International Journal for Housing Science and Its Applications
Publish August 10, 2025. Volume 46, Issue 4 Pages 902-910

https://doi.org/10.70517/ijhsa46483

Topology optimization strategy of flexible interconnected low-voltage distribution network based on mathematical analysis

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Abstract The traditional distribution network structure is solidified and lacks flexibility, which is difficult to adapt to the new situation of large-scale access of distributed energy and rapid growth of electric load. This study proposes a topology optimization strategy for flexible interconnected low-voltage distribution network based on BTB-VSC, and constructs a mathematical model of distribution network with embedded DC and a VSC converter control system. In the methodology, a two-level voltage source converter is used to realize flexible interconnection between feeders, AC circuit equations and DC circuit equations are established, voltage deviation control and voltage sag control strategies are designed, and BTB-VSC optimization algorithm is developed for topology identification. The feasibility of the algorithm is verified by a 12-node network model and simulated in a large distribution network with 120 users connected to 4 stations. The results show that in a Gaussian noise environment with a signal-to-noise ratio of 20 dB, the BTB-VSC optimization algorithm reduces the number of time sampling points required to achieve 100% accuracy in topology identification from 235 to 200, which provides higher identification accuracy and faster convergence speed than the PCA algorithm. The strategy effectively solves the distribution feeder load imbalance problem, improves the terminal voltage quality, enhances the power supply reliability of the distribution network, and provides technical support for the friendly grid-connection of distributed power sources and the intelligent development of the distribution network.

Index Terms Flexible interconnected distribution network, BTB-VSC, topology optimization, voltage quality, distributed power supply, terminal voltage quality

I. Introduction

The new energy unit in the form of distributed power supply (DG) access to the distribution network is an important way of new energy consumption, is to realize the “double carbon” goal of an important initiative [1], [2]. In this context, the related industries are booming, such as “optical storage, direct and flexible” and a series of technologies such as power distribution, photovoltaic, energy storage and other interconnections, but also makes it difficult for the traditional distribution system to meet the needs of the new energy system, thus prompting the industry to explore more flexible and efficient power distribution solutions [3]-[6]. The low voltage distribution network, as the final link from the production of electric energy to the use of users, has the closest connection with users and the most direct impact on them, and the consumption of various distributed energy sources, interaction with the user side, and power transmission between stations need to be accomplished through the low voltage distribution network [7]-[10].

As an emerging technology system means, LV flexible interconnection shows significant advantages in solving these problems [11]. In addition, the topological information of the flexible interconnected LV distribution network is crucial for the safe operation of the distribution network, fault localization, and line loss analysis [12], [13]. With the emergence of intermittent distributed power sources such as wind energy and photovoltaic, as well as devices such as electric vehicles and energy storage, the number of nodes in the LV distribution network is increasing and the structure is becoming more complex [14]-[16]. This implies a high rate of structural heterogeneity in the LV distribution network, which requires timely updating and optimization of the system network topology and parameter configurations to ensure the safe operation of the power grid [17], [18].

In this paper, the topology of low-voltage distribution network is optimized by establishing a mathematical model of BTB-VSC technology and combining it with optimization algorithm. The effectiveness of the BTB-VSC optimization algorithm is verified through simulation experiments. By comparing the effects of different optimization strategies, it is found that the BTB-VSC optimization algorithm is able to improve the accuracy of topology identification while reducing the sampling time, which has a strong potential for practical application. The topology optimization strategy of flexible interconnected low-voltage distribution network based on BTB-VSC proposed in the study realizes the intelligent optimization of distribution network structure and the comprehensive improvement of operation performance, which provides the theoretical foundation and technical path for the construction and development of future smart distribution network.

II. Low-voltage AC/DC distribution network with embedded DC

In this section, the mathematical model of the LVT with embedded DC interconnection is derived, which includes the VSC converter mathematical model, the AC side of the LVT, and the embedded DC.

II. A. Mathematical analysis model for LV stations with embedded DC interconnections

II. A. 1) Mathematical model of VSC converter

In this paper, the embedded DC converter utilizes a two-level voltage source converter (VSC), which is the most basic type of converter and consists of two DC voltage levels, i.e., an AC measured voltage and zero voltage.

The two-level voltage source converter has six bridge arms, each of which is configured with an insulated gate bipolar transistor (IGBT) and a shunt diode. This configuration allows each bridge arm to convert energy in forward and reverse conduction to control the voltage on the AC side. In power electronic conversion systems for "double-high" requirements, in order to enhance the capacity and voltage level of the voltage source converter, IGBTs (insulated gate bipolar transistors) and the corresponding reverse shunt diodes are usually connected in series, which effectively increases the voltage withstand capability of each bridge arm. Key parameters such as the overall voltage level of the converter, its power rating, and the required voltage withstand capability will determine the exact number of IGBT and reverse shunt diode pairs to be connected in series. This ensures stable operation of the system while meeting the demands of higher voltage levels. A two-level converter typically outputs two levels + $U_{dc}/2$ and - $U_{dc}/2$ for each of the three phases. The two-level converter can then produce an output voltage similar to a sinusoidal waveform by utilizing pulse width modulation (PWM) techniques.

The VSC converter, with the two power switching devices contained in the upper and lower bridge arms of each phase, can ideally be treated as single-pole, double-throw (SPDT) switches. Based on this, the corresponding equivalent switching circuit model can be constructed. First, the switching function is defined in this paper as follows:

$$s_x = \begin{cases} 1 & Upper\ bridge\ arm\ device\ conduction \\ -1 & Lower\ bridge\ arm\ device\ conduction \end{cases} \quad (x = a, b, c) \tag{1}$$

Assuming that the voltage on the DC side remains constant, the DC voltage current, the AC current of the converter, and the AC side phase voltage (u_{cxo}) transformation relationship can be obtained as follows:

$$\begin{bmatrix} u_{ca.o} \\ u_{cb.o} \\ u_{cc.o} \end{bmatrix} = \frac{1}{2} u_{dc} \begin{bmatrix} s_a \\ s_b \\ s_c \end{bmatrix} \tag{2}$$

$$i_{dc} = \frac{1}{2} \begin{bmatrix} i_a & i_b & i_c \end{bmatrix} \begin{bmatrix} s_a \\ s_b \\ s_c \end{bmatrix} \tag{3}$$

where, $u_{cx.o}$ is the voltage at the midpoint of the bridge arm of the x -phase of the AC side of the VSC with respect to the midpoint of the DC side, and i_x is the current in the x -phase of the AC system.

Based on Eqs. (2) and (3), the phase voltage u_{crn} on the ac side of the converter can be expressed as follows:

$$\begin{bmatrix} u_{ca.n} \\ u_{cb.n} \\ u_{cc.n} \end{bmatrix} = \begin{bmatrix} u_{ca.o} \\ u_{cb.o} \\ u_{cc.o} \end{bmatrix} + \begin{bmatrix} u_{on} \\ u_{on} \\ u_{on} \end{bmatrix} = \frac{1}{2} u_{dc} \begin{bmatrix} s_a \\ s_b \\ s_c \end{bmatrix} + \begin{bmatrix} u_{on} \\ u_{on} \\ u_{on} \end{bmatrix} \tag{4}$$

where, u_{sx} is the voltage of the x phase of the AC system, and u_{cxn} is the voltage between the midpoint of the bridge arm of the x phase of the AC side of the VSC with respect to the midpoint of the AC supply (point n) [19].

II. A. 2) AC circuit equations

The three-phase circuit equation for the AC side of the VSC is given in the following equation:

$$L\frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = -R\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} u_{sa} \\ u_{sb} \\ u_{sc} \end{bmatrix} - \frac{1}{2}u_{dc}\begin{bmatrix} s_a \\ s_b \\ s_c \end{bmatrix} - \begin{bmatrix} u_{on} \\ u_{on} \\ u_{on} \end{bmatrix} \tag{5}$$

where, i_x is the current in phase x of the three-phase AC system.

In the AC side system of the converter, based on the circuit related theory, the following relationship can be established:

$$u_{sa} + u_{sb} + u_{sc} = 0 \tag{6}$$

$$i_a + i_b + i_c = 0 \tag{7}$$

By adding the three equations in Eq. (6) and combining Eqs. (5) and (7), the following results can be obtained in this paper:

$$u_{on} = -\frac{1}{6}u_{dc}(s_a + s_b + s_c) \tag{8}$$

The equivalent model expression for the switching function of the AC side circuit of the two-level converter can be obtained by (5), (6) and (8) as:

$$\begin{bmatrix} u_{\mathrm{ca.n}} \\ u_{\mathrm{cb.n}} \\ u_{\mathrm{cc.n}} \end{bmatrix} = \frac{u_{\mathrm{dc}}}{6}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}\begin{bmatrix} s_{\mathrm{a}} \\ s_{\mathrm{b}} \\ s_{\mathrm{c}} \end{bmatrix} \tag{9}$$

$$L\frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = -R\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} u_{sa} \\ u_{sb} \\ u_{sc} \end{bmatrix} - \frac{u_{dc}}{6}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}\begin{bmatrix} s_a \\ s_b \\ s_c \end{bmatrix} \tag{10}$$

where, R and L are resistance and inductance in series, respectively, and $x = a,b,c$ [20].

II. A. 3) DC circuit equations

Based on the DC-side equivalent circuit of the VSC and in conjunction with Eq. (10), the following conclusions can be drawn in this paper:

$$C\frac{du_{dc}}{dt} = i_{dc} - i_{load} = \frac{1}{2}\begin{bmatrix} i_a & i_b & i_c \end{bmatrix}\begin{bmatrix} s_a \\ s_b \\ s_c \end{bmatrix} - \frac{u_{dc}}{R_{load}} \tag{11}$$

Eqs. (10) and (11) together form the basic switching function model of the two-level voltage source converter. Obviously, the topology of the circuit can be instantly adjusted by changing the relevant parameters, which in turn can effectively control the voltage u_{cx} and current i_x on the AC side of the voltage source converter.

II. B.Embedded DC System Control Methods

II. B. 1) VSC control method

In the calculation of LV AC and DC distribution networks containing embedded DC, the equivalence of state variables between AC stations and VSC and between VSC and DC system is closely related to the control methods of VSC. Usually there are six control methods below VSC.The VSC control methods are shown in Table 1.Ps and Qs are the active and reactive power on the AC side.Vs is the voltage on the AC side and Udc is the node voltage on the DC side [21].

Table 1: VSC control method

Serial VSC	Control strategy	AC side equivalent	DC side equivalence
1	Ps/Qs	PQ	Definite P
2	Ps/Vs	PV	Definite P
3	Udc/Qs	PV	Definite V

4	Vs/Udc	PV	Definite V
5	Voltage droop/qs	PQ	Voltage drooping
6	Voltage droop/vs	PV	Voltage drooping

II. B. 2) Control Methods for Embedded DC Systems

Build embedded DC system, often need more than one VSC cooperative control to complete, then there is how to coordinate more than one VSC method, at present, the common control methods are the following three:.

1) master-slave control

VSC master-slave control refers to: a master converter to control the key parameters of the system (such as voltage, frequency and power flow, etc.), the rest of the converter from the converter to adjust its operation to follow the parameters and constraints set by the master converter. It has the advantage of improving the stability and reliability of the system and allows for more simplified control. However, the failure of the master controller may cause the control of the whole system to fail, so it is necessary for the master controller to have excellent reliability and fault recovery capability.

2) Voltage deviation control

Voltage deviation control is mainly realized by regulating the active and reactive power of the converter, which can directly affect the voltage level of the connection point.VSC can independently control the active and reactive power output, providing more flexible voltage support and grid stability. It has the advantage of providing fast and accurate voltage control. However, the complexity and cost of the control system is relatively high.

3) Voltage Sag Control

Voltage sag control simulates the voltage reduction that occurs naturally in conventional generators when the load is increased. Sag control is commonly used to improve grid stability, especially in distributed power sources and microgrids. It has the advantage of automatic power sharing, allowing multiple VSCs to automatically share the load according to the target capacity, which avoids the need for complex centralized control and communication techniques. However, since the voltage drops as the load increases, additional regulation equipment or control strategies may be required to keep the voltage within acceptable limits [22].

III. BTB-VSC based flexible interconnection topology optimization strategy

III. A. Topology

The BTB-VSC is installed at the end of the distribution feeder and realizes flexible interconnection between LV distribution feeders through DC lines. Thanks to the bi-directional flexibility and controllability of BTB-VSC port power, this interconnection type network frame has the following characteristics: (1) DC lines are used to realize multi-terminal interconnection.

(1) DC lines are used to realize multi-terminal interconnection, and the interconnection power is controllable without electromagnetic ring network problem.

(2) After DC interconnection, BTB-VSC can realize soft connection of each distribution feeder and each regional distribution network. The inter-network power is highly controllable, which can solve the load imbalance problem of distribution feeder and inter-network, avoid line blocking, reduce network loss, improve feeder utilization rate and optimize the overall operation level of distribution network.

(3) When there is a low-voltage overrun problem at the end of distribution feeder, BTB-VSC can provide active power from DC side to solve the low-voltage problem. When there is a high voltage overrun problem at the end of distribution feeder, BTB-VSC can transfer active power to the medium voltage DC side to solve the high voltage problem, so as to improve the voltage quality at the end of distribution line.

(4) When there is fault removal in distribution lines, end users can realize power supply through BTB-VSC, which improves the reliability of power supply in distribution networks.

(5) The fluctuating power and excess power introduced by renewable energy grid-connected can be shared by each interconnected line and synergistically consumed, thus significantly improving the ability of the distribution network to consume renewable energy.

(6) As a peak load, the EV fast charging station can be configured on the DC side, and the surplus capacity of each AC distribution network can jointly bear the load, thus avoiding the fast charging station from affecting the power quality of distribution users.

(7) BTB-VSC can take part of the functions of STATCOM and APF to improve the power quality of each distribution network by compensating reactive and harmonic power.

It can be seen that the flexible interconnected low-voltage distribution network based on BTB-VSC can solve the basic problems of the existing distribution network such as lack of trend flexibility and controllability, thus greatly improving the operation level of the distribution network and realizing the friendly grid connection of distributed power sources, which is one of the development trends of the future distribution network.

III. B. Topology optimization strategy

The equivalent circuit of a flexible interconnected distribution network is shown in Fig. 1.

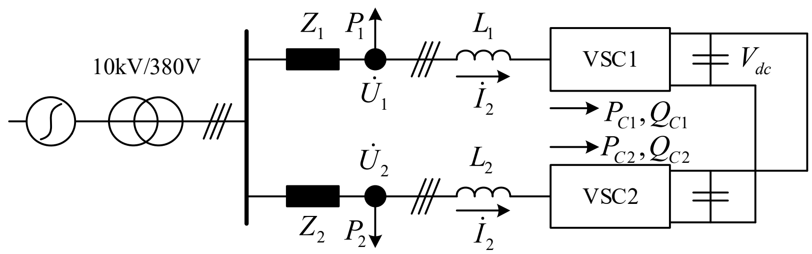

Figure 1: Equivalent circuit of flexible interconnected distribution network

Due to the close proximity of the two feeders, the BTB-VSC can simultaneously collect the AC voltage magnitude at the ends of the two feeders. With the goal of consistent voltage magnitude at the end, the voltage control strategy is shown in Fig. 2. VSC1 adopts the AC voltage deviation control strategy, whose outer loop is the AC voltage magnitude + reactive power control loop, and the inner loop is the d-axis active current + q-axis reactive current control loop. The AC voltage magnitude control loop takes the deviation of AC voltage magnitude at the ends of two feeders as input, and after PI control, its output is the reference value of d-axis active current, i.e., when the AC voltage magnitude is inconsistent, the VSC will realize the voltage magnitude adjustment through the interaction of active power between the feeders. The reactive power control loop takes the deviation of the reactive power and the reference value as input, and after PI control, its output is the q-axis reactive current reference value, and the reactive power of VSC1 can realize the function of harmonic compensation and other functions according to the demand of the line, so as to improve the power quality of the user's side. d, q-axis current control loop compares the d, q-axis components of the grid-side current and the reference value, and its deviation is controlled by PI, and its output is the d, q-axis voltage components of VSC1 reference value, and then the d, q-axis voltage components of VSC1 are compared with the reference value. axis voltage component reference value, and then through the transformation matrix, output the three-phase voltage reference value of VSC1, so as to realize the control objectives of AC voltage and reactive power. VSC2 adopts the DC voltage control strategy, whose outer ring is DC voltage + reactive power control ring and inner ring is d-axis active current + q-axis reactive current control ring. The DC voltage control loop compares the DC voltage with its reference value, and its deviation is the input, and after PI control, its output is the d-axis active current reference value, i.e., this loop controls the DC voltage constant, and the active power required by VSC1 to interact with it is completely provided by VSC2 from the AC side, and the DC is only used as the power transfer path, and does not participate in power regulation. The rest of the rings and VSC1 are consistent, and will not be repeated here.

Under the voltage control strategy in the figure, the BTB-VSC can interact the active power between the feeders through the DC bus, and then realize the consistency control of the magnitude of the end voltage of the two feeders, e.g., if the feeder 1 is overloaded and the feeder 2 is lightly loaded, then the end voltage of the feeder 1 crosses the lower limit. Under the control strategy, feeder 2 will naturally transfer power to feeder 1 terminal voltage for active compensation, and the terminal voltages of the two feeders will gradually approach and maintain consistency in steady state, i.e., the two feeders share the load of feeder 1, thus realizing the improvement of voltage quality. If the distributed generation power of feeder 1 is too high and feeder 2 is lightly loaded, the terminal voltage of feeder 1 exceeds the upper limit. Under the control strategy, feeder 1 will naturally transfer the generation power to feeder 2, and the terminal voltages of the two feeders will gradually approach and maintain the same in steady state, i.e., the two feeders will jointly consume the distributed power generation power of feeder 1, thus realizing the improvement of voltage quality. At the same time, this control strategy can maintain the stability of the DC bus voltage and realize the independent control of BTB-VSC reactive power.

IV. Analysis of examples

IV. A. Phase Recognition

The feasibility of the phase identification algorithm proposed in the paper is first verified by the actual topology of a 2-tier LV distribution station area. The 12-node model is divided into an upper and lower network, with phase nodes, i.e., 3 parent nodes A, B, and C, in the upper tier, and 9 user nodes in the lower tier connected to it. The slack variable σ = 0.15 is set. 12-node network acquisition data is shown in Table 2.

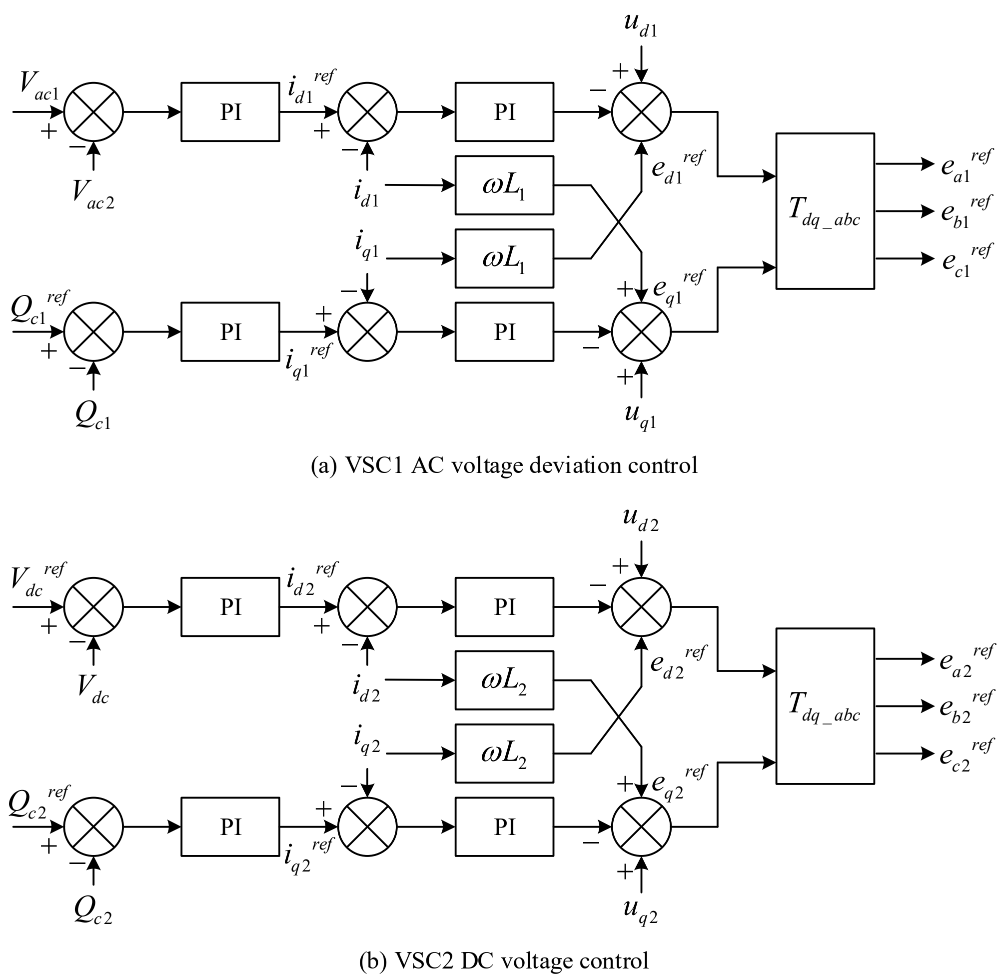

Figure 2: Voltage Control strategy of BTB-VSC

Table 2: Data of network power measurement

	Sampling point								
Node	1	2	3	4	5	6	7	8	9
1	148.36	234.17	148.9	3.6	204.6	154.5	121.7	69.8	66.6
2	585	13.2	43.6	67.2	50.8	153.5	208.4	206.1	201.5
3	88.5	80.4	21.7	100.2	10.5	67.2	24.2	26.9	35.7
4	200.4	382.6	158.3	235.9	247.9	286.1	160.5	346.7	369.7
5	30.8	82.4	15.4	51.7	62.4	72.6	40.9	75.8	90.8
6	58.4	347.9	172.9	166.8	383.2	303.9	393.5	96.3	40.8
7	132.8	145.8	244.3	124.2	100.1	254.7	67.3	170.2	244
8	32.3	55.8	1.2	90.7	41.7	32.3	97.6	48.7	30.4
9	236.6	62.8	30.4	233.5	115.5	147.3	291.1	347	140.7
A	311.5	346.8	221.2	184.6	276.2	392.7	370	316.3	321.3
B	303.9	854.8	364.8	482.1	732	694	627	542.4	528.8
C	413.3	278.9	298.8	470.3	273.2	454.3	482.5	594.6	437.3

The regression matrix R was calculated as shown in Table 3.

Table 3: The return of the topology matrix

	Point								
Node	1	2	3	4	5	6	7	8	9
A	-0.9714	1.1621	1.2056	0.1257	-0.4115	-0.0384	-0.1245	-0.2874	-0.0533
B	-0.0940	0.0722	0.1142	0.112	0.8337	1.0874	-0.1294	-0.2456	-0.0558
C	-0.1142	0.0685	0.0187	0.1242	-0.4562	0.0512	0.9684	0.8527	1.0083

The final topology identification result is obtained by rounding the data in the table. Combining the relationship between regression matrix and directed graph, the 2-layer 12-node distribution network topology can be derived, in which user nodes 1, 2, and 3 are connected to phase node A, user nodes 4, 5, and 6 are connected to phase node B, and user nodes 7, 8, and 9 are connected to phase node C. The topology visualization relationship is shown in Fig. 3.

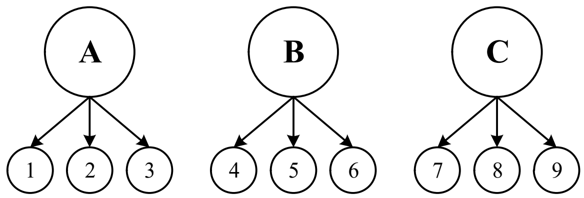

Figure 3: Node topological relationship

IV. B. Simulation analysis of LV distribution network topology identification

The BTB-VSC optimization algorithm proposed in this paper is next validated on a large LV distribution network, which is constructed using a random number generator in Matlab.For ease of computation, a region is set up with 120 customers connected to 4 stations with unknown connection relationships. The meter readings at each node are sampled from a random uniform distribution with mean and maximum values equal to the average and peak load of the consumers.

In this paper, simulation experiments are carried out using different data sets, and network topology identification simulation experiments are carried out using electricity measurements with k-values ranging from 0 to 300, respectively. The optimal solution matrix output from the simulation experiment is compared with the actual network topology topology matrix, and the simulation experiment is repeated for 300 times, and the accuracy of topology identification is defined as the percentage of the number of nodes with correctly identified connectivity relationships to the total number of nodes.

(1) Noise-free simulation: In this case, simulation experiments of BTB-VSC optimization algorithm were conducted separately and compared with 2 PCA algorithms, and the results are shown in Fig. 4. It can be seen that the BTB-VSC optimization algorithm performs better in terms of topology accuracy compared to the PCA algorithms, but the number of time sampling points required for the 3 algorithms to achieve 100% accuracy in topology identification is comparable. Comparing the optimization algorithms alone, the recognition accuracy of the BTB-VSC optimization algorithm is better than the PCA algorithm on the whole. Therefore, the BTB-VSC optimization algorithm can be used in the case of insufficient sampling data to obtain a more accurate topology.

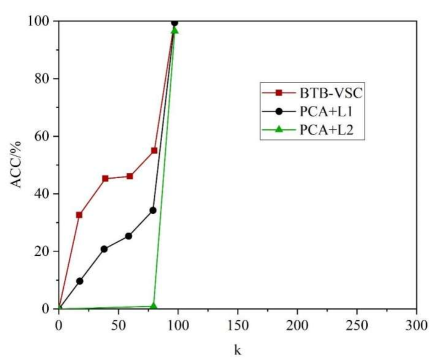

Figure 4: Success rate of topology identification without noise

(2) Noisy simulation:Since Gaussian noise with a signal-to-noise ratio of 20 dB is closer to the statistical properties

of noise in real measurement data, Gaussian random noise with a signal-to-noise ratio of 20 dB is introduced, and the simulation results are shown in Fig. 5. It can be seen that compared with the PCA algorithm, the number of time sampling points required by the BTB-VSC optimization algorithm proposed in this paper is reduced from 235 to 200 when the recognition accuracy reaches 100%, which means that a large amount of sampling time can be saved in reality. If the topology recognition accuracy reaches 100% with sufficient sampling data, the algorithm with better performance in terms of algorithm running time complexity can be chosen.

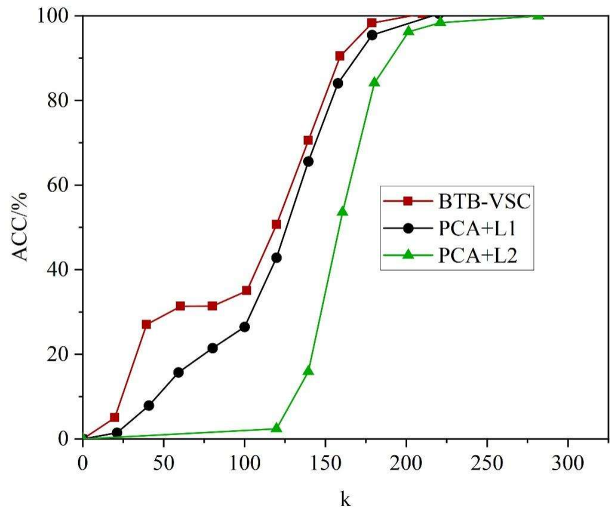

Figure 5: Success rate of topology identification with noise

V. Conclusion

The flexible interconnection topology optimization strategy based on BTB-VSC shows significant technical advantages and application value in low-voltage distribution networks. By establishing a complete mathematical model and control system, flexible interconnection and coordinated control between distribution feeders are successfully realized. Experimental validation shows that in the 12-node network model, the proposed algorithm can accurately identify the connection relationship between user nodes and phase nodes, and the topology identification accuracy reaches the ideal level. In large-scale distribution network simulation, verified by 300 repetitive experiments, the BTB-VSC optimization algorithm shows excellent convergence performance in a noise-free environment, and still maintains a high recognition accuracy under noisy interference conditions. The strategy effectively eliminates the electromagnetic loop problem through DC interconnection, realizes high-precision control of inter-network power, and significantly improves the load imbalance condition of distribution feeder lines. The BTB-VSC device has bidirectional power regulation capability, which can effectively solve the problem of voltage overrun at the end of the distribution line, and improve the voltage quality level. This technical solution creates favorable conditions for the large-scale access of distributed power sources, enhances the ability of distribution grid to consume renewable energy, and at the same time provides technical support for the rational allocation of electric vehicle charging facilities. The flexible interconnected distribution network architecture has good fault recovery capability, which can significantly improve the power supply reliability of the distribution system and lay a solid foundation for the construction of modern intelligent distribution network.

Funding

This work was supported by China Southern Power Grid Company Technology Project (GZKJXM20240015).

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