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A Link-Path Model-Based Load-Transfer Optimization Strategy for Urban High-Voltage Distribution Power System

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ABSTRACT In order to alleviate the congestion and overload in high-voltage distribution network (HVDN), a load-transfer optimization method has been developed based on Link-path model. The topology characteristics of HVDN have been analyzed and the basic topological unit (BTU) is adopted. All the typical connection modes in 110kV substations can be easily described with BTU. Link-path model (LPM) is a modelling method used in the field of communication and routing technologies in which there are similarities between LPM and the connection relationships of HVDN. Thus, based on ideas of LPF, the 'domain', 'set of link', 'set of path' and so on are defined to depict HVDN topology. The Link-path based load-transfer optimization model is much more straightforward and easily obtained. The model only needs to search from each unit based on the network topology and form relative data sets. It avoids the high dimension problem which appears in other methods like incidence matrix and tree model. Thus this model could reduce the nonlinear degree and solving difficulty in load-transfer optimization problem. The method is suitable for system dispatching analysis and strategy-making for HVDN system. A load-transfer optimization model for HVPN has been developed and the results with one real test system proved the feasibility and validity of the proposed LPM method.

INDEX TERMS High-voltage distribution network (HVDN), load-transfer, link-path model, basic topological unit (BTU), load shedding.

I. INTRODUCTION

With the rapid urbanization in China, the town loads, represented by residents, industry and commerce, services, high-end manufacturing, are developing rapidly in recent years. The load sides have heightened the demands for power system, such as reliable dispatching and fast failure restoration. However, due to the construction lag of 220kV and 110kV transmission network (referred to high voltage distribution network, HVDN), many problems are becoming increasingly prominent. Those problems include the highly unbalanced load-distribution, the capacity shortage of 220kV power station, etc. They will easily cause the equipment overload and transmission line congestion (i.e., line overload). So the dispatching control becomes more complex and difficult especially during the peak hours of loads. Only relying on the experiences or by trial and error, it is very difficult to make timely and optimal load-transfer strategies. Moreover, the economy and reliability of HVDN can't be realized, sometimes, there are even some operational risks and power failures.

The load-transfer, as an effective approach to overcome the overloaded or heavily-loaded problems, could balance loads among substations and feeders by network reconfiguration to overcome the line congestion and overload [1]. Essentially, load-transfer is a large-scale, nonlinear, mixed integer (0-1) programming problem with one or several optimal objectives. Nowadays, most load-transfer or network reconfiguration problems are focused on the low & medium voltage distribution network (L&MVDN, the voltage is less than or equals to 35kV) which aims at loss reduction, reliability, voltage quality and load shedding minimum etc. [2]–[5]. The topology of

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L&MVDN is often characterized by incidence matrix or tree model based on graph theory [6], [7] and commonly used algorithms are heuristic methods [5], [8], [9] like branch exchange method and mathematical programming optimization algorithms [2], [10], [11], the meta-heuristic algorithms like GA (genetic algorithm), PSO (particle swarm optimization) or their improved algorithms [12]–[15]. But the HVDN has significant differences from L&MVDN. In HVDN, there are many meshed networks, so there are more choices for power sources or power supply paths selections. Thus, there are more operation modes for 110kV transmission networks and high frequency of load-transfers operations. Those characteristics determine the different modeling ideas and control decisions between HVDN and L&MVDN. Thus, the methods mentioned above may be not suitable or even infeasible for HVDN.

Aiming at HVDN, in [16], in order to achieve the optimal expansion of 220kV station capacities and 110kV transmission lines, a two-stage model for optimal planning of HVDN was set up. An improved Genetic Algorithm (GA) is developed to solve this complex model. In [17], in order to improve the HVDN's power supply capacity, the power supply regions of each substation were divided by weighted Voronoi graph firstly, then with the backward optimization method, the connecting relations matrix among main-transformers were formed to determine reasonable connecting structure among the power stations. But because of the searching difficulty and the high sparsity of the matrix, those methods or even intelligent algorithms can't guarantee the stability and efficiency for the high dimensional nonlinear problem. In order to reduce the solution space, a basic topological unit of HVDN was presented in [18], [19]. In [18], specifically, based on the load balancing function, an optimal model was established by aiming to alleviate congestion of urban power system by means of reconfiguring each basic topological unit. In [19], a bi-level programming model had been built. The upper level aims to guide the reasonable load allocation of system, while in the lower level, the supply channel matrix is used to execute those orders from upper level in each topology unit and then feedback the results. The PSO algorithm is used in those two papers. But considering the non-deep and multi-meshed HVDN, it has several problems like generating massive unfeasible solutions, getting premature convergence solution and having a slow convergence. In addition, the approach in [18], [19] applies DC power flow, and the voltages are not calculated. In general, voltage constraints are important in the operation of distribution networks. Moreover there are few related works which directly to solve the load-transfer problems in HVDN.

The aim of load transfer discussed in this paper is to avoid the 220kV power stations overloaded (heavily loaded) and 220kV transmission line congestion (overloaded or heavily loaded situations) by load transfer with 110kV transmission network reconfiguration. Then a much balanced operation level can be obtained for the whole 220kV networks. The Link-path model (LPM) was used to depict the HVDN's topology here. LPM is one of the modelling methods for large-scale network programming in the field of communication and routing technologies [20], [21]. As a flexible and straightforward describing way, it is widely used in the fields like protection of shared-link network coding path [22], [23], channel assignment [24] etc.. The connection relationships for 'power station to power station' and 'power station to load' in HVDN are similar to LPM. Therefore, combining with the non-deep and multi-meshed features in HVDN, the Link-path based model for HVDN system is defined in this paper. The model can eliminate most irrelevant connecting factors, reduce variable dimension and has a higher linearity. In addition, an improved linear power flow model with accurate estimation of voltage magnitude was applied and the voltage constrains were included in the optimal objective solving. All of those further reduce the solving difficulty. A real urban power system in China was used to test and verify the proposed method.

The main contributions of this paper are twofold.

The basic topological units are applied, and then 'domain', 'Set of link', 'set of path', etc., which are used to depict HVDN topology, are defined based on Link-path model (LPM). The proposed LPM based HVDN model can reduce variable dimension and problem complexity greatly.

A load-transfer optimization method for HVPN has been introduced based on Link-path model. The linear power flow algorithm is adopted to keep model's linearity and can bear easy access to the solutions of optimization problem.

The remainder of the paper is organized as follows. Section II presents a brief description of the HVDN topology and basic topological unit. Section III presents the HVDN modeling based on Link-path. Section IV presents optimization model of load-transfer for HVDN. The numerical results are discussed in section V. The last section concludes this paper.

II. TOPOLOGY ANALYSIS OF HVDN

A. CHARACTERISTICS OF HVDN

As mentioned above, HVDN are significantly different from L&MVDN. HVDN has a multi-meshed structure and normally develops in terms of width (multi-meshed) but not depth (radial, more nodes along one transmission line) around each 220kV power station. As shown in Fig.1, HVDN has much lower average depth along transmission line than L&MVDN. Moreover, each 110kV substation has at least one back-up supply line, so there are so many load-transfer strategies in HVDN. That is, the power can be transferred by multiple parallel lines and the switch-over strategies between the main supplies (220kV power stations) and the back-up supplies (110kV transmission lines or section switches) are very flexible.

To alleviate the congestion and overload of HVDN during load-peak period, the optimal load-transfer strategy has to be put up with by solving the following two problems under the condition that the constraints of HVDN system are met.

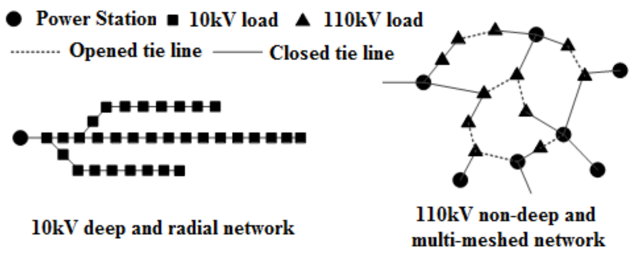


FIGURE 1. Topology differences between 10kV and 110kV distribution networks.

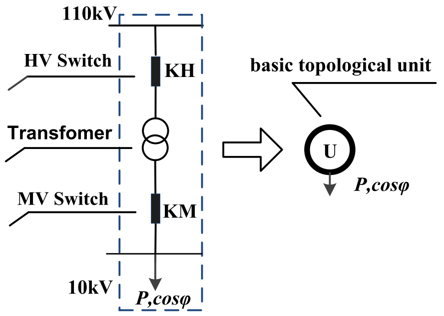


FIGURE 2. The basic topological unit.

1) According the actual dispatching rules, load-transfer strategies are adopted through adjusting the connections among 110kV substations and 220kV power stations with different 110kV transmission line reconfigurations. It aims at the goals like the elimination of heavily-loaded or overloaded main transformers, optimal load balance and the minimum power loss with as few switch operations as possible.

2) When single fault of 220kV system occurs (including 220kV transmission line fault and one 220kV main transformer quits), it needs to transfer enough loads with as few shedding load as possible to guarantee the system stability and safety.

It must be stressed that the congestion and overload problems usually occurs during load peak period. And at the time the load has already changed or will change dramatically. Unlike in L&MVDN, the load predictability in HVDN is much higher. So the peak load value at target time section can be seen as a given constant, that is, the predicted value. Thus, this paper focuses on the congestion and overload alleviations through load-transfer and network reconfiguration. In addition, the power losses in 110kV transmission lines are ignored to simplify the analyses. Moreover, considering that the urban HVDN generally has good reactive compensations on the spot, the active load balance problem is only taken into account in this paper.

B. BASIC TOPOLOGICAL UNIT (BTU)

The basic topological unit (BTU) was defined in [19]. It just describes that the active power is delivered from high voltage side to low voltage side. In HVDN, BTU specifically refers to the 110kV substation equipment group, including 110kV/10kV transformer, high & medium voltage buses and switches etc.. BTU is marked as shown in Fig.2, where P indicates the active power delivered from the source. It focuses on the delivered active power and connected transmission channels (paths or routines), so all the typical connection modes in 110kV substations can be depicted with BTU [19]. When the renewable power sources are connected into the grid on lower voltage substation, that is, the active power will delivered from low voltage side to high voltage side. BTU model can also deal with the situation in which P is negative value.

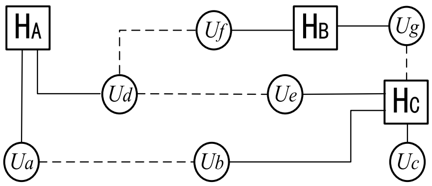


FIGURE 3. A small system of HVDN.

Fig.3 shows a small HVDN diagram with basic topological units. Here, H$_m$ stands for 220kV power station (power source), U_k stands for BTU (110kV substation) and the dashed line indicates the back-up supply path (back-up line or tie-bus switch).

III. HVDN MODELING BASED ON LINK-PATH MODEL

Taking the system in Fig.3 for example, there are three 220kV sources, seven basic topological units (110kV substations), seven supply lines and four back-up lines. The modeling method and process are explained as follow in detail.

A. DOMAINS

Power domain, $\boldsymbol{H}$, refers to the set of all the 220kV power stations. In Fig.3, $\boldsymbol{H} = \{A, B, C\}$.

Basic topological unit domain, $\boldsymbol{D}$, refers to the set of all the basic topological units (110kV substations). In Fig.3, $D = \{a, b, c, d, e, f, g\}$.

B. SET OF POWER SUPPLY PATHS (SP)

For $\forall u \in \boldsymbol{D}_u$, its **SP,** marked with $\boldsymbol{R}_u = \{R_{su}\}$, refers to all the power supply paths that can deliver power from s ($s \in \boldsymbol{H}$) to u (including back-up lines). Each basic topological unit has its own **SP**. In Fig.3, for the basic topological units a and e, $\boldsymbol{R}_a = \{R_{Aa}, R_{Ca}\}$ and $\boldsymbol{R}_e = \{R_{Ae}, R_{Be}, R_{Ce}\}$ respectively. All $\boldsymbol{R}_u$ can be easily obtained by using depth-first search method.

C. POWER SELECT FACTOR (SF)

SF, marked with $\boldsymbol{x}_u = \{x_{su}\}$, is the control variable set which is one-to-one corresponding to $\boldsymbol{R}_u$. The value of x_{su} is 1 or 0. For x_{su} =1, it means that the power are delivered from source s to basic topological unit u (then the R_{su} is a connected and effective path). And x_{su} =0 means that the path R_{su} is disconnected. Taking the original network in Fig.3 for example, $\boldsymbol{x}_a = \{x_{Aa}, x_{Ca}\} = \{1, 0\}$ and

$\boldsymbol{x}_e = \{x_{Ae}, x_{Be}, x_{Ce}\} = \{0, 0, 1\}$. It needs to ensure the 110kV network radial all the time, so in each set $\boldsymbol{x}_u = \{x_{su}\}$, there is only one element whose value is "1". That is, there is only one path which is the connected and effective path for each basic topological unit u.

D. SET OF POWER SUPPLY SOURCE (PS)

PS, marked with $E_u = \{s\}$ (($s \in \boldsymbol{H}$), refers to the source set that can deliver power to unit u. There exists a one-to-one correspondence between $\boldsymbol{E}_u$ and $\boldsymbol{R}_u$. In Fig.3, for the basic topological units a and e, $E_a = \{A, C\}$ and $\boldsymbol{E}_e = \{A, B, C\}$ respectively.

E. SET OF POWER SUPPLY UNITS (SU)

SU, marked with $\boldsymbol{D}_s = \{u\}$, refers to the basic topological unit set that can get power (that is, there exists at least one power supply path) from given source s. In Fig.3, for the sources A, B and C, $\boldsymbol{D}_A = \{a, b, d, e, f\}$, $\boldsymbol{D}_B = \{d, e, f, g\}$ and $\boldsymbol{D}_C = \{a, b, c, d, e, f, g\}$ respectively.

F. SET OF POWER LINKS (PL)

Define one power transmission line or one tie-bus switch between two adjacent s and u or u and u as one power link. All power links of HVDN form the **PL**, marked with $\boldsymbol{L} = \{l_{ij}\}$ ($i, j \in \boldsymbol{H} \cup \boldsymbol{D}$, $i \neq j$, i is adjacent to j). And l_{ij} is a 0-1 integer variable, $l_{ij} = 1$ indicates the corresponding link is connected (like l_{Aa} in fig.3) and $l_{ij} = 0$ indicates the corresponding link is disconnected (like l_{ab} in fig.3). The value of l_{ij} is determined by x_{su} and will be explained below. In Fig.3, there are eleven power links (seven supply (solid) lines and four back-up (dashed) lines).

G. SET OF LINK-PATHS (LP)

Each power link belongs to one or some power supply paths. The power supply paths including l_{ij} form **LP** of l_{ij}, marked with $F_{ij} = \{R_{su}\}$.

In Fig.3, for links l_{Cb} and l_{de}, $\boldsymbol{F}_{Cb} = \{P_{Ca}, P_{Cb}\}$ and $\boldsymbol{F}_{de} = \{R_{Ae}, R_{Ad}, R_{Be}\}$ respectively. Therefore, it can be known that $\forall R_{su} \in \boldsymbol{F}_{ij}$, if $\exists x_{su} = 1$, then $l_{ij} = 1$. That is, if there is an effective and connected path P_{su} which includes power link l_{ij}, then $l_{ij} = 1$, otherwise is $l_{ij} = 0$.

H. OTHER DEFINITIONS

Transferring power, $\boldsymbol{T}_{su}$, there is a one-to-one correspondence between $\boldsymbol{T}_{su}$ and $\boldsymbol{R}_{su}$. When $\boldsymbol{R}_{su}$ is an effective path (x_{su}= *1*), $\boldsymbol{T}_{su}$ equals to the power delivered from s to u through path $\boldsymbol{R}_{su}$, otherwise, $\boldsymbol{T}_{su}$ is zero.

Source capacity,C_s, indicates the rated capacity of power station s.

Link capacity, $\boldsymbol{C}_{ij}$, indicates the maximum transmission capacity of l_{ij}.

Load of unit, $\boldsymbol{L}_u$, represents the total load demand of u.

Power of source, $\boldsymbol{L}_s$, represents the total power delivered from s.

Traditional methods often have to consider massive topology connections, so it will cause combination explosion problem and highly computational burden for large-scale HVDN. The method based on Link-path here doesn't need to list out all the connections. It only needs to search from the load sides to the sources and then forms relative data sets.

IV. OPTIMIZATION MODEL AND SOLVING METHOD

A. OPTIMIZATION GOALS

1) LOAD BALANCE DEGREE

The balance degree is a significant index to evaluate the economic and safe operation of HVDN. The balance degrees for 220kV power station and transmission lines, B_s and B_l, can be calculated by,

$$B_s = \sqrt{\frac{1}{N_s}\sum_{i=1}^{N_s}(\kappa_{si} - \frac{1}{N_s}\sum_{i=1}^{N_s}\kappa_{si})^2} \tag{1}$$

$$B_l = \sqrt{\frac{1}{N_l}\sum_{i=1}^{N_l}(\kappa_{li} - \frac{1}{N_l}\sum_{i=1}^{N_l}\kappa_{li})^2} \tag{2}$$

where N_s is the number of 220kV power stations and N_l is the number of 220kV transmission lines, $\kappa_{si} = L_{su}/C_{si}$ and $\kappa_{li} = S_{li}/S_{li.\max}$ is load-rate of 220kV power stations and transmission lines, $S_{li.max}$ and S_{li} stand for the maximum transmission capacity and real transmission power of 220kV line i(corresponding to $S_{ij.max}$ and S_{ij} in following inequation (16) respectively).

The above balance degrees are solved based on the mean square error (MSE) of load-rates. The smaller B_s and B_l are, the more balance system is. For the overload of transformer has great influence on the safety of HVDN and often happens, but there are few line overloads according to real situation. Thus, in this paper, the main aim is to reduce the load-rate of power stations. When considering load balance of power stations, the optimization objective function, F_1, is formed based on the ∞-norm, that is,

$$F_1 = \min\left(\max\{\kappa_{si} = \frac{L_{si}}{C_{si}}\}\right) \tag{3}$$

2) MINIMUM SHEDDING LOAD

For any unit, u, define load-shedding factor h_u ($0 < h_u < 1$). That is, when the capacity is P_u, if it has to cut off part of load, ΔP_u, to ensure not overloaded, so,

$$h_u = \frac{\Delta P_u}{P_u} \tag{4}$$

Then the total load after load transferring, marked with M_D, can be calculated by using load-shedding factors h_u,

$$M_D = \sum_{s\in \boldsymbol{S}, u\in \boldsymbol{D}} (1 - h_u)L_u \tag{5}$$

In order to minimize shedding load, the load-shedding objective function can be described as,

$$F_2 = \min(1 - \frac{M_D}{\sum_{u\in \boldsymbol{D}} L_u}) \tag{6}$$

B. THE CONSTRAINTS

1) RADIAL CONSTRAINTS OF 110kV NETWORK

In order to ensure the 110kV network radial all the time, each basic topological unit is supplied only by one 220kV power station (that is, there is only one connected and effective path for one basic topological unit). For power select factor x_{su} is a 0-1 integer variable, so the constraint can be described as,

$$\sum_{s\in \boldsymbol{E}_u} x_{su} = 1 \quad (\forall u \in \boldsymbol{D}) \tag{7}$$

For example in Fig.3, $x_{Aa} + x_{CA} = 1$.

2) CONSTRAINT OF LOAD DEMAND AT EACH BASIC TOPOLOGICAL UNIT

$$\sum_{s\in E_u} x_{su} \cdot T_{su} = L_u \quad (\forall u \in \boldsymbol{D}) \tag{8}$$

where $\boldsymbol{L}_u$ is the load demand of u.

For example in Fig.3, $x_{Aa} \cdot T_{Aa} = L_{\mathrm{a}}$, $x_{Ca} \cdot T_{Ca} = 0$.

3) CONSTRAINTS OF CAPACITIES

For 220kV power stations, it needs to meet,

$$\sum_{u\in D_s} x_{su} \cdot T_{su} \le k_s C_s \quad (\forall s \in \boldsymbol{H}) \tag{9}$$

where k_s refers to the safety load-rate parameter of 220kV power station, $0 < k_s \le 1$. And k_s needs to be set based on the maximum thermal capacity of station transformer and network stability (such as dynamic or transient stability thresholds for single condition), etc.

For example in Fig.3, it has,

$$x_{Bd}T_{Bd} + x_{Be}T_{Be} + x_{Bf}T_{Bf} + x_{Bg}T_{Bg} \le k_B * C_B$$

Maximum transmission capacity constraint of 110kV lines,

$$\sum_{x_{su}\leftrightarrow R_{su}\in \boldsymbol{F}_{ij}} x_{su}T_{su} \le C_{ij} \tag{10}$$

where $i, j \in \boldsymbol{H} \cup \boldsymbol{D}$, $i \ne j$ and i is adjacent to j.

For example in Fig.3, $x_{Ab}T_{Ab} + x_{Ca}T_{Ca} \le C_{ab}$.

4) CONSTRAINT OF NO-CROSS CONNECTION

For the units between two 220kV power stations, it means that their power supply path can't have cross overlap. Taking Fig.4 for example, the cross connection should be avoided, that is, when U_a is supplied by H2, U_b has to be supplied by H2 and can't be supplied by H1. Generally speaking, any unit v located in the effective path P_{su} must be supplied by s. Hence, the constraint function can be defined as,

$$x_{sv} \ge x_{su} \tag{11}$$

In Fig.4, the constraints of no-cross connection are $x_{s1a} \ge x_{s1b}$ and $x_{s1b} \ge x_{s1c}$.

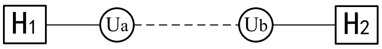


FIGURE 4. One example of no-cross connection.

5) CONSTRAINTS OF NUMBER OF SWITCHING

To ensure the radial structure of 110kV network, the switch operations, "open" and "close", are appear in pairs (called one switch operation). Comparing $\boldsymbol{L}$ after load-transfer optimization with original $\boldsymbol{L}_{\mathrm{ini}}$ before load-transfer optimization, the total switching number could be calculated as,

$$O = \frac{\sum \left| l_{i,j} - l_{\mathrm{ini}\_i,j} \right|}{2} \quad (i, j \in \mathbf{H} \cup \mathbf{D}, i \ne j, \text{i is adjacent to j}) \tag{12}$$

And $\boldsymbol{O}$ should be less than or equal to a certain limit,

$$O \le N \tag{13}$$

where, N is an allowable maximum number of switching.

6) CONSTRAINTS OF 220kV NETWORK POWER FLOW

For the certain connections among 110kV network, the load of each 220kV power station is also specified (not consider the loss). Considering good reactive compensation and the constant power factor model is adopted here. In order to keep optimization model's linearity, an improved linear power flow model with accurate estimation of voltage magnitude, was applied to calculate power flow here [25].

$$\begin{bmatrix} \boldsymbol{P} \\ \boldsymbol{Q} \end{bmatrix} = \begin{bmatrix} -\boldsymbol{B}' & \boldsymbol{G} \\ -\boldsymbol{G} & -\boldsymbol{B} \end{bmatrix} \begin{bmatrix} \boldsymbol{\theta} \\ \boldsymbol{V} \end{bmatrix} \tag{14}$$

where $\boldsymbol{G} + j\boldsymbol{B}$ is the system's admittance matrix; B' is the modified admittance matrix $\boldsymbol{B}$ which does not contain the shunt admittance; $\boldsymbol{P}$ and $\boldsymbol{Q}$ are the active and reactive powers demands of all 220kV power stations.

Then the active power transferred through 220kV transmission line L_{ij} can be deduced as,

$$\begin{cases} P_{ij} = \mathrm{g}_{ij}(V_i - V_j) - \mathrm{b}_{ij}(\theta_i - \theta_j) \\ Q_{ij} = -\mathrm{b}_{ij}(V_i - V_j) - \mathrm{g}_{ij}(\theta_i - \theta_j) \end{cases} \tag{15}$$

where $\mathrm{g}_{ij} + j\mathrm{b}_{ij}$ is the admittance of branch L_{ij}.

And the inequality constraints of power flow are,

$$\begin{cases} \theta_{i\min} \le \theta_i \le \theta_{i\max} \\ V_{i\min} \le V_i \le V_{i\max} \\ S_{ij} = \sqrt{P_{ij}^2 + Q_{ij}^2} \approx \alpha_{ij}P_{ij} \le S_{ij\max} \end{cases} \tag{16}$$

where $\theta_{i\min}$, $\theta_{i\max}$, $V_{i\min}$ and $V_{i\max}$ are the upper and lower bounds of angle θ_i and voltage V_i respectively; $S_{ij\max}$ is the maximum transmission capacity branch L_{ij}; α_{ij} is the scaling factor between branch apparent power and active power, in this paper, $\alpha_{ij} = 1.06$ based on the conclusion of the actual urban HVDN system (used as the test cases in Section 5).

7) LOAD SHEDDING

When the single fault in 220kV power system occurs, in order to keep the power system safe, it needs to cut off some loads in 110kV substations. Define $h_{u.\max}$ as maximum load shedding value, it should satisfy,

$$h_u \le h_{u.\max} \tag{17}$$

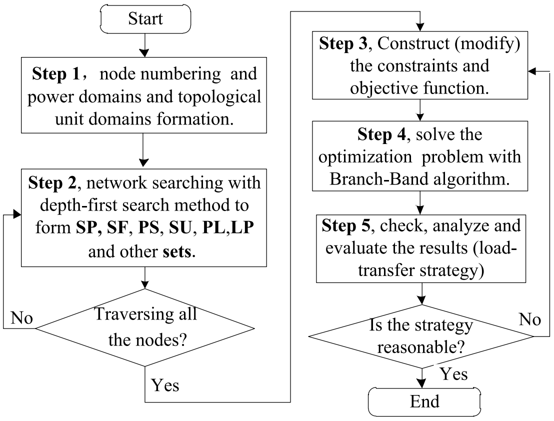


FIGURE 5. The flow chart.

Then, the equality constraint (2) should be modified as,

$$\sum_{s \in \boldsymbol{E}_u} x_{su} \cdot T_{su} = (1 - h_u)R_u \tag{18}$$

C. SOLVING METHOD

For the actual system, it can take the combination of F_1 and F_2 as objective function,

$$\min F = \varepsilon_1 F_1 + \varepsilon_2 F_2 \tag{19}$$

where ε_1 and ε_2 are weight coefficients and $\varepsilon_1 + \varepsilon_2 = 1$.

When the load balance of power station s is much more important, ε_1 needs to be set bigger. Otherwise, when the shedding load is expected to be smaller, ε_2 needs to be set much bigger. In actual situation, those two weight coefficients should be determined by dispatcher. But, when safety can be met, ε_2 should be much bigger in order to minimize shedding load.

Due to the load-transfer model is a mixed integer (0-1) programming problem, the branch and bound (B-B) method is used to solve this problem here. Theoretically, it can obtain the global optimal solution. The flowchart is shown in Fig.5.

In Step 1, the Power domains refer to the 220kV power stations and the Basic topological unit domains refers to the 110kV substations. In Step 3, the constraints include the equations and inequations (7)–(16). The weight coefficients ε_1 and ε_2 in the objection function (19) are set according the actual requirements. In Step 5, the results from step 4 are checked, analyzed and evaluated in this step. The rules here includes, if the results from step 4 is convergent results, if the switch can be operated according to the judgements of dispatcher, etc. If the results are not reasonable, go to step 3, some parameters need to be modified, such as weight coefficients ε_1 and ε_2 in (19), safety load-rate parameter k_s in (9), the maximum load shedding value $h_{u,max}$ in (17) etc. And then new results need to be solved again until the results meet the requirements. This will be further discussed and studied in future.

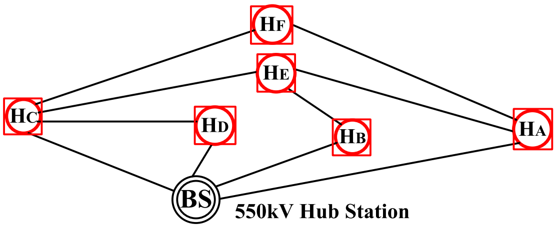


FIGURE 6. The 220kV network topological structure.

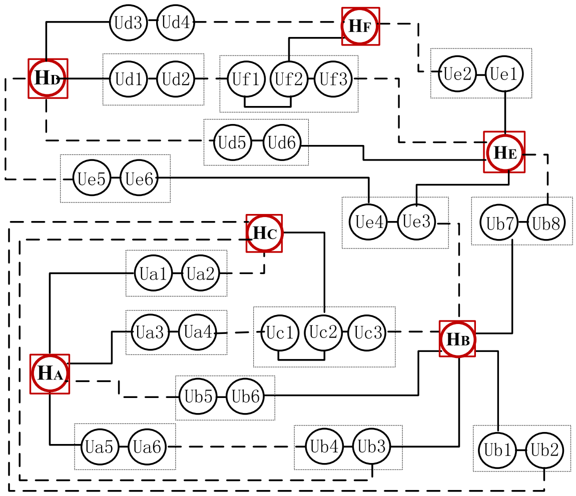


FIGURE 7. The initial state for 110kV stations.

In the proposed model, the optimization of load balance and minimizing load shedding are objectives, the elimination of overloaded transformers and power loss decreasing are the results. Moreover, load shedding is a measure to realize the elimination of overloaded transformers.

V. SIMULATION RESULTS

Part of a real urban HVDN, shown in Fig. 6, is used to test the proposed method. It consists of six 220kV power stations (Hubs, each has two main transformers), ten 220kV transmission lines. The initial state for 110kV stations is shown in Fig.7 based on basic topological unit. There are fifteen 110kV substations which form thirty-two basic topological units, twenty-eight 110kV transmission lines (fourteen of them are back-up lines, the dashed lines) and seventeen bus-tie switches in substations.

The total load of peak period is 830MW and some of the 220kV transformers and lines are heavily loaded. Such as, the power stations D and E are heavily loaded over 80%. But power station C, less than 30% of rated capacity, is lightly loaded. The load-rate of line L_{BE} is 71.15%, but the load-rate of line L_{DC} is only1.93%. The balance degrees of 220kV power stations and transmission lines are $B_s = 0.207$ and $B_l = 0.176$ respectively.

A. LOAD-TRANSFER OPTIMIZATION FOR NORMAL CONDITION OF HVDN

The original state with an unbalanced load distribution may have bad affects to HVDN. Based on the proposed

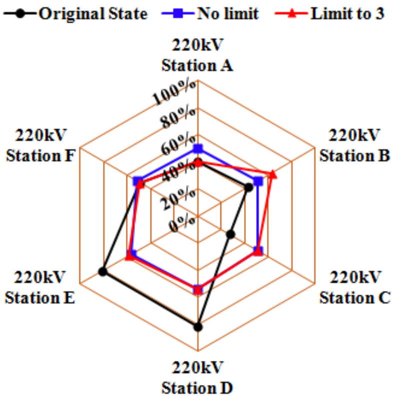


FIGURE 8. Load-rates of power station in different scenarios for normal condition.

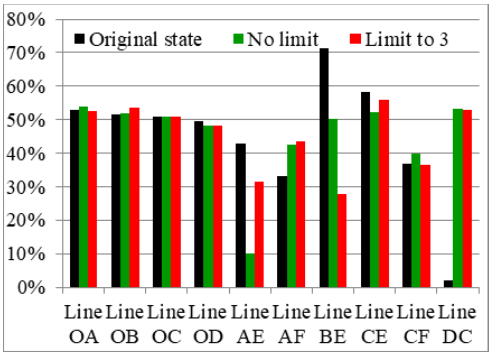


FIGURE 9. Load-rates of transmission lines in different scenarios.

TABLE 1. The optimal results for two different scenarios in normal condition.

State/ Scenario	Actual switch operations	Balance degree	Maximum load-rate	
			Station	Line
Original state	no	B_s=0.207 B_l=0.176	$\kappa_D = 81.25\%$ $\kappa_E = 81.25\%$	$\kappa_{BE} = 71.15\%$
Scenario 'a'	7	B_s=0.021 B_l=0.125	$\kappa_E = 56.25\%$	$\kappa_{OA} = 53.84\%$
Scenario 'b'	3	B_s=0.072 B_l=0.095	$\kappa_B = 62.79\%$	$\kappa_{CE} = 55.95\%$

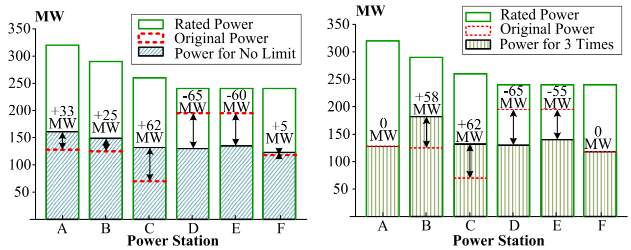
Link-path model, the load-transfer optimization can be done. Equation (3) is used in (19). For normal condition, it mainly considers to minimize the shedding load or even no load shedding, so set $\varepsilon_1 = 0.1$ and $\varepsilon_2 = 0.9$. And set $k_s = 70\%$ and $h_{u.\max} = 30\%$. Two scenarios are adopted to test the method,

Scenario 'a', not to limit the switch operation number.

Scenario 'b', to limit switch operation number to 3.

Lingo 11.0's Global Solver calculating engine is used to solve the problem. The results are listed in Table 1. The load-rates of six power stations and 220kV transmission lines are shown in Fig.8 and Fig.9.

Based on the results, it can be seen that the load distribution of 220kV power stations became more balanced after load-transfer optimization. B_s has an obvious reduction (dropping to 0.021 and 0.072 from 0.207). Although the goal is balance optimization of power station, B_l also reduces obviously because of balanced load distribution (dropping to 0.125 and 0.095 from 0.176). Furthermore, there's no load-shedding in two scenarios when controlling load-rate under 70%. For scenarios 'a' and 'b', the scenario 'a' with more switch operations has a better value for B_s. When limiting switch operations to 3, the distribution shown in Fig.8 has distorted a little with a bigger value for B_s. But two scenarios have much better load distribution than those in original state.



（a）without the limit of switch operation（b）limit switch operation to 3

FIGURE 10. Load level changes in two scenarios for normal condition.

The transferred load profiles for two scenarios are shown in Fig.10. It can be seen that the original heavily loaded stations D&E transferred more loads than others. The load-transfer strategies under different scenarios are different, but both achieved power congestion alleviation with all constraints being satisfied. With more switch operations, it transfers more loads among more power stations and gets a better balanced level.

In general, it can get a better balance with more switch operations, but switch operation increasing may cause operation risk. So here, it is perhaps a reasonable strategy with 3 switch operations as in scenario 'b'.

It should be pointed out that the proposed Link-path model can reduce problem dimension and LACPF algorithm can keep model's linearity. As an exploratory research of load-transfer problem, the presented method has strong practicability and application value. And in order to validate the proposed method, the 'bi-level method' in [19] is used to test and compare with the proposed method in the normal condition of HVDN. The results for Scenario 'a' are showed in Table 2. The platform is Thinkpad with Intel core I3-6006U CPU @2.0GHz, Ram 4G, Win 10.

Here, the transfer strategy, for example, the (B,b6)-(A,b5) in Table 2 means to open the switch between station B and unit b_6 and then close the switch between station A and unit b_5. According to Table 3, it can be seen that the proposed method has less calculation time than the method in [19]. Moreover, the time with the proposed method keeps relatively stable (minimum is 4.7s and maximum is 5.7s) and the time with the PSO algorithm has a larger deviation (minimum is 5.1s and maximum is 13.8s). And for the results, for Scenario 'b' with switch operation limit, the two methods

TABLE 2. **The results from the Link-path model and the Bi-level method.**

Items	Scenario 'a'	
	Proposed Link-path model	Bi-level Method in [20]
Transfer strategy (switch transferring)	(B,b6)-(A,b5);(B,b3)-(C,b3); (B,b1)-(C,b2);(E,e3)-(B,e3); (e1,e2)-(F,e2);(f2,f3)-(E,f3); (D,d5)-(E,d6)	(B,b6)-(A,b5);(a1,a2)-(C,a2); (B,b1)-(C,b2);(E,e3)-(B,e3); (D,d5)-(E,d6
Algorithm	Branch-band algorithm	PSO + enumeration algorithm
Solving time	5.3s (average value of 50 runs)	8.2s (average value of 50 runs)
Balance degree	B_s=0.021 B_l=0.125	B_s=0.059 B_l=0.127
Maximum load-rate	$\kappa_E = 56.25\%$	$\kappa_B = 60.00\%$
Maximum load-rate	$\kappa_{OA} = 53.84\%$	$\kappa_{CE} = 55.32\%$
Switch operations	7	5

TABLE 3. **The optimal results considering the renewable power sources.**

Actual switch operations	Balance degree	Maximum load-rate	
		Station	Line
3	B_s=0.118 B_l=0.169	$\kappa_D = 62.71\%$	$\kappa_{CE} = 59.55\%$

have the same optimal results (which are not listed in the Table 3). But for the Scenario 'a' without switch operation limit, the proposed method has more operations (7 versus 5), but it obtained a much better balanced distribution, like B_S(0.021 versus 0.059), maximum load rate (56.25% versus 60.00%) etc.. Meanwhile, the results with the proposed method are much more stable than those with the bi-level method based on PSO algorithms. In addition, for bi-level method, the lower level model adopted the enumeration algorithm, so the efficiency will reduce obviously when the dimension increases.

When considering the renewable power sources, the active powers of some 110kV substations may be delivered from low voltage side to high voltage side. For example, let c1 be this type BTU, and the active power is −12.5MW (i.e. injecting 12.5 MW active power into the grid) with constant power factor. The other conditions in Scenario 'a' are used to solve the problem, the result are listed in Table 3.

It can be seen from Table 3, the load balance of power stations and the maximum load rates of power stations and line are decreased obviously. It verified the proposed model can deal with the renewable power sources effectively.

B. LOAD-TRANSFER FOR SINGLE FAULT

When single fault occurs, one or more transformers or transmission lines may become overloaded. And this will severely threaten the safety of HVDN. The load-transfer is also the better way to overcome the problem. But sometimes, it can't get a feasible solution just by load-transfer, so the load-shedding may be necessary.

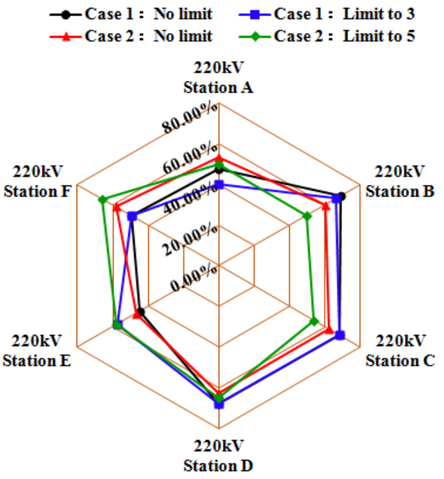


FIGURE 11. **Load-rates of power station in different scenarios for C station fault.**

TABLE 4. **The results for two scenarios for single fault of C station.**

State/ Scenario	Actual switch operations	Shedding load	Balance degree	Maximum load-rate	
				Station	Line
Case1, switch no limit	4	No load shedding	B_s=0.106 B_l=0.149	$\kappa_B = 69.14\%$	$\kappa_{CE} = 57.34\%$
Case1, switch limit to 3	3	h_{e2}=0.049, others are 0. P_{sh}=182MW	B_s=0.106 B_l=0.125	$\kappa_D = 68.13\%$	$\kappa_{CE} = 60.00\%$
Case2, switch no limit	13	No load shedding	B_s=0.057 B_l=0.160	$\kappa_D = 62.71\%$	$\kappa_{CE} = 59.55\%$
Case2, switch limit to 5	5	h_{e2}=0.021, others are 0. P_{sh}=0.89MW	B_s=0.066 B_l=0.168	$\kappa_F = 66.04\%$	$\kappa_{CE} = 60.00\%$

1) SINGLE FAULT FOR 220kV MAIN TRANSFORMER

Supposing that one transformer in station C quitted because of fault and another is running alone. Two cases are discussed too.

Case 1, the optimization objective only considers the load shedding (only F_2 in (20), $\varepsilon_1 = 0$, $\varepsilon_2 = 1$) without considering the load balance of stations. Set $k_s = 70\%$ and $h_{u.\max} = 30\%$.

Case 2, the optimization objective function is the same as above, and $\varepsilon_1 = 0.1$, $\varepsilon_2 = 0.9$, $k_s = 70\%$, $h_u \leq 30\%$.

The results are listed in Table 4. The load distributions of 220kV power stations are shown in Fig.11 with radar graph for those four Scenarios.

It can be seen that, when no switch operation limit, there is no load-shedding in two cases with all constraints being satisfied. But in case 1, because it just considers the load-shedding minimum, so the maximum load-rate is 69.14% in station B which is very close to the limit 70%. And in case 2, it further considers the load balancing of stations, so there are better load balance distribution at the cost of much more switch operations. That is, in case 2, the maximum

TABLE 5. The results for two scenarios for line AE fault.

State/ Scenario	Actual switch operations	Shedding load	Balance degree	Maximum load-rate	
				Station	Line
Case3, switch no limit	4	No load shedding	B_s=0.118 B_l=0.177	$\kappa_D = 67.71\%$	$\kappa_{OB} = 59.63\%$
Case3, switch limit to 3	3	h_{d5}=0.023, h_{f1}=0.031, others are 0. P_{sh}=1.55MW	B_s=0.063 B_l=0.165	$\kappa_B = 60.00\%$	$\kappa_{OB} = 60.32\%$
Case4, switch no limit	8	No load shedding	B_s=0.048 B_l=0.100	$\kappa_E = 56.25\%$	$\kappa_{BE} = 59.66\%$
Case4, switch limit to 5	5	h_{d5}=0.075, h_{f1}=0.030, others are 0. P_{sh}=1.71MW	B_s=0.062 B_l=0.166	$\kappa_B = 59.68\%$	$\kappa_{BE} = 60.28\%$

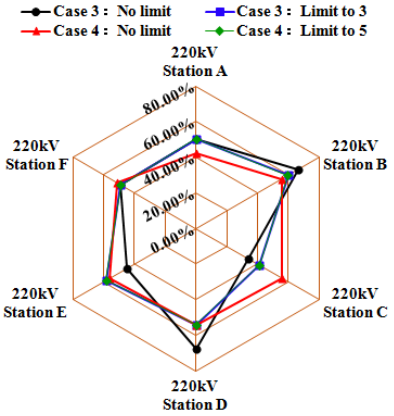


FIGURE 12. Load-rates of power station in different scenarios for line AE fault.

load-rate is 62.71% in station B but with 13 switch operations versus 4 switch operations in case 1. When there is a switch operation limit, the load-shedding is required for two cases. Besides, in case2, there is a better load distribution and less shedding load (marked with P_{sh} in Table 4 and Table 5) with a larger switch limit.

2) SINGLE FAULT FOR 220kV TRANSMISSION LINE

Supposing that line L_{AE} has been disconnected because of fault. Two cases are discussed *as 5.2.1* discussed above.

Here, the optimization strategies for ***Case*** 3 are the same as ***Case*** 1 and for ***Case*** 4 is the same as ***Case*** 2.

The results are listed in Table 5. The load distributions of 220kV power stations are shown in Fig.12 with radar graph for those four Scenarios. Like that discussed in previous section, when no switch operation limit, there is no load-shedding in two cases. In case 4, it considers the load balance of stations in objective function, so the maximum load-rate is lower (56.25% in station E for Case 4 versus 67.71% in station D for case 3). The better result was obtained at the cost of more switch operations. When there is a switch operation limit, the load shedding is required for two cases.

VI. CONCLUSION

The structure of HVDN is significantly different from low & medium voltage distribution networks. The basic topological unit is adopted to depict the characteristic of the power delivering in HVDN. Then Link-path model (LPM) is adopted to form the load-transfer optimization model and the related constraints. Combined with linear power flow method, this optimization model is a mixed integer (0-1) programming problem with higher linear degree. The branch-bound algorithm is used to solve the problem. Based on the proposed method, it doesn't need to list out all the connections and only needs to search from the system topology and form relative data sets. Thus, the variable dimension and solving difficulty are reduced.

A real city HVDN test system proved the feasibility and validity of the proposed method. The method can be used to overcome the congestion and overload problems based on the HVDN load-transfer optimization with the higher efficiency and better results.

Moreover, during the load-transfer switch operation, the time-sequence of switch operating has great influence on the reliability of power supply and the safety of HVDN. It is not considered here and will be studied and discussed in the other research.

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