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CORRELATION-BASED INVESTMENT DECISION FOR MULTI-YEAR DISTRIBUTION NETWORK EXPANSION

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ABSTRACT

With the access of large-scale clean energy and in face of a lot of reconstruction strategies, the problems of complexity and poor convergence exist in the traditional investment planning optimization model which includes optimal power flow (OPF) and network safety constraint (NSC), as well as the iteration calculation of performance index. Thus, an optimal investment decision model of distribution network (DN) is proposed based on correlation mining between reconstruction strategies and reliability index. Based on the correlation constraint, the multi-year rolling investment model is established respectively aiming at maximizing the index and minimizing the total investment cost to obtain the optimal investment plans. Finally, an example is given to verify the rapidity, feasibility and effectiveness of the investment model.

Keywords: multi-year investment decision model of distribution network, correlation constraint, reconstruction strategy, reliability

NONMENCLATURE

Abbreviations

SAIDI	system average interruption duration index
EENS	expected energy not supplied
RS-3	reliability of power supply

Symbols

$F(\boldsymbol{X})$	reliability index of the reconstruction plan
$\boldsymbol{X}$	vector of reconstruction strategies
N_{ep}	total investment period
ep	every epoch of N_{ep}
Ω	set of coordinated strategy
X_{epi}	i-th reconstruction strategy of ep-th epoch
ε_k	k-th coordinated strategy
$C_{ep}^{\varepsilon_k}(X_{epi})$	cost of the reconstruction strategy X_{epi} of ep-th epoch with k-th coordinated strategy
$C_{\max}^{\varepsilon_k}$	maximum total investment with k-th coordinated strategy
$\Psi_{ep}(X_{epi})$	reconstruction strategies library of ep-th epoch
C_i^{In}	initial investment cost of X_i
C_i^{op}	operation and maintenance cost of X_i
$X_{epi}^{\min}$	lower limits of X_{epi}
$X_{epi}^{\max}$	upper limits of X_{epi}
$N_{Ds\_ep}^{\max}$	upper limits of three-remote terminals
$S_{DG\_ep}^{\max}$	upper limits of distributed generation
$S_{ESS\_ep}^{\max}$	upper limits of energy storage system
$\Delta F_{ep\_set}^{\varepsilon_k}$	minimum improve level of reliability index

1. INTRODUCTION

Nowadays, more elements are accessed into energy system, such as distributed generation (DG) and energy storage system (ESS), which makes the investment objects of DN are no longer limited in the upgrading of simple traditional equipment, etc. What's more, the differential operation strategies and elastic demand response of distribution energy resource (DER) make the planning model show strong nonconvex and nonlinearity in high dimensions [1]. Therefore, the study of precise investment optimization model has sprung up.

With the access of DERs, economical efficiency [2] and reliability level [3] are completely involved in the investment optimization model. When considering the investment of DN, one or more of the above factors are

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combined to form a multi-objective or multi-layer model [2-4]. In addition, the constraints in ordinary planning model, such as OPF and NSC, which are most nonlinear and nonconvex constraints [5]. As the above models are generally complex mixed integer nonlinear models which are difficult to solve, fuzzy modeling [6], some numerical methods [4], game theory [7] or improved intelligent algorithm [8] are mostly used in the optimization process. Overall, most of the mentioned methods are centralized optimization, the following problems may appears: ① Ignoration of the mutual influence of various strategies; ②The increasing number of decision variables will make the model difficult to solve; ③The iteration calculation of reliability index will add the solving difficulty.

The above problems make it difficult to realize precise investment considering different coordination strategies of DER and large-scale reconstruction strategies access. Hence, a new method need to be explored. Actually, the machine learning approaches have been a mature tool to approximate complex nonlinear mapping with its good adaptive ability and fault-tolerant ability [9], which can be attempted to establish the relationship between reconstruction strategies and reliability index. Therefore, a direct correlation-based constraint is used to replace the traditional nonlinear nonconvex constrains and iteration of reliability in this paper, and a multi-year correlation-based investment model is constructed.

The rest of this paper consists of three main sections. Section 2 introduces the proposed correlation-based multi-year investment model is described. Then an actual DN is applied in Section 3 to verify the availability of the model. Section 4 is the conclusion of this paper.

2. CORRELATION CONSTRAINT-BASED MULTI-YEAR INVESTMENT MODEL

The traditional investment decision model is integrated with the OPF, NSC and iteration of reliability programming, while a correlation constraint based on machine learning is established in this paper to replace the iteration and nonlinear nonconvex constraint.

2.1 Data generation process for correlation constraint

In order to establish the accurate correlation constraint of reconstruction strategies and reliability indexes, it is crucial to generate enough and effective training data. Considering the temporal coupling and uncertainty of DER in DN, as well as the coordinated operation of DER with the gradual improvement of the power market mechanism, a time-sequential simulation method based on multi-agent model is applied in this paper for training reconstruction plans [11]. And then the values of reliability index of each training plan can be calculated. The obtained training outputs of DERs and corresponding reliability indexes can be set as samples of correlation mining.

2.2 Correlation constraint

The correlation constraint of reconstruction strategies and reliability indexes which is obtained by correlation mining based on machine learning method, such as multiple regression based on Least Squares [12], is utilized to replace the nonlinear and nonconvex constraints, as well as the iteration of reliability index. During the correlation mining process, the load level of DN and implementation of various reconstruction strategies are regarded as the input vectors, while the output is the reliability index. Through the regression analysis, the correlation function of reliability index and strategies can be described as formula (1).

$$\Phi(F(\boldsymbol{X}), \boldsymbol{X}, A, B) = 0 \tag{1}$$

where, Φ represents the correlation function based on multiple regression. A and B represent the regression coefficients and intercepts respectively.

2.3 Correlation-based distribution network multi-year investment decision model

Replacing the nonlinear nonconvex constraints and iteration of reliability calculation, the multi-year investment decision model of DN integrated the correlation constraint can be established. The objective function of the investment decision model can be divided into two categories. One is to maximize the improvement of reliability with upper limit of investment cost as constraint. And the other is to minimize the total cost with lower limit of the improvement of reliability as constraint.

Regarding the reliability improvement as an objective, the investment limit should be a constraint. The objective function and investment limit of the multi-year model are shown as follows:

$$\max \sum_{j=1}^{N_{ep}} F_{ep}^{\varepsilon_k}(\boldsymbol{X}_{ep}) \quad \begin{cases} \forall ep \in 1,...,N_{ep} \\ \forall \varepsilon_k \in \Omega \end{cases} \tag{2}$$

$$\sum_{i=1}^{n} C_1^{\varepsilon_k}(X_{1i}) + ... + \sum_{i=1}^{n} C_{ep}^{\varepsilon_k}(X_{epi}) \le C_{\max}^{\varepsilon_k} \tag{3}$$

$$s.t. \begin{cases} \{X_{11}, X_{12}, ..., X_{1n}\} \in \psi_1(X_{1i}) \\ ...\ ... \\ \{X_{ep1}, X_{ep2}, ..., X_{epn}\} \in \psi_{ep}(X_{epi}) \end{cases} \tag{4}$$

$$\Phi_{ep}^{\varepsilon_k}(F_{ep}^{\varepsilon_k}(\boldsymbol{X}_{ep}), \boldsymbol{X}_{ep}, A_{ep}^{\varepsilon_k}, B_{ep}^{\varepsilon_k}) = 0 \tag{5}$$

$$X_{epi}^{\min} \le X_{epi} \le X_{epi}^{\max} \tag{6}$$

$$\begin{cases} 0 \le X_{epi(remote)} \le N_{Ds\,ep}^{\max} \\ 0 \le X_{epi(DG)} \le S_{DG\,ep}^{\max} \\ 0 \le X_{epi(ESS)} \le S_{ESS\,ep}^{\max} \end{cases} \tag{7}$$

$$X_{i(total)}^{\min} \le \sum_{j=1}^{N_{ep}} X_{epi} \le X_{i(total)}^{\max} \tag{8}$$

$$C_{ep}^{\varepsilon_k}(X_{epi}) = \sum_{i=1}^{n} (R_i C_i^{In}(X_{epi}) + C_i^{Op}(X_{epi})) \tag{9}$$

where, the objective function in (2) is the overall improvement level of the reliability index in every epoch of N_{ep}. Formula (3) describes the total investment cost constraint. R_i is the annual discount factor, $R_i = r(1+r)^{m_i} / ((1+r)^{m_i} - 1)$, r represents the investment recovery rate, m_i is the economic age of the X_{epi}. And the reconstruction strategies library constraints are presented as formula (4). The constraints of reconstruction strategies are shown as formula (6)-(8). The lower limit is 0 meanwhile the upper limit could been set according to different reconstruction strategies. Besides, the constraint of reconstruction strategies must meet the requirement of the whole investment period.

When set the minimum investment cost as the target of the model, the lower limit of improve level that reconstruction strategies taking to reliability is used as a constraint. Therefore, the formula (10)-(11) will be changed as follows.

$$\min \sum_{j=1}^{N_{ep}} C_{ep}^{\varepsilon_k}(\boldsymbol{X}_{ep}) = \sum_{j=1}^{N_{ep}} C_{invest\_ep}^{\varepsilon_k} \tag{10}$$

$$\sum_{j=1}^{N_{ep}} \Delta F_{ep}^{\varepsilon_k}(\boldsymbol{X}_{ep}) \ge \Delta F_{ep\_set}^{\varepsilon_k} \quad \forall ep \in 1,...,N_{ep} \tag{11}$$

where, $\Delta F_{ep}^{\varepsilon_k}(\boldsymbol{X}_{ep})$ is the improvement level of the reliability index in the ep^{th} year with the coordinated strategy ε_k. Formula (11) is the minimum improve level to satisfy the requirement of distribution network, as the constraint of the model. Other constrains are same as the formula (4)-(9).

3. CASE STUDY

An actual regional distribution network is employed to investigate the proposed correlation constraint integrated investment decision model. As shown in Fig 1, the regional distribution network includes 36 10KV buses. There is a 2MW biomass power plant installed at bus 32. And three-remotes terminals are installed at bus 9, 10, 15, 28. The rate of return on investment is 10%. The parameters of the reconstruction strategies are displayed in Tab. I. Taking the EENS index of reliability level as an example for analysis, the initial EENS index of the region is 29.6154MW.

Through multiple regression, the explicit expression of EENS index and alternative reconstruction strategies can be obtained, and the fitting accuracy can reach above 97%, which can fully satisfy the requirement of the precise investment.

Considering the charging and discharging mode of ESS, at fix time or according to time-of-use price, and the participation in coordination of flexible load (FL), there are four different coordinated strategies: FixTime_Coordinated, FixTime_Discoordinated, Time-of-Use_Coordinated and Time-of-Use_Discoordinated. By solving the correlation constraint-based investment model, the optimal multi-year plans can be obtained integrated four various coordinated strategies of ESS and FL, as shown in Tab. II and Tab. III. It can be seen that with the increase of the investment, the reliability level of DN has been improved. And coordinated strategy Time-of-Use_Coordinated shows the best performance, which is owed to the adjustment of ESS and FL.

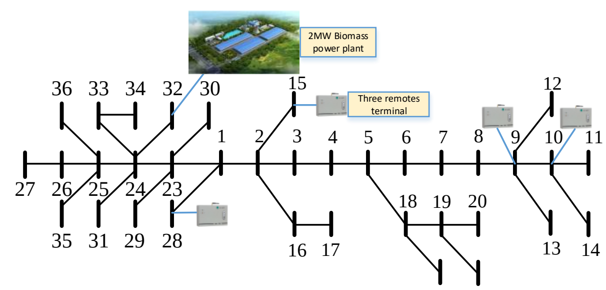

Fig 1 Initial structure of the regional distribution network

Table. I Investment cost parameters of reconstruction strategy

Strategy	C^{In}/ (×10⁴ ￥)	Ratio of C^{Op} to C^{In} (%)	m	Optional location
DG	650/MW	4	20	Bus 7, 11, 17, 19, 24
ESS	400/MW	4	20	Bus 16, 17
Three-remote	3.5/a	4	20	Bus 2, 24

Table. II Optimal investment plan with a certain cost costriant in three years

Coordinated strategy	C_{max}/ 10^4￥	Optimal investment plan	Investment cost/10^4￥	Reliability level EENS (after)/MW	RS-3 (after)/%
	100	First year: 2,24-three-remote, 24-0.96MWDG; Second year: No; Third year: No	99.3570	19.4803	99.9530

Time-of-Use_Coordinated	300	First year: 2- three-remote, 24-1MWDG; Second year: 24- three-remote; Third year: 7-1MWDG, 17-0.92MWDG	299.9606	13.5924	99.9662
	550	First year: 2,24-three-remote, 7,24-1MWDG; Second year: No; Third year: 11-0.87MWDG, 17,19-1MWDG	499.5407	9.5485	99.9785
Time-of-Use_Discoordinated	100	First year: 2,24-three-remote, 24-0.96MWDG; Second year: No; Third year: No	99.3570	19.5059	99.9530
	300	First year: 2- three-remote, 24-1MWDG; Second year: 24- three-remote; Third year: 17-1MWDG, 19-0.92MWDG	299.9606	13.6071	99.9661
	500	First year: 2,24-three-remote, 7,17-1MWDG, 11-0.87MWDG; Second year: No; Third year: 19,24-1MWDG	499.5407	9.7287	99.9784
FixTime_Discoordinated	100	First year: 2,24-three-remote, 24-0.96MWDG; Second year: No; Third year: No	99.3570	23.6045	99.9507
	300	First year: 2- three-remote, 24-1MWDG; Second year: 24- three-remote; Third year: 17-0.92MWDG, 19-1MWDG	299.9606	17.9103	99.9639
	500	First year: 2,24-three-remote, 19,24-1MWDG; Second year: No; Third year: 7,17-1MWDG, 11-0.87MWDG	499.5407	13.6144	99.9781
FixTime_Coordinated	100	First year: 2,24-three-remote, 24-0.96MWDG; Second year: No; Third year: No	99.3570	21.7341	99.9518
	300	First year: 2- three-remote, 24-1MWDG; Second year: 24- three-remote; Third year: 7-0.92MWDG, 19-1MWDG	299.9606	16.0823	99.9649
	500	First year: 2,24-three-remote, 11-0.87MWDG, 17,19-1MWDG; Second year: No; Third year: 7,24-1MWDG	499.5407	12.0571	99.9771

Table. Ⅲ Optimal investment plan with a reuqired level of reliability in three years

Coordinated strategy	ΔF_{ep_set} /MW	Optimal investment plan	Investment cost/10^4￥	Reliability level EENS (after)/MW	Reliability level RS-3 (after)/%
Time-of-Use_Coordinated	14	First year: 2,24-three-remote; Second year: No; Third year: 17,24-1MWDG, 19-0.85MWDG	287.6724	13.9856	99.9760
	12	First year: 2,24-three-remote; Second year: No; Third year: 7,17,24-1MWDG, 19-0.55MWDG	364.4403	11.9933	99.9771
Time-of-Use_Discoordinated	14	First year: 2,24-three-remote; Second year: No; Third year: 17,24-1MWDG, 19-0.86MWDG	293.8197	13.9761	99.9760
	12	First year: 2,24-three-remote, 7-0.61MWDG; Second year: No; Third year: 17,19,24-1MWDG	370.5812	11.9813	99.9771
FixTime_Discoordinated	16	First year: 2,24-three-remote, 24-1MWDG; Second year: No; Third year: 7-0.69MWDG, 17,19-1MWDG	378.7691	15.9938	99.9749
	14	First year: 2,24-three-remote, 19-1MWDG; Second year: No; Third year: 7,17,24-1MWDG, 11-0.79MWDG	491.3528	13.9928	99.9760
FixTime_Coordinated	16	First year: 2,24-three-remote; Second year: No; Third year: 7-0.95MWDG, 19,24-1MWDG	303.0310	15.9975	99.9749
	13	First year: 2,24-three-remote, 11-0.24MWDG; Second year: No; Third year: 7,17,19,24-1MWDG	503.6346	12.9975	99.9771

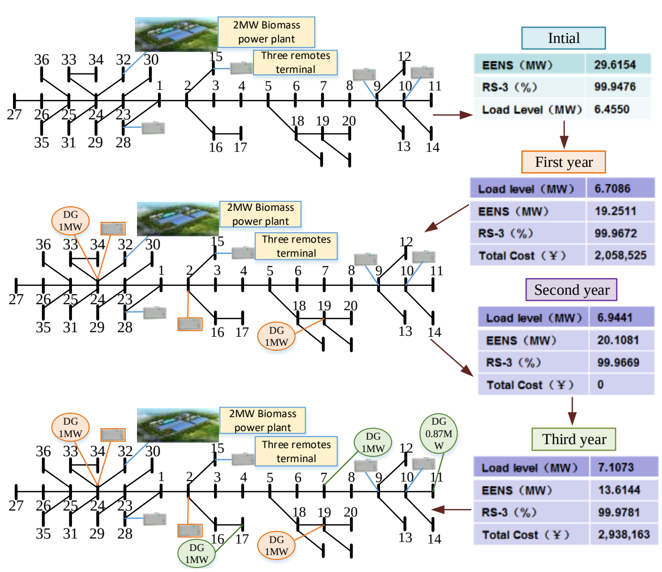

Fig 2 Investment process of three years

Take the maximum investment cost of ￥5,000,000 with FixTime_Discoordinated in Tab. Ⅱ as an example.

As presented in Fig 2, after the investment of the first year, the reliability level has improved. Then, with the increasing load of the second and third year, the reliability level downs a bit, thus the investment plan in the third year makes the reliability back to a better level.

The following Fig 3 demonstrates the visualization system designed based on the proposed investment decision method, which can realize the investment decision calculation and results visualization.

Fig 3 Visualization system for investment-decision

4. CONCLUSION

Orienting the reliability of DN, a correlation constraint integrated multi-year investment decision model is proposed in this paper, which replaces the nonlinear nonconvex constraints and iteration calculation of reliability in traditional model. As the result shown, the proposed model can effectively obtain the optimal investment decision with multi reconstruction strategies integrated accurately, and the reliability level of DN will improve with the increase of investment. Besides, the optimal plans and cost allocation can be demonstrated through the visualization system.

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