Received: 15 November 2023 | Revised: 5 January 2024 | Accepted: 14 January 2024

DOI: 10.1049/stg2.12157

The Institution of Engineering and Technology WILEY

ORIGINAL RESEARCH

Total supply capability of electricity distribution networks considering flexible interconnection of low-voltage service transformers

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Funding information

National Natural Science Foundation of China, Grant/Award Number: 52007130; State Grid Tianjin Electric Power Company Science and Technology Project, Grant/Award Number: Chengdong-R&D 2023-02

Abstract

Under the target of 'emission peak and carbon neutrality', electricity distribution networks will massively access low-carbon technologies, which will result in problems such as insufficient hosting capacity, unbalanced electricity loads, degraded power quality etc. The low-voltage flexible distribution network (LVFDN), which interconnects its low-voltage service transformers using flexible power electronic devices (flexible interconnected devices [FIDs]) is considered an effective means to deal with the challenges above. The total supply capability (TSC) of LVFDN is proposed. Firstly, the typical structures of LVFDN and their operation modes are proposed. Then, the TSC model of LVFDN, which formulates flexible power flow control and multi-level (medium-voltage feeder and low-voltage flexible interconnection) load transfer is proposed. Due to the non-linear non-convex characteristics of the proposed TSC model, a new algorithm based on the 'branch and bound algorithm' is also provided. In the case study, the TSC of an actual electricity distribution network is calculated and tested by the N-1 verification method. Finally, the variations of TSC with different capacities of the low-voltage FID are analysed. Suggestions for the planning and operation of LVFDN are also given. A theoretical basis for the application of flexible interconnection technology in low-voltage electricity distribution networks is provided.

KEYWORDS

flexible interconnection, low-voltage flexible distribution network (LVFDN), service transformer, total supply capability (TSC)

1 | INTRODUCTION

With the transition of the global energy structure to clean and low-carbon, China has set a goal to achieve 'peak CO_2 emissions before 2030 and carbon neutrality by 2060'. Electricity distribution networks will massively access low-carbon technologies, including distributed generation (DG), electric vehicles, energy storage and electric heating. These will result in problems of insufficient hosting capacity, unbalanced electricity loads, degraded power quality etc, which present great challenges for the electricity distribution network planning and operation. Therefore, more flexible network structures are necessary for future electricity distribution networks to achieve low-carbon development.

From the perspective of network structure upgrades, flexible interconnection technology is an effective means to deal with the problems mentioned above. Flexible interconnection in electricity distribution networks refers to using flexible interconnected devices (FIDs) to upgrade the tie-switches and realise flexible closed-loop operation [1]. Taking advantage of the FID's capability in dynamic power flow control and fault isolation, the benefits of flexible interconnection include: (1) real-time capacity sharing of interconnected devices, including load balancing under normal operation and fast load transfer under fault; (2) dynamic reactive power output and voltage fluctuation suppression; (3) convenient access to DC buses for photovoltaic systems, data centres and other DC power sources or electricity loads, reducing the AC/DC conversion and improving the energy conversion efficiency.

The flexible interconnection technology for electricity distribution networks has undergone theoretical research for more than a decade. But the existing pilot projects are principally aimed at high-voltage and medium-voltage distribution networks [2], such as the Network Equilibrium project in the UK [3] and the three-terminal flexible closed-loop distribution network project in Yanqing District, Beijing, China [4]. However, low-voltage flexible interconnection has the potential to surpass medium-voltage in large-scale applications to establish the 0.4 kV low-voltage flexible distribution network (LVFDN), due to the comparatively low costs, simple techniques and diverse application scenarios of low-voltage FID.

Internationally, the research on LVFDN started later than that on high-voltage and medium-voltage distribution networks. UK Power Networks started the 'Flexible Urban Network-Low Voltage' (FUN-LV) project in 2014 [5]. With 24 low-voltage FIDs, the project took 3 years and showed superior economic, social and environmental benefits. In ref. [6], the global control strategy of the low-voltage FID with energy storage was studied to optimise operation. The authors in ref. [7] compared the performance of FID and traditional tie-switch in low-voltage electricity distribution networks, which found that FID can improve asset utilisation, release potential network capacity and improve network operation. In ref. [8], low-voltage FID was used for real-time coordinated control to minimise voltage deviations and improve the power quality. A two-layer FID control considering the economical operation area of the service transformer is proposed in ref. [9] to achieve the LVFDN's economic operation. In ref. [10], a power-voltage control method for voltage source converters based on three-phase four-wire sensitivity matrices on the AC side is proposed for LVFDN, which can effectively address the over-voltage and unbalanced issues. New FID architectures for the flexible interconnection of the electric railway networks and LV distribution networks are studied in ref. [11], which have been shown to provide additional flexibility and controllability for both the networks in ref. [12]. The advantages of deploying FIDs in low-voltage distribution networks have been shown by earlier research: (1) making full use of the available capacity in service transformers, delaying investment and construction in expansion; (2) enhancing the power supply reliability of service transformers, realising the fast and flexible transfer of important loads in case of failure; (3) achieving load balancing in service transformers, raising the utilisation rate and the operation economy of power distribution equipment; (4) improving the DGs accommodation and energy sharing in service transformers, promoting the development of clean energy.

The existing research makes significant advances in network configuration, control strategy and dispatch methods for LVFDN. However, the power supply capability of LVFDN has never been studied. Total supply capability (TSC) is a classic indicator for electricity distribution network planning, evaluation and security analysis. TSC theory has been completely established for traditional 10 kV medium-voltage distribution networks, from model to algorithm to application [13–16]. For 10 kV medium-voltage FDN, the authors in refs. [17, 18] adopted the point-by-point approximation method to calculate its DG hosting capacity. The authors in refs. [4, 19] discuss the load transfer strategy of FID under N-1 fault, but only for 10 kV medium-voltage distribution networks or when service transformers backup each other via FID under N-1 fault [5, 20]. These studies provide references for the LVFDN's TSC research. However, difficulties such as continuous load distribution and N-1 load transfer with FID have not been involved yet. As the 0.4 kV low-voltage side of LVFDN is interconnected for the first time, it faces double load transfer constraints from medium-voltage and low-voltage. Therefore, a new TSC model and algorithm should be developed to meet the more complicated operation of LVFDN. The main contributions of this paper are summarised as follows:

1) The new topology is proposed for the electricity distribution network with flexible interconnections of service transformers using FID, which can delay or avoid the capacity expansion of the electricity distribution networks, saving the investment.
2) The load transfer mode with the coordination of medium-voltage feeders and low-voltage flexible interconnections is proposed.
3) The model and the algorithm of TSC in the new LVFDN are proposed for the first time.

The rest of this paper is organised as follows: The typical structures of LVFDN and their operation modes are studied in Section 2. The TSC model of LVFDN, considering flexible interconnection of service transformers and multi-level load transfer is proposed in Section 3. Aiming at the characteristics of the proposed TSC model, a new algorithm is proposed in Section 4. In Section 5, the accuracy of the proposed TSC algorithm is verified on an actual electricity distribution network and the mechanisms of low-voltage flexible interconnection affecting TSC are also analysed.

2 | NETWORK MORPHOLOGY CONSIDERING FLEXIBLE INTERCONNECTION OF SERVICE TRANSFORMERS

2.1 | Network structures

The basic structures of flexible interconnection for low-voltage service transformers are centralised and distributed, as respectively depicted in Figures 1 and 2, each with three service transformers as examples.

The centralised flexible interconnection for service transformers is shown in Figure 1. The low-voltage side of each service transformer is led out by an AC cable and connected to a common DC bus via an AC/DC converter. The DC bus can provide interfaces for various new energy resources, energy storage, or DC electricity loads. The centralised flexible interconnection of service transformers has been demonstrated in projects such as the Container project in Beilun District, Ningbo, China and the FUN-LV project in the UK. These projects have shown the advantages of easy management and fast communication among different converters. However, since all converters are in the same station, this structure requires a large space for FID installation and the number of DC interfaces is limited, resulting in the fact that limited DC loads can be directly connected to the DC bus. Considering these features, the centralised flexible interconnection is suitable for modest integration of centralised DC sources and DC loads.

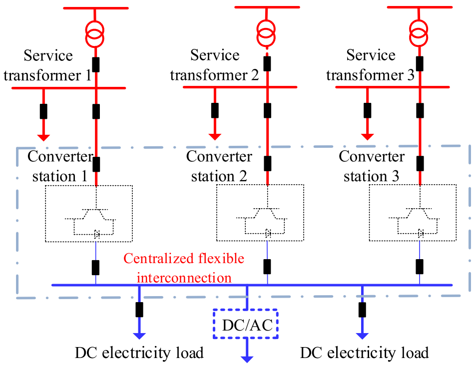

FIGURE 1 Centralised flexible interconnection for low-voltage service transformers.

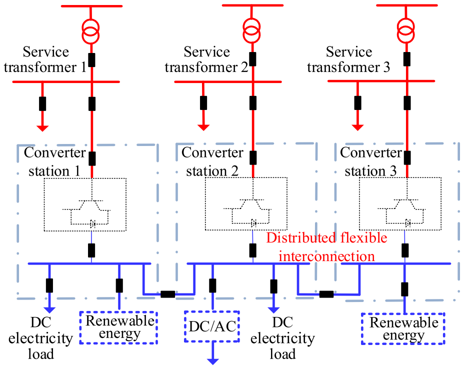

FIGURE 2 Distributed flexible interconnection for low-voltage service transformers.

The distributed flexible interconnection for service transformers is shown in Figure 2. Similar to the centralised structure in Figure 1, the AC power line from the low-voltage side of each service transformer is connected to the local DC bus via an AC/DC converter. The difference is that converters are installed in separate stations and connected to different DC buses (instead of one common DC bus). These DC buses are then interconnected by cables and switches. One advantage of this structure is that the distributed DC buses in different stations allow for more interfaces, enabling large-scale integration of DGs, energy storages, DC loads and other DC equipment. Another advantage is that these separate converters, due to their relatively small volume, can be installed in existing switch cabinets (or expanded ones) without extra sites. However, the relatively long distance between multiple FID converters of distributed flexible interconnection requires more complex communication infrastructure and an increased workload for operation and maintenance compared to centralised flexible interconnection. In the meantime, the cost of DC circuit breakers and other accessories is relatively high.

Figure 3 shows a typical structure of LVFDN, which deployed 10 low-voltage FIDs and omitted some service transformers.

In Figure 3, eleven 10 kV feeders are led out by four low-voltage buses of 110/10 kV substation transformers. Through

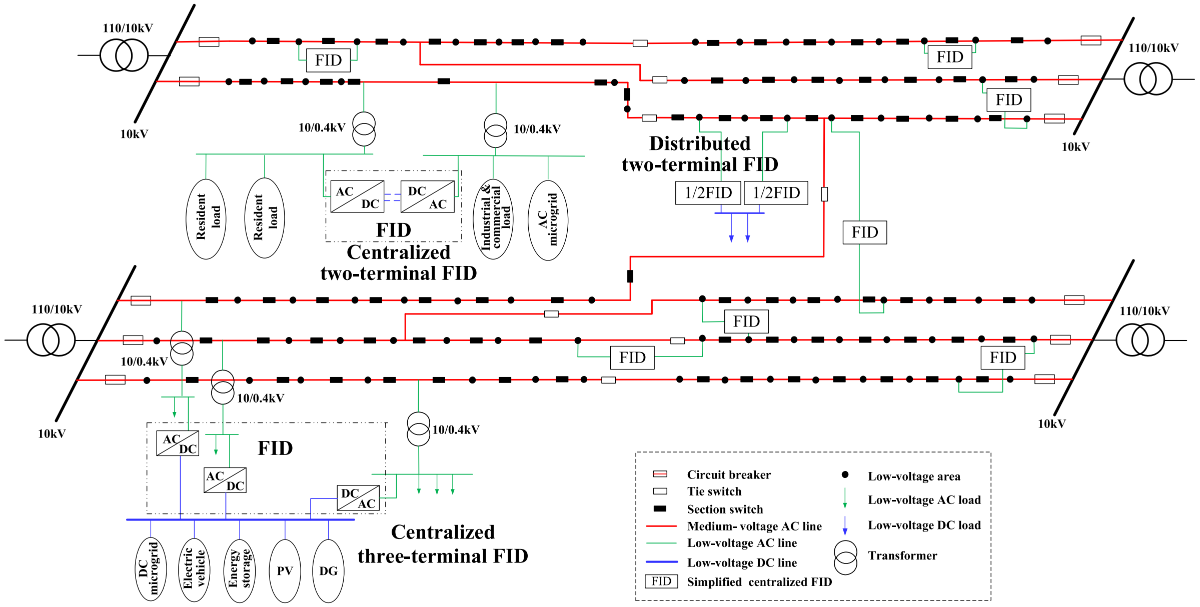

FIGURE 3 Typical structure of large-scale low-voltage flexible distribution network.

the 10/0.4 kV service transformer, the nodes on the 10 kV feeders supply power to the 0.4 kV low-voltage consumers. Three of the 10 deployed FIDs that are shown in more detail are a centralised two-terminal FID, a distributed two-terminal FID and a centralised three-terminal FID. These FIDs interconnect the 0.4 kV buses of the service transformers, which makes part of the low-voltage distribution network operate in a closed-loop. Such a structure serves as the foundation for multi-level load transfer, which enables load transfer to be completed not only through 10 kV medium-voltage lines but also through FID between service transformers, as detailed in Section 2.2.

2.2 | Operation modes

Under normal operation, continuous power regulation via FID can achieve electricity load balancing between interconnected service transformers to reduce their heavy load or overload risk. Furthermore, the independent reactive power output of FID can provide voltage support for service transformers, alleviating power quality problems caused by intermittent DGs.

When a fault occurs at a service transformer, the first step is to determine the electricity loads that must be removed and transferred after assessing the remaining capacity of the other interconnected service transformers. Then, FID will rapidly transfer the loads that can be transferred to other interconnected service transformers.

Particularly, when a fault occurs at a 10 kV feeder, the electricity distribution network will take two measures at the same time to restore service in the non-fault area. One measure is to transfer the loads of non-fault area by reconfiguring the medium-voltage switch to restore service as much as possible. The other measure is to use the low-voltage FID to transfer a portion of the service transformer's load, which requires at least one of the interconnected service transformers in the non-fault area. Both measures work together to reduce load losses. This load transfer mode with medium-voltage feeders and low-voltage flexible interconnection is called multi-level load transfer. Due to the limited flexibility of tie-switches in the traditional distribution network, the electricity load can only be transferred through medium-voltage feeders. However, the low-voltage flexible interconnections in LVFDN can realise multi-level load transfer.

When a fault occurs at a 110 kV substation transformer, it can be equivalent to the failure of several feeders. The load transfer mode is similar to a 10 kV feeder fault.

An LVFDN is presented in Figure 4 to illustrate the above operation modes. Under normal operation, the switches (including load switches and circuit breakers) K1, K2, K4, K6, K7 are closed and K3, K5 are open. The service transformers D1 and D2, which are interconnected via FID, are operating with the goal of load balancing, as are D3 and D4.

After the service transformer D1 fault, the main load switch of D1 is open and the transferable load of L1 powered by D1 is transferred to D2 via FID.

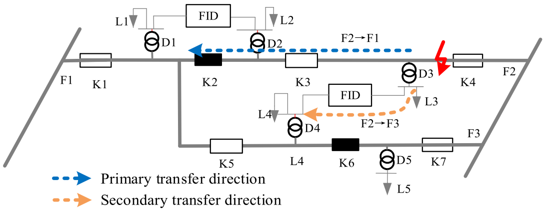

FIGURE 4 Multi-level load transfer of low-voltage flexible distribution network under the feeder F2 fault.

After the feeder F2 outlet fault, the K4 is open and the K3 is closed. At this time, the D3 is powered by the feeder F1. Considering the capacity constraint of F1, a partial load of L3 can be transferred to D4, which is a secondary transfer. The multi-level load transfer process is shown in Figure 4.

The load transfer path under the fault is depicted by the arrows in Figure 4. The power supply for the load changes from F2 at the beginning of the arrow to F1 and F3 at the end. The primary transfer is indicated by the blue arrow, while the secondary transfer is indicated by the yellow arrow. The load transfer modes for LVFDN in more wiring modes are shown in Appendix A.

2.3 | Comparison of traditional electricity distribution network and LVFDN

Table 1 further compares the characteristics of the traditional electricity distribution network and the LVFDN.

Table 1 demonstrates the distinct advantages that LVFDN provides in terms of power flow control capability, reliability and TSC. With the development of power electronics technology as well as intelligent operation and maintenance technology, the cost of FID and its operation and maintenance will decrease. Therefore, in light of the growing size of DGs and DC loads in the future new power system, the technical advantages of LVFDN will further increase.

3 | TSC MODEL CONSIDERING FLEXIBLE INTERCONNECTION OF SERVICE TRANSFORMERS

The TSC model of LVFDN is established in accordance with its network structures and operation modes in Section 2.

3.1 | Assumptions

Urban regions, which have high load densities but limited land resources, are most likely to lead in the application of low-voltage flexible interconnection technology because of the inadequate power supply capacity of service transformers. This paper focused on low-voltage flexible interconnection in urban electricity distribution networks. Considering the characteristics of urban electricity distribution networks, the following

TABLE 1 Comparison of traditional electricity distribution network and LVFDN.

Items	Traditional electricity distribution network	LVFDN
Power flow control capability	Uncontrollable low-voltage side, power flow is distributed naturally based on network parameters	Continuous fast dynamic control, active and reactive power decoupling control
Low-voltage power supply reliability	Users will encounter a power outage after a service transformer fault. Even if there are connections among low-voltage sides, switching operations require a short-term power outage	Users hardly ever encounter power outages thanks to FID's rapid transfer load
TSC	/	Higher
Operating economy	/	Power flow optimisation can minimise network loss
Maintenance	Relatively simple	FID maintenance is relatively complex
Future power system adaptability	Relatively low	High. The access to the DC source and load is convenient and efficient

Abbreviations: FID, flexible interconnected device; LVFDN, low-voltage flexible distribution network; TSC, total supply capability.

assumptions are made, referring to previous TSC research [21, 22].

1) The direction of the power flows is defined as positive when the power flows are out of the service transformers, following the practice of electricity distribution network operators.
2) Considering the feeders are normally short in length and the network loss ratio is relatively low in urban electricity distribution networks, DC power flow [23] is used in the power flow model, where the network loss can be added to the power flow of the feeder outlets [13].
3) The fault set in the process of TSC calculation contains the faults on the substation transformer, the feeder outlet and service transformers, while faults on the 10 kV branches and 0.4 kV power lines are not included.

3.2 | Normal operation constraints

Let the number of service transformers in the electricity distribution network be n. The service transformer i ($1 \le i \le n$) supplies users with a total apparent power of $S_{\mathrm{D},i}$. The injected powers of DG and FID into the service transformer i are denoted as $S_{\mathrm{G},i}$ and $\Delta S_{\mathrm{FID},i}$, respectively. The $\Delta S_{\mathrm{FID},i}$ is positive when the power flow is from the service transformer to the FID (the FID terminal is equivalent to a load), while it is negative when the power flow is from the FID to the service transformer (the FID terminal is equivalent to a power supply).

The net power of the high-voltage incoming line of the service transformer i is equal to the sum of $S_{\mathrm{D},i}$, $S_{\mathrm{G},i}$ and $\Delta S_{\mathrm{FID},i}$. Given that the $S_{\mathrm{D},i}$ must be less than the capacity of service transformer i and reverse power flow is not permitted under normal operation, the following equation can be obtained:

$$0 \le S_{\mathrm{D},i} + S_{\mathrm{G},i} + \Delta S_{\mathrm{FID},i} \le \beta c_{\mathrm{D},i} \tag{1}$$

where $c_{\mathrm{D},i}$ represents the rated capacity of the service transformer Di. β is the overload coefficient, which typically ranges between 0.7 and 0.8 under normal operation and approximately 1 after an N-1 fault (short-time heavy-load operation is allowed). The transfer power of the FID terminal should satisfy its capacity constraints.

$$\left|\Delta S_{\mathrm{FID},i}\right| \le c_{\mathrm{FID},i} \tag{2}$$

where $\Delta S_{\mathrm{FID},i}$ represents the power flow of the FID terminal i. c_{FID} represents the FID capacity. The Kirchhoff equation should be satisfied by the sum of the power flows from each FID terminal, which disregards the power loss:

$$\sum_{i \in \Omega_{\mathrm{FID}}} \Delta S_{\mathrm{FID},i} = 0 \tag{3}$$

where Ω_{FID} represents the set of all FID terminal numbers.

With DC power flow, the power flow of the electricity distribution network is simplified to the power balance equation [22]. The power flow of branch i (denoted as $S_{\mathrm{B},i}$) is equal to the sum of the net power of its downstream service transformers. The branch capacity constraints are formulated as (4).

$$S_{\mathrm{B},i} = \sum_{j \in \Lambda_{\mathrm{B},i}} \left(S_{\mathrm{D},j} + S_{\mathrm{G},j} + \Delta S_{\mathrm{FID},j}\right) \le c_{\mathrm{B},i} \tag{4}$$

where $\Lambda_{\mathrm{B},i}$ represents the set of downstream service transformers of branch i. Similarly, the capacity constraints for the substation transformers are formulated as (5).

$$S_{\mathrm{T},i} = \sum_{j \in \Lambda_{\mathrm{T},i}} \left(S_{\mathrm{D},j} + S_{\mathrm{G},j} + \Delta S_{\mathrm{FID},j}\right) \le c_{\mathrm{T},i} \tag{5}$$

where $\Lambda_{\mathrm{T},i}$ represents the set of downstream service transformers of substation transformer i.

3.3 | N-1 security constraints

The TSC defines the maximum load supply capability of an electricity distribution network that complies with the N-1 security criterion. Therefore, in addition to the security constraints under normal operation, the N-1 security constraints should be considered. In LVFDN, N-1 security refers to the capability of the electricity distribution network to provide power supply in the non-fault area after any component fault while the security constraints (1)–(5) can be satisfied. Power supply restoration can be achieved by network reconstruction, FID regulation and other techniques.

In this paper, three types of N-1 faults are considered: the single service transformer fault, the feeder outlet fault, and the substation transformer fault. After the fault, network reconfiguration and FID regulation are considered to restore the power supply. Their optimal strategies are achieved through the optimisation model in Section 3.4, where load loss is minimised while the operation constraints (1)–(5) are satisfied with the new topology and FID power allocation.

The fault set is denoted as Ψ. After a single fault $k \in \Psi$, the sets of numbers of the downstream service transformers for branch i and substation transformer i in the new topology are $\Lambda_{\mathrm{B},i}^{(k)}$ and $\Lambda_{\mathrm{T},i}^{(k)}$, respectively. Similar to the normal operation constraints (4) and (5), the N-1 security constraints for each fault can be expressed as (6) and (7).

$$S_{\mathrm{B},i} = \sum_{j \in \Lambda_{\mathrm{B},i}^{(k)}} \left(S_{\mathrm{D},j} + S_{\mathrm{G},j} + \Delta S_{\mathrm{FID},j} \right) \le c_{\mathrm{B},i} \tag{6}$$

$$S_{\mathrm{T},i} = \sum_{j \in \Lambda_{\mathrm{T},i}^{(k)}} \left(S_{\mathrm{D},j} + S_{\mathrm{G},j} + \Delta S_{\mathrm{FID},j} \right) \le c_{\mathrm{T},i} \tag{7}$$

The existing research on TSC did not consider the N-1 fault of the service transformers, mainly because the low-voltage lines of the service transformer are all radial structures that do not meet the N-1 security. In the case of a service transformer fault, a power outage is normally required until service is restored, while only a few service transformers powered by DGs can be avoided. In LVFDN, after a service transformer fault, the load can be transferred to the interconnected service transformers via FID. In other words, the FID serves as a new power source for the load of the faulty service transformer. When a fault occurs at service transformer i, its interconnected FID terminal will transfer the load $S_{\mathrm{D},i}$ and DG output $S_{\mathrm{G},i}$ to other terminals as much as possible. Taking advantage of the flexible power flow control of FID among multiple terminals, $S_{\mathrm{D},i}$ and $S_{\mathrm{G},i}$ are essentially transferred in a certain proportion to other interconnected service transformers, which can be expressed as (8).

$$\begin{cases} \alpha_j \left(S_{\mathrm{D},i} + S_{\mathrm{G},i} \right) = \Delta S_{\mathrm{FID},j} \\ \displaystyle\sum_{j \in \Omega_{\mathrm{FID}}, j \ne i} \alpha_j = 1 \end{cases} \tag{8}$$

where α_j represents the ratio of net power transferred from FID terminal j to service transformer j after service transformer i fault.

3.4 | Comprehensive model

3.4.1 | TSC model of LVFDN

The TSC defines the maximum load supply capability of an electricity distribution network that complies with the N-1 security criterion. According to the definition of TSC, the objective function of the LVFDN TSC model is consistent with the traditional TSC model, which is the sum of all loads $S_{\mathrm{D},i}$.

$$\max T_{\mathrm{TSC}} = \sum_{i=1}^{n} S_{\mathrm{D},i} \tag{9}$$

where T_{TSC} denotes the TSC of the electricity distribution network.

For the traditional electricity distribution network, the load $S_{\mathrm{D},i}$ is the only variable in the TSC model. But in the TSC model of LVFDN, the power of the FID terminal $\Delta S_{\mathrm{FID},i}$ is also a variable. In addition to at least one set of load distributions, the TSC result also corresponds to at least one set of feasible power distributions for FID terminals. It should be noted that the optimisation objective of the TSC model in (9) is uniquely determined, while the power distribution of FID is the optimisation variable but not the optimisation objective.

After an N-1 fault, the TSC model will once again optimise the power distributions of FID terminals, which is essentially the secondary load transfer for the flexible interconnected service transformers. The primary transfer is the reconfiguration of medium-voltage rigid switches, while the secondary transfer is the power adjustment of FID terminals. Due to limitations in switch operation flexibility, service life, labour cost and other factors, the traditional electricity distribution network generally does not support secondary transfer. By contrast, LVFDN can solve this problem and enhance the flexibility and reliability of the electricity distribution network through secondary transfer.

In conclusion, the TSC model of LVFDN is formulated as (10).

$$\max T_{\mathrm{TSC}} = \sum_{i=1}^{n} S_{\mathrm{D},i}$$

$$s.t. \begin{cases} A: \text{Normal operation state constraints} \\ Eq.(1) - (5) \\ B: \text{N} - 1 \text{ security constraints} \\ \forall k \in \Psi \\ Eq.(6) - (8) \end{cases} \tag{10}$$

Formula (10) is a non-linear non-convex programming model. The reason is that α_j and $S_{\mathrm{D},i}$ in (8) are optimisation variables and the system security is determined by taking 'union' from schemes with different topologies and FID multi-terminal power distribution after an N-1 fault.

3.4.2 | Load balancing model

The model in (10) has numerous solutions, some of which have unbalanced load distributions. It is quite different from the actual electricity distribution network. From the perspectives of planning and operation, it is desired that the differences in load distribution among service substations at the TSC level should be as small as possible, avoiding situations of overload or underload. Thus, further adjustments are made to the TSC model. With reference to ref. [4], the secondary optimisation is done with the intention of load balancing in the service transformers on the basis of TSC. The objective function is formulated as (11).

$$\begin{cases} \min D_{\mathrm{VLR}} = \dfrac{\sum\limits_{i=1}^{n} \left(R_{\mathrm{D},i} - \overline{R_{\mathrm{D}}}\right)^2}{n}, \\ R_{\mathrm{D},i} = \dfrac{S_{\mathrm{D},i} + S_{\mathrm{G},i}}{c_{\mathrm{D},i}}, \overline{R_{\mathrm{D}}} = (1/n) \sum\limits_{i=1}^{n} R_{\mathrm{D},i} \end{cases}, s.t.(9) \quad (11)$$

where D_{VLR} represents the variance of the load ratio of service substations. R_{D} represents the average load ratio of n service substations.

4 | ALGORITHM OF TSC MODEL

The TSC model of LVFDN proposed in (1)–(11) is a non-linear non-convex programming model. It cannot be solved using the linear programming method utilised in the traditional TSC model [13, 14]. Therefore, this paper uses the branch and bound algorithm in accordance with ref. [24], while the linear programming relaxation and convex envelope approximation are used to deal with the sub-problems of load transfer verification under various faults. This approach, with strong robustness, can easily navigate through all sub-problems and converge on the global optimal solution. The flow chart of the TSC model algorithm is shown in Figure 5.

The steps of TSC model algorithm are summarised as follows.

Step 1: Generate the substation transformer set, feeder set, service transformer set and DG set based on the network topology. Initialise the variables for the apparent power of service transformers $S_{\mathrm{D},i}$ and the injected power of FID terminals $\Delta S_{\mathrm{FID},i}$.

Step 2: The N-1 verification is performed for all the faulty components k in a single fault set to establish the TSC

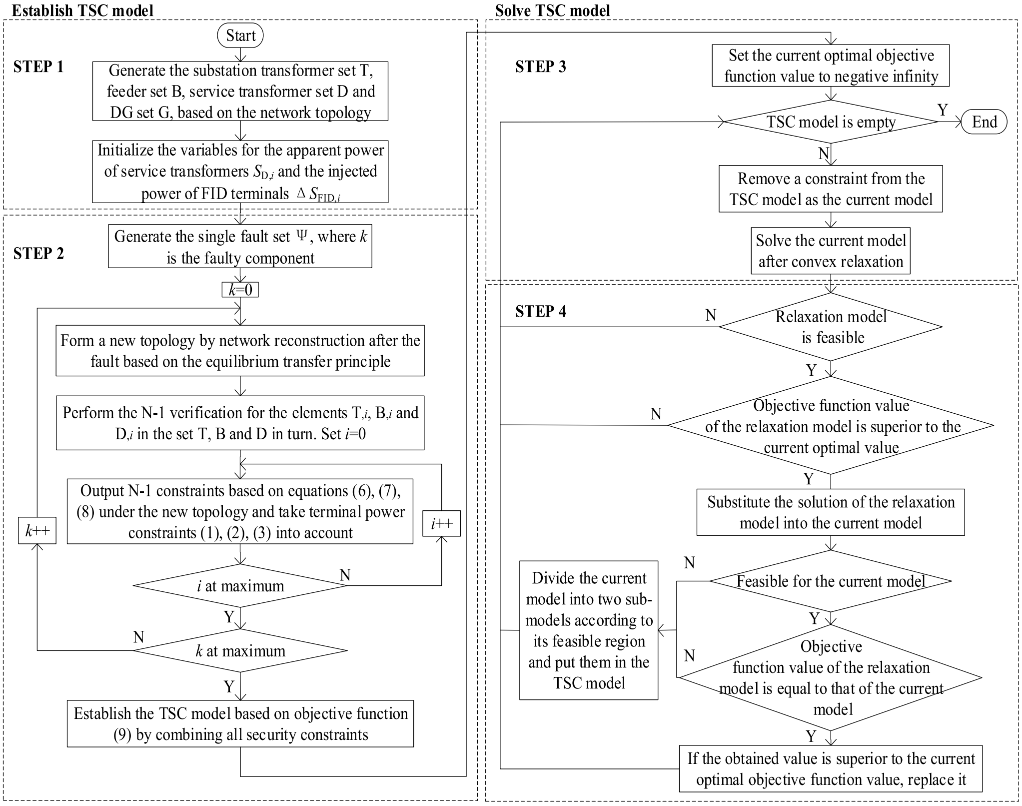

FIGURE 5 Flow chart of TSC model algorithm based on branch and bound algorithm. TSC, total supply capability.

model. The traditional medium-voltage distribution network reconstruction method [25] is used to determine the new topology after the fault.

Step 3: The convex relaxation constraints, which correspond to the original constraints for any non-linear constraints in the TSC model, are constructed under given boundary values for the variables to calculate the TSC value.

Step 4: The branch operation is carried out and then returned to *Step 3*, if the solution for the convex relaxation model is not the feasible solution for the original model; or if it is, but the target values for the two problems are very different. In the branch operation, the original feasible region is divided into two sub-feasible regions and the variable range of each sub-problem is recalculated.

Compared with the existing TSC model and the solution algorithms [13, 14], this paper for the first time considers the load transfer among service transformers. The load balance can be further achieved through the load secondary transfer. Different from the fixed power load transfer among connected power lines, the power load can be transferred in any proportion via FID, especially when FID connects multiple backup power sources (i.e. service transformers).

5 | CASE STUDY

5.1 | Case description

The case grid in Figure 3 is used to verify the proposed method. For conciseness, the grid diagram in Figure 3 is simplified to a point-edge diagram in Figure 6.

In Figure 6, the case grid consists of 4 substation transformers, 11 medium-voltage feeders and 5 FIDs (including 4 two-terminal FIDs and 1 three-terminal FID, for a total of 11 terminals). The FID capacity, that is, c_{FID} in Equation (2), is 0.3 MVA. The substation transformer T1 has a capacity of 15 MVA, while T2, T3 and T4 each have 20 MVA. The feeder capacity is 8 MVA. The service transformer capacity is 0.6 MVA. The DG capacity is 0.5 MVA. It should be mentioned that this paper only considers the N-1 fault at the service transformer, feeder outlet and substation transformer. In the case study, the low-voltage flexible interconnection on the same line is simplified by omission because it has no impact on the N-1 load transfer.

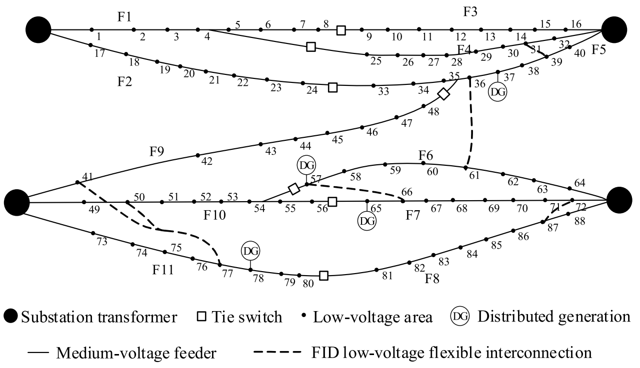

FIGURE 6 LVFDN case topology including 5 LV FIDs. FIDs, flexible interconnected devices; LVFDN, low-voltage flexible distribution network.

5.2 | TSC calculation results

The TSC model of the case grid is built using the method proposed in Section 3 and solved using the algorithm proposed in Section 4. The algorithm is programmed in the MATLAB language and an i5-8300H-8G computer calculates a group of TSC equilibrium solutions for the case grid on average in 2.14 s.

The calculated TSC value is 55.9 MVA. In the equilibrium solution obtained through (11), the loads of 11 feeders and 11 flexible interconnected service transformers are shown in Table 2. The load distribution of all 66 service transformers with the TSC of 55.9 MVA is shown in Table B1.

5.3 | N-1 verification

The method proposed in ref. [22] is adopted to conduct the N-1 verification for the TSC load distribution in Table 2. The results show that the electricity distribution network exactly meets N-1 security with the existing TSC, that is, at least an N-1 fault will render the case grid unsafe if any load is increased by any size in any way. This demonstrates the efficacy of the TSC model and algorithm for LVFDN proposed in this paper.

The verification result for a load distribution slightly above TSC is shown in Table 3. The total load is 56 MVA, as shown in Table B2. It is found that F1 has out-of-limit capacity after the feeder outlet faults of F3 and F4, which is just equal to the increased 0.1 MVA based on TSC.

5.4 | Mechanism analysis of low-voltage flexible interconnection affecting TSC

5.4.1 | N-1 load transfer analysis

The F2 and F9 faults are taken as examples to analyse the features of N-1 load transfer at the TSC level, as shown in Table 4.

It can be seen from Table 4 that the proposed method can reflect the medium-voltage feeder reconstruction coordinated with the flexible load transfer of the low-voltage FID, which enables the TSC of the case grid to achieve a high level. Take F9 as an example. When the fault occurs at F9, its load is first transferred to F5, putting F5 at an overload risk. Then, the loads D39 and D36 of F5 are quickly transferred to other service transformers via FID, realising the fast secondary transfer after N-1, which is not possible in the traditional electricity distribution network.

TABLE 2 Load of feeders and flexible interconnected service transformers at TSC level.

Feeder number	Load (MVA)	Service transformer number	Load (MVA)
F1	2.30	D31	0.30
F2	7.00	D39	0.30
F3	5.70	D36	0.30
F4	6.00	D61	0.30
F5	2.10	D57	0.80
F6	6.50	D66	0.30
F7	7.00	D72	0.30
F8	4.30	D87	0.30
F9	7.30	D41	0.30
F10	2.90	D50	0.30
F11	4.80	D77	0.30

Abbreviation: TSC, total supply capability.

TABLE 3 The N-1 verification results of a load level higher than TSC.

Faulty component	Feeder or service transformer for load transfer				Residual capacity of feeder or service transformer after load transfer (MVA)				Whether operation constraints are violated (yes/no)
F1	F3		F4		0		1.9		No
F2	F5	D39		D36	0	0		0	No
F3	F1				**−0.05**				**Yes**
F4	F1		D31		**−0.1**		**0**		**Yes**
F5	F2	F9	D39	D36	0	0.7	0	0	No
F6	F10	D61	D57	D50	0	0	0	0	No
F7	F10	D66	D72	D50	0	0	0	0	No
F8	F11	D87		D77	0	0		0	No
F9	F5	D41	D39	D36	0	0	0	0	No
F10	F6	F7		D50	0	1.7		0	No
F11	F8	D77		D87	0	0		0	No

Note: The bold type in Table 3 indicates cases of out-of-limit capacity.

Abbreviation: TSC, total supply capability.

TABLE 4 The features of N-1 load transfer at TSC level.

Fault type	Medium-voltage feeder reconstruction scheme	FID terminal power (MVA)							N-1 verification	Component at critical capacity
		$\Delta S_{\mathrm{FID},31}$	$\Delta S_{\mathrm{FID},39}$	$\Delta S_{\mathrm{FID},36}$	$\Delta S_{\mathrm{FID},61}$	$\Delta S_{\mathrm{FID},41}$	$\Delta S_{\mathrm{FID},50}$	$\Delta S_{\mathrm{FID},77}$		
F2 fault	F2 load transfer to F5	**0.3**	**−0.3**	**−0.3**	**0.3**	0	0	0	Pass	F5
F9 fault	F9 load transfer to F5	**0.3**	**−0.3**	**−0.3**	**0.3**	**−0.3**	**0.15**	**0.15**	Pass	F5

Note: The bold type in Table 4 indicates changes in FID terminal power.

Abbreviations: FID, flexible interconnected device; TSC, total supply capability.

5.4.2 | Mechanism of FID capacity affecting TSC

While the capacities of feeders, substation transformers and service transformers remain constant in Figure 6, let the FID terminal capacity c_{FID} increase from 0 to 0.6 MVA synchronously (normally, the FID terminal capacity is not greater than that of the corresponding service transformer). The TSC for different FID terminal capacities is shown in Table 5.

Based on Table 5, the curve of TSC changing with c_{FID} is depicted in Figure 7.

As shown in Figure 7, the TSC increased from 53.5 to 56.2 MVA, a 5% increase, as the FID terminal capacity increased. This increase will become more significant if the low-voltage interconnection density rises. The growth characteristics of TSC with FID terminal capacity can be divided into three parts: the first interval shows linearly rapid growth; the second interval shows sluggish growth; and the third interval shows no growth, generating two visible inflection points. The mechanism of this feature change is analysed below.

First, the spinning reserve formed by the service transformer interconnection via FID will obviously increase the regional power supply capability. The increasing range is determined by the capacity that the interconnected service transformers may share, which is based on FID terminal capacity. Therefore, the extremely small capacity of the FID terminal barely increases the power supply capability of the service transformer, which renders the power supply capacity of LVFDN close to that of the traditional electricity distribution network (TSC = 53.5 MVA). The high capacity of the FID terminal maximises the spinning reserve capacity of the service transformer, which increases the TSC to its maximum (TSC = 56.2 MVA). During this period, TSC growth can be divided into three stages, which are mainly induced by changes in the bottleneck components that limit TSC growth.

TABLE 5 TSC and its load distribution for different FID terminal capacities.

C_{FID} (MVA)	TSC (MVA)	C_{FID} (MVA)	TSC (MVA)
0.00	53.50	0.25	55.50
0.05	53.90	0.30	55.90
0.10	54.30	0.35	56.05
0.15	54.70	0.40	56.20
0.20	55.10	0.45	56.20

Abbreviations: FID, flexible interconnected device; TSC, total supply capability.

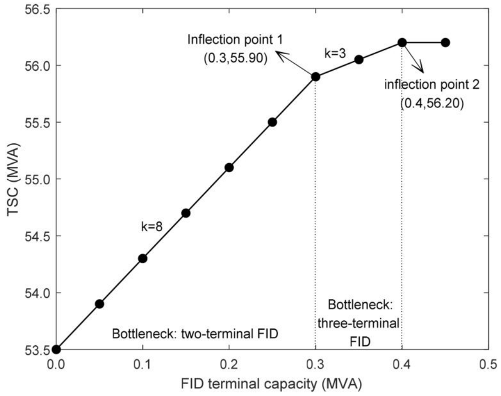

FIGURE 7 TSC curve changing with FID terminal capacity. FID, flexible interconnected device; TSC, total supply capability.

At the first interval, TSC increases linearly by the slope $k = 8$, because the two-terminal FID capacity restricts TSC growth. At the first inflection point, c_{FID} is just half the capacity of the service transformer interconnected by a two-terminal FID. At this point, because the capacity of service transformers interconnected by two-terminal FID begins to restrict the TSC value, the maximum load of the corresponding service transformers D1 and D2 is (0.3 MVA, 0.3 MVA). Since then, even if the c_{FID} keeps increasing, TSC can no longer increase quickly; otherwise, the capacity of the service transformer interconnected by the two-terminal FID will not meet N-1 security.

At the second interval, TSC increases by the slope $k = 3$, which goes down compared to the first interval. At this interval, TSC growth is limited by the capacity of the service transformer interconnected by two-terminal FID, as well as the capacity of three-terminal FID. When c_{FID} increases to inflection point 2, because the capacity of service transformers interconnected by three-terminal FID begins to restrict TSC value, the maximum load of the corresponding service transformers D9, D10 and D11 is (0.4 MVA, 0.4 MVA, 0.4 MVA). Since then, any extra load will cause the service transformer capacity to not meet the N-1 security.

Further analysis in a mathematical sense: Let the service transformer capacity for n-terminal FID flexible interconnection be c_{DT}. The bottleneck component of TSC growth is FID terminal capacity when $c_{\text{FID}} < c_{\text{DT}}(n-1)/n$, while it is service transformer capacity when $c_{\text{FID}} > c_{\text{DT}}(n-1)/n$.

At the third interval, TSC remains constant. The service transformer capacity restricts TSC growth at this interval. In conclusion, in order to improve TSC, the capacity configuration of c_{FID} should primarily refer to the service transformer capacity. For n-terminal FID, the maximum installation capacity is recommended not to exceed $(n-1)c_{\text{DT}}/n$. As shown in Figure 7, the recommended c_{FID} for the case grid is between 0.3 and 0.4 MVA.

6 | CONCLUSION

This paper first proposes the typical structures and operation modes of the LVFDN with FID. Secondly, the TSC model of LVFDN is proposed, which considers both the flexible power flow control of FID and the secondary transfer characteristics of LVFDN. Further, a new algorithm based on the branch and bound algorithm is developed for the LVFDN TSC model to address the non-linear non-convex programming model. Finally, the TSC of the actual LVFDN is calculated and the result's accuracy is verified by the N-1 verification.

The TSC in LVFDN increased by 5%, according to the quantitative analysis of the case study. The influence mechanisms of low-voltage flexible interconnection on TSC are as follows.

1) The essential reason for the TSC increase in LVFDN is the increase in medium-voltage and low-voltage load transfer capability, including the implementation of fast secondary transfer.
2) As FID terminal capacity increases, the increase in TSC shows a fast-to-slow trend, which is limited by different components at different growth stages.
3) The recommended capacity for an n-terminal FID should not exceed $(n - 1)/n$ times the capacity of the interconnected service transformer. The TSC increase will be more significant as low-voltage interconnection density increases, as can be predicted.

Low-voltage flexible interconnection technology is critical for relieving the stress of low-voltage electricity distribution network transformation as well as dealing with large-scale DC source and load access. Future research will further consider the uncertainty of node power introduced by photovoltaics and electric vehicles. Additionally, the influence of low-voltage flexible interconnection on power quality and DG accommodation in the electricity distribution network will be analysed. And the siting and sizing of the low-voltage FID based on TSC will also be studied.

AUTHOR CONTRIBUTIONS

Guoqiang Zu: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; resources; software; supervision; validation; visualization; writing – original draft; writing – review & editing. **Ying Wang**: Conceptualization; data curation; formal analysis; investigation; methodology; software; supervision; validation; visualization; writing – original draft; writing – review & editing. **Xun Jiang**: Formal analysis; investigation; methodology; supervision; validation; visualization; writing – original draft; writing – review & editing. **Ziyuan Hao**: Supervision; validation; visualization; writing – original draft; writing – review & editing. **Xin Zhang**: Supervision; validation; visualization; writing – review & editing.

ACKNOWLEDGEMENTS

This work is supported by the National Natural Science Foundation of China (52007130); State Grid Tianjin Electric Power Company Science and Technology Project (Chengdong-R&D 2023-02).

CONFLICT OF INTEREST STATEMENT

I or any of my co-authors have no conflict of interest to disclose.

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the appendix of this article.

PERMISSION TO REPRODUCE MATERIALS FROM OTHER SOURCES

None.

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How to cite this article: Zu, G., et al.: Total supply capability of electricity distribution networks considering flexible interconnection of low-voltage service transformers. IET Smart Grid. 1–14 (2024). https://doi.org/10.1049/stg2.12157

APPENDIX A Load transfer modes for LVFDN with various wiring modes

1) **Single-tie wiring mode with feeder outlet fault**
In Figure A1, when feeder F2 outlet fault, the circuit breaker K4 is open and the switch K2 is closed. The service transformer interconnected via FID is not affected by the fault. From the perspective of power supply protection, FID can maintain the state before the fault; that is, there is no need for secondary transfer. However, from the perspective of optimising the feeder power flow distribution, the FID can be further operated to optimise the line power and voltage distribution.

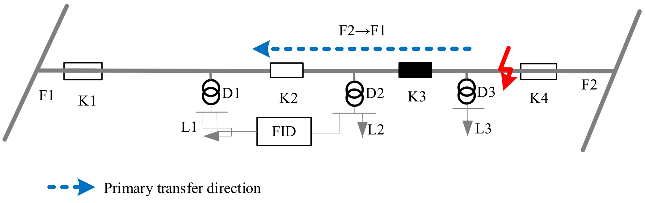

FIGURE A1 Single-tie wiring mode with feeder outlet fault.

2) **Single-tie wiring mode with service transformer fault**
In Figure A2, when service transformer D2 fault, the switch K3 and the low-voltage switch of D2 are both open and the load of D2 is completely powered by D1 via FID.

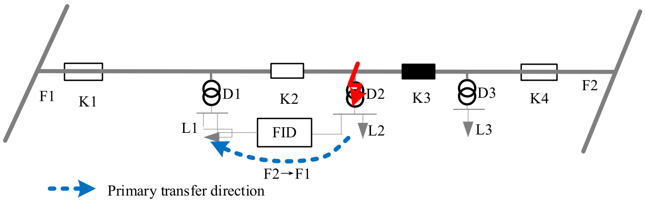

FIGURE A2 Single-tie wiring mode with service transformer fault.

3) **Two-section-and-two-tie wiring mode with feeder outlet fault**
In Figure A3, when the feeder F2 outlet fault, the circuit breaker K4 is open and the switch K3 is closed. The load of D3 is supplied by F1. If the load of F1 is heavy or overload, a portion of the load of D3 will be secondary transferred to D4 via FID.

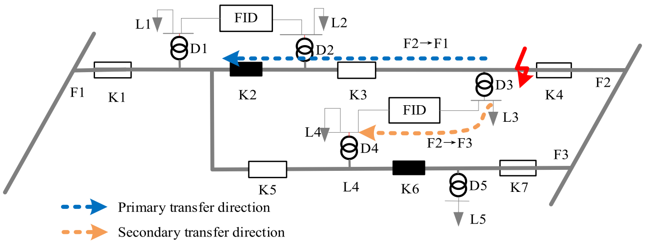

FIGURE A3 Two-section-and-two-tie wiring mode with feeder outlet fault.

4) **Two-supply-one-backup wiring mode with feeder outlet fault**
In Figure A4, when feeder F1 outlet fault, the circuit breaker K1 is open and the switch K4 is closed. The load of F1 is supplied by F3. If the load of F3 is heavy or overload, a portion of the load of D3 will be secondary transferred to D6 via FID.

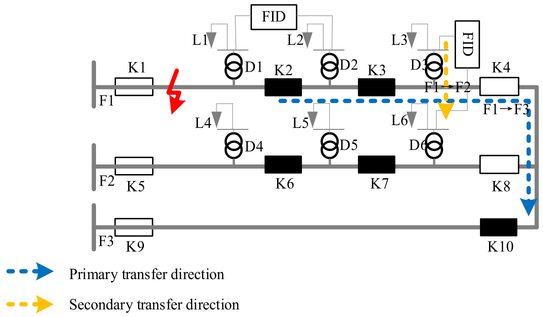

FIGURE A4 Two-supply-one-backup wiring mode with feeder outlet fault.

5) **Double-loops wiring mode with feeder outlet fault**
In Figure A5, when F1 feeder outlet fault, the circuit breaker K17 is open and the switch K6 is closed. The load of F1 is supplied by F3. If the load of F3 is heavy or overload, a portion of the load of D1 will be secondary transferred to D2 via FID and a portion of the load of D7 will be secondary transferred to D6 via FID.

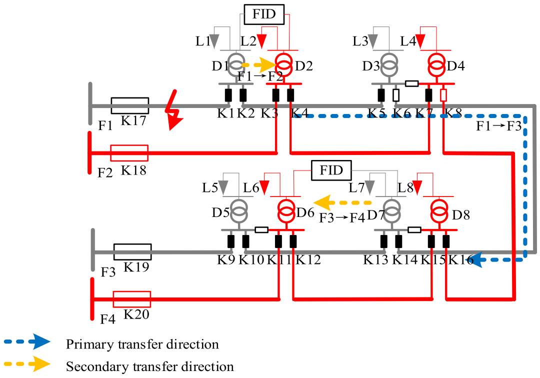

FIGURE A5 Double-loops wiring mode with feeder outlet fault.

6) **Double-loops wiring mode with feeder middle section fault**
In Figure A6, when the middle section of feeder F4 feeder fault, the switches K12 and K15 are open and switch K8 is closed. A portion of the load of F4 is supplied by F2. If the load of F2 is heavy or overloaded, a portion of the load of D2 will be secondary transferred to D1 via FID. The service transformer D6 is not affected by the fault. From the perspective of power supply protection, the FID can maintain the state before the fault; that is, there is no need for secondary transfer. However, from the perspective of optimising the feeder power flow distribution, the FID can be further operated to optimise the line power and voltage distribution.

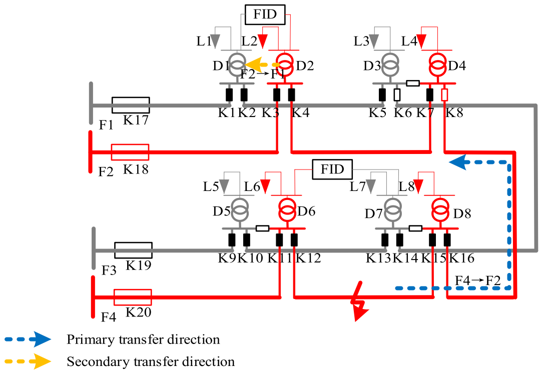

FIGURE A6 Double-loops wiring mode with feeder middle section fault.

APPENDIX B Detailed load distribution of service transformers for case grid

TABLE B1 Load of service transformers at TSC level.

Service transformer number	Load (MVA)	Service transformer number	Load (MVA)	Service transformer number	Load (MVA)	Service transformer number	Load (MVA)
D1	0.2875	D23	0.4375 × 2	D45	0.5000 × 2	D67	0.4500 × 2
D2	0.2875	D24	0.4375 × 2	D46	0.5000 × 2	D68	0.4500 × 2
D3	0.2875	D25	0.4072 × 2	D47	0.5000 × 2	D69	0.4500 × 2
D4	0.2875	D26	0.4072 × 2	D48	0.5000 × 2	D70	0.4500 × 2
D5	0.2875	D27	0.4072 × 2	D49	0.3714	D71	0.4500 × 2
D6	0.2875	D28	0.4072 × 2	D50	0.3000	D72	0.4500 × 2
D7	0.2875	D29	0.4072 × 2	D51	0.3714	D73	0.5714
D8	0.2875	D30	0.4072 × 2	D52	0.3714	D74	0.5714
D9	0.3563 × 2	D31	0.3000	D53	0.3714	D75	0.5714
D10	0.3563 × 2	D32	0.4072 × 2	D54	0.3714	D76	0.5714
D11	0.3563 × 2	D33	0.1667	D55	0.3714	D77	0.3000
D12	0.3563 × 2	D34	0.1667	D56	0.3714	D78	1.0714
D13	0.3563 × 2	D35	0.1667	D57	0.8000	D79	0.5714

(Continues)

TABLE B1 (Continued)

Service transformer number	Load (MVA)	Service transformer number	Load (MVA)	Service transformer number	Load (MVA)	Service transformer number	Load (MVA)
D14	0.3563 × 2	D36	0.3000	D58	0.4500 × 2	D80	0.5714
D15	0.3563 × 2	D37	0.6667	D59	0.4500 × 2	D81	0.5714
D16	0.3563 × 2	D38	0.1667	D60	0.4500 × 2	D82	0.5714
D17	0.4375 × 2	D39	0.3000	D61	0.3000	D83	0.5714
D18	0.4375 × 2	D40	0.1667	D62	0.4500 × 2	D84	0.5714
D19	0.4375 × 2	D41	0.3000	D63	0.4500 × 2	D85	0.5714
D20	0.4375 × 2	D42	0.5000 × 2	D64	0.4500 × 2	D86	0.5714
D21	0.4375 × 2	D43	0.5000 × 2	D65	0.9500 × 2	D87	0.3000
D22	0.4375 × 2	D44	0.5000 × 2	D66	0.3000	D88	0.5714

Abbreviation: TSC, total supply capability.

TABLE B2 Load of service transformers at the level higher than TSC.

Feeder number	Load (MVA)	Service transformer number	Load (MVA)
F1	**2.35**	D31	0.30
F2	7.00	D39	0.30
F3	5.70	D36	0.30
F4	6.00	D61	0.30
F5	2.10	D57	0.80
F6	6.55	D66	0.30
F7	7.00	D72	0.30
F8	4.30	D87	0.30
F9	7.30	D41	0.30
F10	2.90	D50	0.30
F11	4.80	D77	0.30

Note: The bold type in Table B2 is the increased load relative to the TSC in Table 1.
Abbreviation: TSC, total supply capability.