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DECENTRALIZED EXPANSION OF TRANSMISSION NETWORKS INCORPORATING ACTIVE DISTRIBUTION NETWORKS

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ABSTRACT

In a current power system, numbers of distribution networks are physically connected to a transmission network at different boundary buses. As the planning solution of one network significantly influences the decisions made by planners of other networks, the transmission and distribution networks should coordinate and cooperate with each other to design the entire power system in a secure and economic manner. Inspired by hierarchical and distributed optimization theories, this paper proposes a coordinated decision-making framework to determine the planning scheme and scenario based generation schedule for hybrid transmission and distribution networks (HTDNs). A stochastic bi-level hierarchy is presented to decompose the centralized optimal planning of HTDNs. The obtained subproblems for independent transmission and distribution networks are formulated and solved using an iterative solution process. The simulation results demonstrate the effectiveness of the proposed coordinated planning framework.

Keywords: hybrid transmission and distribution network (HTDN), hierarchical and distributed model, coordinated optimization, stochastic planning

1. INTRODUCTION

The penetration of distributed generations (DGs) at different power and voltage levels has greatly changed the passive characteristics of conventional distribution networks and consequently introduces active distribution networks in the current power systems [1,2]. Numbers of problems, such as voltage rising and bi-directional power flow, associated with integrating DGs are difficult to solve using the current separate planning manner. Moreover, the power system planning should cover the secure and economic operation issue, especially when uncertainties related to DG output power and load variation are considered [3]. Thus, coordination between transmission and distribution networks and stochastic analysis in each independent system should be simultaneously concerned. However, to the best of our knowledge, coordinated planning of HTDNs has not been fully investigated in the existing publications.

Numerous papers have focused on either independent transmission network (ITN) planning [4,5] or independent distribution network (IDN) planning [6]. A few researches have addressed the coordination between generation and network planning (i.e.., generation and transmission expansion [7,8], as well as DG and distribution expansion [2]). Note that all the above works cannot coordinate the transmission planning with distribution planning although there are some published literatures on the coordinated optimal power flow problem for hybrid systems. Reference [9] presents a system of systems based decision-making framework to determine a secure and economic hourly generation schedule for integrated transmission and distribution networks in a decentralized manner. A coordinated AC optimal operation model for HTDNs is proposed in [10]. This centralized model is solved using a new decomposition algorithm, called heterogeneous decomposition. In [11], a hierarchical optimization algorithm is addressed to evaluate the risk level of a transmission network incorporating numbers of distribution networks. Reference [12] formulates a three-level optimal operation problem for hybrid AC distribution networks, voltage source converter stations and DC distribution networks. Thus, coordination between HTDN planning is urgently needed to fully exploit its advantages.

In this paper, a stochastic decentralized expansion optimization approach for HTDNs is proposed to determine a secure and economic planning scheme in terms of an integrated system. The contributions of this paper include: 1) Developing a stochastic hierarchy including transmission and distribution networks to decompose the original centralized expansion optimization problem into several subproblems; 2) Optimizing the expansion and scenario based generation dispatch in a secure and economic manner.

2. DISTRIBUTED HTDN PLANNING FORMULATION

2.1 Problem decomposition

An HTDN can be physically decomposed into three kinds of networks, including the transmission network, the distribution network, and the boundary network interacting the coupled transmission and distribution networks. For the above network structure, Fig. 1 shows a bi-level hierarchy proposed to represent the HTDN. This hierarchy contains a transmission network and numbers of distribution networks, where the element at level 1 represents the transmission network, and the element q at level 2 represents the distribution network q.

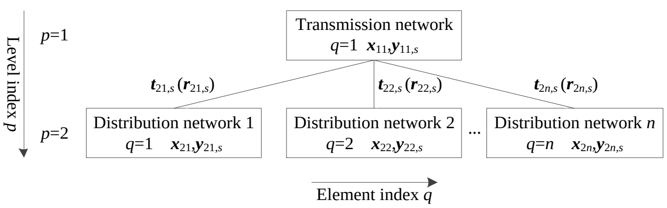

Fig 1 Hierarchical bi-level structure of HTDN

As shown in Fig. 1, each element has its own local investment-related variables $\boldsymbol{x}_{pq}$ and operation-related variables $\boldsymbol{y}_{pq,s}$ in scenario s, and is coordinated with other elements through shared variables $\boldsymbol{z}_{pq,s}$ in scenario s. To fully formulate the self-governing objective and constraints in terms of each independent system, two sets of operation-related variables including target variables $\boldsymbol{t}_{pq,s}$ and response variables $\boldsymbol{r}_{pq,s}$ in scenario s are introduced, while guaranteeing the consistencies $\boldsymbol{c}_{pq,s} = t_{pq,s} - \boldsymbol{r}_{pq,s} = 0$.

In order to satisfy the above consistency demand, a penalty function is regarded in the objective in each scenario to relax these consistency constraints. Then, for the element q at level p, the original centralized expansion problem can be decomposed into subproblems deploying the augmented Lagrangian function as the penalty function [13]:

$$
\begin{aligned}
min \quad & f_{pq}^{inv}\left(\bar{\boldsymbol{x}}_{pq}\right)+\sum_{s=1}^{m} D_s f_{pq}^{ope}\left(\bar{\boldsymbol{y}}_{pq,s}\right) \\
& +\sum_{s=1}^{m} D_s\left(\boldsymbol{v}_{pq,s}^{T}\left(\boldsymbol{t}_{pq,s}-\boldsymbol{r}_{pq,s}\right)+\left\|\boldsymbol{w}_{pq,s}\circ\left(\boldsymbol{t}_{pq,s}-\boldsymbol{r}_{pq,s}\right)\right\|_2^2\right) \\
& +\sum_{s=1}^{m} D_s \boldsymbol{v}_{(p+1)q,s}^{T}\left(\boldsymbol{t}_{(p+1)q,s}-\boldsymbol{r}_{(p+1)q,s}\right) \\
& +\sum_{s=1}^{m} D_s\left\|\boldsymbol{w}_{(p+1)q,s}\circ\left(\boldsymbol{t}_{(p+1)q,s}-\boldsymbol{r}_{(p+1)q,s}\right)\right\|_2^2 \\
s.t. \quad & \boldsymbol{g}_{pq}\left(\bar{\boldsymbol{x}}_{pq},\bar{\boldsymbol{y}}_{pq,s}\right)\le 0 \\
& \boldsymbol{h}_{pq}\left(\bar{\boldsymbol{x}}_{pq},\bar{\boldsymbol{y}}_{pq,s}\right)=0
\end{aligned} \tag{1}
$$

where m is the number of scenarios, and D_s is the number of hours in scenario s. $\boldsymbol{v}_{pq,s}$ and $\boldsymbol{w}_{pq,s}$ are the vectors of Lagrangian multipliers and penalty weights, respectively, and they will be updated during the iterative solving process. The symbol $\circ$ represents the Hadamard product. Thus, the subproblems for transmission network and distribution networks can be solved separately in each element of the hierarchy.

In this paper, the active power exchanged between the transmission network and the distribution network q in scenario s is defined as the target variable $\boldsymbol{t}_{2q} = P_{T,q,s}$ in the transmission network subproblem, and the response variable $\boldsymbol{r}_{2q} = P_{D,q,s}$ in the distribution network subproblem, respectively.

2.2 Distribution network planning subproblem

The expansion subproblem for the distribution network allows alternatives to be considered for line reformation and line construction. Meanwhile, the load of a distribution network can be supplied by the transmission network and the local DGs. Thus, the optimization objective of the distribution network q can be formulated as:

$$
\begin{aligned}
min \quad & \sum_{ij\in\Omega_0} u_{ij}^{ref} C_{ij}^{ref} l_{ij} + \sum_{ij\in\Omega_C} u_{ij}^{new} C_{ij}^{new} l_{ij} \\
& +\sum_{s} D_s \sum_{i\in\Omega_{DG}} C_{DG,i}\left(P_{DG,i,s}\right)-\sum_{s} D_s \rho_{D,q} P_{D,q,s} \\
& +\sum_{s} D_s\left(v_{2q,s}\left(P_{T,q,s}-P_{D,q,s}\right)+\left[w_{2q,s}\left(P_{T,q,s}-P_{D,q,s}\right)\right]^2\right)
\end{aligned} \tag{2}
$$

where u_{ij}^{ref} and u_{ij}^{new} are binary variables. u_{ij}^{ref} takes the value 1 if the line ij is reformed and 0 otherwise, and u_{ij}^{new} takes the value 1 if the line ij is constructed and 0 otherwise. C_{ij}^{ref} and C_{ij}^{new} are, respectively, the reformation and construction costs for line ij per unit length. l_{ij} is the length of line ij. $C_{DG,i}(\bullet)$ is the DG cost function at bus i, and $P_{DG,i,s}$ is the active power generated by DGs at bus i in scenario s. $\rho_{D,q}$ is the price of energy exchanged between the transmission network and distribution network q from the distribution's perspective. Ω_0, Ω_C and Ω_{DG} are, respectively, the set of existing lines, the set of new lines and the set of DG installation buses. It should be noted that the positive direction of $P_{D,q,s}$ is transferred from the distribution network q to the transmission network, so the fourth term is written as a minus sign.

For security purpose, the following constraints should be satisfied for the distribution network subproblem.

1) Line reformation number limits.

$$0 \le n^{ref} \le n^{ref,max} \tag{3}$$

where n^{ref} and $n^{ref,max}$ are, respectively, the number of reformed lines and its upper limit.

2) AC Power balance constraints.

$$P_{i,s} - U_{i,s} \sum_{ij \in \Omega_L} U_{j,s} (G_{ij} \cos\theta_{ij,s} + B_{ij} \sin\theta_{ij,s}) = 0 \quad \forall i \tag{4}$$

$$Q_{i,s} - U_{i,s} \sum_{ij \in \Omega_L} U_{j,s} (G_{ij} \sin\theta_{ij,s} - B_{ij} \cos\theta_{ij,s}) = 0 \quad \forall i \tag{5}$$

where $P_{i,s}$ and $Q_{i,s}$ are, respectively, the active and reactive power injected to bus i in scenario s. G_{ij} and B_{ij} are, respectively, the conductance and admittance of line ij. $\theta_{ij,s}$ is the phase difference between the voltages at buses i and j in scenario s. $U_{i,s}$ is the voltage magnitude at bus i in scenario s. $\Omega_L = \Omega_0 \cup \Omega_C$, which represents the set of all lines.

3) AC bus voltage limits.

$$U_i^{min} \le U_{i,s} \le U_i^{max} \quad \forall i \tag{6}$$

where U_i^{min} and U_i^{max} are, respectively, the lower and upper limits of the voltage at bus i.

4) Tie line capacity limits at distribution side.

$$P_q^{min} \le P_{D,q,s} \le P_q^{max} \quad \forall q \tag{7}$$

$$Q_q^{min} \le Q_{D,q,s} \le Q_q^{max} \quad \forall q \tag{8}$$

where P_q^{min} and P_q^{max} are, respectively, the lower and upper limits of active power exchange between the transmission network and distribution network q. $Q_{D,q,s}$ is the reactive power exchange between the transmission network and distribution network q in scenario s from the distribution's perspective. Q_q^{min} and Q_q^{max} are, respectively, the lower and upper limits of reactive power exchange between the transmission network and distribution network q.

5) DG output power limits.

$$P_{DG,i}^{min} \le P_{DG,i,s} \le P_{DG,i}^{max} \quad \forall i \tag{9}$$

$$Q_{DG,i}^{min} \le Q_{DG,i,s} \le Q_{DG,i}^{max} \quad \forall i \tag{10}$$

where $P_{DG,i}^{min}$ and $P_{DG,i}^{max}$ are, respectively, the lower and upper limits of active power generated by DGs at bus i. $Q_{DG,i,s}$ is the reactive power generated by DGs at bus i in scenario s. $Q_{DG,i}^{min}$ and $Q_{DG,i}^{max}$ are, respectively, the lower and upper limits of reactive power generated by DGs at bus i.

6) Distribution line capacity limits.

$$\left|S_{ij,s}\right| \le S_{ij}^{max} \quad \forall ij \tag{11}$$

where $S_{ij,s}$ is the apparent power transferred through line ij in scenario s. S_{ij}^{max} is the upper apparent power capacity limit of line ij.

2.3 Transmission network planning subproblem

The reinforcement deemed in the expansion subproblem for the transmission network is the line construction. The transmission network exchanges power with different distribution networks through multiple physical connections. Thus, the corresponding optimization objective can be expressed by:

$$\begin{aligned} min \quad & \sum_{ij \in \Omega_C} u_{ij}^{new} n_{ij}^{new} C_{ij}^{new} l_{ij} \\ & + \sum_s D_s \sum_{i \in \Omega_G} C_{G,i}\left(P_{G,i,s}\right) + \sum_s D_s \sum_{q \in \Omega_D} \rho_{T,q} P_{T,q,s} \\ & + \sum_s D_s \sum_{q \in \Omega_D} \left(v_{2q,s}\left(P_{T,q,s} - P_{D,q,s}\right) + \left[w_{2q,s}\left(P_{T,q,s} - P_{D,q,s}\right)\right]^2 \right) \end{aligned} \tag{12}$$

where n_{ij}^{new} is the number of new lines for line ij. $C_{G,i}(\bullet)$ is the generation cost function at bus i, and $P_{G,i,s}$ is the active power generated by generations at bus i in scenario s. $\rho_{T,q}$ is the price of energy exchanged between the transmission network and distribution network q from the transmission's perspective. Ω_G and Ω_D are, respectively, the set of generation installation buses and the set of distribution networks.

The constraints of expansion and operation which should be met by the transmission network are:

1) New line number limits.

$$0 \le n_{ij}^{new} \le n_{ij}^{new,max} \quad \forall ij \tag{13}$$

where $n_{ij}^{new,max}$ is the upper limit of new lines for line ij.

2) DC Power balance constraints.

$$P_{i,s} - \sum_{ij \in \Omega_L} B_{ij} \theta_{ij,s} = 0 \quad \forall i \tag{14}$$

3) Tie line capacity limits at transmission side.

$$P_q^{min} \le P_{T,q,s} \le P_q^{max} \quad \forall q \tag{15}$$

4) Generation output power limits.

$$P_{G,i}^{min} \le P_{G,i,s} \le P_{G,i}^{max} \quad \forall i \tag{16}$$

where $P_{G,i}^{min}$ and $P_{G,i}^{max}$ are, respectively, the lower and upper limits of active power generated by generations at bus i.

5) Transmission line capacity limits.

$$\left|P_{ij,s}\right| \le P_{ij}^{max} \quad \forall ij \tag{17}$$

where $P_{ij,s}$ is the active power transferred through line ij in scenario s. P_{ij}^{max} is the upper active power capacity limit of line ij.

3. CASE STUDY

In order to testify the performance of the proposed decentralized optimal planning approach for HTDNs, case T24D9 is designed to study where nine 33-bus distribution networks are connected to the modified IEEE RTS 24-bus transmission network at buses 1, 2, 3, 5, 6, 7, 10, 13 and 19. The parameters of generations in the transmission network and DGs in the distribution network 6 are shown in Tables 1 and 2, respectively.

Table 1 Generation data of transmission network

Generation bus	P_{min} (MW)	P_{max} (MW)	a ($/h)	b ($/MWh)	c ($/MW²h)
1	30	192	186	12.0	0.108
2	30	192	156	7.2	0.036
7	50	300	288	12.0	0.084
13	200	591	138	6.0	0.072
15	50	215	180	9.6	0.060
16	40	155	198	7.2	0.048
18	80	400	156	8.4	0.072
21	80	400	132	6.0	0.084
22	60	300	144	7.2	0.060
23	200	660	126	4.8	0.012

Table 2 DG data of distribution network 6

DG bus	P_{min} (MW)	P_{max} (MW)	a ($/h)	b ($/MWh)	c ($/MW²h)
13	0	19	60	30.0	0
25	5	25	168	6.0	0.048

The prices $\rho_{T,q}$ and $\rho_{D,q}$ are simultaneously set as 125 $/MWh. The initial value of the shared variable $P_{T,q,s}^{0}$ is set as 0. The penalty parameters $v_{2q,s}^{0}$, $w_{2q,s}^{0}$ and β are respectively set as 0, 1 and 2. The convergence thresholds ε_1, ε_2 and ε_3 are set as 0.01, 0.001 and 0.001 respectively. The upper iteration limits $l^{\max}$ and $k^{\max}$ are respectively set as 20 and 100. The data clustering method in [6,14] is adopted to reduce the number of yearly load scenarios to 20.

3.1 Planning comparison of HTDN and ITN

The transmission planning results of the HTDN method and ITN method are shown in Table 3. It can be observed that the HTDN planning can not only decrease the investment, but also reduce the amount of energy generated by generations in the transmission network. This is because the distribution's specific configuration and available controls are being considered in the HTDN planning. Thus, the objective of HTDN planning is smaller than that of ITN planning, which indicates that the HTDN method contributes to the economic performance of the transmission planning.

Table 3 Transmission network planning results for HTDN and ITN

Planning Method	New Line	Inv. Cost (M$)	Ope. Cost (M$)	Total Cost (M$)
HTDN	14-16, 16-17(2)	6.94	201.83	208.77
ITN	14-16, 16-17, 17-18, 16-19, 17-22	9.26	216.64	225.90

*16-17(2) indicates that two new lines would be constructed between buses 16 and 17.

Fig. 2 shows the amount of active power exchanged between transmission network and distribution network 6 in each scenario. It can be seen that, for the HTDN method and ITN method, the active powers exchanged between transmission network and distribution network 6 in all scenarios are positive. This indicates that the distribution network 6 needs to import electricity from the transmission network all the time. Moreover, the results of the HTDN method and ITN method are clearly different, and the active power exchange profile for the HTDN method is below those for the ITN method. Under this circumstance, the HTDN planning can benefit a lot in reducing carbon emission generated by the transmission generations.

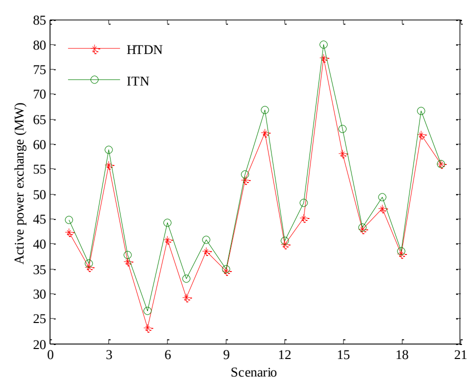

Fig 2 Active power exchange between transmission network and distribution network 6

3.2 Planning comparison of HTDN and IDN

This part compares the optimal planning of HTDN and IDN to verify the HTDN planning benefits from the distribution's perspective. Taking the distribution network 6 as an example, the planning results are given below. Note that the same conclusions can be drawn when other distribution networks are observed in the same way.

Table 4 shows the distribution network 6 planning results of the HTDN and IDN methods. The HTDN method can contribute to reducing the number of reformed lines, and the new load allocation solutions of the HTDN and IDN methods are differential. As a result, the investment cost of the HTDN method is less than that of the IDN method with respect to the distribution network 6. Although the operation cost of the distribution network 6 in the HTDN method increases compared with that in the IDN method, the total cost of the HTDN method decreases. This illustrates that the HTDN method contributes to obtaining a more economic planning scheme for distribution network 6.

Table 4 Distribution network 6 planning results for HTDN and IDN

Planning Method	Reformed Line	New Line	Inv. Cost (M$)	Ope. Cost (M$)	Total Cost (M$)
HTDN	5-6, 6-7	29-34, 22-35, 13-36, 19-37	0.75	1.29	2.04
IDN	5-6, 6-7, 7-8, 6-26, 26-27, 27-28	28-34, 21-35, 11-36, 19-37	1.17	1.18	2.35

*Buses 34-37 are the new load buses in the distribution network 6.

As shown in Fig. 3, for each local distribution network in scenario 13, the DGs of the HTDN method can generate more power compared with those of the IDN method, indicating that the HTDN planning contributes to accommodating more DGs in the distribution network.

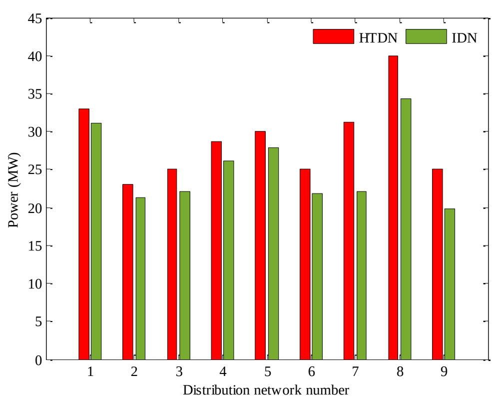

Fig 3 Active output powers of DGs in scenario 13

4. CONCLUSION

In this paper, a stochastic decentralized optimal planning method for HTDNs is proposed to optimize the expansion solution and generation dispatch for a transmission network incorporating numbers of distribution networks in a secure and economic manner. A hierarchical bi-level structure is presented and the subproblems for the transmission and distribution networks are respectively formulated. The benefits of the HTDN planning method are verified for both the transmission and distribution networks. The HTDN method contributes to the economic performance of the configuration design in terms of an independent transmission or distribution network. The carbon emitted from the generations in the transmission network can be reduced and the DG accommodation can be improved via the stochastic decentralized optimization method.

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