

Synergistic Dispatching Model of Power Source and Electric Network Considering Transmission – Distribution Connection Topology Optimization

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Abstract. For the large-scale integration of renewable generation into power grid and strengthening of active load regulation ability, the power transmission and distribution network coupling has become closer, and the contradiction between the source and network has been more prominent, which has brought new challenges to power system operation dispatching. In order to further enhance the coordination and interaction ability of the power grid, a synergistic dispatching model of power source and electric network is constructed on the basis of the traditional economic dispatching. By optimizing the transmission-distribution network connection topology, the operation economy has improved while ensuring system reliability. Case studies on a realistic power system show that the mathematical model is advantageous to the optimization of the whole power grid operation.

1. Introduction

Since 1920, as the basic means of power system optimal operation, the traditional economic dispatching aims at meeting load demand efficiently and minimizing operation cost by optimizing the generation unit output in advance, based on the load forecast and fixed power network topology. After nearly a hundred years of development, the power system economic dispatching theory and practice has been mature [1-5].

In recent years, with the increasing attention on the energy and the environment issues, it has been a human consensus to develop the Global Energy Internet and achieve sustainable development. Due to the changes of power grid pattern, the dispatching operation has faced a series of challenges: 1) With the large-scale integration of renewable resources, massive curtailment occurs due to the randomness and fluctuation characteristics of renewable energy, and contradiction between the source and network will be further intensified; 2) The development of energy storage, electric vehicle and flexible load has switched the power grid dispatching from the “generation schedule traces the changes of the load” to the “power source-electric network-load interacts”, which leads to a distributed trend; 3) The regional intelligent agents represented by the micro-grid and the active distribution network cannot only realize the optimal operation of the internal network, but can also coordinate with the whole power grid. The operation status of network equipment has been seen as decision variables in the economic dispatching to improve the efficiency of power system and realize synergy between power source and electric network [6-10]. Additionally, the concept of economic dispatching from transmission network economic dispatching and regional intelligent agents to the transmission-distribution network synergy [11-14], and provided an important theoretical foundation for the development of the Global Energy Internet.

It can be seen that achieving synergistic dispatching is the fundamental for the optimal operation

of the future power grid. At present, the electric network topology optimization is mainly concentrated in optimal transmission switching (OTS) or distribution network reconstruction (DNR). While the power flow analysis, optimal dispatching and voltage support of the transmission and distribution synergy are mostly based on fixed transmission-distribution connection topology. In fact, most of the distribution substations are supplied with dual-supply and dual-loop electrical system, and the connection branch switching can be achieved through the remote control. In this way, the key indicators such as load mode, locational marginal prices (LMP) and voltage quality can be improved. This paper focuses on synergistic dispatching of power source and electric network, and proposes a mathematical model of economic dispatching considering transmission-distribution connection topology optimization.

The paper is organized as follows. Section 2 introduces several typical transmission-distribution network connection topology. Section 3 presents the mathematical model for dynamic economic dispatching model with distribution network branch switching. In Section 4, case studies are conducted to illustrate the effectiveness and feasibility of the proposed method. Section 5 is the summary and prospect.

2. Transmission-distribution connection redundancy topology architecture

In the stage of power network planning, considering factors such as load demand, geographical location and line corridor, a variety of transmission-distribution network connection topology structures are formed. Several transmission and distribution connection topologies based on actual network in China are shown in Fig.1- Fig.5 respectively.

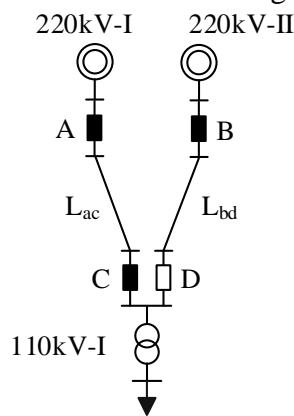


Fig.1 Dual-supply and dual-loop power supply of 110kV substation.

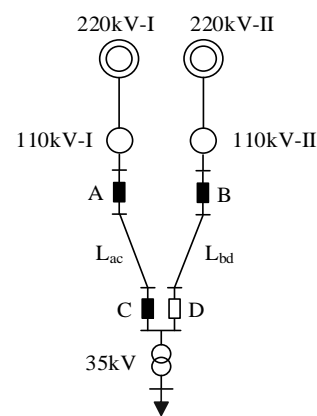


Fig.2 Dual-supply and dual-loop power supply of 35kV substation.

The dual-supply and dual-loop power supply of 110kV substation is shown in Fig.1. The substation 110kV station I can be connected to 220kV station I and 220kV station II through the branches L_{ac} and L_{bd} respectively by remotely switching C and D. In case of normal operation, switch A and switch B are online, one of switch C and switch D is online and the other is regarded as the hot standby. The two 220kV substations can be regarded as two independent power supplies for 110kV station I as they belong to different buses. Similarly, the schematic diagram for the typical 35kV substation dual-supply and dual-loop power supply is as shown in Fig.2.

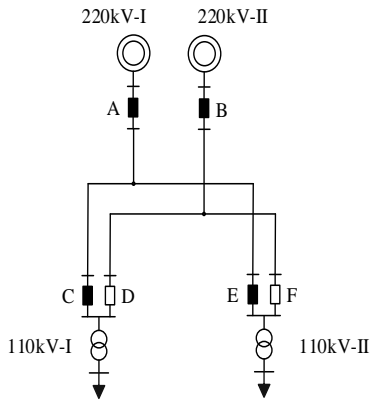


Fig.3 Dual-supply under T connection mode

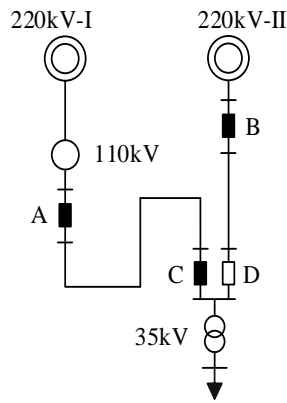


Fig.4 Distribution substation connect to substation at different voltage levels

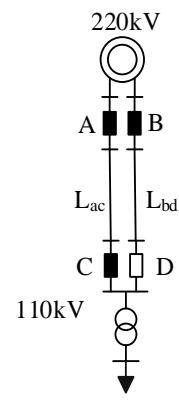


Fig.5 Single-supply and dual-loop power supply of 110 kV substations

Considering the practical limit of power grid planning, the completely independent power supply branches are difficult to achieve. In fact, T connection mode are more common as shown in Fig.3. Compared with Fig.1, although the branches are not directly connected to the superior substation, the online switching can still be achieved through controlling switches (switch C and switch D, switch E and switch F) at the substation side.

As shown in Fig.4, this power supply mode is applied to some 35kV substations that a branch is connected to 35kV bus of 110kV substation, and the other is connected to 35kV transformer side of 220kV substation. Normally, 220kV transformer is the three-winding transformer. Therefore, if 110kV transformer is the two-winding transformer, online switching can be achieved, otherwise, if 110kV transformer is the three-winding transformer, online operation is not allowed. The branch switching can only be operated after power cut of distribution substation.

In the realistic power grid, there are a few dual-loop power supply modes as shown in Fig.5. The distribution substation has two power supply branches that are from the same 220kV substation, which has no effect on the power flow of transmission network and optimal operation of power grid.

In summary, it can be known that transmission–distribution connection topology has inevitably effects on the power flow of transmission network. Optimizing the topology of the transmission–distribution can achieve the synergy between power source and electric network, and improve operation efficiency of the power grid.

3. Synergistic dispatching model of power source and electric network considering transmission–distribution connection topology optimization

In order to illuminate the influence of the transmission–distribution connection topology on the power system optimal operation, this paper ignores the impact of voltage magnitude and network loss. Considering transmission–distribution connection topology optimization, based on DC power flow, synergistic dispatching model of power source and electric network is proposed.

3.1. Objective function

The objective of the traditional economic dispatching problem is to minimize the system operation cost. In this paper, the load balance degree is added to the objective function. The load balancing is important for safety of power systems [15], especially in the system with large-scale renewable generation integration. Under the guidance of load balance degree, the unique optimal solution will be found.

$$\min \sum_{t \in T} \sum_{g \in G} (c_{ng} P_{ng,t} + b_{ng}) + K \cdot \sum_{t \in T} \sqrt{\sum_{j \in L} \left(R_j - \frac{\sum_{k \in L} R_k}{N} \right)^2} \quad (1)$$

where T , G and L denote the sets of period, generators and branches respectively; N is the total number of branches; c_{ng} and b_{ng} are the cost coefficients of generator g ; $P_{ng,t}$ is the active power injected into bus n by generator g in period t ; $R_{k,t}$ is the load balance degree of the branch k^{th} in period t , $R_{k,t} = P_{nk,t} / P_{nkmax}$; $P_{nk,t}$ is the active power flow on branch k^{th} to bus n in period t ; P_{nkmax} is the maximum active power on branch k^{th} ; K is the proportional coefficient of objective function.

3.2. Constraint conditions

3.2.1. Generator active power constraint

$$P_{ng}^{\min} \leq P_{ng,t} \leq P_{ng}^{\max} \quad (2)$$

where P_{ng}^{\min} and P_{ng}^{\max} are the minimum and maximum of active power injected into the bus n by the generator g respectively.

3.2.2. Voltage angle constraint

$$\theta_n^{\min} \leq \theta_{n,t} \leq \theta_n^{\max} \quad (3)$$

where $\theta_{n,t}$ is the voltage angle of bus n in period t ; θ_n^{\min} and θ_n^{\max} are the minimum and maximum voltage angle of bus n in period t respectively.

3.2.3. Nodal power balance constraint

$$\sum_{k \in L} P_{nk,t} + \sum_{g \in G} P_{ng,t} = \sum_{d \in D} P_{nd,t} \quad (4)$$

where D denotes the set of buses; $P_{nd,t}$ denotes the active power load at bus n in period t .

3.2.4. Branch transmission power constraint

$$P_{nk}^{\min} z_{k,t} \leq P_{nk,t} \leq P_{nk}^{\max} z_{k,t} \quad (5)$$

where P_{nk}^{\min} and P_{nk}^{\max} are the minimum and maximum active power on branch k^{th} ; $z_{k,t}$ represents the status of the branch k^{th} that $z_{k,t}=1$ reflects a closed status, and $z_{k,t}=0$ reflects an open status.

3.2.5. Branch power flow balance constraint

In the proposed model, we assume that the transmission network topology has been fixed. Thus, the branch power flow balance constraint need to be satisfied for transmission branches.

$$B_k (\theta_{n,t} - \theta_{m,t}) - P_{nk,t} = 0 \quad k \in LT \quad (6)$$

where LT is the set of transmission branches; B_k is the electrical susceptance of the branch k^{th} ; n and m are the buses at two ends of the branch k^{th} .

The branch power flow balance constraints for the distribution substation branches are as shown in formula (7). The branch status variable $z_{k,t}=1$ reflects that two constraints are transformed into an equation. If the variable $z_{k,t}=0$, the formula (7) will be transformed into two unconstrained inequalities due to the large value M .

$$\begin{aligned} B_k (\theta_{n,t} - \theta_{m,t}) - P_{nk,t} + (1 - z_{k,t}) M &\geq 0 \\ B_k (\theta_{n,t} - \theta_{m,t}) - P_{nk,t} - (1 - z_{k,t}) M &\leq 0 \end{aligned} \quad k \in LD \quad (7)$$

where LD is the set of distribution substation branches; M is a given large value which takes $B_k (\theta_{n,t}^{\max} - \theta_{m,t}^{\min})$ in this paper.

3.2.6. Uniqueness constraint for power supply branch

There is only one power supply branch for each distribution substation at bus d . The sum of the power supply branch status variables for bus d equal to 1.

$$\sum_{k \in dK} z_{k,t} = 1 \quad (8)$$

where dK is the set of power supplying branches to the distribution substation at bus d .

4. Case study

To illustrate the effectiveness of the proposed mathematical model, a 6-bus transmission system and actual transmission-distribution connection topology in Shandong province is considered. The 6-bus transmission system is as shown in Fig.6.

The parameters of branch and generator are listed in Table 1 and Table 2, the transmission-distribution network connection topology architecture is as shown in Table 3, and load curve at four time periods are shown in Fig.7.

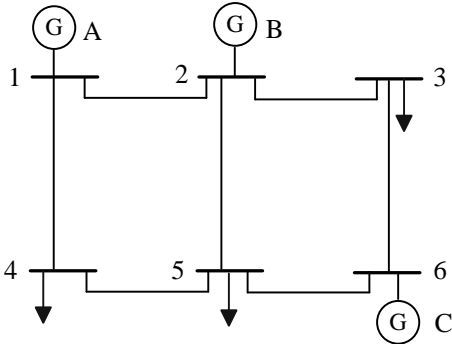


Fig.6 6-bus transmission system diagram

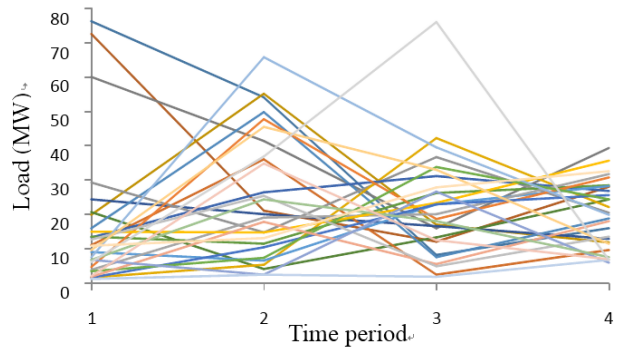


Fig.7 Load curve of the actual power system

Table 1 Branch parameters for the 6-bus system

Transmission branch	Reactance (pu)	Transmission capacity (MW)
1-2	0.17	200
1-4	0.258	300
2-3	0.037	300
2-5	0.197	100
3-6	0.018	200
4-5	0.037	200
5-6	0.14	200

Table 2 Generator parameters for the 6-bus system

Generator	Capacity (MW)	Marginal cost (USD/MWh)
A	300	20
B	200	29
C	500	40

Table 3 Transmission-distribution network connection topology

Distribution bus	Superior connection bus	Distribution bus	Superior related bus
7	3, 4	20	18, 21
8	3, 4	21	11
9	3, 4, 5	22	3
10	3, 5	23	4
11	3, 5	24	5
12	3, 5	25	5
13	4, 5	26	4
14	4, 5	27	4
15	4, 5	28	4
16	8, 15	29	5
17	14, 10	30	3
18	10, 11	31	3
19	11, 12	-	-

Two economic dispatch schemes are carried out as follow.

Scheme I: Economic dispatch is carried out based on the fixed transmission-distribution connection topology designated at random during the study period.

Scheme II: Economic dispatch is carried out considering transmission–distribution connection topology optimization.

Table 4 Fixed transmission-distribution connection topology in Scheme I

Distribution bus	Connection branch	Branch status	Distribution bus	Connection branch	Branch status
7	3-7	0	14	4-14	0
	4-7	1		5-14	1
8	3-8	1	15	4-15	0
	4-8	0		5-15	1
9	3-9	1	16	8-16	1
	4-9	0		15-16	0
10	3-10	0	17	10-17	0
	5-10	1		14-17	1
11	3-11	0	18	10-18	1
	5-11	1		11-18	0
12	3-12	1	19	11-19	1
	5-12	0		12-19	0
13	4-13	0	20	18-20	1
	5-13	1		21-20	0

Note: 1 is the closed state, 0 is the disconnected state

Table 5 Optimal generator output results in Scheme I

Time period	t1	t2	t3	t4
Unit A (MW)	300.0	300.0	259.2	300.0
Unit B (MW)	82.9	0.0	0.0	0.0
Unit C (MW)	82.9	328.2	360.8	270.8
Total cost (USD)	67299.5			
Load balance degree	19.01			

The fixed topology is shown in Table 4 and the optimization results of Scheme I are as shown in

Table 5. Total operating cost is 67299.5USD and the balance degree is 19.01. It can be seen that the output of unit C is much more than the more economical unit B. It is because that, with more distribution substations connected to bus 4 and 5, larger power flow passing through branch 2-5 which is of smaller transmission capacity and other branches with abundant transmission capacity cannot play a role.

Table 6 Optimal transmission-distribution connection topology results in Scheme II

Distribution bus		7		10		11		13		14	
Connection branch		3-7	4-7	3-10	5-10	3-11	5-11	4-13	5-13	4-14	5-14
Branch status	t1	1	0	0	1	1	0	1	0	0	1
	t2	1	0	1	0	1	0	1	0	1	0
	t3	1	0	1	0	1	0	0	1	1	0
	t4	1	0	1	0	1	0	1	0	1	0
Distribution bus		15		17		18		19		20	
Connection branch		4-15	5-15	10-17	14-17	10-18	11-18	11-19	12-19	18-20	21-20
Branch status	t1	1	0	0	1	0	1	0	1	0	1
	t2	1	0	1	0	1	0	0	1	0	1
	t3	1	0	1	0	1	0	1	0	1	0
	t4	1	0	1	0	1	0	0	1	1	0

Table 7 Optimal generator output results in Scheme II

Time period	t1	t2	t3	t4
Unit A (MW)	300.0	300.0	300.0	300.0
Unit B (MW)	165.8	196.5	200.0	199.5
Unit C (MW)	0.0	221.0	120.0	116.4
Total cost (USD)	64389.6			
Load balance degree	16.87			

The optimization results of Scheme II are as shown in Table 6 (only the topology connections different from Scheme I are listed) and Table 7. Total cost is reduced to 64389.6USD and the load balance degree is reduced to 16.87. By making full use of economic units and large-capacity transmission branches, the bottleneck effect caused by some weak parts has been alleviated.

It can be seen that the optimal power supply branches of the distribution buses are different due to the different load pattern. Considering the inconsistency of active distribution network and increase of distributed generation, it is necessary to seek for the optimal transmission-distribution connection topology.

5. Summary and prospect

In this paper, an economic dispatching model based on DC power flow is established by taking the transmission-distribution topology structure into the power grid optimization operation as decision variables. The positive effects of transmission-distribution coordination on power system economic dispatching has been illuminated.

Modern transmission network are connected with numerous distribution networks which are controlled by different subordinate control centres. For meeting the actual demand of the power grid, it is necessary to improve coordination between transmission and distribution network and enhance synergy between power source and electric network.

In addition, with the large-scale integration of renewable generation into distribution networks, the voltage fluctuations has become more and more serious. Further study need to be done based on the AC power flow.

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