote that the relevant decision variables are 0,1 variables.

The second level of damage phase reflects the damage constraints related to the ice disaster: constraint (6) denotes the low-level number of attacks constraint; constraint (7) denotes the high-level number of attacks constraint. Constraint (8) indicates that a transmission line can only be subjected to one level of damage, which is consistent with the actual situation, assuming that both levels of disasters occur simultaneously, and in practice, only high-level damage can be exhibited. Constraints (9)-(10) indicate whether a transmission line is subject to low or high level of damage as 0,1 variables.

The third level is the constraints related to the scheduling aspect of ice melting, constraint (11) denotes the rate equilibrium at node n such that inflows and outflows are equal. Constraint (12) ensures that the size of the dumped load at the load line does not exceed its nominal demand and is always non-negative. Constraint (13) limits the active power of the generating unit at each node n to between zero and its maximum active power. Constraint (14) states that the active power flow on line e will be limited to $[-U_e, U_e]$; similarly, constraint (15) limits the phase angle at node n to $[-\theta_{n\max}, \theta_{n\max}]$. Constraints (16)-(18) indicate the ice melting capacity of fixed DC ice melting equipment installed at 500 kv substations or inter-station mobile types available in 220 kv substation areas, and according to the literature [11], it is known that each set of ice melting device can ensure the normal operation of a maximum of four transmission lines subject to high-level attack or six transmission lines subject to low-level attack. (19) shows that if a line is subject to a low-level attack, only one protection measure can be applied to the line in order to eliminate the redundancy of protection. Similarly, (20) indicates that if the line is subject to a high-level attack, only one high-level protection measure can be applied to the line. (21) captures the active DC current on the grid using Kirchhoff's law with additional protection and attack decision variables. If transmission line e is subjected to a low-level attack, i.e., x_e^l, the line can pass current if it is protected by either a low-level protection or a high-level protection or an ice-melting operation, i.e., $\sigma_e^l+\sigma_e^h+\sigma_e^{l,n}+\sigma_e^{h,n}=1$; and vice versa if $\sigma_e^l+\sigma_e^h+\sigma_e^{l,n}+\sigma_e^{h,n}=0$,the line cannot pass current. If the transmission line is attacked at a high level, i.e., x_e^h, the line can pass current if it is protected by a high level of protection or ice-melting operation, i.e., $\sigma_e^h+\sigma_e^{h,n}=1$; and conversely if the line cannot pass current. If it has not been damaged, the line can pass current. (22)-(24) indicate whether or not ice melting operation is performed on the transmission line as 0,1 variables.

IV. Case Study

In this paper, the proposed model is solved using the column and constraint generation algorithm, which firstly divides the model of this paper into an outer master problem and an outer subproblem. Since the outer subproblem in this paper's model cannot be solved directly, it is solved again using the column and constraint algorithm.

The example analysis considers the resilience optimisation problem of 500kv and 200kv high-voltage transmission network in Qujing City, Yunnan Province, China, under ice and snow disaster. As the second largest economic region in Yunnan Province, Qujing is one of the main pillar industries for power supply, and it is also the main channel for sending electricity from west to east and is responsible for transmitting electricity to Guangdong. For this reason, we take it as the main object of the arithmetic study to optimise the grid toughness. The Qujing 500kv and 200kv high-voltage transmission network as Fig. 1, in which nodes 1,2 are the generating end, nodes 3,4,5 represent the transmission nodes, which are the 500kv substations with no demand, nodes 6-14 are the 220kv substations with demand, and area 9 is the important user, with the corresponding weight of 2, and the rest of the weights are taken as 1. The algorithm uses MATLAB as a method to optimize the grid resilience, and the algorithm uses MATLAB as a method to optimize the grid resilience, which is the main object of the study. This algorithm uses MATLAB2014Bb to solve the outer subproblem.

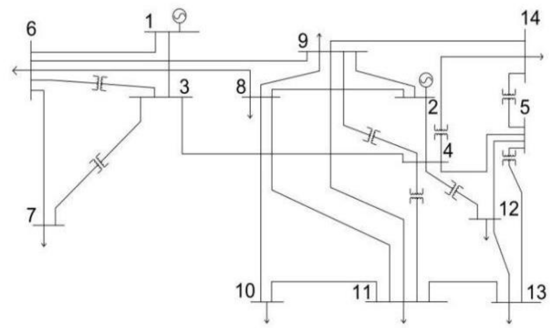

Fig. 1. Qujing power grid sketch

Node-specific supply and demand are not listed here first, where the demand at each node is determined by the ratio of GDP in each region; the price of transmission line protection is shown in Table II, in which the price of the fixed DC ice melting equipment equipped at 500 kv is 60 million yuan/set, and the mobile DC ice melting equipment equipped at 220 kv is 40 million yuan/set; and the relevant parameters of the line are shown in Table III.

TABLE II. Transmission Line Protection Price

Categorisation	220kv transmission line	500kv transmission line
Low-level protection price	160000yuan/km	240000yuan/km
High Level Protection Price	400000yuan/km	600000yuan/km

TABLE III. Line parameters

Line	1/impedance (Ohm)	Line Capacity (MW)	Line	1/impedance (Ohm)	Line Capacity (MW)
1-3	0.24	2000	5-12	1.222	500
1-6	0.408	500	5-13	4.187	500
2-4	0.612	2000	5-14	1.88	500
2-8	1.407	500	6-7	2.762	500
2-9	1.192	500	6-8	1.548	500
3-4	1.309	2000	6-9	2.877	500
3-6	0.302	500	8-9	1.023	500
3-7	1.755	500	8-10	3.209	500
4-5	0.893	2000	8-11	4.092	500
4-9	1.55	500	9-11	3.277	500
4-11	4.018	500	9-14	1.782	500
4-12	1.092	500	10-11	2.602	500
4-14	1.672	500	11-13	1.524	500
			12-13	2.377	500

TABLE IV. Running result

Q_l	Q_h	Load shedding size (MW)	Running time (s)
1	0	0	2.3
2	0	126.8	3.7
3	0	126.8	4.7
4	0	260.3	7.5
5	0	1702.9	4.5
6	0	1702.9	3.6

When the investment budget is 0, Table IV reflects the toughness level of the system at this time, and it can be obtained that when = 5, the grid system is completely paralysed and none of the users' demands can be met. When the investment budget is 80 million yuan and 100 million yuan respectively, the operation results are shown in Table V and Table VI, and the results obtained from all the arithmetic examples are within 0.5% of GDP. Among them, AB denotes the investment model with only absorptive power, i.e., only line reinforcement; AP denotes the investment model with only adaptive power, i.e., only adding DC ice-melting equipment; and AB & AP denotes the investment model with both absorptive and adaptive power taken into account.

TABLE V. RUNNING RESULT

Q_l	Q_h	Load shedding size (MW)			Running time (s)		
		AB	AP	AB&AP	AB	AP	AB&AP
0	2	0	0	0	11.4	36.2	40.7
0	3	35.3	94.2	35.3	25.3	33.2	109.2
0	4	80.5	160.3	80.5	53.5	87.9	163.5
0	5	140.3	187.1	109.8	118	109.6	209.8
0	6	225.1	225.1	160.3	207.9	183.5	238.3

TABLE VI. RUNNING RESULT

Q_l	Q_h	Load shedding size (MW)			Running time (s)		
		AB	AP	AB&AP	AB	AP	AB&AP
0	2	0	0	0	9.3	36.2	40.1
0	3	35.3	35.3	35.3	25.8	33.2	113.2
0	4	35.3	80.5	35.3	59.4	87.9	167.9
0	5	130.2	110.2	100.3	157.9	109.6	360.2
0	6	166.4	119.7	119.7	189.1	183.5	317.3

From Table V to Table VI, it can be seen that the toughness enhancement effect of the AB & AP investment models is better than that of the AB and AP investment models under the same investment budget; and in most cases, the toughness enhancement effect of the AB investment model is better than that of the AP model, which demonstrates the importance of improving the design standard of the power grid.

When considering the hierarchical protection measures, $I_{\max}$ is also chosen to be 80 million yuan, 100 million yuan and 12,000 million yuan, and the scenario with the total number of attacks of 6 is taken as an example, because the number of high-level attacks is much smaller than the number of low-level attacks in practice, so the scenario $B_{low} < B_{high}$ is chosen for analysis. In order to satisfy the situation of minimizing the dumping load and minimizing the investment amount, the actual investment amount can be introduced into the objective function. Setting:

$$I = \sum_{e \in E} C_e^{low} w_e^{low} + \sum_{e \in E} C_e^{high} w_e^{high} + \sum_{n \in N \setminus N^s} C_n w_n \tag{25}$$

Then the objective function is changed to:

$$\max_{w_e^{low}, w_e^{high}, w_n} [\rho \star I + \tag{26}$$

$$\min_{x_e^{low}, x_e^{high}} \min_{w_e^{low,n}, w_e^{high,n}, f_e, \theta_n, LS_n, s_n} \left(\sum_{n \in N^d} \omega_n LS_n \right)] \tag{27}$$

Where ρ is the weight of the investment component, in order to make investors focus on the effect of resilience enhancement, here ρ is a very small value of 0.005. Table VII represents the results of the graded and ungraded levels. Where CP denotes a hierarchical investment model, Non-CP denotes a non-hierarchical investment.

From Table VII, it can be seen that when $I_{\max}$ is certain, for scenario 1,3,5, grade-separated investment can better enhance the toughness of the grid system; and for scenario 4, grade-separated can reduce the investment cost of the system when it is not possible to enhance the toughness level of the system. Note that for scenario 3,5, CP model improves the actual investment cost while improving the system toughness, this is because the model is risk averse, the primary purpose of the model is to improve the system toughness under certain investment constraints, when it is not possible to improve the toughness, this is when it is more meaningful to compare the actual investment amount. Therefore, for scenario 3, we take the actual cost equal to scenario 3, Non-CP model, and get scenario 7, we can see that the scenario has less cost, and for this scenario 7, the toughness of the system is still best modeled by Non-CP.

TABLE VII. RUNNING RESULT

	Q_l	Q_h		Load shedding size (MW)		actual cost (million yuan)		Running time (s)	
				CP	Non-CP	CP	Non-CP	CP	Non-CP
1	5	1	8000	125.7	159.0	7720	10880	4422.0	882.3
2	4	2	8000	159.0	159.0	7880	10880	7589.1	2458.1
3	5	1	10000	33.8	113.1	9963	9230	4651.1	858.3
4	4	3	10000	113.1	113.1	9023	9230	7420.4	2654.2
5	5	1	12000	0	33.8	11299	10880	2441.1	956.3
6	4	2	12000	33.8	33.8	10222	10880	8122.6	2897.5
7	51	1	9280	106.5	113.1	9640	9230	3892.3	833.4

V. CONCLUSIONS

This paper studies the planning decision-making problem of power transmission grid in the context of snow and ice disaster. Based on the three-layer structure of the power grid system divided according to the control level, this paper comprehensively considers the measures that can enhance the resilience of the power grid in the face of ice and snow disasters from the perspective of resilience, and takes the controlled system level as the main research object, selects improving the design standard as the main measure to enhance the absorptive force of the system, and adds DC ice melting equipment as the main measure to enhance the adaptive force of the system. On this basis, a designer-attacker-protector model with multi-party participation and hierarchical protection is established, and a corresponding solution method is designed for this problem.

The innovations of this paper are: 1) to comprehensively study the grid system's ability to cope with snow and ice disasters from the perspective of resilience, consider the absorptive and adaptive capacity of the grid system, and improve the system's ability to resist snow and ice disasters from the aspects of anti-icing and de-icing before and during the disaster;2) to incorporate the DAD model into the protection against snow and ice disasters, and design the corresponding solution algorithms; 3) to take the hierarchical protection into account in the design of the system according to the actual situation; 4) to fill the gap in the study of the power grid under snow and ice disasters and optimization of investment benefits. design, which optimizes the investment benefits; 4) Filling the gap of research on improving the resilience of power grids under snow and ice disasters and optimizing the investment.

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