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Review and prospect of active distribution system planning

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Abstract The approach to planning, design and operation of distribution networks have significantly changed due to the proliferation of distributed energy resources (DERs) together with load growth, energy storage technology advancements and increased consumer expectations. Planning of active distribution systems (ADS) has been a very hot topic in the 21st Century. A large number of studies have been done on ADS planning. This paper reviews the state of the art of current ADS planning. Firstly, the influences of DERs on the ADS planning are addressed. Secondly, the characteristics and objectives of ADS planning are summarized. Then, up to date planning model and some related research are highlighted in different areas such as forecasting load and distributed generation, mathematical model of ADS planning and solution algorithms. Finally, the paper explores some directions of future research on ADS planning including planning collaboratively with all elements combined in ADS, taking into account of joint planning in secondary system, coordinating goals among different layers, integrating detailed operation simulations and regular performance based reviews into planning, and developing advanced planning tools.

Keywords Active distribution system (ADS) planning, Distributed energy resources (DERs), Distributed generations (DGs), Demand response (DR), Electric vehicle (EV), Active network management (ANM), Integrated planning

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1 Introduction

Nowadays when DERs gradually increase in the distribution network, an attention is paid to the progress of low carbon economy [1, 2], meanwhile the distribution network planning and operation have become more and more complex [3].

A traditional distribution network (TDN) usually relies on a large capacity margin to cope with the uncertainty of load in order to ensure the security of power system, and its operation control method is relatively simple [2]. Plus TDN planning only considers system security under conditions of maximum load, which is appropriate without DER in many cities and regions in China. After the integration of DER many scholars have done a lot of studies from different aspects such as impacts on consumers' reliability, improvement of power quality, decrement of network loss [4–8]. However, their research concerns passive distribution networks, and either traditional or passive distribution network will not well cope with the high penetrated distributed generation (DG) and not well satisfy the consumers' demand for reliability and power quality.

A shared global definition of active distribution networks (ADNs) was developed by CIGRE C6.19 [3]: Active distribution networks have systems in place to control a combination of DERs, defined as generators, loads and storage. It is possible for distribution system operators (DSOs) to manage the electricity flows in a flexible network topology. DERs take some degree of responsibility for system support according to a suitable regulatory environment and connection agreement. In 2012 CIGRE conference, CIGRE C6.19 workshop "planning and optimization methods for active distribution systems" extended the ADN to active distribution systems (ADS). It highlights that the future distribution grid will not only be a "network", but an unified system with some active control approaches for distributed generation, energy storage systems (ESS), electric vehicles (EV) and demand response (DR).

Although a lot of studies have focused on the planning of traditional and passive distribution networks, they have laid the foundation for the development of ADS planning which has also been studied in the literature. Currently, some studies on ADN are comprised of load forecasting [9], distribution network planning [10, 11], power management [12–16], and voltage regulation [17]. This paper concludes the research status of ADS planning from a technical perspective. Firstly, the influence of DER on ADS planning is briefly analyzed and the characteristics of ADS planning are summarized. Then, according to the general process of distribution network planning, the research achievements are presented as the following: 1) the forecasting of the load demand and DER generation; 2) the review of ADS planning model including the assessment on uncertainty and time-sequence characteristics of DG and loads, the optimization model for the planning, and the solution algorithm; 3) an analysis on cost-benefit of planning scheme. Finally, some directions and advice in this field are put forward on the basis of current research developments.

2 Influence of DER on ADS planning

Distribution networks especially low and medium voltage ones, are important links between transmission networks and consumers, though the low and medium voltage distribution networks are actually designed to be the "passive" load in the power system. The operation mode and technical rules of TDN are relatively simple, and either open-loop or radial pattern is existing nearly all over the world. The operators mainly use TDN for quick fault-processing without any active network management (ANM) strategies even when it is equipped with the distribution management system (DMS), distribution automation or advanced metering infrastructure (AMI). ADN is a public network with many active units as DG including photovoltaic generation and wind turbine generation, ESS, DR, etc. Besides, a flexible topology is necessary to ensure power reliability. ADS structure in [1] is shown in Fig. 1.

There are many examples of distributed control of DERs and ADS demonstrative projects, for example ADINE, ADDRESS, GRID4EU in EU countries, Fort Collins in US, ENMAX in Canada, and "regional power grids with various new energies" in Japan [1, 18]. China also has many projects such as "research and demonstration of key technologies in ADN" supported by National High Technology Research and Development Program of China, and it includes the planning work.

At present, most of the studies in ADS are still at the theoretical stage [19]. In order to conduct the ADS planning work better, we must have an in-depth understanding of the characteristics of distribution system. Therefore, analysis on the influence of DER integration on the ADS and ADS planning should be presented at first. EES is not particularly addressed in this paper because it can be regarded as a controllable load or generator depending on the charging-discharging status.

2.1 Influence of DGs on ADS planning

Many problems exist in the distribution system with/-caused by the high penetration of DG (Many problems are caused by the high DG penetration). Reference [4] summarized the influences of DG on the system such as load forecasting, power flow, power quality, supply reliability, short-circuit current, relay protection, etc. It is shown that different DG types or capacities would make special

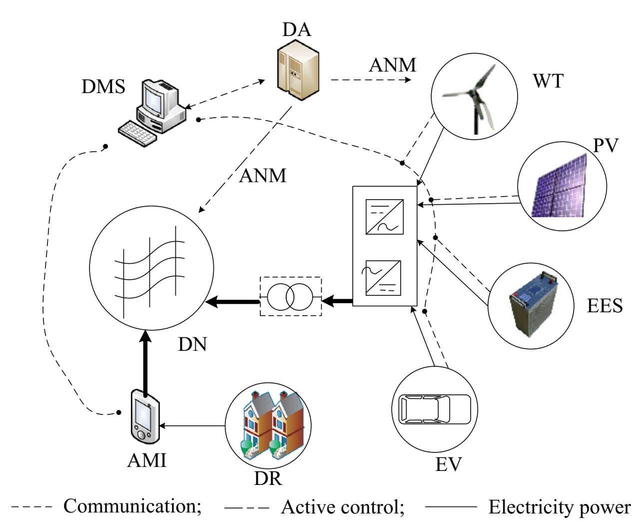

Fig. 1 Representative structure of ADS

influence on voltage distribution and network loss in [20]. References [5–8] analyzed the influence of DG integration on voltage, network loss and environment, etc., from the perspective of distribution system benefits.

We can see that technically there are more uncertainties in ADS due to the high penetration of non-dispatchable generation [21] because of such problems which DG integration brings to the distribution network. So the uncertainty of DG and active control strategies should be taken full consideration of at the planning stage. Other factors such as bi-directional current and closed-loop operation should be included in the planning model as well. The traditional constraints such as voltage limit, short-circuit current limit, power quality (flicker, harmonic) may put much more limits on. The ADS planning should involve all the DG units in the network and integrate with the transmission network constraints. Furthermore, integrated regional energy planning including gas and oil energy is likely to be a good direction in the future [19].

2.2 Influence of DR on ADS planning

Demand response can be divided into the following two categories [22, 23]: Non-dispatchable (price-based) DR load such as time-of-use pricing, critical peak pricing and real-time pricing require, and dispatchable (incentive-based) DR load such as direct load control and interruptible load service, etc. Dispatchable DR is easier to be implemented and allows more certainties in the planning stage compared with non-dispatchable DR. Reference [24] applied the direct load control method to a planning model as a virtual active generator with example of an air condition load, a kind of controllable one. Reference [25] used a real-time electricity model to construct a planning scheme for low carbon policy. The integration of controllable load or demand response has great effect on the peak load shifting, and it obviously has much more positive effect on the ADS planning, such as investment deferral, increase of renewable energy in the system [26], etc.

2.3 Influence of EV on ADS planning

There are a lot of articles about the effect of electric vehicle charging load on the distribution network including reliability, power quality (e.g. voltage drop, harmonic pollution, unbalance load) and economic operation (e.g. network loss) [27–29].

The uncertainty of EV load leads to more complicated conditions in the ADS planning. If a planning scheme is not appropriate, both the consumers' convenience and power supply reliability will be affected and the network loss and voltage drop may increase as well (an inappropriate planning scheme will bring impacts on both the consumers' convenience and power supply reliability and increase the network loss and voltage drop as well). So at the stage of ADS planning, we should pay more attention to the interaction between EV and distribution network, and should develop some coordinated charging strategies. It is a new research direction to explore how to enforce some controls over charging time and how to apply special EV charging tariffs to encourage off-peak charging in ADS planning.

3 Characteristics of ADS planning

Based on the analysis on the influence of DER on distribution network, the ADS planning can target at the following three aspects.

3.1 Low-carbon characteristic for society

From the previous discussion, it can be seen that ADS projects are mainly developed for the integration of DG and EV which is an important requirement of low-carbon policy. Furthermore, EES and DR are actually implemented to tackle the problems caused by DG and EV loads. ADS developments contribute to investment deferral and promotion in the renewable energy. The significantly growing renewable energy investment is emphasized in the objectives of the planning model in many studies, such as environment cost [30], the penalty cost of carbon emissions [25], as well as penalty cost for curtailed clean energy, etc.

3.2 Power quality and reliability for consumers

The consumers' requirements have been paid much more attention to in the ADS planning because uncertainties and volatilities in uncontrollable resources like wind power would impact power quality and reliability (e.g. voltage fluctuation) in the user-end. Reference [31] presented the permission capacity of DG based on constraints of harmonic limit in the distribution network, and indicated that the harmonic constraints should be fully taken into account in planning period so that it is feasible for distribution network operators to take corresponding measures to prevent harmonic problems at the operation stage. Besides, it is essential in ADS planning to carry out research from other aspects such as voltage deviation, voltage fluctuation, not supplied energy and network loss.

3.3 Economics, security and flexibility for the distribution system

In ADS, the distribution system companies are facing with some new challenges to the demand of economics, security and flexibility because of short-circuit current [32], voltage stability and transient problems [33] after the high penetration of DG integration. Reference [34] put forward the planning framework including the network solutions and non-network solutions. The network solutions can assess the host capacity for load demand through reconfiguration or DR instead of investing new equipment under the constraints of network security. Reference [35] proposed the similar planning thought from the priority planning perspective which began with load reallocating, then feeder planning, and ended with substation planning. It is pointed out that if the total load demand is less than total supply capability, only load reallocating measures, instead of changing the network topology, can balance the loads among different feeders or substations. It can be figured out that both non-network solution and load reallocating approach are in similar operation modes. They cannot only improve the investment economics but also increase distributed generation hosting capacity via different operation modes by switch-on and switch-off [36].

4 Forecast of load demand and DER generation

ADS planning requires a probabilistic representation of customers' daily load profiles to take account of uncertainties that characterize their behavior. Load forecasting is a key step in a distribution network planning process, and more accurate forecast may achieve better performance for the planning scheme. Currently, because of the high penetration of various DERs (e.g. electric vehicle, distributed generation, flexible load), research on load demand forecast should be conducted with operating characteristics of variable DERs and uncertainties in macroscopic development considered together from the planning perspective [1]. Reference [1] summarized that load forecast methods take into account of customer participation into ADN on the background of power market. These forecast models were mainly based on influences of the dynamic electricity pricing mechanism on load demand. Reference [9] overviewed load classification approaches in ADN, then a whole load forecasting method with proposed friendly loads. The forecasted total amount of friendly load and its spatial distribution in planning area were obtained on the basis of friendly load indices, such as expected total amount and spatial distribution of interruptible load, EV charging and discharging load, transfer load, etc. In addition, Reference [9] established a forecasting model of installed capacity and DG., Reference [1] summarized multiple factors that affect the DG capacity and proposed the forecasting method with credible output power in consideration of the probability of distributed generation.

$$Y_{\mathrm{DG}} = f(a_{\mathrm{nature}}, b_{\mathrm{geography}}, c_{\mathrm{policy}}, d_{\mathrm{load}}) \tag{1}$$

where Y_{DG} is forecasting power of DG; $a_{\mathrm{nature},}$ $b_{\mathrm{geography}}$, c_{policy} and d_{load} are the influence factors, respectively.

Reference [19] included that load growth will be affected by much more complicated factors in new environment of ADS, e.g. dynamic electricity pricing mechanism, active network management, demand response, etc. Advanced ADS model with more complex DR and DG integration should be built on the basis of accurate time-varying model instead of several typical scenarios. At the same time, inherent uncertainties of loads and DG would also affect ANS in many ways, which leads to a new requirement for prediction work.

Thus, the development of ADS makes correlations among elements in ADS more intricate. Moreover, forecast of load demand and DG output becomes more difficult when some active strategies (e.g. active control, active network management) are applied to ADS [18]. Forecasting process should involve both load demand and DER development in different time scales and time intervals. Forecasting uncertainties of loads and DG should also be taken into consideration.

5 ADS planning model

5.1 Optimal ADS planning model

5.1.1 Mathematic model

ADS planning in the optimal mathematic model is similar to traditional distribution networks planning, and it can be formulated as a multi-objective optimization problem with lots of parameters ξ_t including uncertainty, time-varying, and control strategy parameters, etc.

$$\begin{cases} \min \quad f(x_t, \xi_t) = [f_1, f_2, \ldots, f_{\mathrm{N}}] \\ \text{s.t. } g(x_t, \xi_t) = 0 \\ \qquad h(x_t, \xi_t) \le 0 \\ \qquad\quad 1 \le t \le \mathrm{T} \end{cases} \tag{2}$$

where x_t is a vector with decision variables; $f(x_t, \xi_t)$ is an objective vector mainly including investment cost, maintenance cost, power loss cost, expected energy not served (EENS), etc.; $g(x_t, \xi_t)$ represents equality constraint, e.g. power flow equations; $h(x_t, \xi_t)$ represents inequality constraints, e.g. voltage limitation, branch current limitation, total investment limitation. It is a single-stage model when $\mathrm{T} = 1$ while it is multi-stage (e.g. multi time scale planning or dynamic planning) when $\mathrm{T} > 1$. The life-cycle cost of investment equipment should be taken into account in the multi-stage model. N is the total number of objective functions. Similarly, when $\mathrm{N} = 1$, it is a single-objective model, e.g. total costs or total incomes [24].

References [1, 37] pointed that compared with TDN, ADN had more flexible technical standards, more distributed management modes, more flexible network topologies, more accurate simulation processes, more active protection and control strategies. Theoretically, all contents of traditional distribution networks planning are included in ADN planning. The basic contents of traditional distribution network planning are presented in Fig. 2 and Fig. 3 where the extended parts of ADS planning are also included.

As shown in Fig. 2, in contrast to traditional planning, active management cost is especially added in ADS planning objectives, which actually ought to contain investment cost of active management equipment (system or terminal equipment) [38], to be discussed in the later sections.

In addition to those extended constrains such as OLTC regulation limit, DR limit, constrains caused by transmission network) shown in Fig. 3, the specific planning demand may ask for other constraints including requirements for distribution network automation and communication [39].

Some other differences such as decision variables and model parameters between traditional planning and ADS planning are compared in Table 1. ADS planning problem can be divided into two levels [10, 40–42]: investment level (upper model) and operation level (lower model), which can be formulated as follows:

$$\begin{cases} \min\limits_{x_t^{\mathrm{inv}}} \ F(x_t^{\mathrm{inv}}, x_t^{\mathrm{ope}}) = \sum\limits_t Z_t + O_t \\ \text{s.t.} \ \ G(x_t^{\mathrm{inv}}) = 0 \\ \quad H(x_t^{\mathrm{inv}}) \le 0 \\ \qquad \min\limits_{x_t^{\mathrm{ope}}} f(x_t^{\mathrm{inv}}, x_t^{\mathrm{ope}}) = O_t \\ \qquad \text{s.t.} \ \ g(x_t^{\mathrm{inv}}, x_t^{\mathrm{ope}}) = 0 \\ \qquad\qquad h(x_t^{\mathrm{inv}}, x_t^{\mathrm{ope}}) \le 0 \end{cases} \tag{3}$$

where Z_t and O_t are investment objective and operation objective at time period t, respectively. As shown in (3),

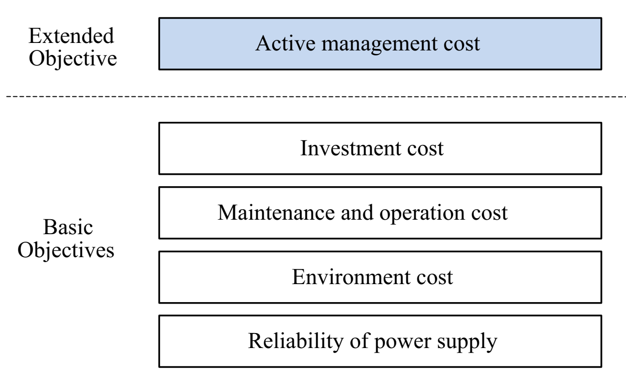

Fig. 2 Objectives of planning in both ADS and TDN

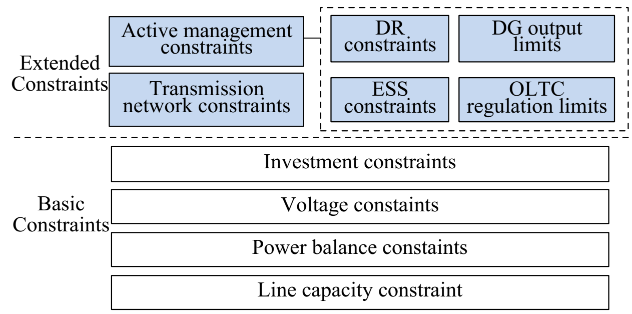

Fig. 3 Constraints of planning in both ADS and TDN

decision variables in ADS planning contains both investment variables x_t^{inv} and operation variablesx_t^{ope}. $G(x_t^{\mathrm{inv}})$and $H(x_t^{\mathrm{inv}})$ are the equality constraints and inequality constraints in the investment level, respectively. The operation level will feed back the optimal results to investment level. The comparisons of planning time-scale, decision variables and uncertainty analysis are listed in Table 1.

5.1.2 Development of ADS planning

Currently research on ADS mainly focused on operation and control problems [17]. In terms of planning, much attention was paid to the field of improving hosting capacity of distributed generations [43] or allowable maximum penetration of renewable generation [36]. At present, the application of active network management (ANM) is the most advanced research in ADS planning to control system voltage. In the beginning, ANM included three traditional strategies: 1) Regulation of DG active power; 2) Regulation of OLTC;3) Voltage regulation though reactive devices.

Afterward, regulation of DG power factor [10] was introduced, and the ANM method was applied to the branch power flow management. No matter how these models were organized, they were security-constrained optimal power flow models.

These planning models just added active strategies to traditional models, however, they are not completed to ADS planning design. References [44, 45] started to study configurations of energy storage system (ESS) in ADN. Optimal sitting and sizing model was proposed in [44] considering both active and reactive regulation ability by ESS. Reference [46] developed a multi-objective optimal placement model for ESS in ADN with three objectives, peak shaving capacity, voltage quality and power self-regulation capacity. DR is another important aspect which attracts much attention in ADS planning. Demand side management through interruptible load was applied as a supplement to active management control strategies in [40]. Thus, ANM can be widely used in almost all elements in ADS including OLTC, DG, ESS, DR, etc.

Table 1 Comparisons between ADS planning and TDN planning

Category	TDN planning	ADS planning
Simulation time	Typical segments	Time-varying, detailed simulation
Uncertainty	Typical scenarios	Stochastic probabilities, fuzzy distribution, etc
Decision variables	Investment variables	Investment variables, operation variables

The ADS planning only considering active management in researches mentioned above are still with the traditional realm. A real breakthrough was made when ADS planning involved active management equipment (AME) investment decision-making. Investment of AME may include control system cost, and control device cost for DG and controllable load, etc. In [38] the optimal size and DG units location were simultaneously determined and well as whether to install AME on controllable units in ADS or not, so AME was implemented as a whole with fixed installed cost and variable cost related to installed capacity. The ratio of AME in the distribution network was calculated in [47] to evaluate the active control level.

As seen in (3), AME investment mainly existed in the upper level while ANM contributed to the lower level. So far, ANM has been studied so comprehensively that only more management strategies need to be added in the later research. However, integrated planning with AME is just at the primary stage and more studies need to be done in the future.

5.2 Uncertainty modeling

Recently, scenario sets [48] and fuzzy sets [49] are used to model the load uncertainty. In scenario methods, the Monte Carlo simulation is the most commonly used in describing scenarios [10], and load duration curve is usually utilized to simulate the load condition [50], as shown in Fig. 4. It is a stochastic or probabilistic methodology. Some other measures including chance-constrained programming [14], blind number theory [51], connection number mode [52] and point estimation [53] are used in the literature. After integrating the distributed generation (DG), there are many more uncertain factors in the planning process. Many researchers try to apply probabilistic method, fuzzy method, info-gap decision theory, robust optimization and interval analysis for dealing with the DG uncertainty [54]. For the stochastic factors, uncertainties are mostly described by statistics based probability density function, such as Weibull distribution in wind power model, Beta distribution in solar power model, and normal distribution in load model. For fuzzy factors, membership function is appropriate to model the experience based logic [1].

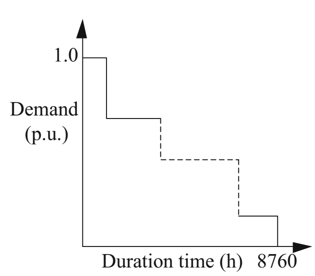

Fig. 4 Load duration curve

Generally, it is rare to see that innovative methods handle the uncertainty model in active distribution system [55, 56]. The Weibull distribution and Beta distribution are still commonly used to simulate wind power and solar power uncertainties. However, in some times, the uncertainties for some elements do not satisfy with probabilistic distribution, such as the uncertainty of installed capacity, and it needs to be further researched. Furthermore, there is a large correlation among load demand, DERs and distribution network development in the future, the approaches to represent the uncertain relationships among above factors are worthy of research [9].

5.3 Time-varying characteristics

Different types of uncontrollable DG (mainly for wind generation and photovoltaic generation) and load represent time-varying characteristics. The complementary characteristics between wind and solar power and the regulation for peak load have attracted researchers' attention recently. In [57] the time-varying fluctuation of load and wind speed was simulated at the same time, and real-time price was also considered. Reference [58] proposed a decision model for photovoltaic (PV) penetration including different kinds of load models for example residential load, commercial load and industrial load. Several studies [59, 60] proposed the DG sitting and sizing model using typical days to represent the time-varying characteristic in different seasons, along with different DG types. Although the time-varying model was included in [57–60], the potential of complementary characteristics peak load regulation should be further evaluated after integrating different DG types with respective time-varying features.

The main purpose of active distribution network planning is to consume more renewable energy so as to reduce the carbon emission. But some renewable energy, especially wind power, has a strong anti-peak regulation characteristic. It is necessary to integrate ESS and demand response to the distribution system because peak load shifting will reduce the amount of wind power curtailment and increase the installed DG capacity in the distribution system at the same time. Moreover, current models mostly focus on static (e.g. snapshot) or pseudo-dynamic simulation [11], therefore there is not enough detailed simulation process on successive time windows. Consequently, time-varying model will be more significant in ADS planning in the future.

5.4 Solution algorithms

It can be seen from the mathematical model (3) that the planning model can be divided into two stages. At the investment stage, variables for investment decision mainly include 0–1 variables (e.g. line upgrade or not [38]), and integer variables such as the number of DG units are equipped [10, 40]. It is a complex integrated programming problem due to the numerous decision variables. Either in the ADS planning or TDN planning, the solution algorithms mainly concentrate on intelligent algorithms such as genetic algorithm, particle swarm optimization, etc. These meta-heuristic methods are easy to use and very straightforward, but it is time-consuming and easily leads to local solution instead of global minima.

As shown in (3), the essential influence of ADS on the entire mathematical model focuses on the operation stage. The optimization model is actually an optimal power flow model when the power flow equality constrain is considered in ADS planning at the operation stage. There are only successive variables at this stage in many traditional planning literatures. Primal-dual interior point algorithm [40, 42] is often used to solve these non-linear programming (NLP) problems besides the traditional meta-heuristic algorithms. Obviously, the discrete variables also exist at the operation stage such as capacitor banks operating [61], etc. Likewise, the most popular solution is the intelligent algorithms (e.g. Tabu Search [44]). The continuity of discrete variables in optimal power flow of distribution network has attracted many researchers' attention, and has achieved some satisfactory performances. But the convexity of the original problem may be changed with non-convex penalty function or non-convex relaxation constraints added, which may result in local minima [62]. To solve above difficult problems second-order cone programming with Distflow branch model was proposed and it could transform the original optimal power flow model to second-order cone optimization problem by convex relaxation techniques [61].

Solving the planning model at investment and operation stage separately will cause poor convergence and long computation time in the upper programming (investment stage). In [30], iterations the algorithms may converge to its final result after 20,000. Another approach is to solve the investment and operation stage as a whole as a mixed integer non-linear programming problem. But until now the solution process of this model has not been addressed clearly. In many studies, it is just presented by using commercial optimization tools including GAMS or YALMIP platform combined with some software packages such as CONOPT, GUROBI, CPLEX [11, 36, 38, 45, 63].

Generally, the research on solving algorithm of distribution system planning is still at the developing stage. The solution must become more sophisticated because the requirement of detailed simulation with more operation processes, uncertainties and time-varying characteristics will increase more variables and enlarge the dimensions of problems in the ADS planning. Simultaneously, the increasing dimension of variables and the relationship between variables of different operation scenarios may also extend the search space to make the problems more difficult to handle. It is meaningful to explore some suitable solving algorithms for ADS planning.

6 Analysis of cost-benefit for ADS planning

In order to evaluate the effectiveness of the planning scheme, it is necessary to conduct a cost-benefit analysis. Traditionally, benefit is just defined as reduced economic cost. Reference [64] analyzed the decrease in investment costs after introducing active distribution network management, and assessed the potential of investment deferral caused by ANM. In [65] the annual benefit with different penetrations of DG was assessed after ANM configuration. References [64, 65] were based on a real distribution system and adopted annual time-varying data to simulate the whole operation process. In essence, according the previous section, ADS planning not only involves the distribution network layer, but also the consumer layer and the social layer. Benefit assessment of planning with respect to user reliability, power quality and other aspects, and the assessment of low-carbon benefits in the social dimension only have brief comparative analysis in the examples of some literature. There is currently little literature that considered AME investment planning, and research on the cost-benefit analysis assessment of AME is not progressing. From the application point of view, international current research on ADS planning and evaluations is still in the exploratory stage. An assessment system is needed to properly design and evaluate ADS system planning [19]. Therefore, it is necessary to have an depth discussion on the cost-effectiveness of AME investment, such as the economic and safety benefit analysis at grid level, reliability and power quality efficiency analysis at user level, as well as the assessment of low-carbon at social level, in order to assess the effectiveness of ADS planning.

7 Prospect of future research

Five aspects in future research on ADS planning are presented as follows.

7.1 Collaborative planning with all the elements combined in ADS

An ADS is an organic and integrated system in which DG, energy storage, demand response, electric vehicles [3], and many components in ADS can be controlled via the ANM scheme (e.g. OLTC, DG, energy storage, demand response, reactive devices, etc.). Obviously, it is inadequate to plan every component separately. It is essential to make collaborative planning for all the elements of ADS so as to achieve global optimization for the model and better performance for the planning scheme. Based on the above analysis, the following topics in this area should receive more attention.

1) Collaborative ADS planning with EV charging stations considering the active management of EV. So far there is no study on ADS planning including electric vehicles, however, lots of work in traditional planning with EV has been done and laid the foundation of future research. References [66, 67] analyzed the impact of EV integration on the distribution network planning and operation, including load forecasting, substation construction, feeder upgrade, etc., and proposed a planning model.

2) Collaborative planning considering the transmission network. Currently, only substation adjustment is included in some studies. In fact, an increasing penetration of DG may result in the reverse current. Therefore, how to deal with the coordination between generators in the transmission network and DG in the distribution network is a significant challenge [21].

3) The flexibility of ADS including tie-lines as a supplement to the current ANM schemes. The operators can transfer some loads or DG to other feeders by changing some switch states. By this means the hosting capacity of distribution network can be improved, and the power quality and reliability seen by consumers can be increased as well [56].

7.2 Integrated planning taking into account the secondary system

Although the concept of "ADN" has been expanded to "ADS", its research scope remains in the primary system which is the distribution network itself. However, optimal control of an ADS usually depends on the secondary system, and this will be increasingly true in the future. Additionally, the progress of intelligent information and communication technology (ICT) and advanced metering infrastructure (AMI) [37] makes real-time control more feasible. At the same time ICT and AMI can provide more useful information for planners to implement a more accurate operational simulation. The realization of ANM will require ICT and AMI in the future. Furthermore, active management system (AMS) should be added to ADS planning to realize the unified modeling for the whole system. AMS contains all elements in the distribution system except primary system, such as the operational control system, data acquisition units, control equipment, communication network, etc. Reference [50] integrated distribution automation in a distribution system planning model where distribution automation was used for voltage regulation and fault handling. The study gave a new perspective for collaborative planning with both primary and secondary systems. Several stages in distribution network planning progress are presented in Fig. 5 showing that a lot of research work has been done in the primary stage of ADS, some preliminary work has already been started in the secondary stage, however, it need to be strengthened deeply, in order to achieve an advance in collaborative planning.

7.3 Coordination among society, consumers and distribution system

It is evident in the previous section, whether ANM or AME is considered, that most current studies of ADS planning aim at the promotion of renewable energy. In other words, they focus on the low-carbon development for the societal benefit. But for consumers, traditional reliability, voltage deviation [45] and some other targets may

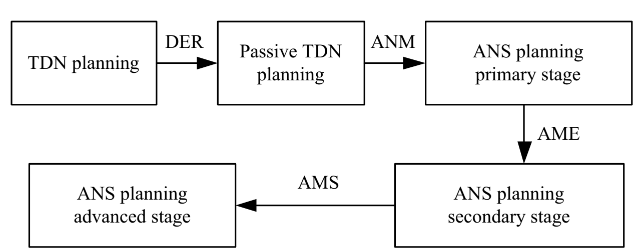

Fig. 5 Development of distribution system planning

have failed to meet ADS planning requirements with high penetration of DG. How to coordinate the objective differences and even conflicts between the societal benefit, the consumer benefit and the distribution system companies is a significant issue. Currently, multi-objective programming is the most mature method to deal with this kind of problem. However, it is difficult to achieve satisfactory outcomes because the contradiction among various objectives is not taken into account when the model is solved in single-objective form after transformation or in multi-objective form (e.g. using NSGA-II algorithm). In addition, game theory and multi-agent methods which can well reflect the incompatibility among different goals have already been studied in [68, 69].

7.4 Integrated planning considering detailed operational simulation of ADS and performance-based reviews

Reference [19] pointed out that operation process should be considered in distribution system planning stage by modeling the DG and DR resources. It requires detailed characteristics of every unit for constructing accurate simulation platform to make the planning scheme more efficient. Meanwhile, the uncertainties and time-varying characteristics should be discussed in the simulation of operation in order to achieve the integration of planning and operation in ADS.

Besides, there are more uncertainties in the real development of ADS, such as whether the scheme will be implemented or not, how many units will be put into practice and whether the real load growth rate will coincide with anticipated range, etc. Any of those uncertainty factors may make the original planning scheme unavailable. So in the practical application the planning makers usually ought to evaluate the actual performance and may revise the original planning scheme so that ADS will develop in the expected direction.

7.5 Development of advanced planning tools

Methods and tools need to be developed to allow optimal distributed ESS and DG sizing and siting as well design and integration of microgrids and multi-microgrids. Some interesting methodologies and models can be extracted from relevant publications. Particular attention must be paid to developing planning tools for large-scale application by means of strong interaction between distribution network companies and academia. Reliability models of active distribution systems, algorithms for active distribution system expansion and upgrade, and planning suitable to different scenarios and regulatory frameworks all need to be carefully developed for practical application.

8 Conclusion

This paper summaries the development of ADS planning. All aspects of ADS planning are just starting to receive attention, such as developing forecast models of load demand and DG, uncertainty simulation, time-varying characteristics, solution algorithms, and cost-benefit analysis in ADS. It is urgent to collaborate with distribution network companies to investigate existing practices and accelerate the progress of practical application. This paper also analyzes the impact of DERs on ADS planning, the characteristics of ADS planning, key issues in the planning process, and the future prospects. It aims to provide some useful references for future research of ADS planning, operation and optimization.

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