Optimal Operation Control Strategies for Active Distribution Networks Under Multiple States: A Systematic Review

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Abstract—**With the large-scale integration of distributed renewable generation (DRG) and increasing proportion of power electronic equipment, the traditional power distribution network (DN) is evolving into an active distribution network (ADN). The operation state of an ADN, which is equipped with DRGs, could rapidly change among multiple states, which include steady, alert, and fault states. It is essential to manage large-scale DRG and enable the safe and economic operation of ADNs. In this paper, the current operation control strategies of ADNs under multiple states are reviewed with the interpretation of each state and the transition among the three aforementioned states. The multi-state identification indicators and identification methods are summarized in detail. The multi-state regulation capacity quantification methods are analyzed considering controllable resources, quantification indicators, and quantification methods. A detailed survey of optimal operation control strategies, including multiple state operations, is presented, and key problems and outlooks for the expansion of ADN are discussed.**

Index Terms—**Multi-state control strategy, active distribution network (ADN), identification indicator, regulation capacity quantification.**

I. Introduction

A new round of energy revolutions is sweeping across the globe to deal with socioeconomic problems associated with energy production, delivery, and utilization, and realize sustainable energy development [1]. Global power generation has been increasing rapidly. For the first time, solar and wind power generation has increased to more than 10% of the global electricity supply [2]. In 2020, China proposed a significant energy policy, referred to as Carbon Peaking and Neutrality. The policy aims to change existing energy systems dominated by fossil fuels. In 2021, China became the first country that installed more than 1 TW of renewable generation [3].

The International Energy Agency (IEA) has proposed that large-scale restructuring of global and regional energy system architectures is essential by 2040 [4]. This shift can help achieve net-zero global carbon dioxide emission and drive the dominance of renewable energy in the global energy supply. In recent decades, the global renewable energy landscape has been rapidly changing as the installed capacities of photovoltaics (PVs) and wind turbines (WTs) continue to increase. However, the variability in distributed renewable generation (DRG) has changed the characteristics of traditional distribution network (DN). The Anhui Jinzhai microgrid project in China is a typical demonstration of large-scale distributed generation (DG) integration. It has the largest scale (800 m^2) in the world and the highest penetration ratio (310%). Reference [5] proposed a cyber-physical fusion model of DG cluster integration and a hierarchical spatiotemporal synergy method, which further increased the power generation capacity of DG by 40%.

It is imperative to develop an active distribution network (ADN) that includes DRG as its main component on a global scale [6]. As shown in Fig. 1, an ADN is a new power system with a large-scale DRG and a high proportion of power electronic equipment [7]. An ADN can control various grid-connected resources such as microgrids, distributed energy resources, and interruptible loads by utilizing a flexible network topology and advanced communication and automation technology. However, the double-terminal uncertainty of the source and load causes reverse flow and mismatch between supply and demand, which has a negative impact on the safe and reliable operation of the ADN [8], [9]. In addition, large-scale DRGs are characterized by substantial uncertainty, weak observability [10], [11], and low controllability [12]. Simultaneously, grid-connected power electronic equipment has a low inertia [13], [14] and weak anti-interference characteristics. These shortcomings present significant challenges to traditional DN control strategies [15], [16]. If the power dispatch is unreasonable, it may cause serious opera-

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tion problems such as serious branch congestion, voltage and frequency violations, unnecessary network loss, and harmonic pollution. Therefore, it is necessary to develop control strategies for flexible scheduling in DRG to ensure the stability of ADNs.

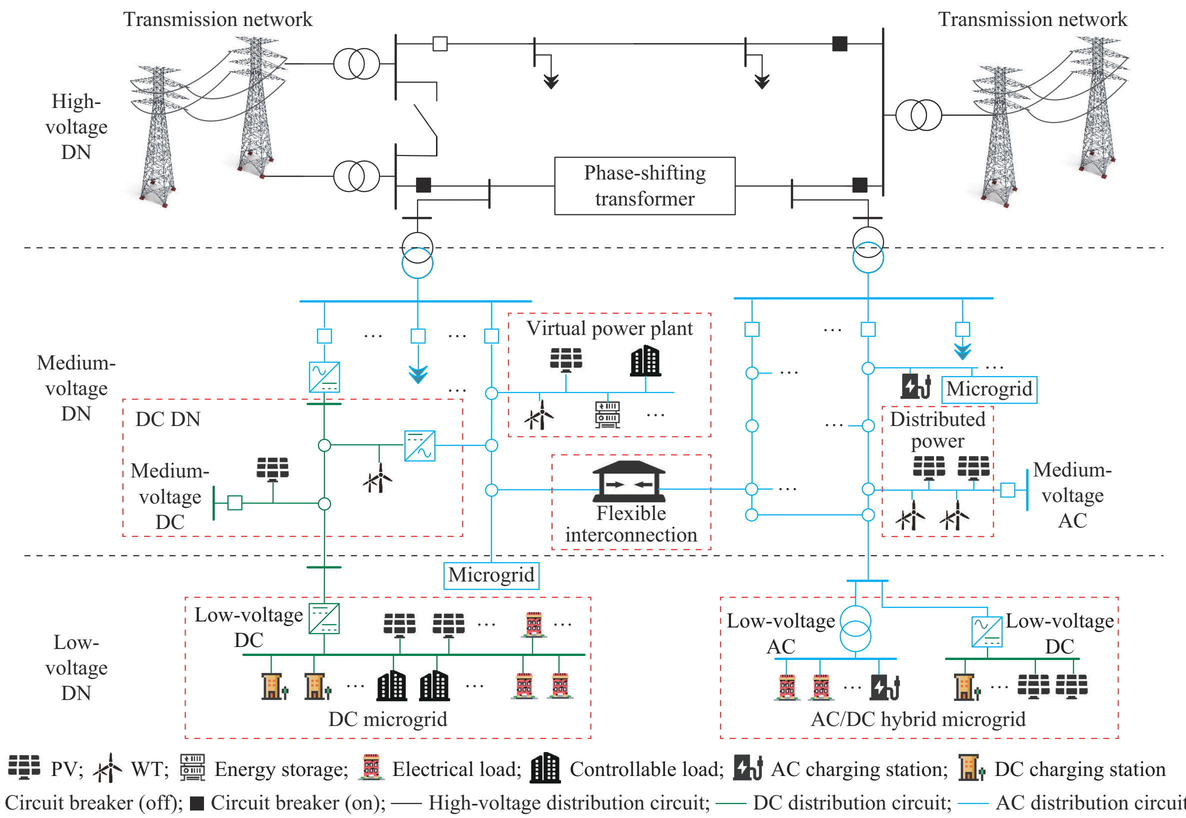

Fig. 1. Diagram of an ADN.

An ADN has several operation states, and the control strategies differ accordingly under the prevailing operation states [17]. The existing source-grid-load-storage control strategy must clarify the ADN operation state at all levels, where the proposed control objectives are primarily economic-based, and could pose significant operation limitations. First, the ADN operators are challenged to achieve a global optimum by adopting planned scheduling strategies. Second, ADN operators are unwilling to provide proprietary information on the active capabilities of DRG resources to upper-level power grid operators. Moreover, considering the variable nature of DRG, ADNs generally adopt intraday rolling optimization, which cannot prevent control problems that can arise in subsequent hours and future states of ADN operation.

The primary goal of the ADN operation control strategy is to clarify the operation states and control objectives. First, it adopts hierarchical partitioning as a collaborative strategy to achieve global complementarity in an ADN by aiming to curb the limitations of existing control strategies [18], [19]. Concurrently, it fully taps the operational support capability of DRG equivalents as virtual synchronous generators. Furthermore, it conducts multi-level state awareness and preventive control in shorter timescales such as 6-12 hours [20].

With the ongoing changes in the power supply structure and load characteristics of ADN, power grid adjustment methods have undergone tremendous changes. The load characteristics have changed from inductive and resistive linear loads to large-scale nonlinear loads represented by power electronic devices. System regulation has changed from the voltage and frequency regulation on the power supply side to the coordinated regulation control of multiple energies, flexible loads, and energy storage located behind the meters. Finally, the grid stability adjustments have changed from relying on generator inertia to introducing advanced control strategies for ADN equipment. Research on ADN control strategies has posed several ongoing problems.

1) The operation state of the ADN is no longer limited to the binary stable and fault states. The DRG introduced in the ADN includes multiple types of energy, configurations, and fusion forms. The safe and stable operation domain of an ADN is significantly different from that of a traditional DN. Higher and more stringent requirements for the risk perception, exception warning, and stability control of ADN have been proposed. Accurate identification of the operation state of the ADN is a priority in an uncertain environment, which could otherwise result in the grid being unable to support flexible switching of ADN control strategies.

2) The difficulty in evaluating the resource regulation capacity gradually increases with an increasing proportion of DRG in the ADN. Multi-level DRG systems are widely distributed in ADNs. ADN dispatching requires the coordination of large and distributed resources with various regula-

tion characteristics and response time. Such characteristics make it difficult to quantify the resource regulation capacity of the ADN under multiple and uncertain operation states and significantly limit the support ability and responsiveness of proliferated DRGs.

3) Massive DRGs in the ADN increase the complexity of control strategies. Owing to the complex and changeable operation states of ADN, traditional top-down control strategies have been challenged by flexible and uncertain interactions in ADNs. In traditional DN control strategies, it is difficult to ensure safe, economical, and reliable operations with large-scale DRG resource access. Traditional methods cannot achieve the optimal energy complementarity, synergistic energy supply, or shear linkage designated in ADNs under multiple states.

This study focuses on the development of optimal operation control strategies of the ADN from three aspects: operation state identification, regulation capacity quantification, and smart management and control. The key technical routes and control strategies of the ADN under multiple operation states, combined with the latest research results, are summarized in this paper. Subsequently, the corresponding research directions and prospects are presented. This study provides references and explores ideas for enhancing control strategies of the ADN.

II. Operation State Classification of ADN

Massive DRGs result in frequent changes in the ADN operation state. The operation state classification is the basis for state estimation and self-healing control [21]. Previous studies have analyzed the ADN operation states. In [22], the state division of a generation-transmission system was proposed for the first time. The power grid was divided into three operation modes: alert, emergency, and recovery. Considering the security level of the DN, [23] provided a definition of the critical state between normal and emergency states, where the electrical equipment in the DN was about to exceed its operation limit conditions. Furthermore, emergency states were subdivided into emergency, extreme, and collapse states [24]. Moreover, a hierarchical classification method was proposed to classify the operation states based on the importance of the real-time performance requirements of an ADN [25].

In this study, the ADN operation state is divided into three different states, i.e., steady, alert, and fault, to facilitate the subsequent summary of state evaluation and control strategies and consider the reliability requirements of an ADN. Accordingly, multiple control objectives must be adopted for different operation states.

A. Steady State

Under the steady state, no electrical component in the ADN can operate beyond its permissible limit. Under this state, the ADN operates with a large power flow safety margin, voltage safety margin, and strong anti-disturbance ability. This can satisfy the security and reliability requirements of power supply. The control objective under the steady state is supposed to improve the power quality, economic efficiency, and utilization of DRGs. The timescale is generally seconds class or longer. Common control measures such as topology reconfiguration, load voltage regulation, and demand response improve the power quality by reducing network losses.

B. Alert State

Under the alert state, an ADN is still under the power supply state without failure, but some component operation limits are exceeded, such as voltage out-of-limit, $N-1$ security criterion violation, and local heavy overload. Since some areas of the ADN cannot guarantee the desired power quality, it follows that the system has potential safety hazards and poor anti-interference ability. The operation state of the ADN transits to the fault state if the abnormal indicators continue to deteriorate. The control objective in the alert state is to maximize the capacity margin of the ADN to prevent further degradation while satisfying the power demands to the greatest extent possible. The response timescale under the alert state usually depends on upper-level instructions to achieve flexible cooperative support.

C. Fault State

The fault state indicates that the power supply to certain loads is interrupted owing to failure. The operations of the relay protection devices may cause partial loads to temporarily lose power and enter the fault recovery stage. Considering customer satisfaction, the control target of the fault state is to maximize the restoration load capacity as quickly as possible after troubleshooting. Generally, the control response time under the fault state must be within the allowed threshold moments of the current, frequency, and voltage. The operation time of the protection devices must be determined based on the specific situation instead of the speed requirement.

A DN under steady state is unable to maintain a normal state due to the uncertainty of DG output, load fluctuations, and external disturbances. The severity of a disturbance determines whether the operation state changes to the alert or fault state. The alert state is unstable, because further disturbances may change the operation state into a fault state. Therefore, the dispatcher should prioritize the safety and reliability of the system and take preventive measures to recover the operation state. When the DN is under a fault state, the operators improve the reliability in the non-fault area by operating adjacent tie switches to transfer the load or island microgrids. Accordingly, it can realize the transition from a fault state to an alert state.

III. Operation State Identification for ADN

Rapid and accurate operation state identification for the ADN is conducive to the stable operation of the distribution management system, thus ultimately improving the safety and economy of the DN operation. To accurately identify the operation state of an ADN, it is necessary to consider its operation characteristics, establish a reasonable multi-state evaluation indicator system for the DN, and adopt a systematic operation state identification method.

A. ADN State Identification Indicators

In the process of state identification for an ADN, the selection of evaluation indicators is the basis for identifying the operation state of the DN. Currently, relatively mature smart grid evaluation indicators include the IBM Smart Grid Maturity Model, DOE Smart Grid Development Evaluation Indicator System, EPRI Smart Grid Construction Project Cost/Benefit Evaluation Indicator System, and European Smart Grid Revenue Evaluation System [26]. However, the aforementioned DN assessment indicator systems primarily focus on the building and operation management of ADN and lack a systematic and scientific identification of multiple states of the DN.

A state identification evaluation indicator system has been developed and further enhanced by many academics in response to the aforementioned problems by using the conventional comprehensive evaluation indicator system of the DN and the operation characteristics of the ADN. A DN economic operation evaluation indicator system with 7 primary and 21 secondary indicators was created in [27] based on the characteristics of the ADN. However, the indicator system only considered the steady-state operation of the ADN, which cannot accurately identify the fault state and alert state of the ADN. From the perspectives of system self-reliability, fault monitoring, operation and maintenance, control efficiency, and system redundancy, a DC transmission operation state evaluation indicator system with 31 indicators was developed in [28]. The indicators covered a wide range but failed to consider the difficulty in obtaining pertinent data or the complexity of calculating indices.

With the increasing scale of the ADN and the massive integration of the DRG, the complexity and variability of the ADN operation situation have led to a large number of indicators for evaluating the operation state of the ADN. Generally, these indicators can be divided into six categories: spare capacity margin, independent power supply capacity, real-time controllability, fault risk rate, power supply quality, and reliability. The connotations and related indicators for each dimensional indicator are listed in Table I. The value ranges of the indicators in the six categories can be used to determine the ADN operation states. The range for the DN of different areas must be adjusted based on the actual operation conditions.

TABLE I
CONNOTATIONS AND RELATED INDICATORS OF SIX CATEGORIES OF INDICATORS

Category	Connotation	Related indicator
Spare capacity margin	Reserve capacity of DN for load fluctuations and distributed resource fluctuations	Probability area reserve, transformer power margin, line power margin, generator standby capacity, power plant standby capacity, and power structure standby capacity [29], [30]
Independent power supply capacity	Ability of the microgrid formed by DN to independently supply loads after losing external power supply	Partition load average, partition independent, power supply duration, islanding imbalance, lost load ratio, and important load loss rate [31]-[33]
Real-time controllability	Ability to control distributed resources, loads, and other controllable resources in real time through distribution automation and Internet of Things	Controllable load ratio, DG power factor, electric vehicle (EV) state of charge, DG real-time power output, and load response rate [34], [35]
Fault risk rate	The maximum risk probability of failure of important power supply equipment in DN	10 kV line failure rate, distribution transformer failure rate, switchgear failure rate, downtime rate, and repeat trip rate [36]
Power supply quality	Comprehensive quality of DN power supply in terms of voltage deviation ratio, frequency deviation ratio, etc.	Overvoltage risk, over total harmonic distortion, and frequency limit rate [37], [38]
Reliability	Ability of DN to provide electricity to consumers without interruption at acceptable quality standards and in required quantities	System average interruption frequency index, system average interruption duration index, average service availability index, average power supply time, and expected energy not served [39]-[41]

In addition, to understand the correlation between the indicators and the overall operation state of the ADN, [42] established a comprehensive evaluation indicator system for the ADN by calculating the coordination coefficient among the indicators with respect to the relationships among multiple indicators. To examine the innate connection between various influencing factors and the operation state of the ADN, [43] and [44] proposed a correlation analysis method based on random matrix theory. The method permits the real-time and quantitative analysis of correlations within complex systems, even with vast amounts of data. The methods proposed in [43] and [44] can reveal the influence of one or more influencing factors on the operation state of a network and provide theoretical support for the selection of multi-state identification indicators for DNs.

Researchers studying the indicator system for the operation state of an ADN have made some progress in their work. Various indicators have been established, and their selection has a comparatively developed theoretical foundation. However, the indicator systems suggested by most scholars only consider one or two operation states of the ADN and fail to fully consider the operation characteristics of the ADN under the three states, namely steady, alert, and fault. Therefore, research on state indicator systems for different operation states is ongoing, and it is still challenging to establish a systematic and feasible indicator system.

B. Online Identification Methods for ADN Operation States

Traditional identification methods for the power system operation state are based on the effects of faults (outage indicators), while also considering the causes and modes of faults. With the rapid development of ADNs, the large number of distributed resources, and the high proportion of power electronic access, it is obvious that the traditional principles of operation state identification methods are not applicable to ADNs with increasing complexity and variation.

In terms of the operation state identification for the ADN, [45] applied a wavelet transform to extract the characteristic frequency band energy and decompose the fault current or voltage signal inside a substation. The fault phase can then be determined by comparing the fault current or voltage signal to the prescribed threshold value; however, as the threshold value was set using an expert empirical method, it was influenced by the setting value. To reduce the adverse effects caused by artificially set thresholds, an online smart identification method for the operation state was proposed in [46] using wavelet packet time entropy and support vector machine (SVM). However, the method cannot be adapted to complex distribution systems including massive controllable resources, and the solution speed is not sufficiently fast to satisfy online applications. On this basis, [47] used an adaptive fuzzy inference system for ADN fault classification to support the identification of normal, abnormal, and fault states of an ADN, which provided better adaptability for multiple DN topologies than the SVM method.

However, these online state identification methods rely on accurate information regarding the topology of the DN. When measurements are limited to real time, they cannot accurately identify the operation state of the DN. In [48], a distributed state estimation strategy was proposed for multi-feeder DNs to address the challenges posed by large-scale DNs and the limited coverage of field measurements. An efficient optimization model based on mixed-integer quadratic programming (MIQP) was proposed in [49] to address the challenge of accurately identifying the real-time network topology and estimating the system state in a DN with limited measurements. In practice, compared with the methods proposed in [46] and [47], these methods have been proven to achieve online operation state identification of the DN with the minimal data exchange.

To ensure the safe and stable operation of an ADN, it is crucial to accurately depict the current operation state and further state changing trends. However, the identification method for the DN operation state described above does not consider the future state of the ADN. Researchers have applied prediction models to the online identification process of the ADN operation state. In [50], a DN operation trend prediction method was proposed based on an optimized long short-term memory (LSTM) network by relying on the characteristics of historical operation data and considering the volatility of the long time series of DRG, flexible load (FL), etc. The method can carry out early warning of DN operation risk but cannot accurately identify the operation state. Therefore, based on the systematic and comprehensive prediction of distributed resources in an ADN, combining advanced deep learning methods to achieve accurate operation state identification will be the focus of future research.

IV. Regulation Capacity Quantification of ADN Under Multiple States

Regulation capacity quantification is crucial for ADNs to guide the dispatch of variable resources, thereby exploiting the resource adjustment potential to respond flexibly and quickly to uncertain power fluctuations. Furthermore, the quantifying results of the regulation capacity can provide the necessary boundary conditions for ADN control strategies. With respect to ADN operation under multiple operation states, the corresponding controllable resources are not completely consistent. The response speeds and regulation characteristics of the diverse resources under multiple states also differ. Therefore, quantifying the regulation capacity of ADNs that can satisfy diversified operation requirements under multiple operation states is becoming increasingly complex.

It is necessary to clarify the controllable resources and ranges under multiple operation states. Table II summarizes the operation requirements of controllable resources under multiple operation states of the DN, where BESS stands for battery energy storage system, MESS stands for mobile energy storage system, SOP stands for soft open point, and FMSS stands for flexible multi-state switch. In terms of the reactive power output of DRGs, in neither the steady state nor the alert state it is allowed to abandon the electricity generated by DRGs. However, the adjustable range of the inverter under the alert state is larger than that under the steady state.

TABLE II
Operation Requirements of Controllable Resources Under Multiple Operation States of DN

Controllable resource	Operation requirement		
	Steady state	Alert state	Fault state
DRG (PV, WT, …)	Satisfy power factor constraint −0.98-0.98 without generation curtailment [51]	Satisfy power factor constraint −0.95-0.95 without generation curtailment [51]	Adjust power factor arbitrarily and discard generation [51]
Load (FL, EV, …)	Manage by demand response [52]-[54]	Shed contracted interruptible load [55]	Shed regular load [56]
Energy storage (BESS, MESS, …)	Clip peak, fill valley, or improve power quality [18], [57]	Provide emergency backup to reduce operation risk [57], [58]	Guarantee important loads or isolated operation [59], [60]
Tie switch (SOP, FMSS, …)	Reconfigure topology [61], [62]	Reconfigure topology [11] or reduce load rate [63]	Isolate fault [64] or transfer load [65]

Table III summarizes a variety of evaluation methods for ADN regulation capacity quantification from five perspectives: the system state, timescale, schedulable resources, quantification indicators, and quantification models. In Table III, ESS stands for energy storage system, OLTC stands for on-load tap changer, CB stands for capacitor bank, MBCV stands for mobile battery-carried vehicle, and MAS stands for multi-agent system.

TABLE III
EVALUATION METHODS FOR ADN REGULATION CAPACITY QUANTIFICATION

State	Reference	Timescale	Schedulable resource	Quantification indicator	Quantification model
Steady state	[52]	Minute	FL, EV, and ESS	Available average regulation power	Sum of schedulable active power and remaining demand response capacity
	[66]	Hour	FL, MT, EV, and ESS	Power supply capacity evaluation index	Multiple grid connection time with schedulable power
	[67]	Hour	FL and ESS	The maximum allowable volatility of net load	Available regulation capacity quantification model
	[68]	Hour	WT and OLTC	The maximum grid-connected capacity of DG	The maximum capacity optimization model
	[69]	Hour	BESS and heating system	Flexible resource power setpoint	Flexible resource control model
Alert state	[58]	Second	FL, DG, and ESS	Recourse cost requirement	Extreme point
	[64]	Hour	Tie switch	Available supply capacity	$N-1$ security operation model
	[70]	Hour	FMSS	Expected energy not supplied	Sum of expected power shortage
	[71]	Minute	PV, WT, OLTC, and Shunt CB	Dynamic reactive power reserve	*P*-*Q* capacity curve calculation
	[72]	Minute	PV, EV, CB, and OLTC	Reactive power reserve	Reactive power regulation of PVs and EVs
Fault state	[55]	Minute	MBCV, SOP, and microgrid	Total restored active power	Multi-period restoration model
	[59]	Hour	PV, WT, ESS, and tie switch	Load priority restoration set	Breadth-first search
	[60]	Second	FL, DG, ESS, and tie switch	Total restore load	MAS-based service restoration method
	[63]	Minute	PV, WT, and ESS	Reliability indicators in island mode	Adjustable interval optimization
	[73]	Hour	FL, DG, WT, and ESS	Load control capability	Sum of scheduled active load control in microgrids

A. Regulation Capacity Quantification Under Steady State

Under the steady state, most research has quantified the regulation capacity of DN to improve economic benefits and renewable energy utilization. Among these, quantification indicators are based on the active power of controllable resources or the capacity of the demand response. The quantification timescale was typically in hours.

The combination of real-time controllable capacity and remaining grid-connection time was adopted to evaluate the power supply capability of controllable resources [66]. Reference [67] defined the maximum allowable fluctuation rate of the load to quantify the controllable capacity of an ADN with a high DRG penetration rate. Reference [68] evaluated the maximum DG capacity that can be connected to an ADN based on multi-period AC optimal power flow solutions.

To address the variability in PV generation, [52] established an available regulation capacity quantification model of demand response resources, including constant temperature control loads, ESS, and EV clusters. The available average controllable output was developed to estimate the contract for demand response and the controllable system potentials provided by the load aggregators. Several recent studies have focused on the flexibility of ADNs. Reference [67] established an ADN flexibility evaluation index to quantify the system potential for controllability. Reference [69] exploited ADN flexibility as a controllability target in DRG-based systems.

B. Regulation Capacity Quantification Under Alert State

Currently, there are few studies and discussions on the quantification of the ADN regulation potential under the alert state. Many regulation measures that consider both economy and safety based on multiple timescales are essential for studying ADN control under steady and alert states [71], [72]. It can be deduced that the reactive power margin is a crucial indicator for quantifying the controllable potential under an alert state. In [71], the OLTC and shunt CB were adopted under the steady state considering the response speeds of reactive power compensation equipment, and the dynamic reactive power compensation of the DRG was obtained by model predictive control under the alert state. In contrast, to address the fast voltage ride-through problem, [72] quantified the reactive power regulation of PVs and EVs based on real-time measurements under an alert state.

In addition, under the active reconfiguration strategy of the ADN, the maximum total power supply capacity was quantified online based on the $N-1$ security criterion [64]. Faced with the problem of feeder overloading caused by load fluctuations, [63] adopted the FMSS to transfer active power. The controllable capability of the reactive power was quantified by the deviation between the FMSS capacity and the transferred active load. In [58], the recourse cost was proposed to indirectly quantify the potential upper bound of the controllable resource for redispatch.

C. Regulation Capacity Quantification Under Fault State

In the case of DN failure or insufficient power supply, a direct control strategy and an incentive demand response mechanism have been utilized to change the flexible loads. Considering the stability of island operations, [59] obtained the available restoration capacity based on the storage output and the importance of the load. Reference [63] proposed two operation reliability metrics in the islanded mode and applied an adjustable interval optimization model to quantify the active support capability of a microgrid.

To achieve the rapid recovery of critical loads, a multi-period recovery model was developed to maximize the total weighted loads restored by optimal routing of repair crews, MBCVs, and microgrids [55]. In [73], the load control capability was employed to quantify load-side tunable resources. Reference [60] proposed a hierarchical multi-agent system method for restoration, and the total recovered load was skillfully integrated into the method as a quantification indicator.

The controllable capacity quantification indicator under a fault state is generally exerted at the second or minute level. The source and storage sides primarily consider the load transfer capability of controllable resources in the ADN. The load side focuses on the load recovery priority and cuts off interruptible loads if necessary. In contrast to the ADN topology reconstruction in optimal economic operations, the network side prioritizes the security and reliability of network reconstruction and considers short-term island operations. In addition, most existing studies only focus on several factors that pertain to generation, grid, storage, and load, rather than providing a holistic view that covers the entire DN.

V. ADN Operation Control Strategies Under Multiple States

When an ADN operates under different states, different control objectives must be achieved from the perspectives of the system coordination, grid coordination, and station area autonomy. Owing to the large number of DGs connected to the ADN and different dynamic responses of DGs, the collaborative optimization control based on mutual supply or assistance control and the uninterruptible power supply control under extreme conditions need to be developed. Several studies have been conducted to address the control problems of the ADN under different operation states. From the perspective of coordinated source-network-load-storage control, this section analyzes the control objectives under steady, alert, and fault states. Relevant control strategies are introduced, which are presented in Table IV.

TABLE IV
Multi-state Control Strategies in ADN

State	Control objective	Control strategy
Steady state	Economic operation	Demand response control [74]
		Network reconfiguration optimization and control [61]
	Reliable operation	Source-network-load-storage control [75]
		Hierarchical scheduling and control [76]
Alert state	Restoration to steady state	Topology optimization and reorganization [77]
	Safe and stable operation	Load transfer control [78]
Fault state	Uninterruptible power supply	Fault diagnosis and clearance [79], [80]
	Fault restoration	Interconnection switch adjustment [81], [82]
		Active support of distributed resources [83], [84]

A. Economic Optimal Control Under Steady State

Under steady state, the optimal control objective is to achieve the minimum total operation cost and carbon emissions. Nevertheless, the uncertainty of renewable energy sources such as PV, WT, and FLs complicates optimization control, and makes effective optimization difficult. Existing studies have proposed several control strategies for the steady state, including the electricity price incentive, grid reconfiguration, ESS regulation, and voltage regulation.

The introduction of demand response into electricity market competition was proposed in [74], which showed the interaction mechanism of DRG sources and multiple loads through price signals and incentive mechanisms. These strategies can effectively promote DRG consumption to alleviate power supply shortages. However, it is difficult to promote these strategies considering the high penetration of DRG owing to existing regulatory policies in the electricity market environment. A reconfiguration optimization strategy based on multi-objective optimization was proposed in [61], where network losses, load balancing indices, and the minimum node voltages were instantly considered as the criteria to determine whether it was necessary to reconfigure the ADN.

Moreover, the economic benefit evaluation index for the ADN transformation from the current topology structure to the optimal topology structure was given in [62]. The corresponding source, network, load, and storage regulations were comprehensively considered in [75] to minimize ADN losses. This study evaluated the perspectives of optimal source power allocation, network reconstruction, and load optimization in an ADN. However, DRG dynamics cause significant uncertainties in the system stability evaluation. To address this problem, the ADN was divided into several levels in [53], [54], [85], and the ESS was controlled to cooperate with DRGs through a hierarchical decentralization control strategy. Under these conditions, the ESS can be utilized to efficiently reduce the uncertainty at various levels. Optimal steady-state control strategies have also been proposed based on the advantages of various strategies. In [76], a novel control strategy aimed at minimizing the adjustable amount and maximizing the consumption rate of renewable energy was proposed on a much longer timescale. An optimal control model with two complementary timescales was established by combining differential evolution and empirical competition algorithms. The results showed that the renewable energy consumption rate could be effectively improved using this strategy.

B. Predictive Control Under Alert State

When an ADN operates under an alert state, the key parameters of DNs are within the critical stable operation range, whereas the safe operation margin is relatively low, which means that the system can be easily driven into an unstable state. Along with the connection of the DRG, the uncertainty of the DN is significantly increased, which poses significant challenges to the safe operation of the system. To guarantee the safety of the DN under an alert state and return it to a steady state as soon as possible, it is necessary to evaluate its operation state. With improvements in real-time monitoring equipment, real-time risk assessment is possible. In [86], the continuous oscillation caused by the DRG was accurately detected using the wide-area measurement system (WAMS) coherent detection algorithm, and preventive control was activated to dampen the oscillation.

Existing control strategies for an alert state can be divided into two categories. One is topology optimization and reorganization, and the other is load transfer control. Both strategies rely on controllable DRGs, ESSs, and FLs for power regulation. From the perspective of topology optimization and reorganization, the conditional value-at-risk theory was introduced in [77], which considers the power regulation cost to achieve the minimum operation cost. Furthermore, the uncertainty of the DRG was considered, and optimal control was proposed through network reconfiguration. In terms of load transfer control, to deal with the operation risks introduced by system uncertainty, various control strategies, including SOP, OLTC, ESS, and demand response, are combined to guarantee the operation efficiency of the ADN based on stochastic optimization and conditional value-at-risk theory [78]. This strategy can achieve a balance between the operation costs and risks.

C. Restoration Control Under Fault State

The fault state control of an ADN can be divided into two stages: fault location and isolation, and recovery control. Accurate and reliable fault locations form the basis for effective fault isolation. The limited thermal capacity of DGs would reduce fault current injection, and bidirectional power flow would bring challenges to the fault location. The existing literature mainly focuses on two topics [79]-[84], [87]-[93]. The first is a modified strategy based on traditional methods such as adaptive threshold setting based on various conditions [79]. The second is to adopt smart algorithms to construct new fault detection and location strategies, such as signal longitudinal comparison and information fusion in fault detection [80], [87]. However, existing strategies cannot deal with a high proportion of DGs.

In addition to fault location and isolation strategies, the essence of fault recovery control ensures rapid recovery, stable operation, and maximum protection of load supply after grid faults. The control objectives during the recovery stage include the minimum power outage load, maximum feeder capacity margin, and minimum number of switching operations. Based on the importance level, several PV and WT units and ESSs were combined to establish a mixed integral linear model that aimed to restore the maximum economic value of the load to determine the optimal control strategy during the fault recovery period [81], [82], [88]. In [89], a novel recovery control strategy was proposed by constructing a fault prediction set for DNs, derived from the immune mechanisms of organisms. Furthermore, various control strategies for the honeycomb ADN under steady and fault states were compared in [90]. However, the simulation conditions were rather ideal, and only a control strategy between the ADN and microgrid was considered, which meant that the multi-state control strategy among various microgrids needs to be further studied. In [83], [84], [91], a distributed control strategy with high control precision and strong robustness against communication failure was proposed to simultaneously achieve fast fault recovery with low computational complexity. However, network reconfiguration and multilevel control strategies must be considered simultaneously to achieve a better performance. In [92], a double-layer optimization-based fault recovery strategy was proposed to address the simultaneous occurrence of communication and physical layer faults. Experiments using various scenarios based on the CPS-160 test case demonstrate that this collaborative recovery strategy is capable of achieving concurrent fault recovery.

The objectives of the control strategies under multiple states include ensuring that the ADN operates efficiently and safely by optimizing the economy under a steady state, reducing the duration of the alert state, and minimizing the propagation range and processing time of the fault state [56], [94], [95]. Nevertheless, most current research works have proposed corresponding control strategies for a specific state. Steady-state control rarely considers the optimal scheduling scheme under a fault state, and fault restoration control seldom links the predictive result or feedback to the early warning effectiveness. Hence, the existing strategies still lack multi-state cross-consideration and control compatibility for flexible and reliable ADN.

VI. Key Issues and Outlooks of ADN Operation Control Strategies

A. State Identification of ADN

With the large-scale integration of DRGs and FLs, the operation state of the ADN changes rapidly with spatial and temporal distributions. Currently, the identification of the operation states of an ADN must explore the following two challenges.

1) State Identification Indicators

Although several identification indicators have been proposed to evaluate the operation state of an ADN, a widely recognized indicator system for identifying the operation states of an ADN is still lacking. By summarizing the existing indicators and considering the distinctive features of the ADN, six important categories should be considered, which are explained in Table I. However, ADNs show various features and have multiple operation objectives, so the identification indicators might need to be amended according to the practical ADNs.

2) State Identification Methods

When the state identification indicators are determined, the next task involves providing the value ranges for each indicator under the steady, alert, and fault states. However, only a few studies have focused on this topic. It is challenging to determine the value ranges under various operation states because multiple ADNs have multiple operation rules and strategies. However, it is meaningful to provide a typical reference. In addition, historical operation data as well as predictive data should be considered simultaneously when identifying online operation states; therefore, various data mining methods can be used to identify the operation states of the ADN.

B. Regulation Capacity Quantification of ADN Under Multiple States

Regulation capacity quantification is necessary to provide boundary conditions for ADN control strategies. In general, there has been a paucity of studies on the quantification evaluation of the controllable potential of the ADN. It is imperative to explore how to incorporate state transitions into the regulation capacity quantification of the ADN.

1) Regulation Capacity Quantification Indicators of ADN

The main idea of the regulation capacity quantification of an ADN is to calculate the individual controllable ability of each resource and then aggregate them to obtain the cluster regulation ability. However, the existing quantification indicators often ignore the acceptable dynamic operation limits of the ADN. The operation constraints of a DN are likely to cause a slight reduction in the controllable potential. Therefore, the regulation capacity quantification on multi-timescale should fully consider the dynamic operating limits of the ADN.

2) Regulation Capacity Quantification Methods of ADN

Current quantification methods for the controllable potential do not consider the influence of the adjustment direction. To quantify the controllable ability precisely, the upward and downward regulation capacities of the ADN need to be calculated separately. However, the existing research works focus only on one or several factors in terms of generation, grid, storage, and load resources. Therefore, quantifying the regulation capacity of the generation, grid, load, and storage resources under multiple states is a major challenge for further research.

C. ADN Operation Control Strategies Under Multiple States

The ADN operation control objective under multiple states guarantees reliable operation and improves the operation efficiency. The integration of DRGs brings challenges to the ADN under multiple states while simultaneously increasing control complexity. How to guarantee stable and safe operation under multiple states and smooth state switching among multiple states remains to be solved.

1) Control Strategies During State Switching

Although several control strategies have been proposed to deal with the serious problems of ADNs, the existing literature focuses on one or two operation states separately, and cannot deal with the switching period among various operation states. Transient switching between multiple states is complex. For example, several differences exist in the control objectives between the steady and fault states. How to identify the two states and design a proper control is a problem. It is feasible to ensure smooth state switching by setting appropriate margins among multiple states. In Fig. 2, the typical control objectives under the steady, alert, and fault states are illustrated together with the state-switching conditions. The odd numbers summarize the main reasons for undesired state transitions. The even numbers suggest management and control measures for intentional state transitions.

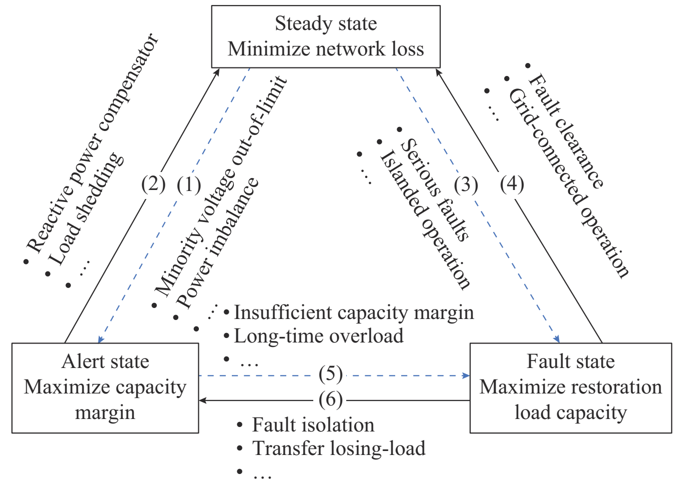

Fig. 2. Transitions among ADN operation states.

2) Control Strategies Under Multiple States

Considering the integration of DRGs and flexible loads, all the controllable sources must be coordinated to achieve smart control. Furthermore, a hierarchical control strategy can be designed according to the dynamic response of DRGs at multiple timescales. Specifically, from the perspective of control strategies under the alert state, existing research works have introduced the conditional value-at-risk theory to quantify the operation risk of an ADN. However, its applicability and accuracy must be further considered.

Concurrently, the coordinate control among multiple sources and loads such as EVs should also be considered.

VII. Conclusion

This paper presented an overview of the optimal operation control strategies for an ADN under multiple states. First, the concepts of the steady, alert, and fault states were explained, as well as the control objectives under the three states. Second, current research advances in state identification indicators and identification strategies were summarized. Third, the regulation capacity quantification methods were reviewed from the perspectives of controllable resources, quantification indicators, and quantification methods. Fourth, various operation control strategies for the three states were summarized. Finally, key problems and outlooks were presented to advanced related research.

Based on the proposed review presented in this paper, we believe that with the large-scale integration of DRGs, FL, etc., smart control will play a key role in the safe and economic operation of ADNs. However, many critical problems regarding state identification, regulation capacity quantification, and control strategies remain unsolved. It would be especially beneficial if a smart control framework could be established to manage ADNs more efficiently.

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