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Optimization study of feeder consumption carrying capacity of low and medium voltage distribution networks with deep learning support

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Abstract This paper addresses the lack of simple and effective informatization analysis tools for the selection of new energy and user access points by the planners of medium and low voltage distribution networks, considers the different types of new energy accessed by different distribution networks at different levels, proposes the objective function of assessing the new energy maximum carrying capacity of the distribution network by using the minimum of the maximum access capacity of the distribution network under each scenario and sets the constraints of assessing the safe operation of the grid at all levels, the power of the contact line and the power of each node to form a cooperative assessment model of the new energy carrying capacity of multi-level distribution networks. A hybrid optimization algorithm based on Gray Wolf algorithm and cone planning is applied to solve the carrying capacity optimization model. Compare the solution speed and accuracy of this algorithm with those of BONMIN solver, GA, PSO, SCOP and GWO. Analyze the distributed PV carrying capacity under different access methods and the effect of PV carrying capacity improvement. In the typical scenario of distributed PV, when the average value of PV output increases, the single power system starts to show light abandonment near the peak of PV output. Compared with the single power system, the Jieyang regional integrated energy system has a shorter abandonment period and a smaller amount of abandoned light, which indicates that the Jieyang regional integrated energy system based on the new energy carrying capacity assessment platform of the multilevel distribution grid has a better access scheme, produces a smaller amount of abandoned light, and has a higher level of distributed PV consumption.

Index Terms photovoltaic consumption, new energy carrying capacity, gray wolf algorithm, second-order cone relaxation, low and medium voltage distribution network

I. Introduction

In recent years, China is in the key stage of constructing a new type of power system under the “dual-carbon goal”, in which the new distribution system is an important part of the construction of the new type of power system [1]. Low-voltage distribution network for power users, in addition to providing users with high-quality power services, but also need to meet the inherent requirements of carbon neutrality, distributed photovoltaic (DPV) in the low-voltage distribution network of the wide access is to achieve the “dual-carbon goals” of the main means [2]. However, with the PV power generation showing a large-scale growth trend, more and more PV access to the medium and low voltage distribution network caused by the obvious impact of the impact, some regions have appeared to consume the problem of limited carrying capacity [3]-[5]. In this context, the construction of a new type of medium- and low-voltage distribution system with stronger new energy consumption and carrying capacity is crucial for realizing China's “dual-carbon” goal. However, the continuous surge of DPV makes the distribution network face the challenge of consumption, which has a serious impact on its operation [6]. Currently, most of the distribution grids in China are designed according to unidirectional currents, and when the PV power output is large, the excess power is sent backward, forming a reverse current in the feeder, which leads to serious overvoltage problems in the distribution grid [7]-[9]. Therefore, there is an urgent need to conduct a study of distributed PV carrying capacity (PVHC) in distribution networks to characterize the maximum installed PV capacity that the grid can access under the safe operation constraints, and to provide guidance for the local government as well as relevant enterprises on DPV grid integration in distribution networks to adapt to China's low-carbon development requirements [10]-[12].

Currently, some studies have used mathematical optimization methods to establish optimal tidal current models to obtain PVHC by solving under safe operation constraints with the objective function of maximum installed PV capacity or minimum transmission power from the higher-level grid to the regional grid [13]-[15]. Literature [16] used the Sticky Mushroom Algorithm (SMA) as a bionic optimization method for optimal reactive power (Volt/VAr) control of PV and BESS smart inverters in order to improve the PV consumption carrying capacity of the distribution grid. Literature [17] determined a method to maximize the PV carrying capacity (PVHC) based on the equilibrium optimizer (EO) under various constraints such as reverse current (RPF) limitation and smart inverter voltage reactive control (WC). Literature [18] in his study proposed a method for calculating the optimal tidal current of multicarrier energy systems based on mixed integer linear programming (MILP) method and in examined that the method can provide fast and accurate PVHC solutions for large-scale distributed PV systems. Literature [19] improved the traditional simulated annealing algorithm to model the consumption carrying capacity of distributed PV systems based on the constraints and limitations of the distribution network and achieved good dynamic optimization. Literature [20] used Monte Carlo simulation (MCS) to establish the distribution function of voltage and PV grid-connected capacity to evaluate the distribution network PVHC under economic constraints. Taken together, the above research results show that the mathematical optimization-based evaluation method needs to be predetermined for a specific few potential grid-connected nodes. In fact, the number, location and capacity of DPV access are determined by user investment, which cannot be decided by the power company in advance, although guided by relevant policies [21]-[23]. Therefore, this type of approach has limitations in considering the diversity of DPV configurations (number, location and capacity of DPVs connected to the network, etc.) in the medium- and low-voltage distribution networks, and suffers from insufficient adaptation scenarios, which cannot be applied to the scenarios of large-scale DPVs connected to the network [24], [25].

In contrast, existing studies generally agree that deep learning methods facilitate sufficient traversal of DPV access scenarios in distribution networks and are more suitable for PVHC optimization in distribution networks [26]. Literature [27] used a deep learning model based on convolutional neural networks (CNN) and gated recurrent units (GRUs) as a method to evaluate the carrying capacity of distributed PV power consumption in distribution networks under different scenarios. Literature [28] proposes a deep reinforcement learning algorithm based method to assess the real-time consumption carrying capacity of low-voltage distribution networks, which only needs to consider real-time customer voltage and solar irradiation data and allows for fast estimation and optimization of real-time PVHC. Literature [29] proposed a deep learning model incorporating Deep Recursive Double Q Networks (DR-DQN) and Deep Convolutional Neural Networks (DCNN) for optimizing the distributed power carrying capacity of a power system. In addition to this, the vast majority of PVHC optimization studies are oriented to regional grids, and although some results have been developed, the research on PVHC optimization for low- and medium-voltage distribution networks is still insufficient.

METHODS OF THIS PAPER: This paper interprets the concepts of distribution network planning and construction, distribution network photovoltaic carrying capacity, and new energy carrying capacity. Starting from optimizing the regional access scheme of medium and low-voltage distribution networks, the new energy maximum carrying capacity assessment model is proposed, i.e., the new energy carrying capacity collaborative assessment model of multi-level distribution networks, and the optimization algorithm composed of a mixture of the gray wolf algorithm and the second-order cone relaxation model is used for the carrying capacity optimization model solving. Combining the hybrid optimization algorithm based on the Gray Wolf algorithm and cone planning, a distributed new energy carrying capacity analysis platform is constructed to visually monitor the overall access situation of distributed new energy in the region. Analyze the development of low and medium voltage distribution networks in Jieyang region, and discuss the carrying capacity of distributed PV under different energy systems and inaccessible access methods.

II. Brief description of the new energy carrying capacity of distribution networks

II. A. Overview of distribution network planning and construction

In order to realize the development of the city in line with the demand for electricity, and to ensure the reliability as well as the safety of the power supply of the distribution network, the construction and planning of the medium and low voltage distribution network should be strengthened [30]. For the planning of distribution network, it specifically includes the following aspects.

(1) The current distribution network conditions for investigation, and the future development of urban power supply demand to make scientific predictions for the distribution network planning techniques to be adopted to be determined.

(2) Divide the power supply area according to certain standards, design a reasonable 10 kV distribution network design program, and roughly estimate the investment cost of planning.

(3) In the planning process, in order to ensure the feasibility of the design scheme and improve the reliability of power supply, the level of investment in the distribution network should be analyzed comprehensively, and the specific network wiring method should be adopted, as well as the investment period.

For the planning of the power grid, can be divided into "three-step" approach:

(1) Initial construction of the long-term use of the power grid.

(2) Comprehensive analysis of the linear grid conditions and reasonable forecasts of future loads to design a near-term plan.

(3) Design a meta-plan. Among them, for the prediction of load, it must be combined with the actual situation and the development of the city to make a scientific prediction, it is the most basic link of urban power grid planning, and it is extremely significant for the construction of medium and low voltage distribution network, which can affect the power supply capacity and power supply quality of the distribution network to a large extent.

II. B.Distribution network carrying capacity

Transforming the energy structure and creating a new energy supply and consumption system is a must for realizing the dual-carbon goal. In this context, a series of new energy generation such as photovoltaic has ushered in new development opportunities.

Distributed photovoltaic power generation in the distribution network accounted for an increasing proportion of a series of economic, technical and environmental benefits, but also to the safe and stable operation of the system brings over-voltage, reverse power flow and power quality degradation and other risks.

Medium and low voltage distribution network planning and construction need to consider more and more factors, in addition to the grid's consumption and carrying capacity, but also need to consider the impact of users and new energy on the distribution network short-circuit current level, voltage amplitude and other indicators. At present, medium and low-voltage distribution network planners for new energy, the choice of user access points mainly rely on manual calculation and empirical judgment, the lack of simple and effective information technology analysis tools. There is an urgent need to analyze and calculate the types and capacities of users and new energy sources that can be accessed by regional and local distribution networks, so that the medium- and low-voltage distribution network can realize the optimal access scheme in the region. All of the above issues will affect, or even determine, the capacity of the whole system to access PV, i.e., the PV carrying capacity (HC) of the distribution network.

Regarding the concept of HC, it is defined as the distributed power capacity when the power system operation index (voltage and current during normal system operation) exceeds the acceptable interval. Nowadays, with the increasing proportion and diversification of renewable energy penetration in distribution networks, the definition of HC is more abundant and specific. It can be broadly categorized into static HC and dynamic HC, which are defined as intervals. Static HC is a specific value of distributed PV output when overvoltage and other phenomena occur in the distribution network.

The mathematical description of HC is defined as an interval $[H_{\min}, H_{\max}]$, and $H_{\min}$ is the PV minimum outgoing power under the first overvoltage scenario in the distribution network. $H_{\max}$ is the minimum PV output in the distribution network that can cause overvoltage in all scenarios, and the detailed mathematical description is shown in Eq. (1) and Eq. (2):

$$H_{\min} = \min_{i \in S} \left\{ PV_{pen}^{i} \middle| \max\left(V_{\max}^{i}\right) > 1.05 \right\} \tag{1}$$

$$H_{\max} = \min_{i \in S} \left\{ PV_{pen}^{i} \middle| \min\left(V_{\max}^{i}\right) > 1.05 \right\} \tag{2}$$

The key to HC assessment and determination lies in the handling of uncertainty in distribution network operation, which is caused by demand-side customer loads, volatility of PV output, and data processing of terminal equipment. The uncertainty can be categorized into objective uncertainty (AU) and subjective uncertainty (EU) according to the root cause of the uncertainty.

In the research for objective uncertainty random variables, scenario sampling, stochastic planning modeling, and robust optimization are mostly used. To deal with subjective uncertainty, in addition to the three methods mentioned above, the distribution network operating conditions are also analyzed by methods such as trend calculation software or linear regression to determine the HC, but it is not universal.

II. C.New energy carrying capacity

The "new energy carrying capacity" of the power system refers to the safe, reliable and economic operation level and its margin relative to the target requirements that can be achieved by a new type of power system with access to a specified scale and distribution of new energy power stations under a determined conventional power supply configuration, grid structure and load distribution. It is jointly described by a series of indicator values and their distance from the target value constituting the indicator system.

The "new energy carrying capacity" of the power system is described by a series of evaluation indicators that reflect the impact of new energy on the security, reliability and economy of grid operation. The margin of these indicators relative to the system's allowable threshold reflects the margin of the power system's ability to carry the specified new energy scale. The analysis of "new energy carrying capacity" can be analyzed from the medium and long term power abundance, day-to-day peaking capacity, and short-term system security in multiple dimensions.

As can be seen from the above definition, the "new energy carrying capacity" of the power system is related to the scale and geographical distribution of new energy generation such as wind power and photovoltaic power in the system, and is quantitatively described in the given new energy and conventional power supply planning program for the determined grid structure and load level.

III. Collaborative assessment of new energy carrying capacity of multilevel distribution networks

III. A. Model for assessing the maximum carrying capacity of new energy sources

The distribution network is the part of the power system that distributes and uses electricity, and its topological structure is radial. From the overall view, the multi-level distribution network is connected and transmits power through contact lines, which can still be regarded as a large-scale distribution network without loop line structure, and there is generally no power interaction between distribution networks of the same level, and the model of the multi-level distribution network is shown in Fig. 1. In the figure, the three voltage levels A, B and C constitute the multilevel distribution network model, which are called high, medium and low voltage distribution networks, respectively. Circles indicate individual distribution networks, and individual distribution networks within each tier are connected to multiple distribution networks of lower voltage levels, and the regional distribution network composed of medium- and low-voltage distribution networks can be regarded as a distribution network connected to the high-voltage power grid. Therefore, the regional distribution network composed of medium- and low-voltage distribution networks is the basic structure for the assessment of multilevel distribution networks. The evaluation of multilevel distribution network is equivalent to a nested optimization problem containing multiple basic architectures. After solving the problem of carrying capacity evaluation of two-level distribution network, the evaluation of new energy carrying capacity of multilevel distribution network will be solved.

In this paper, the new energy carrying capacity assessment problem of multilevel distribution grid is studied by taking the regional two-level grid in the dotted line box as an example, where B_1 is called the upper-level grid and C_m is called the lower-level grid. Assuming that each node of the distribution network can access new energy, and characterizing the new energy carrying capacity of the two-level distribution network by the sum of the new energy access capacity of each node, a new energy maximum carrying capacity assessment model is established.

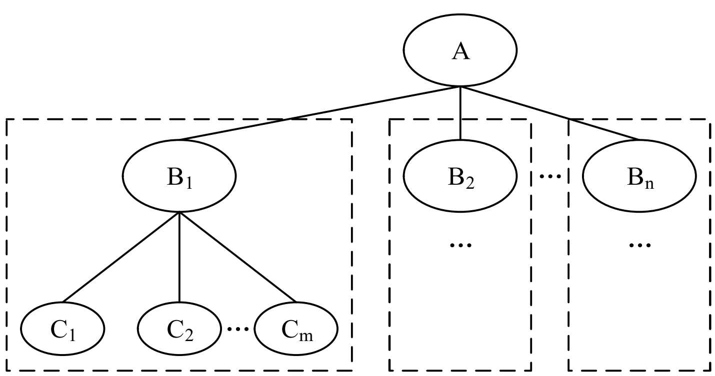


Figure 1: Multi-scale distribution network model

III. A. 1) Objective function

Considering the different types of new energy accessed in different levels of distribution grids, two new energy sources of wind power and photovoltaic are accessed in the upper level grid, and only photovoltaic is accessed in the lower level grid. To describe the uncertainty of the two new energy types of wind and light in the distribution network with multiple scenarios, the maximum carrying capacity of new energy in the distribution network is evaluated with the minimum value of the maximum access capacity in each scenario, and the objective function is shown in Eq:

$$f=\min_{s}\max\left[\sum_{i=1}^{N_1}\left(S_{PV,i,s}^{T}+S_{WT,i,s}^{T}\right)+\sum_{n=1}^{N}\sum_{j=1}^{N_{2,n}}S_{PV,j,s}^{D}\right] \tag{3}$$

where s is the operation scenario. $S_{PV,i,s}^{T}$ and $S_{WT,j,s}^{T}$ are the PV, wind access capacity of the i node of the upper grid of the s scenario. $S_{PV,j,s}^{D}$ is the PV access capacity of the jth node of the lower grid for the sth scenario. N_1 is the number of nodes of the higher-level grid. $N_{2,n}$ is the nth lower grid node number. N is the number of lower grids connected to the upper grid.

III. A. 2) Constraints

The constraints related to the new energy carrying capacity assessment problem of distribution network studied in this paper mainly include the safe operation constraints of power grids at all levels, the power constraints of contact lines and the new energy access capacity constraints of each node.

(1) Currents constraints

a/ Superior grid current constraints:

$$\begin{cases}P_{i,s}^{T}-P_{i,s}^{d}=V_{1i}\sum_{j=1}^{N_1}V_{1j}\left(G_{1ij}\cos\theta_{1ij}+B_{1ij}\sin\theta_{1ij}\right)\\ Q_{i,s}^{T}-Q_{i,s}^{d}=V_{1i}\sum_{j=1}^{N_1}V_{1j}\left(G_{1ij}\sin\theta_{1ij}-B_{1ij}\cos\theta_{1ij}\right)\end{cases} \tag{4}$$

where $P_{i,s}^{T}$, $Q_{i,s}^{T}$ represent the new active, reactive power of the new energy at the s scenario superior grid node i, respectively. $P_{i,s}^{d},Q_{i,s}^{d}$ represent the active, reactive power of the loads at the ith scenario superior grid node s, respectively. G_{1ij},B_{1ij},B_{ij}, and B_{ij} represent the conductance, conductivity, and voltage phase angle between the upper grid nodes i and j, respectively.

b/ Lower grid current constraints:

$$\begin{cases}P_{j,s}^{D}-P_{j,s}^{d}=V_{2i}\sum_{j=1}^{N_2}V_{2j}\left(G_{2ij}\cos\theta_{2ij}+B_{2ij}\sin\theta_{2ij}\right)\\ Q_{j,s}^{D}-Q_{j,s}^{d}=V_{2i}\sum_{j=1}^{N_2}V_{2j}\left(G_{2ij}\sin\theta_{2ij}-B_{2ij}\cos\theta_{2ij}\right)\end{cases} \tag{5}$$

where $P_{j,s}^{D}$, $Q_{j,s}^{D}$ represent the new energy active, and reactive power at the jth scenario lower grid node s, respectively. $P_{j,s}^{d}$, $Q_{j,s}^{d}$ represent the active, reactive power of the loads at the jth scenario lower level grid node s, respectively. G_{2ij}, B_{2ij}, θ_{2ij}, and θ_{2ij} represent the conductance, conductivity, and voltage phase angle between the subordinate grid nodes i and j, respectively.

(2) Nodal voltage constraints:

$$V_{i,\min}\le V_{i,s}\le V_{i,\max} \tag{6}$$

where $V_{i,s}$ is the voltage amplitude of the sth scene node i. $V_{i,\min}$ and $V_{i,\max}$ are the minimum and maximum values of voltage at node i.

(3) Branch current constraints:

$$P_l\le P_{l,\max} \tag{7}$$

where P_l is the branch current and $P_{l,\max}$ is the maximum value of the branch current.

(4) Contact line power constraint

The coupling relationship between the two levels of the grid is reflected in the contact line power transfer, so the contact line power transfer is used as an effective means to coordinate the consumption capacity of each level of the distribution grid and improve the new energy carrying capacity. Let the probability of backward transmission of power from the lower level grid be δ, then the value of transmitted power on each contact line is constrained as follows:

$$P_{l,i,\min}\le P_{l,i,s,t}\le P_{l,i,\max} \tag{8}$$

$$\Pr\left\{P_{l,i,s,t} \le 0\right\} \le \delta \tag{9}$$

where $P_{l,i,s,t}$ is the transmission power of the i th contact line at the t th moment in the s th scenario, and a negative value indicates power backward transmission. $P_{l,i,\min}$, $P_{l,i,\max}$ are the minimum and maximum values of the i th contact line transmission power.

III. B. Load-bearing capacity optimization model solution

Based on the constructed new energy carrying capacity optimization model of multilevel distribution network, this paper adopts a hybrid optimization algorithm based on grey wolf algorithm and cone planning to solve the problem.

III. B. 1) The Gray Wolf Algorithm

Gray Wolf Algorithm (GWO) is a heuristic optimization algorithm derived from the social behavioral characteristics of gray wolves in nature, and its basic idea is to solve the optimization problem by simulating the social structure and behavioral patterns of the gray wolf group [31], [32]. During the execution of the algorithm, the optimization space of the problem is regarded as the grey wolf group searching for prey. The location of the gray wolf in the D -dimensional search space is $X = (X_1, X_2, \ldots X_D)$, and the individual update and group collaboration are carried out by modeling the hunting behavior and social hierarchy with a view to finding the global optimal solution. During the execution of the algorithm, the positions of the individual gray wolves represent the candidate solutions of the optimization problem, and the relative positions between the individual gray wolves and their prey reflect their fitness in the solution space.

In the GWO algorithm, the higher rank of the gray wolf corresponds to the better fitness of the solution, and the location of the prey corresponds to the globally optimal solution. The wolves are divided into α wolves, β wolves, δ wolves and the rest of the wolves individually ω according to their rank from high to low, the wolves are commanded to search by the α, β and δ wolves, and ω wolves obey the command of the previous 3 types of wolves towards the prey location (global optimal solution) surrounded by a mathematical model:

$$D_q = CX_q(n) - X(n) \tag{10}$$

$$X(n+1) = \frac{1}{3}\sum_{q\in\{\alpha,\beta,\delta\}}\left(X_q(n) - AD_q\right) \tag{11}$$

$$C = 2r_1 \tag{12}$$

$$A = 2ar_2 - a \tag{13}$$

where D_q is the distance between the gray wolf and the prey. n is the current number of iterations and $X_q(n)$ is the position of the prey after n iterations. q is the head wolf individual for α, β and δ wolves, and $X(n)$ is the location of the gray wolf after n iterations. A, C are the coefficients of synergy, and r_1 and r_2 are random numbers between 0 and 1. a is the convergence factor, whose value decreases linearly from 2 to 0 during the iteration.

The gray wolf group searches for the optimal solution in the global range by updating its position through the random change of the coefficient of synergy. Applying the gray wolf algorithm to the new energy carrying capacity optimization problem, 1 group of new energy access capacity and RPFC access position are regarded as the position of the initial gray wolf group, and the objective function under this combination, i.e., the carrying capacity level, is regarded as the adaptation degree of the gray wolf group in space. As the gray wolves adjust their positions according to their fitness and distance from the optimal solution, the DNE access capacity and RPFC access position are changed to update the optimal solution of the problem.

III. B. 2) Second-order cone relaxation

In the transconvex part of the model using second-order cone, the variables $\sigma_{i,t} = U_{i,t}^2$ and $\varsigma_{ij,t} = I_{ij,t}^2$ are introduced for the second-order cone relaxation. And combined with the large M method to introduce relaxation coefficients M to relax the distflow equation so that the current and power on the disconnected line is 0. The current constraint of the closed branch is transformed to:

$$\sigma_{i,t} - \sigma_{j,t} - 2\left(r_{ij}P_{ij,t} + x_{ij}Q_{ij,t}\right) + \left(r_{ij}^2 + x_{ij}^2\right)\varsigma_{ij,t} + M\left(1 - \varepsilon_{ij}\right) \ge 0 \tag{14}$$

$$\sigma_{i,t} - \sigma_{j,t} - 2\left(r_{ij}P_{ij,t} + x_{ij}Q_{ij,t}\right) + \left(r_{ij}^2 + x_{ij}^2\right)s_{ij,t} - M\left(1 - \varepsilon_{ij}\right) \le 0 \tag{15}$$

$$\left\| \begin{bmatrix} 2P_{ij,t} & 2Q_{ij,t} & \varsigma_{ij,t} - \sigma_{i,t} \end{bmatrix}^T \right\|_2 \leq \varsigma_{ij,t} + \sigma_{i,t} \tag{16}$$

In addition, some of the constraints in the demand response constraints and the RPFC constraints are also nonlinear constraints that can be converted to the second-order cone form, i.e:

$$\left\| \begin{bmatrix} P_{i,t}^{RPFG} Q_{i,t}^{RPFG} \end{bmatrix}^T \right\|_2 \leq S_i^{RPFG} \tag{17}$$

$$\left\| \left[\xi_t^{\frac{1}{2}} \rho_t^{ear} - \frac{1}{2}\left(\rho_t \xi_t^{\frac{1}{2}} + P_t \xi_t^{-\frac{1}{2}} \right) \right]^T \right\|_2 \leq \sqrt{\sum_{t=1}^{T} \left[\frac{1}{4}\left(\rho_t \xi_t^{\frac{1}{2}} + P_t \xi_t^{-\frac{1}{2}} \right)^2 - P_t \rho_t \right]} \tag{18}$$

Therefore, the new energy carrying capacity optimization model of the distribution network considering RPFC and DR can be transformed into a mixed-integer second-order cone planning problem. The solution of the model is realized by calling the MOSEK solver through the YALMIP toolbox in Matlab.

III. B. 3) Load carrying capacity optimization model solution process

The solution flow of the hybrid optimization algorithm based on gray wolf algorithm and cone planning is as follows:

The gray wolf algorithm is used as the framework of the hybrid algorithm to determine the access capacity of new energy and the access location of RPFC, and the access capacity of new energy and the location of RPFC inputs are regarded as the individual wolves in the gray wolf pack, and the upper objective function is regarded as the fitness function of the gray wolf pack. During each iteration of the gray wolf algorithm, the second-order cone relaxation is used to transconvex solve the model to obtain the optimal operation mode of the distribution network system in each scenario, so as to calculate the adaptation degree of the individual in the gray wolf algorithm. The optimal solution of the problem is considered to be obtained when the fitness function no longer changes after multiple updates of the gray wolf position.

III. C. Distributed New Energy Carrying Capacity Assessment Platform

On the basis of hybrid optimization algorithm based on Gray Wolf algorithm and cone planning, a distributed new energy carrying capacity analysis platform has been constructed, and the analysis results are visualized by relying on a single map of the whole network in an integrated way of "map model library". The platform realizes the visualization and measurement of distributed new energy carrying capacity, which is conducive to planning and designing personnel to visually monitor the overall access situation of distributed new energy in the region, and provides support for coordinated regulation and risk prevention of distributed new energy.

III. C. 1) Assessment of program design

The assessment process of distributed PV carrying capacity can be roughly divided into four stages.

First is the data preparation, to carry out a certain area of the carrying capacity analysis and calculation need to provide relevant data, generally should contain power installed information, power supply characteristics data, grid equipment parameters, historical operation data, power quality real-time measurement data and safe operation boundary data.

Then, based on the data provided, the thermal stability assessment and the calculation of accessible capacity are carried out, and the voltage deviation, short-circuit current, harmonics and other constraint indexes are checked. Then, based on the results of the calculation and analysis, we assess the level of distributed PV carrying capacity of the grid in accordance with the principle of hierarchical classification.

Finally, specific measures are taken for the regional power grids in each assessment level to increase the accessible capacity as much as possible under the premise of meeting the safe and stable operation.

In this paper, the assessment results of distributed PV carrying capacity are visualized with different colored grades. The assessment grades are divided according to the satisfied condition A and condition B. Among them, Condition A is the range of values of the maximum reverse load ratio λ_{max}, and Condition B is that the voltage deviation, short-circuit current, and harmonic calibration are passed. The specific grading principles are as follows:

(1) Condition A: $\lambda_{max} \in (80\%, 100\%]$

Condition B: FALSE, or the main network at voltage level 220 kV and above has a back-feeding current.

Level: Class I, red.

Conclusion: Grid back-feeding current exceeds 80% of the equipment limit, and there is a security risk in grid operation. It is recommended to suspend new distributed PV access until the grid carrying capacity is effectively improved.

(2) Condition A: $\lambda_{max} \in (0, 80\%]$
Condition B: TRUE
Grade: Class II, yellow.
CONCLUSION: Grid back-feeding currents are within 80% of the equipment limit, and access to distributed PV is provided that a special analysis is carried out.
(3) Condition A: $\lambda_{max} \in (-\infty, 0]$
Condition B: TRUE
Grade: Class III, green.
CONCLUSION: There is no back-feeding current from the grid, and distributed PV access is recommended.

III. C. 2) Overall platform architecture

The multi-layer distributed PV carrying capacity analysis platform for distribution networks designed in this paper gives full consideration to business scalability, adopts micro-service technology to realize business module division and standardized services, and abstracts three layers from the bottom up, which are the data resource layer, the platform service layer and the application management layer.

The data resource layer is configured with storage and security communication equipment such as servers and security gateways as the infrastructure of the platform.

The platform service layer builds a model data platform to support the data communication, access and storage of distributed photovoltaic equipment and power consumption collection system, and provides six component services: topology analysis, data parsing, file management, log management, data security and timed tasks. It interacts with the dispatch automation system in a friendly way through safe interaction to ensure the safety of power grid operation.

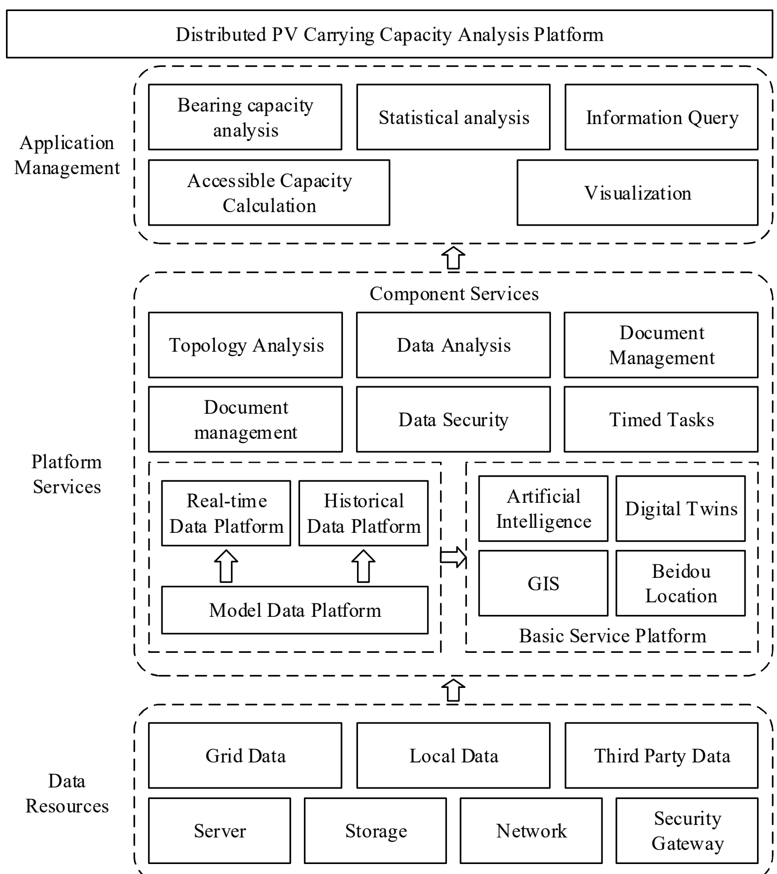


Figure 2: Distributed PV bearing capacity analysis platform architecture

The application layer provides data and services based on the data resource layer and platform service layer, realizing functions such as carrying capacity analysis, statistical analysis, information query and accessible capacity. And combined with GIS maps, it realizes the visualization display of distributed PV carrying capacity assessment results, and supports the full-time multi-dimensional analysis and assessment of distributed PV carrying capacity.

The architecture of distributed PV carrying capacity analysis platform is shown in Figure 2.

IV. Analysis of examples

This paper relies on the “distributed power access grid carrying capacity assessment guidelines” DL/T 2041-2019 in the new energy access to the distribution network requirements, according to the current situation and development trend of regional distributed new energy development, combined with the government can use new energy development resources, research 110kV, 35kV, 10kV power supply range to carry out the distribution of power access grid carrying capacity assessment calculation principles, to carry out research The study will be carried out.

IV. A. Development of Medium and Low Voltage Distribution Networks in the Jieyang Region

(1) Situation of medium-voltage distribution network

In 2024, Jieyang City has a power supply area of 1024 km^2, all of which belong to the management system of direct supply and direct management, with a power supply population of 1,412,000 people, the rate of one-household meter is 96%, and there are 18 substations. The annual maximum load of the network supply is 701MW, the electricity supply is 4.15 billion kWh, and the electricity sale is 3.95 billion kWh. The reliability of the electricity supply in the area of 10kV and below is 99 %, the comprehensive line loss rate is 5.37%, and the comprehensive voltage pass rate is 98%..

(2) Overview of medium voltage distribution network

At present, there are a total of 128 10kV and 291 dedicated and utility lines in Jieyang area. In the distribution network of Jieyang area, the total length of utility lines reaches 2975.1km, including 2653.2km overhead lines, 321.9km cables, 3654 sets of column switches and 872 faces of switchgear.The statistics of utility lines and equipments of Jieyang medium-voltage and low-voltage distribution network of 10kV and below in 2024 are shown in Table 1.

Table 1: Statistics of the current voltage distribution network equipment

Power area	Voltage rating	Common feeder						Special feeder (gyrus)
		Common feeder (gyrus)	Overhead wire(km)	Cable (km)	Total (km)	Post switch (time)	Switch cabinet (surface)	
C	10kV	112	1124.03	121.4	1245.43	1620	362	45
D	10kV	179	1529.17	200.5	1729.67	2034	510	83
Total	10kV	291	2653.2	321.9	2975.1	3654	872	128

(3) Analysis of the current status of the low-voltage distribution network

Overall analysis of the current status of the low-voltage distribution network part of the low-voltage grid, the level of equipment and the size of the network frame statistics. The statistics of current distribution facilities of low-voltage distribution network in Jieyang region are shown in Table 2. There are 13 box-type distribution stations and 47 indoor distribution stations. In the region with large population movement, the heavy overloading of distribution transformers caused by the change in direction of loads and the influx of population during the Spring Festival homecoming tide, this type of distribution transformer heavy overloading phenomenon will have a very large impact on users.

According to the relevant regulations, the voltage at the end of the low-voltage line is below 90% of the rated voltage as low voltage, and above 107% of the rated voltage as high voltage, which means that the voltage at the end of the line must be 198V~235V to be reasonable.

According to the statistics, Jieyang District, a total of 369 stations have terminal voltages below 198V, of which 22 stations have terminal voltages below 180V and 347 stations have terminal voltages between 180V and 198V.

Table 2: The distribution and distribution facilities of low voltage distribution network

Partition	Voltage rating(kv)	Platform station(time)	Box distribution station(seat)	Indoor distribution station(seat)
Total	10kV	5683	13	47
Categories	Special distribution transformer		Public distribution transformer	
Total	Number of tables(times)	Capacity (10,000 kV)	Number of tables(times)	Capacity (10,000 kV)
	2136	98.635	2379	40.121

Type	The voltage is out of the building area		
	Low voltage(<180V)	Low voltage(180~198V)	High voltage(>235V)
Quantity	22	347	0
The proportion of the total	0.95	18.37	0

IV. B. Results of distributed PV carrying capacity analysis

IV. B. 1) Analysis of distributed PV carrying capacity under different energy systems

In this paper, the IEEE 33-node power distribution network and the 32-node thermal network in Jieyang area are used as the regional integrated energy system examples.

In order to illustrate the advantages of the new energy carrying capacity collaborative assessment system of multilevel distribution grid in enhancing the distributed PV carrying capacity, the IEEE 33-node power system is set up to compare the distributed PV configuration capacity with the comprehensive energy system example of the study area (Jieyang) in this paper, and the results of the analysis of the distributed PV carrying capacity are compared as shown in Table 3. The total system configuration capacity and total cost of the Jieyang regional integrated energy system are 6.94 MW and 35.004$/day, respectively, which are slightly higher than the IEEE 33-node power system. Both energy systems are configured with distributed PV at four node locations, which reaches the upper limit of the number specified by the system, indicating that with the goal of minimizing the system distributed PV configuration cost, operation cost, and light abandonment cost, the system tends to build a larger number of distributed PVs, which reduces the fuel cost due to the unit outage within the system to a certain extent.

Table 3: Comparison of distributed pv capacity analysis results

Energy system	Categories				
Ieee 33 node power system	Distributed pv access node location(No.)	22	26	27	31
	Each node configuration capacity(MW)	2.15	2.48	0.66	1.01
	Total system configuration capacity(MW)	6.30			
	The total cost of the system(Yuan/d)	33.107			
Jieyang regional integrated energy system	Distributed pv access node location(No.)	21	26	10	31
	Each node configuration capacity(MW)	2.53	2.59	0.45	1.37
	Total system configuration capacity(MW)	6.94			
	The total cost of the system(Yuan/day)	35.004			

IV. B. 2) Distributed Photovoltaic Consumption

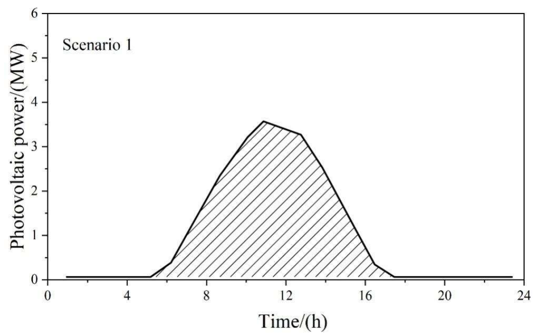
The distributed PV consumption of Jieyang regional integrated energy system is shown in Fig. 3, which demonstrates six typical distributed PV output scenarios.

As shown in Scenario 2 and Scenario 3, when the average value of distributed PV power in the typical scenarios of distributed PV power is small, both the power system and the Jieyang regional integrated energy system are able to realize the complete consumption of distributed PV power. In Scenario 3, the value of PV power is less than 3 MW, but as the average value of PV power increases, the single power system begins to experience the phenomenon of light abandonment near the peak value of PV power, as shown in Scenario 1 and Scenarios 4, 5, and 6.

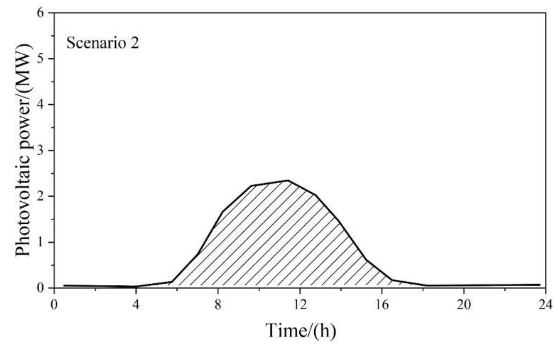
Compared with the single power system, the Jieyang regional integrated energy system has shorter abandonment periods and less abandonment, indicating that the Jieyang regional integrated energy system has a higher level of distributed PV consumption. That is to say, it is more advantageous to optimize the Jieyang regional integrated energy access scheme by using the multilevel distribution network new energy carrying capacity cooperative assessment system.

In order to further compare the consumption of distributed PV in the two systems, a typical scenario of distributed PV output with a larger average value of output and less volatility is selected6.

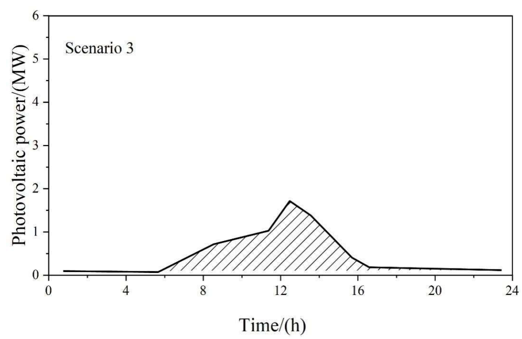
The electric power balance curve of the IEEE 33-node power system is shown in Fig. 4. The theoretical maximum output of the system is around 10h and 18h. The blue area in the figure is the distributed PV power abandonment, and the distributed PV power abandonment exists obviously.



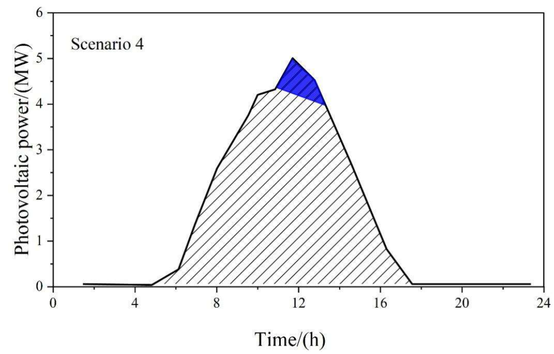
(a) Scenario 1



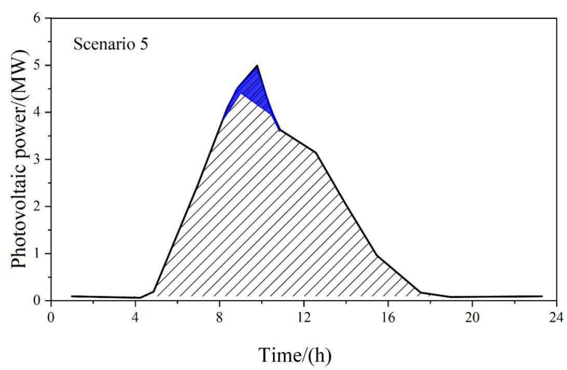
(b) Scenario 2



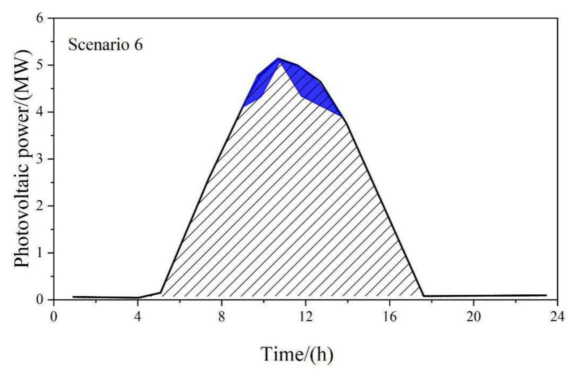
(c) Scenario 3



(d) Scenario 4



(e) Scenario 5



(f) Scenario 6

Figure 3: Distributed pv information of integrated energy system

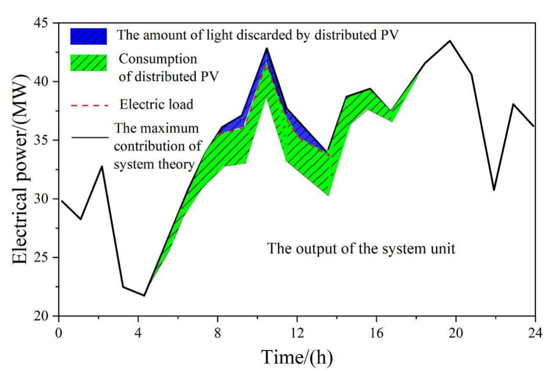


Figure 4: The electric power balance curve of the IEEE 33 node power system

The electric power balance curve of the integrated energy system in Jieyang area is shown in Fig. 5. The peak value of the electric power balance curve remains unchanged, but the amount of abandoned light from distributed PV decreases.

From the electric power balance curve of the IEEE 33-node power system and the electric power balance curve of the Jieyang regional integrated energy system, it can be intuitively seen that the consumption of the Jieyang regional integrated energy system has been improved, while the amount of discarded light has been decreased. The reason is that when the peak PV output occurs, the Jieyang district integrated energy system converts electric energy into thermal energy through the electric-to-thermal equipment, which makes the electric load of the system increase and improves the consumption of distributed PV in the system.

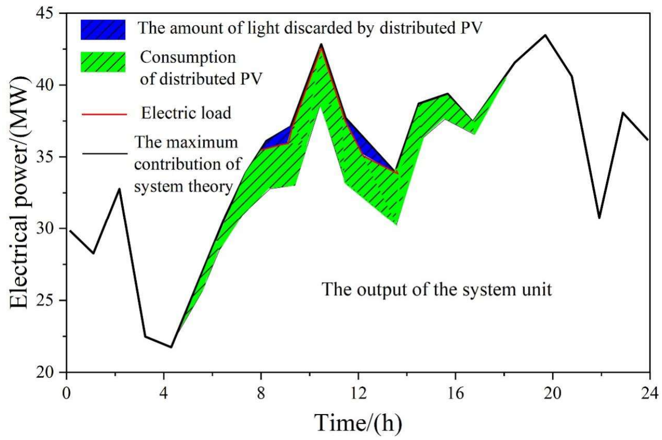


Figure 5: The electric power balance curve of the integrated energy system in the region

IV. C. Proof of effectiveness of the proposed algorithm

In order to take into account the computational efficiency and assessment accuracy, this paper simplifies the distributed photovoltaic carrying capacity assessment model of Jieyang regional integrated energy system based on the hybrid optimization algorithm of the gray wolf algorithm and cone planning.

In order to quantitatively illustrate the computational efficiency and assessment results of the model, a mixed-integer nonlinear distributed PV carrying capacity assessment model without the above simplification method and containing nonlinear equation constraints is set up as a control model, and it is respectively utilized with the BONMIN solver, Genetic Algorithm (GA), Particle Swarm Optimization Algorithm (PSO), Second-Order Cone Relaxation (SCOP), and Gray Wolf Algorithm (GWO) to Solving.

The computational speed and accuracy comparison of different algorithms for evaluating distributed PV carrying capacity is shown in Table 4.

The performance of the method proposed in this paper outperforms other methods: in terms of the obtained distributed PV carrying capacity results, the hybrid optimization algorithm based on the Gray Wolf algorithm and cone planning improves the total allocated capacity of distributed PV by 1.59% and 72.55%, respectively, when compared with the results obtained by the BONMIN solver and the GA algorithm.

In terms of solution speed, the method proposed in this paper greatly reduces the computation time, and its computation rate is 7881 times higher than that of the BONMIN solver and 942 times higher than that of the GWO algorithm.

Therefore, the above results illustrate that the hybrid optimization algorithm of Gray Wolf algorithm and cone planning constructed in this paper for the collaborative assessment of new energy carrying capacity of multilevel distribution networks can obtain a better distributed PV allocation strategy in a shorter computation time, which verifies the advancement of the method proposed in this paper.

Table 4: Comparison of different algorithms

Algorithm	Total configuration capacity (MW)	Total cost (Yuan/d)	Calculate the time (s)
BONMIN	3.47	15264	80625
GA	5.21	17073	2636
PSO	6.73	20155	21001
SCOP	4.04	16129	15550

GWO	3.26	18796	9637
The algorithm proposed in this article(GWO+SCOP)	8.99	26596	10.23

IV. D. Qualitative Analysis of Carrying Capacity under Different Access Methods

IV. D. 1) Example data

In this paper, based on the IEEE 33-node distribution grid system, the maximum carrying capacity of the distribution grid is investigated under different PV access states, and at the same time, the effectiveness of the hybrid optimization algorithm based on the grey wolf algorithm and cone planning is verified.

The IEEE 33-node distribution grid system topology contains a total of 33 nodes, the balancing node is 1 node with 32 branches, and the baseline apparent power and voltage are 10 MVA and 12.66 kV, respectively.The total active and reactive loads are 3.715 MW and 2.300 Mvar, respectively.

According to the requirements of 10kV low voltage distribution network, the upper and lower voltage constraints are taken as 1.07 and 0.93 times the Mississippi value, and the maximum transmission power of the line is set to be 6MW.Meanwhile, the distributed PV access point is treated as a PQ node, and its power factor is set to be 1. The power factors of the PV and the loads are treated as constant values.

IV. D. 2) Qualitative Analysis of Carrying Capacity under Different Access Methods

In this paper, the IEEE 33-node distribution network system is divided into 6 segments, which are firstly divided into line Ⅰ segments 2-18 and line Ⅱ segments 19-33 according to the turning point 18, and then divided into line Ⅰ beginning segments 2-6 and line Ⅱ beginning segments 19-25, line Ⅰ middle segments 6-10 and line Ⅱ middle segments 25-28, line Ⅰ end segments 10-18 and line Ⅱ end segments 28-33 based on the difference of the voltage magnitudes, and According to the different locations of the six segments, the PV access mode is defined based on the access principle.

Finally, the centralized access line start section, centralized access line middle section, centralized access line end section, distributed centralized access line start section, distributed centralized access line middle section, distributed centralized access line end section, and distributed uniform access are formed in 7 main access methods.

According to different access methods, 12 access schemes are formed. The magnitude of carrying capacity and tidal current index is calculated, and the differences in carrying capacity and factors affecting carrying capacity are qualitatively analyzed.

The PV access schemes are shown in Table 5. In the case of the beginning section of the access line, the factor that usually restricts the improvement of the carrying capacity is that the transmission power of the branch reaches the limit value, such as Scenarios 1, 4, and 7. In the case of the end section of the access line, the most important factor that restricts the improvement of the carrying capacity is that the voltage of the node reaches the limit value, such as Scenarios 2, 3, and 9. In contrast, the node voltage constraints and the branch transmission power constraints usually work together as a limitation in the mid-access line and decentralized uniform access cases, such as Scenarios 8 and 12.

Table 5: Photovoltaic access scheme

Access scheme	Access node	Access principle	Limit bearing capacity factor
Solution 1	3, 5	The centralized access line Ⅰ	The power limit of branch road 3
Solution 2	8, 9, 10	The centralized access line Ⅱ	The voltage limit of node 8
Solution 3	15, 16	The centralized access line Ⅰ	The voltage limit of node 15
Solution 4	25, 27	The centralized access line Ⅱ	The power limit of the branch road 25
Solution 5	30, 31	The centralized access line Ⅰ	The voltage limit of the power and node 30 of the branch road
Solution 6	32, 33	The centralized access line Ⅱ	The voltage limit of the node 32
Solution 7	2, 5, 6, 8	Distributed centralized access	The power limit of branch road 2
Solution 8	7, 8, 10, 14	Distributed centralized access to the initial stage	The power of branch 4 and the voltage limit of node 8
Solution 9	16, 18, 20, 30	Distributed centralized access intermediate	The voltage limit of node 16 and node 30
Solution 10	4, 6, 9, 12	Distributed centralized access to the final phase	The power of the branch 6 and the voltage limit of the node 9
Solution 11	20, 21, 25, 32	Distributed uniform access	The power limit of branch road 20
Solution 12	3, 6, 10, 15	Distributed uniform access	The voltage limit of the power and the node 15

The distribution network carrying capacity under different access methods is shown in Fig. 6. The distribution grid carrying capacity of Scheme 1, Scheme 4, Scheme 7 and Scheme 10, which are accessed at the initial stage of the line, reaches more than 7400 kW respectively. While accessing at the end of the line, the distribution grid carrying capacity is limited. The distribution grid carrying capacity is only 2965kW for scheme 3 access method.

Many obvious patterns can be drawn from the figure:

(1) For the same line section, it can be intuitively seen that the PV access line beginning section than access line in the middle and end of the line on the distribution grid carrying capacity of the greater improvement. Both centralized access and distributed access have the same law, but the centralized access mode this gap is more obvious. This is because the end section of the PV access line has a greater effect on voltage enhancement than the beginning section of the access line.

(2) For centralized access, compared with the access line Ⅰ section and the access line Ⅱ section, the carrying capacity of the distribution network is larger in the case of the access line Ⅱ section. Moreover, the closer to the end of the line, the more obvious this enhancement is.

(3) Comparing the distributed centralized access and distributed uniform access, the distributed centralized access has the law that the carrying capacity of the beginning section is larger than that of the end section similar to the centralized access. And distributed uniform access has a small difference in carrying capacity, and is the same as the first section of the distributed centralized access line. Overall, uniform access is more conducive to improving the carrying capacity of the distribution network.

(4) Comparing centralized access and distributed access, no matter which section of the centralized access line, distributed access is more capable of improving the carrying capacity of the distribution network.

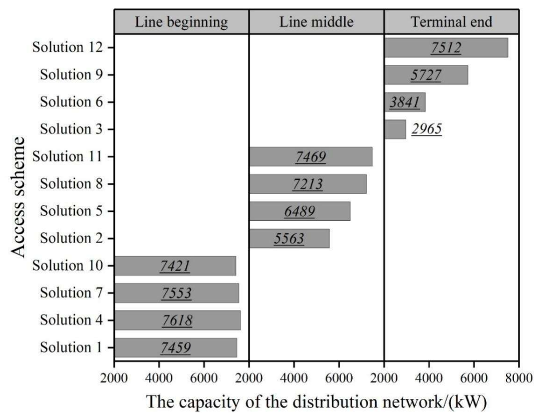


Figure 6: The capacity of the distribution network under different ways

IV. E. Analysis of the effect of the improvement of the carrying capacity of distributed new energy sources

In order to verify the effectiveness of the distributed new energy carrying capacity enhancement method based on the cooperative operation of multilevel distribution networks, that is, the effectiveness of the distributed new energy carrying capacity assessment platform built with a hybrid optimization algorithm based on the hybrid optimization algorithm of gray wolf algorithm and cone planning. Taking the previous day stage as an example, two scenarios are set up for comparative analysis.

Scenario 1: Only the electric power subsystem participates in the optimization scheduling in the day-ahead phase.

Scenario 2: Electricity-gas-heat multilevel distribution network coordinated scheduling model participates in the optimal scheduling in the day-ahead phase.

The optimization results of the branch node voltage of the electric power subsystem under Scenario 1 are shown in Fig. 7. The node 33 voltage value rises and falls in 16-24h, and the voltage value reaches the highest value of the day.

The optimization results of the branch node voltages of the power subsystem under Scenario 2 are shown in Fig. 8.

It can be seen that compared with Scenario 1, the occurrence of reverse flow of branch circuit active in Scenario 2 is greatly reduced, and the operating network loss is also significantly reduced. This is mainly due to the fact that coupling devices such as electricity-to-gas and ground source heat pumps connected near the distributed new energy node directly convert the surplus new energy generation into other types of energy, greatly reducing its reverse flow within the grid, thus enhancing the carrying level of distributed new energy.

In addition, in the coordinated scheduling scenario of the multi-energy distribution network, the voltage value near the distributed new energy access node is also significantly reduced within the voltage allowable range. Due to the existence of coupling devices, the lifting effect of distributed new energy on the node voltage is weakened, which helps the system to carry more distributed new energy.

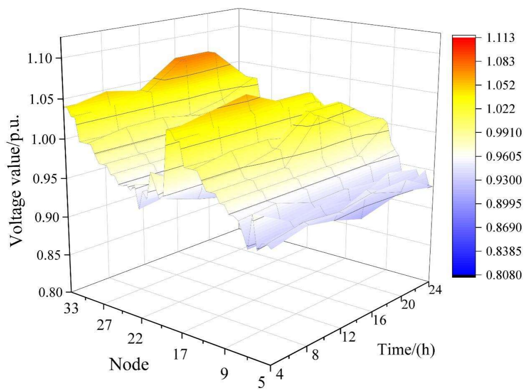


Figure 7: Optimization results of the voltage of the power subsystem branch

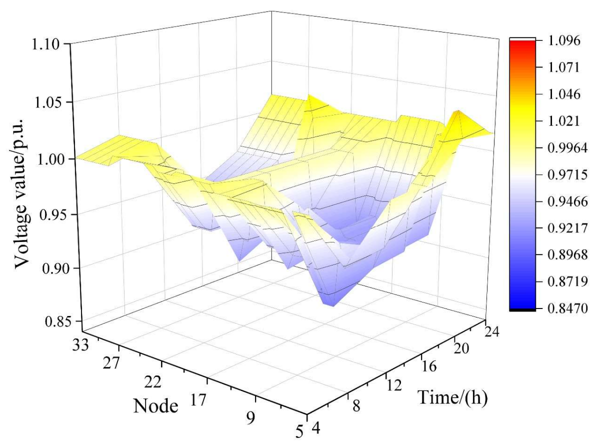


Figure 8: Scenario 2 the optimal result of voltage

V. Conclusion

This paper combines the planning and construction of medium- and low-voltage distribution networks, considers the types and capacities of users and new energy sources that can be accessed by distributed distribution networks, and proposes a collaborative assessment model for the new energy carrying capacity of multilevel distribution networks. A hybrid optimization algorithm based on the Gray Wolf algorithm and cone planning is applied to solve the problem and analyze the PV carrying capacity of the energy system of the medium- and low-voltage distribution network in Jieyang area.

For the MV distribution network, there are currently 128 10kV and 291 dedicated and utility lines in Jieyang area. For the low voltage distribution network, a total of 347 stations have had terminal voltages between 180V and 198V. The total system configuration capacity of the Jieyang regional integrated energy system is slightly higher than that of the IEEE 33-node power system. However, the optimization of the Jieyang regional distribution grid access scheme through the use of a multilevel distribution grid distributed PV carrying capacity analysis platform has led to a higher level of distributed PV consumption in the Jieyang regional energy system. Comparing the optimized dispatch voltage values of only the power subsystems involved in the day-ahead phase, the distributed new energy bearing optimized dispatch method proposed in this paper for the coordinated operation of multilevel distribution grids reduces the branch reverse flow in the day-ahead phase, reduces the operating network loss, and improves the level of distributed new energy bearing.

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