Optimal Planning of AC-DC Hybrid Transmission and Distributed Energy Resource System: Review and Prospects

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***Abstract*—With the highly-extensive integration of distributed renewable energy resources (DER) into the grid, the power distribution system has changed greatly in the structure, function and operating characteristics. On this ground, An AC-DC hybrid DER system becomes necessary for effective management and control over DER. This paper first summarizes the physical characteristics and morphological evolution of AC-DC hybrid DER system. The impact of these new features on system configuration planning is analyzed with respect to its flexible networking, rich operation control modes, and tight source-network-load-storage coupling. Then, based on a review of the existing research, problems and technical difficulties are figured out in terms of converter modeling, steady-state analysis, power flow calculation, operating scenarios management, and optimization model solution. In light of the problems and difficulties, a framework for the configuration optimization of AC-DC hybrid DER systems is proposed. At last, the paper provides a prospect of key technologies from six aspects including morphology forecasting, coupling interaction analysis, uncertainty modeling, operation simulation, optimization model solving algorithm and comprehensive scheme evaluation.**

***Index Terms*—AC-DC hybrid, configuration optimization, collaborative planning, distribution system, distributed energy resource system, microgrid.**

I. Introduction

INTEGRATING renewable energy resources (DER) into the power distribution system not only increases the utilization ratio of DER at the local terminal but also decreases the investment in the capacity of the distribution system [1]. At the same time, due to the increasing demand for power supply capability and power quality, and therewith the various demands for customized power supply [2], distributed power generation, DC load, energy storage and source-containing load have been surging up. The traditional AC power distribution system cannot achieve effective energy management and control under this new pattern. The main problems are as follows:

1) It is difficult to track the output fluctuation of distributed generation effectively by means of electromagnetic and mechanical regulation [3]. Distributed renewable energy with strong randomness and volatility makes its power generation fluctuate greatly. Massive integration will lead to frequency offset and voltage fluctuation in the distribution system, which will affect the power quality. Various power electronic and synchronization devices supporting distributed generation access also greatly increase the system complexity and affect the stability of the system. It is limited in the response speed and adjustment accuracy for traditional AC distribution system implement regulation by means of tie switches, transformer taps, switching capacitors, etc. Furthermore, the centralized and passive control mode in AC distribution system lacks autonomy and initiative.

2) The electromagnetic primary equipment in AC distribution system cannot adapt to the bidirectional power flow. The integration of DER and the extensive application of interactive flexible loads with power return capability have led to the bidirectional power flow in distribution systems. As a result, the traditional relay protection is no longer applicable [4]. Most AC transformers do not allow reverse power flow as well. In addition, it is difficult for electromagnetic primary equipment to support the precise, fast and active voltage regulation under large-scale decentralized integration of DER.

3) Topological structures, with the poor capacity for interconnection and mutual aid [5], are unable to hold a high proportion of DER. Power balance can hardly be ensured within the region due to the fluctuation and intermittent impact of DER. Flexible networking capabilities are required to achieve a wider range of energy mutual aid. Traditional AC systems generally adopt zoned operation for high-voltage distribution networks, ring topology design with open-loop operation for medium-voltage distribution networks and radial design with weak feeder connection for low-voltage distribution networks. Therefore, they lack flexible power dispatch ability in networking.

4) The large amount of AC-DC conversion results in excessive running losses: DC-AC conversion must be implemented when DC generators and DC load are connected to AC systems. In many cases, to ensure the output power and the voltage stability at the access port, AC-DC-AC conversion is

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also required where AC generators are integrated into the AC system. A large number of converters, rectifiers and inverters are used for these conversion, which leads to a great loss for the overall operation of the system and reduces the energy efficiency.

The AC-DC hybrid DER system is seen as an innovative solution to deal with the above problems. Compared with the traditional distribution system, this new system characterized by power electronization can achieve more efficient conversion and more flexible regulation for the innovative network structure and power electronic devices. Therewith, the DER system is obviously superior to the traditional system in addressing the fluctuation of DER, limiting the scale and complexity of synchronous systems, realizing distributed control and reducing losses.

For the AC-DC hybrid DER system, the current researches mainly concentrate on design analysis and control strategy simulation of individual device [6], [7] such as DFACTS devices [8], [9], DG accessing converter and synchronization devices [10], and DC relay protection device [11]. In terms of system level research, the focus is put on the optimization of operation control strategy and energy dispatch [12]–[19], while the planning and configuration of the system are relatively less concerned. Research has been carried out on voltage classification [20], location and capacity determination of DGs and DFACTS converter [21], [22], network structure of AC-DC hybrid system [23], [24], networking mode [25]–[28] and reliability analysis [29]. There is also morphological structure design of AC-DC hybrid integrated energy system based on intelligent energy management (IEM) [30]. However, these planning methods and models, mostly being transplanted from traditional AC distribution system or HVDC, fail to take into account the new characteristics of AC-DC hybrid DER system, such as flexible networking, controllable power flow, tight source-network-load-storage coupling, and the impact of highly-dispersed sustainable energy integration.

In this paper, the physical and morphological characteristics of AC-DC hybrid DER system are systematically analyzed, and the impact of these new features on system configuration planning is summarized. By scoping the current work, the main difficulties facing the optimal planning of AC-DC hybrid DER system in the context of high proportion DER integration and power electronization are addressed. Finally, this paper proposed a research framework for existing difficulties and some key technologies and research contents were prospected.

II. New Features of AC-DC Hybrid DER System

A. Morphological Evolution of System Structure

Driven by high proportion DER integration and power electronization, the structure, composition and interaction mode in distribution systems have undergone profound changes.

At system level, as shown in Fig. 1, there is a large-scale integration of distributed wind power and photovoltaic power at the source side. At the same time, electric vehicles and energy storage could also integrate as a flexible regulation power supply, which results in greater uncertainty at the source side. In terms of networking, there are diverse modes of power interaction coupling between AC and DC sub-grids and micro-grids vary with the functions of the converters. The operation of the AC-DC hybrid DER system is more complicated due to the diversified networks and multi-function power conversion devices. At the load side, a large number of source-containing loads featuring active response and bidirectional interaction capabilities have emerged, which makes a new request of user participation in energy management, adding the uncertainty of the load side. In terms of secondary systems, the new technologies such as DC line fault diagnosis, network power quality governance, distributed computing and autonomous control, are applied to more power electronic intelligent devices.

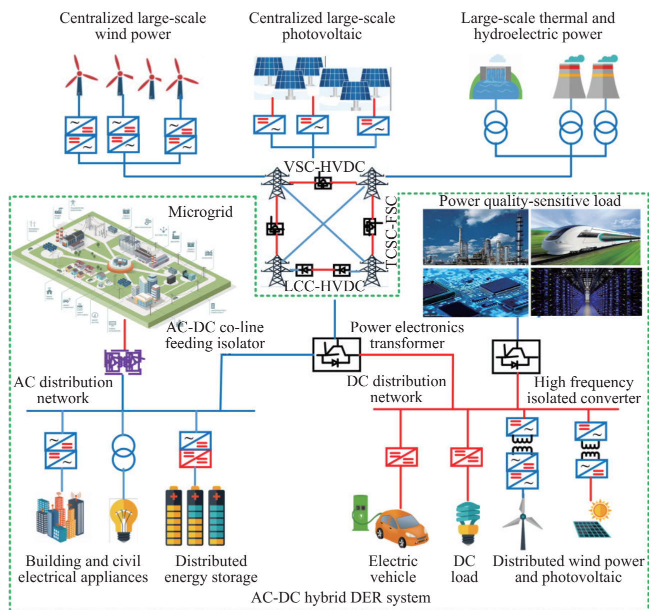

Fig. 1. The structure and element of the future power system.

At device level, the key equipment of distribution systems including DG accessing converter and synchronization devices, DFACTS devices, power quality governance devices, DC protection, isolation devices and integrated distribution terminal units (IDU) show the development trend of intelligence, modularity and high power density. This trend has enabled the power flow of the distribution network changing from free to semi-controllable and finally to fully controllable. Consequently, this fully controllable power flow makes it possible to realize system-level intelligentization. Specific features of device evolution in AC-DC hybrid DER systems are as follows:

1) The integration of power unit and communication control unit is becoming more inseparable, which creates the basic conditions for large-scale coordinated control.

2) Power conversion technologies such as modular multi-level converter (MMC) and pulse-width modulation (PWM) have been more widely applied, giving the converters high power density and energy efficiency.

3) Higher modularity makes functional units flexible to combine, which can be multi-cascade, multi-port, and multi-direction.

4) Fully controlled components such as GTO and IGBT

are widely used, creating a high degree of discreteness and nonlinearity.

B. Key Equipment and its Model

Converters, whose function is AC-DC power conversion, are the basis for efficient interconnection of AC-DC hybrid DER systems. It can be mainly divided into Current Source Converter (CSC) and Voltage Source Converter (VSC), the latter has a wider application because it is easier to be remoulded or extended. For example, soft open points (SOP), and power electronics transformers (PET) are constructed based on VSC and have diversified function. In recent years, the role of a converter is also increasingly diversified, because it integrates the functions of unified power flow control, high frequency voltage conversion, fault isolation, reactive power compensation, power quality management, port plug and play, and hierarchical communication as a result of benefits from the development of solid state switch, DFACTS and energy router.

VSC, SOP and DC transformers are more frequent in existing studies. VSC integrates rectifier and inverter functions and is capable of bidirectional and fast power conversion, with its conversion unit being composed of modular multilevel elements or wide band gap power semiconductor elements. For example, the VSC with pulse width modulation technology could control parameters including AC side reactive power, AC side voltage, DC voltage, DC current, PWM phase angle, and modulation degree. In addition, VSC can also independently control d axis component and $q$axis component (the coordinate transformation) of the transmission current to decouple the active power from the reactive power on the AC side. Therefore, the above-mentioned control parameters can be divided into active power control variable and reactive power control variable. When determining the VSC steady state model, it is often necessary to select an active power control variable and a reactive power control variable and keep their values constant or change them according to a certain sag coefficient. Other model parameters include the equivalent impedance of the port and the equivalent reactance of the filter. Then the basic models of power and voltage output-input relationship, control equation and power balance equation could be derived.

SOP, usually structured with two VSCs in back to back connection, conducts power conversion following the process of AC-DC-AC. The steady state modeling process is similar to that of VSC. Because SOP has the function of power regulation of contact line, its control mode is different from that of VSC. Various operation control modes of SOP are detailed in [25]. In different scenarios, the control modes of the two VSCs may also be different. Under normal conditions, in order to improve power flow distribution and reduce losses, one VSC is often used to stabilize DC voltage while the other controls power transmission. Under fault conditions, to isolate faults and realize load transfer and fast recovery, the non-fault side VSC provides DC voltage control while the fault side VSC is responsible for frequency stabilization.

DC transformers are used to change the DC voltage value on both primary and secondary sides, thus connecting the multi-voltage level of DC network. The control variable in steady state model is DC voltage ratio and DC voltage on one side, similar to the model of traditional transformers in AC system.

In the planning stage, the internal transient process of converter equipment can be neglected to generalize external characteristic modeling. For example, in the steady-state modeling of multi-port PET, each port being counted as an independent converter or transformer, despite the complex coupling between ports in actual operation.

C. AC-DC Networking Mode and Network Structure Features

AC-DC networking mode, which is mainly restricted by the form and function of interconnection devices, can be divided into the following categories:

Mode I: Point to point [25]. This networking mode, with AC structure as its backbone, uses DC lines with converters at both ends to replace some AC lines. At the same time, flexible AC interconnection devices such as SOPs are used to replace traditional contact switches. As a result, DC load and DC-type distributed generation and energy storage devices are connected to DC bus through DC-DC converter. Continuing the networking form of HVDC, this structure is the primary form of AC-DC DER system networking, suitable for application scenarios where new elements such as distributed power, DC load and energy storage are concentrated and small in scale.

Mode II: AC-DC co-line feeding [26]. This networking mode is characterized in that AC and DC sub-networks share a common transmission path and isolators are used to prevent them from affecting each other: AC isolator injects or extracts DC current equally to the three-phase AC transmission line, forming a loop with the earth through the grounding pole, to ensure the three-phase balance of the original AC line. At the same time, the DC isolator ensures that DC current is transmitted only within a specific range. The study [26] proves that at low voltage level, the line loss of AC-DC co-line feeding is smaller than that of independent transmission. Moreover, the operational reliability of AC and DC isolators needs to be verified in practice. Therefore, this networking mode is more suitable for low-voltage distribution network.

TABLE I
FEATURES OF AC-DC NETWORKING MODE

AC-DC Networking		Mode I	Mode II	Mode III	Mode IV
Grid form	Radiation		√	√	√
	Double end	√	√	√	
	Multi-terminal			√	√
	Ring	√			
	Star				√
Application scenarios	HVDS				√
	MVDS	√		√	√
	LVDS	√	√	√	
Core components		SOP, DC Transformer, CSC inverter	AC-DC isolator, CSC inverter	VSC, DC transformer, DFACTS	PET, Power-hub, Power-switcher

Mode III: Multi-level nesting [27]. In this networking mode, the AC and DC distribution networks are divided into pico-networks, nano-networks, micro-networks and sub-networks [27] according to the voltage level from low to high. The low-level networks are connected with the upper distribution buses through power electronics converters, and the same-level AC and DC networks can be interconnected at multiple terminals through converter devices, thus forming a hybrid distribution network with hierarchical AC and DC systems nested in each other. Because of its sound adaptability of radial, multi-terminal interconnected and ring-shaped grid structures, it is the most popular networking mode in current researches and applications.

Mode IV: Flexible and seamless integration [28]. This networking mode features the application of multi-port electric energy router based on flexible power conversion devices such as multi-port PET. It is a device level integration which combines multi-port energy router, control unit and information unit, providing compatible integrated ports and power switching ports for multiple AC and DC distribution networks with different voltage levels. In other words, this networking mode realizes seamless connection and closed-loop operation of AC and DC power distribution with different voltage levels. Compared with other AC-DC interaction modes, it has the advantages in control coordination and energy efficiency. However, as the conditions for the engineering application of its core equipment, such as multi-port PET and power collector are far from mature, it is mostly at the theoretical research stage.

D. System Operation Characteristics and Control Strategy

The high proportion of distributed generation and power electronics equipment in AC-DC hybrid DER system has brought tremendous changes to system characteristics, stability and protection mechanism, as shown in Fig. 2. In terms of system characteristics, as the extensive use of DFACTS devices such as converters and PETs bring profound changes to the distribution network structure and power flow control mode, the distribution characteristics of the system have also changed. For example, the integration of a large number of flexible resources changes the power balance mechanism of the system. The introduction of the DC system and a large number of distributed devices results in increasing operation constraints and complicated operation boundary. Converters, which can generally realize active power and reactive power decoupling control, cause great changes in active-frequency and reactive-voltage characteristics of the system. In addition, the extensive use of frequency converters has significantly changed the dynamic load characteristics. Power electronics equipment generally responds in very short time (millisecond level), which greatly broadens the frequency band of the system. At the same time, the short-circuit capacity of the system is reduced by its fast locking characteristics.

In terms of system stability, as shown in Fig. 2, the control response speed of AC system differs by orders of magnitude from that of DC system, and the duration of transient process is different. This not only complicates the analysis of system transient process, but also makes coordinated control difficult. At the same time, the difference in time constants between AC and DC makes the quasi-steady-state calibration more difficult.

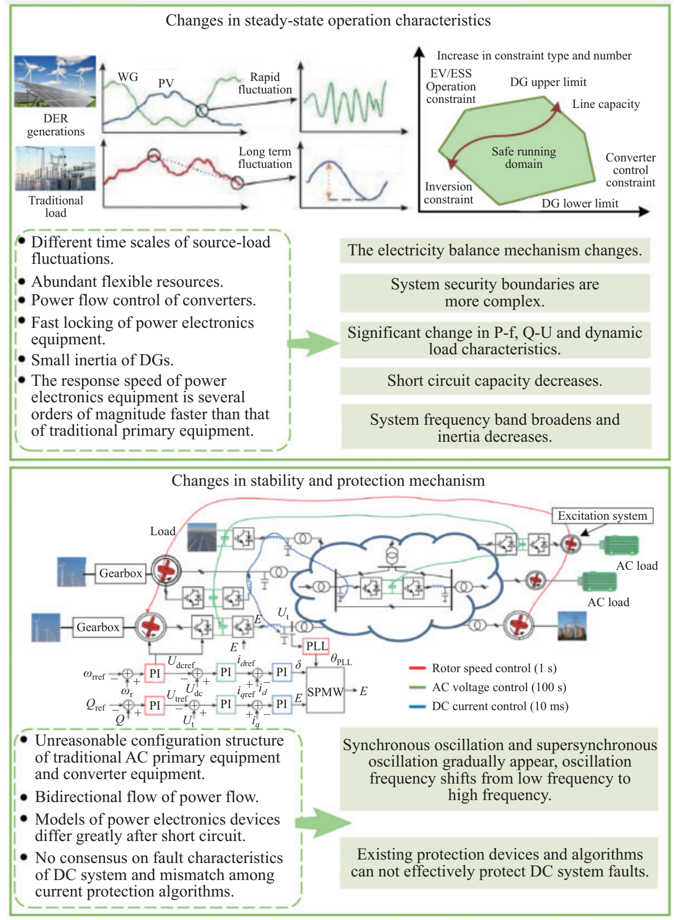

Fig. 2. The change mechanism of operation characteristics for AC-DC hybrid DER system comparing with traditional distribution system.

In addition, the unreasonable configuration of power electronics devices will also lead to transient stability problems such as high frequency oscillation of the system. In addition, the traditional relay protection mechanism is no longer applicable due to the large difference in the short-circuited model of power electronics device and the bidirectional power flow.

In the future, more participants will autonomously join in the energy management of the system. Therefore, it is necessary to change the current mode of centralized control and passive management, establishing a hierarchical and progressive control system. The structure design of AC-DC hybrid system and the use of a large number of power electronic equipment create conditions for the construction of this control system. Hierarchical progressive control system uses different control strategies in different system levels and time scales.

System-level control strategies generally include master-slave control, droop control, PQ control, V/f control and so on. Master-slave control and droop control are more common. In master-slave control, one converter port is subjected to constant voltage control to keep the node voltage tracking the voltage reference value. At the same time, this port serves as a power balance node to maintain the balance of network voltage and power. Featuring good real-time performance and high accuracy, this control method suits the centralized control between adjacent upper and lower layers of hierarchical system architecture.

In droop control, the automatic coordination of voltage and power between ports can be achieved by restraining the slope relationship between power and voltage at each converter port. With fast response speed and no need for communication, this control mode is suitable for distributed control. Because it is conducive to exploiting the advantages of the underlying user-side system, such as strong expansibility and plug-and-play interface.

Table II lists the control modes of AC-DC hybrid DER system in a hierarchical progressive control framework. It can be seen that the essence of this control mode is to achieve the optimal allocation of resources and energy distribution at all levels from user level to distribution network level through operation control and scheduling optimization in different time scales and different ranges, and to achieve the best overall performance and energy efficiency level of the system while taking into account the maximum benefits of all energy management participants.

TABLE II
THE CONTROL MODE OF AC-DC HYBRID DER SYSTEM

Control level	Time scale	Control objectives	Control means
User level	Millisecond	Quick response to user load change	DGs outputs the given voltage and power in a decentralized control manner
Microgrid level	Minute	Power balance in microgrid	Centralized control to adjust voltage and frequency deviation
Distribution network level	Hour	Optimal scheduling of energy	Overall coordination, Optimize operation by saving energy, reducing emission and optimizing power

III. REVIEW OF RESEARCH ON OPTIMAL PLANNING OF AC-DC HYBRID DER SYSTEM

A. Planning Subject and Basic Planning Model

Optimal planning is a process of selecting the best scheme or combination of schemes from all system designs or equipment parameters (including installation quantity and location) by using mathematical optimization and comprehensive evaluation, while taking into account the constraints of various resources, environment and system operation. It aims to support the system to the maximum extent by satisfying all operating conditions of the system. It is the core problem to address in the stage of system planning.

Figure 3 shows the main planning contents of the AC-DC hybrid DER system. The planning subjects mainly include design of voltage classification, source-load-storage zoning and network topology at the system level, and configuration of conversion equipment, distributed generation, energy storage, electric vehicle charging station at the equipment level. The optimal planning of AC-DC hybrid DER system is a multi-dimensional and multi-stage complex problem, because the subject of planning involves all aspects of source-network-storage-load.

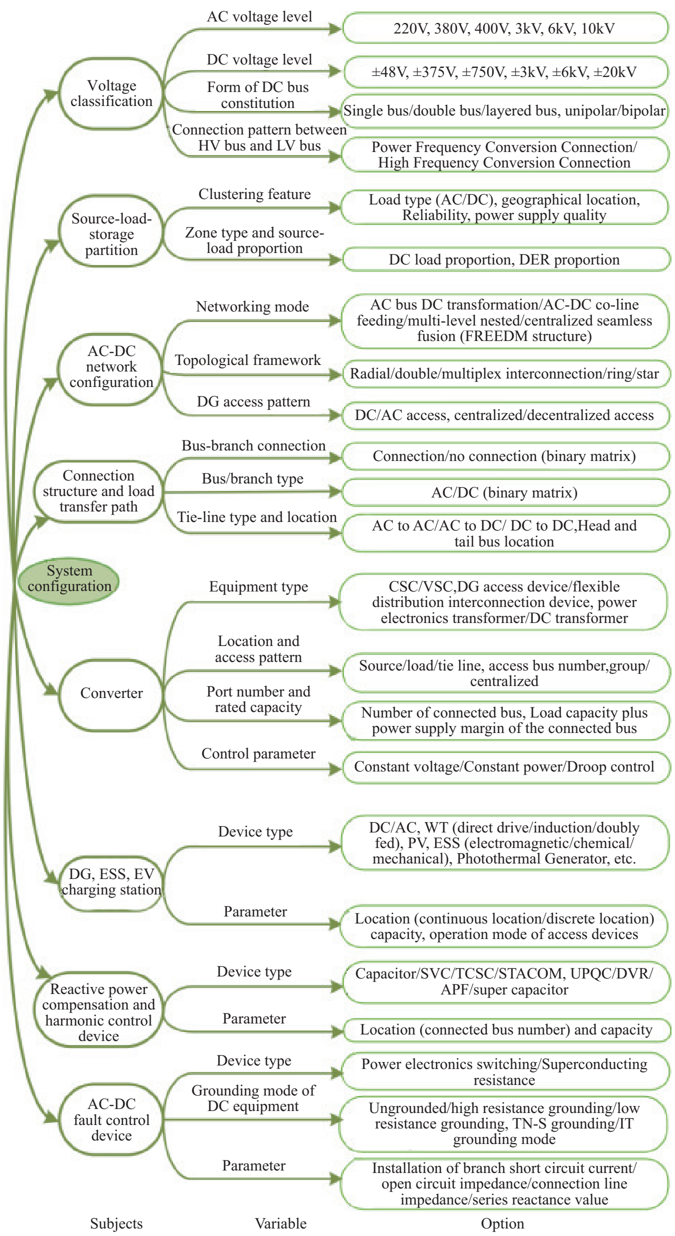

Fig. 3. Planning contents in an AC-DC DER system.

These planning subjects need to be abstracted into mathematical variables when modeling. The general form of the optimization model is shown in the equation set (1), in which the decision variables include discrete variable d (e.g. in or out of the equipment, 0-1 variable) and continuous variable c (e.g. equipment capacity).

ED is the upper limit of energy demand, $EENS$ is the upper limit of insufficient energy supply, CE is the upper limit of carbon emissions or emission penalties. Variables t and i represent the planned time and the serial number of the equipment, respectively. Variable j represents the type of system to which the planning equipment belongs, 0 represents the AC system and 1 represents the DC system. T is the total planning period, N is the total number of equipment.

The objective function $f(d_{i,j,t}, c_{i,j,t})$ is generally set to minimize the total cost of investment, construction and operation. $g(d_{i,j,t}, c_{i,j,t})$ represent the configuration boundary conditions, such as capacity and service life of equipment, network topology, scale of investment and renewable energy permeability constraints.

$$\begin{cases} \min \sum_{i=1}^{N} \sum_{t=1}^{T} f(d_{i,j,t}, c_{i,j,t}) \\ \text{s.t. } g(d_{i,j,t}, c_{i,j,t}) \leq 0, & \forall i \in \{1, N\} \\ \quad\; h(d_{i,j,t}, c_{i,j,t}) \leq ED, & \forall t \in \{1, T\} \\ \quad\; \Phi(d_{i,j,t}, c_{i,j,t}) \leq EENS, & \forall j \in \{0, 1\} \\ \quad\; \Psi(d_{i,j,t}, c_{i,j,t}) \leq CE, & \forall d \in \{0, 1\} \end{cases} \tag{1}$$

where $h(d_{i,j,t}, c_{i,j,t})$ shows the system operation constraints, mainly the system power flow equation and safe boundary. It is more complex due to the use of converter equipment, for converter constraints such as the range of port control parameters change (droop control coefficient, modulation degree, etc.) and control mode switching restrictions should also be considered. $\Phi(d_{i,j,t}, c_{i,j,t})$ means reliability constraints. Reliability constraints in AC-DC hybrid systems mainly describe the requirements of the planned scheme for interconnection and interoperability of AC-DC subsystems in the case of failure or partial power shortage. $\Psi(d_{i,j,t}, c_{i,j,t})$ can express environmental compatibility constraints, i.e. carbon emission limitation and emission penalty cost limitation.

B. Optimized Modeling Method

Considering the large amounts of planning variables as shown in Fig. 3 and each variable has different stages and levels, it is very difficult to unify the modeling. Therefore, most of the current studies only focus on one of the planning contents in Fig. 3. In modeling process, decision variables, objectives and constraints are set on the basis of model (1) according to the specific configuration subjects. In [31], the voltage level of DC distribution network is optimized considering the constraints of load demand level, grid topology, distribution mode and equipment manufacturing level. The study in [32] aims to minimize the total cost of construction investment and operation, taking the investment constraints, topology constraints and network security constraints into the establishment of a mixed integer programming (MIP) model with AC-DC node connection relationship as decision variables. However, this method, based on a specific source-load location, ignores the impact of different source-load partition combinations on the system network configuration. In paper [33], taking the comprehensive optimization of total supply capability (TSC), $N-1$ checking pass rate, network loss rate and load transfer balancing degree as the objective, discrete location and capacity determination of multi-port converter is carried out. However, the model in [33] defaults the mapping relationship between the location model and the constant capacity model, ignoring the influence of the demand for load transfer and the selection of AC-DC partition tie switch on the port capacity decision of converter. Paper [34] introduces a multi-objective distributed generation capacity optimization model of AC-DC hybrid microgrid based on unit generation cost, conversion loss and self-balancing rate. In another study [35], to minimize the total cost of investment and operation of hybrid energy storage, the optimal allocation of energy storage in DC system is realized by chance-constrained programming considering the reliability constraints of wind power generation backup and ultimately achieving the purpose of tracking the output fluctuation of uncontrollable distributed power generation with a hybrid energy storage system on the premise of minimizing energy storage loss. Although the models of [34] and [35] take into account the difference of control cost between AC and DC system, they fail to take into account the technical and economic impact of different access modes for high proportion DER.

AC-DC hybrid DER systems can make full use of the complementary characteristics of source-load-storage and flexible AC-DC networking capability to optimize the dispatching operation of the system. Therefore, in the planning process, it is necessary to consider the modeling of the relationship between the source, network, load and storage. However, the temporal and spatial distribution characteristics of distributed renewable energy has complex impacts on the power system. Modeling needs to deal with a large amount of data in different ranges and time scales inside and outside the system. At the same time, the planning model also needs to satisfy the conditions of DER multi-point access, free and mutual redundant connection between AC and DC buses. In the decision-making and optimization of such complex systems, it is difficult to establish a model by using holistic, unified and undifferentiated analysis methods. Although some scholars have studied the temporal coupling characteristics of source-load-storage and the collaborative planning of generation and network, the application scenarios are mostly in the transmission system and AC system. As the research considering the characteristics of DC distribution system and complementary relationship between AC and DC systems is still limited, the problem of collaborative modeling still needs to be solved.

C. Review and Scope of Current Work

1) Steady State Modeling of Converter

The coupling mechanism between AC system and DC system is determined by converter for its connection and power conversion between two kinds of sub-systems. As the planning focuses on the steady-state characteristics, it is necessary to establish a steady-state model which can reflect the interaction mechanism of AC and DC systems. At present, there are two main approaches for steady-state modeling of a converter.

The first approach works from inside to outside, i.e., the equivalent circuit of the converter is derived strictly according to the internal component connection topology, and then the basic equation is written according to the relationship between the input and output of the equivalent circuit port using the state variable and the control variable. For example, in study [36], the CSC converter station in HVDC is equivalent to a circuit consisting of commutation resistance and equivalent controlled voltage source, in which the trigger delay angle of current source is related to the leading angle of arc extinguishing. The basic equation based on equivalent circuit can describe the function relationship between converter state and control parameters more completely. However, this method is often based on the existence of fixed circuit equivalent modes in some semi-controlled power electronics device combinations. As the converter used in AC-DC hybrid system is mostly a flexible power equipment consisting of fully controlled components with a complex structure, it is difficult to obtain its equivalent circuit on this condition. Moreover, the use of fully controlled devices makes the system highly discrete and non-linear, so it is very difficult to deduce the relationship between external variables according to its internal characteristics.

The second one works from exterior to interior, which aims to establish a converter mathematical model by its external power characteristics modulation strategy. This method highlights the main aspects of the problem, ignoring the secondary factors for it establishes equivalent circuit by directly equating external characteristics and is easy to operate. Therefore, it is suitable for modeling the converter consisting of fully controlled devices and the multi-port converter with complex internal topology. In [37], a power flow model is established by equating VSC to the series connection of controlled voltage source and controlled impedance. In [25], a SOP steady-state equation with power balance equation and limits of port transmission power for optimal scheduling is established so as to reduce the complexity of the optimization model. However, this method, which ignores the internal control variables of converter, seems too inaccurate and may lead to conservative operation or potential risks. Study in [38] establishes PET practical power flow calculation model by dividing the operation mode of dual-port PET into load mode and source mode. The steady-state model of the generalized multi-port converter is established in [39] using the equivalent impedance of converter port power loss and the equivalent admittance of reactive power loss to equivalent the complex constraints of the internal components. This method can be used as a reference for fast computing and extending application scenarios in multi-scenarios. However, it does not fully characterize the operation characteristics of multi-port converter because only two DC voltage levels integrated converter can be analyzed. Subsequent modeling researches based on this method still need to be further deepened.

2) Power Flow Calculation

Power flow analysis is the basis of optimal planning. In terms of establishment of power flow equation, as the time scale considered in the planning stage is large enough to neglect the transient process, the steady-state analysis model, which is an algebraic equation satisfying Kirchhoff's law and following the corresponding physical characteristics of the AC-DC system, is usually used in the AC-DC hybrid power flow calculation for planning. Unlike traditional AC systems, the AC-DC hybrid system, whose power flow is controllable, requires adding control equations to the system steady-state model equation to form a non-linear power flow calculation equation group.

Algorithms can be divided into two categories: unified iteration method and alternating iteration method. Paper [40] details the advantages and disadvantages of the two algorithms. The alternating iteration method draws more attention for its faster calculation speed and better expansibility.

At present, the power flow calculation of AC-DC hybrid DER system mainly faces the following two problems:

Firstly, there are abundant types of converters and DC equipment with more complex power characteristics and control methods in the distribution system, making the power flow modeling more difficult. Therefore, in addition to traditional converters and DC lines, the steady-state models of various new devices, such as DGs, DC loads, DC transformers, SOPs and PETs need to be supplemented. Modeling needs to take into account the external power characteristics, operation and control mode of various new equipment. In [37], DG and ESS are divided into controllable and uncontrollable and AC and DC types for controllable sources, summing up the equivalent types of nodes in power flow calculation respectively. But this equivalent method, which assumes that the distributed power grid connection device only has two control modes of constant power and constant voltage, cannot equate the drooping control grid-connected point. Study [39] compares the ZIP load model of AC distribution network and divides DC loads into three basic types of constant resistance, constant current and constant power for power flow modeling. The DC transformer is modelled with DC voltage ratio and active power loss in [41] by analogizing the model of AC transformers. On this basis, [37] adds the DC voltage control equation of the original secondary side, making the DC transformer model more precise.

Secondly, the AC-DC hybrid distribution system has more DC links and a distinctly different structure from HVDC. As traditional algorithms are difficult to guarantee effective convergence with large-scale multi-DC feeds or strong DC network with weak AC sub-network, it is necessary to improve the traditional AC-DC hybrid power flow algorithm or model. In response to the problem of the traditional alternating iteration method, i.e. the DC variable is too sensitive to the normal voltage fluctuation on the AC side of a converter when it comes to the multi-DC centralized feed receiver system, study in [42] proposes a hypothesis checking method; it first idealizes the DC system, only iterates the AC system, and then deduces the DC variable after the AC power flow converges. This can effectively avoid the oscillation divergence of DC variables in the process of alternating iteration and has good robustness. Study [40] achieves the same purpose by using Newton method in DC power flow. Study [43] analyzes that when the DC system is large in scale and has many landing points, it is necessary to set up several DC relaxation nodes to achieve power flow convergence. According to [44], the dynamic model of converter should be used to establish quasi-steady-state power flow calculation model of AC-DC system in a weak AC environment with strong DC subsystems.

To achieve the power flow calculation of AC-DC hybrid distribution systems, one should first establish the steady-state model composed of AC state variables, DC state variables and DC control variables in light of the external power characteristics and operation modes of the equipment. It is necessary to establish a simultaneous basic power balance equation of the system, and to add the control equation of the converter to make the number of variables equal to the number of equations. In view of the DC multi-feed and the possible strong DC with weak AC phenomena in the distribution system, it is important to study the relationship between the change of DC control parameter and the equivalent node of the converter's AC side. We should further study how a fast AC-DC decoupled power flow algorithm can reduce the computational complexity while improving the convergence. In configuration optimization, the reasonable operation state of the AC-DC hybrid system is determined by the effective feasible solution obtained from power flow calculation. And in each operation state, the control variables of DC systems should have better adjusting flexibility with given AC side state variables, so as to obtain the operation coordination and the overall economy between AC and DC systems.

3) Uncertainty Handling

The AC-DC hybrid DER system creates mature infrastructure conditions for users to actively participate in system energy management and energy trading. In the future, with the maturity of the market mechanism of energy and service trading, the number of participants in system energy management and market trading will gradually increase. The participants with different market participation patterns and habits will make different decisions because of the fluctuation of energy prices, which will lead to uncertainty in energy production and consumption. This constitutes the source of multiple uncertainties along with the intermittence, fluctuation of high proportion DER and the random switch among AC-DC system operation control modes.

There are two main methods to deal with the uncertainty in planning: stochastic programming and robust programming, which describe uncertainties through scenario sets and uncertainity sets, respectively. As robust programming is conservative in scheme and cannot describe the relationship between uncertainties, the stochastic programming method is still the mainstream at present. Study [43] uses Monte Carlo method to simulate the random faults of equipment, transforms the uncertainty of equipment faults into a restrain condition and adds it to the planning model of AC-DC hybrid microgrid. To accurately describe the impact of uncertainties on operation costs, the study in [45] obtains the typical mode and running time of various running scenarios by simplifying and clustering a large number of random running scenarios. In [46], the probability of different scenarios is taken into account when constructing the objective function of optimal planning. However, these stochastic programming methods, which depend on scenario and probability, have problems such as the difficulty in obtaining the stochastic characteristics of low-frequency events in highly uncertain environment. A chance-constrained programming method which is also one of the stochastic programming methods is used to solve the planning problem in [47], considering source-load uncertainty, but the calculation is sophisticated. Therefore, the clustering technology should be combined to scenarios reduction in stochastic programming methods.

4) Structural Optimization of Network for AC-DC Hybrid System

The optimization of network structure for the AC-DC hybrid DER system should take into account the flexible AC-DC networking modes and power flow regulation capability of converters, as well as the load transfer path optimization of AC-DC sub-network partition. Firstly, it is necessary to express the network topology mathematically by mainly describing the node and branch configuration of AC-DC hybrid DER system in the form of matrix. In view of the zone partition of source-load-storage, it is of great value to abstract the network structure into a directed weighted network composed of vertices and edge sets by using network graph theory. For example, in [32], the configuration of AC-DC network is described by using three binary matrices: correlation matrix, node type (AC or DC) matrix and branch type (AC or DC) matrix. Another study reported in [48] uses transmission demand matrix, path loss vector and transmission volume vector for a more comprehensive description of the network configuration, in which the converter or DC transformer is recorded as a node. When it comes to optimization modeling, it is important to integrate the objective of minimizing the total cost of AC-DC hybrid DER system construction and operation with maximizing the proportion of accessing renewable energy, while considering the number of node connections, output power limitation of generations, network security constraints and converter constraints.

Load transfer path optimization is a sub-optimization problem nested in network structure optimization, which is similar to the distribution network reconfiguration. The reconfiguration of traditional AC systems is a process of optimizing the operation structure of the network, in which the status of sectional switches and contact switches is periodically adjusted according to the change of load, so as to improve the reliability and economy of the system under normal operation or to ensure the early restoration of power supply under fault condition. In the AC-DC hybrid DER system, however, as the converter has the function of actively regulating the power flow distribution, reconfiguration and load transfer is no longer targeted at a simple sectional switch and tie switch, but also needs to take into account the operation state of the converter port. When planning the AC-DC hybrid DER system, it is import to partition the load according to clustering results of the load type, geographical position, reliability and power quality requirements, based on which, the optimal access structure of source-load-storage is selected. In order to meet the demand of power transfer between different partitioned zones and the transfer capability under fault conditions, it is necessary to study the distribution and structure of load transfer paths between partitioned zones, i.e. the form and location of interconnection between partitioned zones. When it comes to the establishment of the optimization model, it is important to integrate the objective of optimizing network traffic with minimizing the operation cost, while considering the constraints of partition transfer demand, network power allocation strategy and network configuration.

5) Location and Capacity Determination of Multi-port Converter

Multi-port converters have been widely used in AC-DC hybrid DER systems. Unlike two-port converters, multi-port converters provide not only AC-DC power conversion, but also multi-terminal interconnection and mutual aid, flexible networking and flexible loop network hierarchical control of AC-DC micro-grid cluster. Therefore, although the distribution system/microgrid is a local area energy supply system, the location and capacity of multi-port converter equipment is still important for its flexible and efficient operation.

The location of multi-port converter is a discrete location problem. Spatial discretion is solved to obtain a predetermined alternative site. The alternative site is given by the upper model of source-load-storage partition and grid structure optimization. To solve the discrete location problem, the comprehensive evaluation method is generally adopted, i.e., to calculate, compare and rank the evaluation values of multi-dimensional indicators of sites to be selected, and to get the scheme with highest comprehensive evaluation value. The studies in [33] and [49] present a method of location evaluation for multi-port converter equipment. However, this method points out that the port capacity of converter equipment should be determined entirely by its location while the port capacity should be determined by the sum of the feeder capacity connected to the port. This method is obviously too rough and may not be able to support large-scale mutual aiding load transfer and broader interconnection between subnetworks of AC-DC hybrid DER systems. Therefore, the capacity of each port in multi-port converter should be modelled and optimized separately under the location scheme. To this end, an optimization model should be established by taking the overall investment and operation economy of the system as the objective and considering the transfer demand between broad partitions and the investment constraints.

D. Main Technical Difficulties in Existing Research

The main technical difficulties in the existing research can be summarized as follows:

1) Analysis of coupling relationship between AC system and DC system. The mechanism of interaction between AC system and DC system is not clear at the steady-state level [50], because of the lack of complete theoretical support for the distribution of electrical and thermal losses in AC-DC hybrid systems, and the relevance between the power exchange of AC-DC system and the operation mode of converters. Although the planning process takes into account a large time scale, the coupling of AC and DC systems is often divided into several stages due to the different time constants between AC and DC systems. When checking the optimal power flow of a hybrid system, the dynamic process will also have an impact on the operating cost of the system. Current planning studies seldom explore the influence of coupling complementarity of AC-DC system on configuration optimization from the perspective of quasi-steady state.

2) Power balance calculation considering high proportion DER integration and wide area balance of supply and demand. On one hand, the high proportion access of distributed renewable energy in AC-DC hybrid DER systems has a great impact on the power balance of the system due to its fluctuation [51]. The traditional method of reserving sufficient capacity margin is not economically feasible. Distributed energy storage, demand side response and other schedulable flexible resources play an increasingly prominent role in power balance, which increases the complexity and computational difficulty of power balance and needs to be fully considered in planning. On the other hand, the AC-DC hybrid system, which could realize active energy allocation, can achieve interconnection and mutual aid in a wider range when local coordination and complementarity cannot meet the requirements of safe, stable and economic operation of the system in the case of high proportion DER access. Traditional power distribution system planning, which only focuses on power balance and local optimization within the system, regards the upper power grid as infinite power supply. This practice is not advisable in the planning of the AC-DC hybrid system. Although some studies [52] draw lessons from the concept of distributed optimization to coordinate the allocation of multi-microgrid resources, these methods are based on the assumption that all distributed generations are integrated through the microgrid [53]. Considering the coordination between AC-DC subnetworks, it is still difficult to achieve the power balance calculation of the wide-area balance between massive distributed resources and demand in AC-DC hybrid DER systems.

3) User-side modeling under market framework. As AC-DC hybrid DER systems provide many plug-and-play interfaces and power return control equipment for users, the process of demand side response is more complex. There will be more ways for users to participate in system energy management, such as the active access of the residual capacity of distributed resources on the user side to the Internet, microgrid energy trading, electric vehicle V2G, etc. If the user-side behavior is not taken into account in load modeling, the intrinsic relationship and possible interaction among source, network and load are neglected in essence, which may lead to the failure to obtain the global optimal planning scheme. Excessively precise user-side modeling needs to consider new links such as electricity price and human factors, making the model too complex. There is no explicit analytical relationship between some factors and decision variables, which makes it difficult to model effectively. Therefore, a proper description of the user-side energy management participation form in the planning model is another major difficulty in the research on the optimization planning of AC-DC hybrid DER systems.

4) Typical scenario acquisition considering AC-DC hybrid system operation mode switching. Traditional power system planning configuration can be evaluated by several typical operation scenarios. Because of the dual uncertainties of the interaction between distributed generation fluctuation and load fluctuation, it is necessary to comprehensively evaluate the system operation limitation of the system planning configuration in order to grasp its economic and security adaptability. In an AC-DC hybrid system, the converter has various operation modes [34], the combinations of which correspond to the multiplied increase in the number of scenario sets and the interrelation of multiple uncertain information in the planning process [54], making it more difficult to acquire typical scenarios.

5) The solution of the optimization model. Compared with the AC system planning model, the introduction of DC variables greatly increases the dimension of the AC-DC

hybrid DER system planning problem. The basic equation of converter with continuous variables and discrete variables is introduced into the AC-DC hybrid power flow equation, and the steady-state model parameters of converters are affected by the modular cascade and pulse width modulation. In the basic equation, the power balance equation and the control equation often contain high order terms, sinusoidal terms and tangent terms, which greatly enhance the non-linearity and non-convexity of the planning problem. The spatial distribution of the decision variables solution is very complex and irregular, for the multiple objectives are often considered in the planning model [34] and new constraints such as port parameters constraints of converters and reliability constraints of DC systems are added to the planning model constraints. All these make it difficult to solve the planning model [55]. It is necessary to continue to study the simplified method of the model and the optimization algorithm with strong global search ability and high local optimization efficiency.

IV. Framework and Prospect

A. Research Framework

The optimal planning framework of AC-DC hybrid DER systems proposed in this paper is shown in Fig. 4. In view of the technical difficulties in the existing research, the planning of AC-DC hybrid systems should have the following technical characteristics:

1) As source-network-load-storage characteristics are more closely coupled, more consideration should be taken to collaborative complementary optimal allocation. The fast energy routing function of converter equipment creates mature conditions for the complementary scheduling and operation of source-load-storage in the system. At the same time, due to the change of operation mode of AC-DC systems, the interaction between generation planning and network planning is more obvious. Therefore, more attention should be given to the complementary correlation characteristics of source, load and storage and the coordination of source-network planning.

2) The impact of flexible complementary AC-DC network-

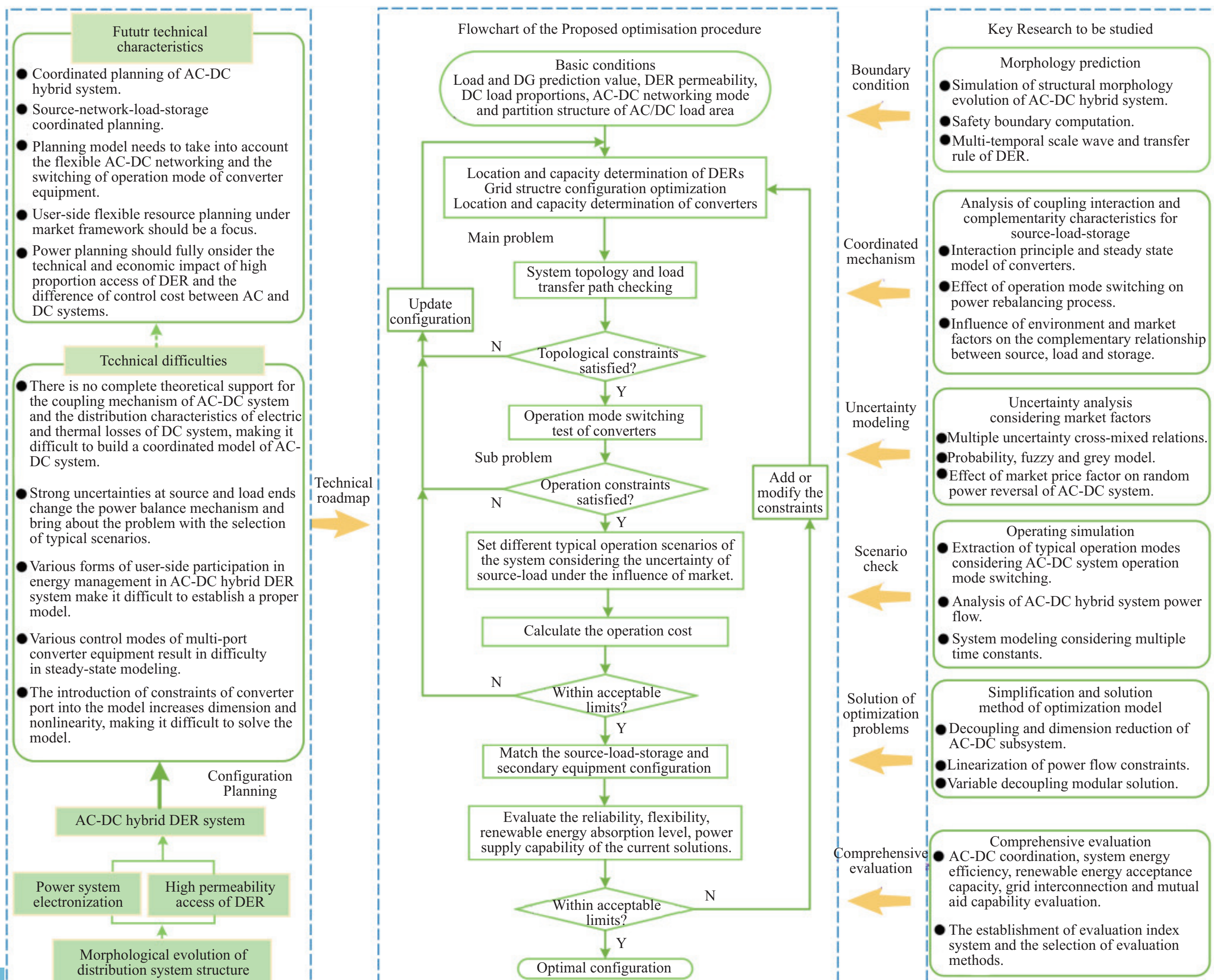

Fig. 4. Research framework for configuration optimization of AC-DC hybrid DER system.

ing and operation mode switching of converters should be taken into account in the planning configuration. As the power electronics devices in AC-DC hybrid system essentially changes the operation characteristics and control modes of power distribution system, the system configuration needs to support new conditions such as the flexible networking and operation modes of the AC-DC hybrid DER system.

3) Under the market framework, user-side flexible resource planning should be a key focus. The distinguishing features of AC-DC systems, such as fast control of power flow and multi-terminal interconnection of micro-grid cluster, make it possible for users to participate deeply in energy trading and system energy management. As a series of user-side schedulable flexible resources are playing an increasingly prominent role in system configuration, the changes of user energy strategy under the market framework and the game among multiple stakeholders should be taken into account in configuration optimization.

4) Generation and network planning should fully consider the technical and economic impact of high proportion DER access with the control cost difference between AC and DC systems. The traditional planning method underestimates the technical and economic impact of high proportion penetration of DER, which leads to the lack of scientific capacity calculation. In addition, the strong controllability of a DC system for distributed generation and the ability to achieve fast spatial transfer of regional energy make it more flexible to decide the capacity and access mode (centralized/decentralized) of generations in planning. Different access modes and capacities of the generation correspond to different operating costs. Therefore, it is important to select the reasonable access mode and capacity in distributed generation configuration, considering the regional DER distribution and the difference of control cost between large capacity and small capacity or between AC and DC.

The flowchart of the proposed optimization procedure is shown in Fig. 4. Firstly, the planning boundary is determined according to the load, the forecast value of renewable energy and the existing network structure in the region. At the same time, the initial conditions and basic scenarios of DC load proportion, renewable energy permeability, source-load-storage partition and network configuration are determined according to the morphological evolution model or energy planning model. Secondly, considering the planning boundary as input data, with complementary and synergistic characteristics of source-load-storage being taken into account, the objective function and constraints of a comprehensive optimization model are established as formula (1). Then, to solve the optimization model, the model is divided into a main problem and a sub-problem while a modular iterative algorithm is executed. The main problem works by generating a comprehensive planning configuration for network structure, together with the location and capacity determination of distributed generation, energy storage, and converter of the AC-DC hybrid DER system. The sub-problem checks the configuration by testing the topology and operation constraints. Topology checking makes sure that the load transfer paths meet the connection requirements of AC-DC partitions and avoid the generation of electrical islands. Operation checking verifies the adaptability of the planning configuration to various operation modes of converters and source-load fluctuation scenarios by calculating the operation cost under different power flow distribution within the security domain of voltage and power. Under the market framework, user behaviors such as demand side response should be factored in operation checking, for user behaviors such as changing energy consumption strategies according to energy prices or returning their surplus resources to the network will affect the power flow distribution of the system. The configuration generated by the main problem is checked one by one in the sub-problems. If one of the above inspection links in sub-problems is not satisfied, it will be re-optimized to generate a new plan. Finally, the reliability and environmental compatibility are evaluated according to the power flow distribution under different operating scenarios in sub-problems of the checked planning configuration. If it is beyond the acceptable range, the corresponding constraints are added to the optimization model or penalty function is added to the objective function and update the configuration. This optimization process obtains the optimal configuration by alternately iterating and checking the main problem and the sub-problem, which gives consideration to the interaction and compatibility between the whole (system) and the part (device).

B. Prospects of Research on Key Technologies

In the proposed framework, several key technologies should be focused on. The prospects for their research are as follows:

1) Morphology forecasting of AC-DC hybrid DER systems. Firstly, study morphological evolution law of AC-DC hybrid system, for its adaptability to high proportion DER has brought revolutionary changes to the power system. Then, describe the safety boundary of AC-DC hybrid system by analyzing the topological properties of the safe operation boundary and the mechanism of losing stability at the operating point outside the safe operation domain. Lastly, explore the response of distributed generation and load to external factors such as meteorology and electricity price under complex and uncertain environment. Moreover, improve the prediction accuracy by considering multi-temporal scale fluctuation and transfer law of load and DER so as to determine the boundary conditions of the programming model more accurately.

2) Analysis of coupling interaction and complementarity characteristics of source-load-storage in AC-DC hybrid DER system. It is necessary to study the power flow conversion principle of converter and establish a steady-state model according to its external characteristics, because the working principle of converter can be seen as the coupling mechanism between AC system and DC system. On the basis of steady-state power flow, the rebalancing process of power after the switching of AC-DC networking state and converter operation modes is analyzed. Study the temporal correlation between DER and load demand, and explore the influence of season, meteorology, electricity price and other factors on the complementary relationship between source-load-storage. In addition, it is important to study the distribution of energy loss in AC-DC hybrid system so as to analyze the influence of AC-DC

coupling mechanism on system energy efficiency [56].

3) Uncertainty analysis considering the impact of market factors. It is essential to clarify the sources of uncertainty in AC-DC hybrid DER systems and analyze its characteristics where the cross-mixed association among multiple uncertainties can be modelled by using mathematical tools such as probability model, fuzzy model, and grey model. To analyze the impact of these uncertainties on the planning model, the mathematical method such as Monte Carlo simulation, Latin Hypercube sampling and chance constrained programming should be developed.

Under market conditions, distributed generation owned by users will be allowed to participate in market competition on the same footing as power generation companies. Therefore, it is necessary to evaluate the impact of this random power reversal on the AC-DC hybrid system with controllable power flow, in which case sensitivity can be used to analyze the impact of energy prices fluctuations on operating costs [57]. Besides, it is a recommended practice to take into account the demand side response [58], the change of energy trading volume among microgrid clusters and the game among different stakeholders in the capacity planning and modeling of distributed generation where game theory such as Nash equilibrium is also a viable method to model the user behaviors [59].

4) Operating simulation of AC-DC hybrid system. Firstly, considering the large scale of scenario set and the difficulty in obtaining typical scenarios caused by the change of operation mode of AC-DC hybrid network and the uncertainty in both source and load, it is necessary to study scenario reduction techniques while the extreme operation conditions are preserved. Then, the benchmark scenario of the planning scheme is verified by AC-DC hybrid OPF (Optimal Power Flow) analysis. Current analysis of the OPF for coupled AC-DC systems is essentially based on the steady-state models of each equipment, considering factors such as energy conversion efficiency. However, as transient processes in AC system and DC system differ in duration, further researches need to be carried out on the impact of dynamic processes on power flow in AC-DC hybrid DER systems with various devices. Considering the different time constants of AC system and DC system, the coupling process of the two kinds of systems can be divided into several stages, each of which is a quasi-steady state model. On this basis, a quasi-steady-state power flow model of regional AC-DC hybrid systems should be established to analyze the coupling and interaction characteristics of AC-DC systems. The fault operation characteristics of AC-DC hybrid system should be studied, and the reliability constraints of the planning model should be modified by using stochastic production simulation to verify the reliability of the planning scheme configuration.

5) The simplification and solution method of the optimization model. The AC-DC hybrid DER system optimal planning model is characterized by high dimension, strong non-linearity and non-convexity, irregular distribution of solution space, mixed discrete and continuous variables. In order to solve the model efficiently, on one hand, it is of great value to study the simplification of converter model, realizing the dimension reduction of decoupling optimization model for AC-DC hybrid DER systems. On the other hand, the optimization model can be stratified according to the different types of variables, with some of the non-linear power flow constraints in the model being linearized to reduce the non-linearity and non-convexity of the model. Finally, the global optimal search ability, solution efficiency and multi-objective processing ability of various optimization algorithms should be compared to select the appropriate algorithm for solution.

6) Comprehensive evaluation of planning scheme. Considering the new characteristics of AC-DC hybrid systems in terms of energy efficiency and coordination, new evaluation indicators should be added. It is necessary to determine rational weight and build the index system considering the objectives of economy, reliability, renewable energy utilization and environmental compatibility. The evaluation method matching the index system should be selected to evaluate the optimized planning configuration comprehensively and provide the optimal decision support.

V. Conclusion

This paper analyzes the physical characteristics of AC-DC hybrid systems from the two aspects of system and equipment. It argues that the application of multi-functional converters makes the AC-DC hybrid system flexible in networking, diversified in operation modes and rich in control objects, which enhances the coupling relationship between source, network, load and storage. In the planning and design of such complex dynamic systems, it is necessary to consider not only the complementary coordination of source-load-storage in local partition, but also the balance and mutual aid of electric energy in the system scope. The change of continuous variables such as the output of distributed renewable energy, the discontinuous variables such as the morphological transformation of network and the switching of working mode, as well as the multiple objectives of the system such as economy, reliability and energy efficiency should also be considered. In view of the new characteristics mentioned above, based on the review of the existing achievements, this paper proposes a framework and technical roadmap for planning and optimization of hybrid systems to solve the problem of multi-dimensional and non-linear system configuration. This paper also lays out prospects for researches on such key technologies as structural morphology prediction of AC-DC hybrid systems, exploring AC-DC coupling interaction, uncertainty modeling, operation simulation, improving model solution algorithm and comprehensive scheme evaluation.

As one of the development directions of power distribution system for energy internet, AC-DC hybrid DER systems further utilize the flexible control capability of AC-DC hybrid systems. Exploring collaborative planning with gas, heat and cooling systems in the framework of multi-energy complementarity may become a hot research topic in the future.

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