Energy Reports 9 (2023) 501–509

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Review on optimal planning of new power systems with distributed generations and electric vehicles

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ARTICLE INFO

Article history:
Received 21 September 2022
Received in revised form 6 November 2022
Accepted 26 November 2022
Available online xxxx

Keywords:
Planning
New power systems
Distributed generation
Electric vehicles

ABSTRACT

As distributed generations (DG) and electric vehicles (EV) are widely integrated into power systems, the power network has undergone significant changes in structure, function, and operational characteristics. Therefore, effective management and control of distributed energy sources and EV charging power by power system operators becomes necessary. In this paper, the physical characteristics of new power systems are summarized. The influence of DG and EV connected to power systems on system planning is analyzed. Then, based on the review of the existing planning models, the problems and technical difficulties are reviewed from the aspects of control strategy, power flow calculation, uncertainty processing, network planning, and equipment planning. Considering the problems and challenges, key technologies are presented. Finally, future directions are provided in four aspects, including system interdependence, various EV charging response, system resilience, and planning evaluation.

1. Introduction

In new power systems, the integration of renewable-based distributed generations (DGs) and electric vehicles (EVs) is seen as a promising solution to alleviate dependence on depleted fossil fuel reserves, increase energy security, and provide an environmentally friendly solution to the growing demand for electricity (Coster et al., 2010). The increasing penetration of DGs and EVs has brought many technical and economic challenges to power systems (Mahat et al., 2011). The main problems are as follows:

(1) It is difficult to effectively forecast fluctuations of the renewable-based DG output and EV charging power (Kang and Yao, 2017). On the one hand, distributed renewable energy with strong randomness and volatility makes its power generation fluctuate considerably. On the other hand, the charging power of EVs is greatly influenced by the subjective charging behavior of EV users, which is also unpredictable. Massive integration leads to frequency and voltage fluctuations in the distribution network, affecting the operation quality.

(2) It is difficult to centrally manage all components in the distribution system (Wang et al., 2020). Due to poor interconnection capability and optimization calculation, each subsystem operator usually manages the energy within the area or the subsystem independently. Due to the fluctuating and intermittent effects of renewable energy and EVs, the power balance is challenging to ensure. Therefore, they lack flexible power dispatch ability in networking.

(3) It is challenging to optimize the location and capacity of EV charging equipment and distribution generations (Liu et al., 2013, 2021). Investment costs, renewable energy utilization, and network operational efficiency need to be considered to increase economic performance and energy efficiency.

New power systems with DGs and EVs are considered an innovative solution to address the above issues. Compared with conventional power systems, new power systems allow for a more efficient dispatch strategy and more flexible regulation and, therefore, significantly outperform conventional systems in addressing the fluctuation, realizing distributed control, and reducing losses.

For new power systems, current research has focused on system-level studies emphasizing operational control strategies and optimization of energy dispatch (Guo et al., 2020), while system planning and configuration are relatively less concerned. Research has also been conducted on the location and capacity determination of DGs and EV charging equipment (Liu et al., 2013), the network structure of the distribution network (Xiao et al., 2021), and the centralized dispatch model (Li et al., 2021b). However, these planning methods and models do not consider the new features of new power systems, such as flexible networking, controllable power flow, tight source-network-load-storage

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https://doi.org/10.1016/j.egyr.2022.11.168
2352-4847/

coupling, and the impact of highly-dispersed sustainable energy integration.

The main contributions of the paper are the following:

- To the best of the authors' knowledge, this review paper is among the first to systematically summarize the physical and morphological characteristics of new power systems for implications of these new characteristics for system planning.
- Modeling classification of system planning in new power systems is proposed including modeling from system-level aspect and modeling from equipment-level aspect.
- A comprehensive review of the related literature is summarized to provide future research directions on some critical technologies in new power system planning problems.

This paper systematically analyzes the physical and morphological characteristics of new power systems and summarizes the implications of these new characteristics for system planning in Section 2. By scoping the current work, the main difficulties faced in the optimal planning of distribution networks in the context of a high proportion of renewable energy and EV integration are addressed in Section 3. Finally, in Section 4, the paper provides future directions on some critical technologies in new power system planning problems.

2. New features of new power systems

2.1. System structure

Compared with the traditional power system, the new power system is characterized by the dominance of renewable energy sources (Li et al., 2022). With the goal of carbon peaking and carbon neutrality, the proportion of renewable energy in primary energy consumption is increasing, accelerating the replacement of traditional fossil energy (Zhou, 2022). Furthermore, to fully support the efficient development and utilization of renewable energy, demand response technology is another essential feature of new power systems, which is also a necessary part of "source-network-load-storage" coupling in the power system. Demand response technologies can reallocate electricity demand promptly and potentially support the system to balance and limit peak demand, significantly improving the cost-effectiveness of low-carbon power systems. Among these flexible demand technologies, EVs offer outstanding flexibility potential due to their inherent capabilities, batteries to store electricity, and vehicle-to-grid (V2G) capabilities that allow EVs to inject stored electricity into the grid. The charging and discharging power of electric vehicles on the power demand side will also become a flexible and schedulable resource in new power systems. Therefore, in view of the two main characteristics of the new power system, the traditional power system's structure, composition, and interaction mode have undergone profound changes driven by the convergence with a higher proportion of renewable energy.

The structural diagram of new power systems are shown in Fig. 1. Large-scale integration of distributed wind power and photovoltaic power generation on the power supply side. At the same time, EVs and energy storage can also be integrated as flexible regulating power supplies, resulting in uncertainty at the source. On the power demand side, much active response and two-way interaction capabilities have emerged, which puts forward new requirements for users to participate in energy management and increases the uncertainty of the power demand side.

2.2. Key equipment and its model

2.2.1. EV charging loads

The new power system charging load for the power system will include two crucial flexible charging technologies: smart charging and V2G charging.

Smart charging: According to Ref. Ding et al. (2018), smart charging loads can be classified into two categories to account for the peculiarities of various consumers: contract charging fleets and price-sensitive commercial charging clients. It might be argued that price-sensitive commercial clients can respond to the charging prices published by the EV charging stations in earlier days. It is representative of the vast majority of EV users who have flexible charging schedules and who can base their charging choices on the cost of charging and their sensitivity to price changes. Price elasticity varies between them in their responses. The contracted EV charging fleet, namely the second kind of charging load, is expected to be in dispatchable demand. A commercial EV bus or taxi fleet that contracts with a charging station is the second form of charging load. As long as they adhere to requirements like final state of charge (SoC) and completion time, charging stations can make charging plans based on time-varying operational expenses.

V2G charging: V2G, short for Vehicle-to-Grid, is a charging technology showing that EVs interact with the grid (Western Power Distribution, 2017). When the EVs are not in use, the electricity from the onboard battery in EVs can be sold to the power system. If the onboard battery in EVs needs to be recharged, the power flows from the grid to the EV. V2G is more efficient than smart charging due to the ability to make the stored energy from the EVs back into the power system during the peak electricity price period. In this way, V2G technology is similar to distributed power generation. This helps provide additional energy to the power system, reducing the demand on the grid.

2.2.2. Distributed Generations (DGs)

DGs have the characteristics of smaller size, a larger number, and a shorter construction period than traditional generations. These characteristics put forward new requirements for the planning of new power systems. In order to provide efficient and high-quality grid-connected operation services for large-scale development of DGs, the power system needs to be transformed and technically upgraded in advance, optimizing the management mode of grid-connected services, transaction settlement, operation and maintenance regulation, and control, and improving the management system and technical standard system. The large-scale access of DGs brings more uncertainty and randomness to new power systems, and the operation mode would be more complex. It is difficult for traditional deterministic planning to adapt to new power systems construction, and the network planning needs to change to multi-scene probabilistic planning.

Wind turbine: One of the most well-known renewable energy sources, wind energy has been used in various ways. Recent years have seen a considerable increase in the installation of wind turbines worldwide due to environmental issues, rising fossil fuel prices, and advancements in wind technology. It should be underlined that the need to develop renewable energy sources, particularly wind energy, is inescapable given the depletion of fossil fuels and the release of greenhouse gases. As a result, there is a global movement to find solutions to every problem relating to the advancement of wind turbines. Wind turbines are devices that transform mechanical energy from wind's kinetic energy. The most common application for this mechanical energy is the creation of electrical energy. Wind farms, which are made up of several wind turbines that may either be connected to the main grid or generate electricity on their own, can be built using

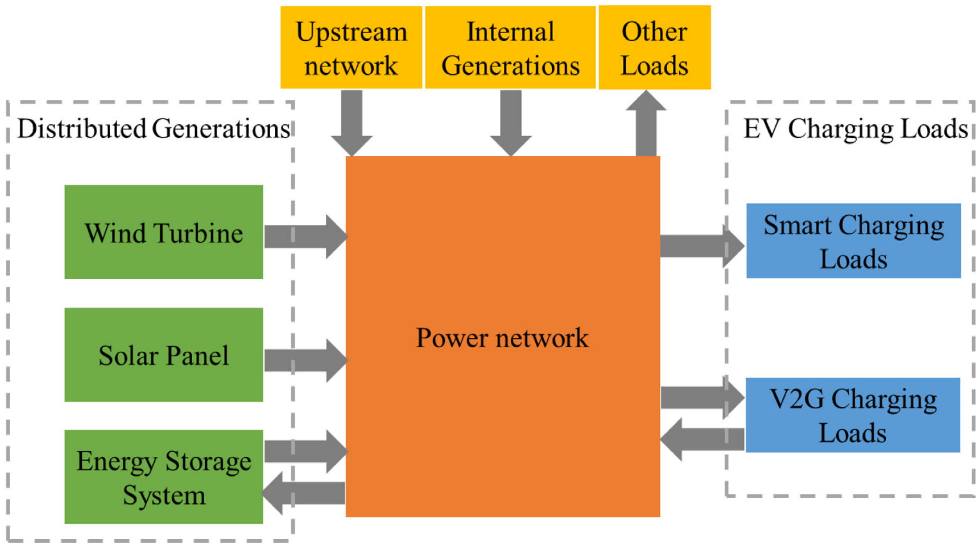

Fig. 1. Framework of a new power system.

wind turbines. Nowadays, a single wind turbine is most often used in distribution networks. A wind turbine's capacity cannot be increased because of practical, economical, and technical constraints.

Solar panel: The source of solar energy is the sun. Photons, the tiny energy particles that make up solar light, are used by solar panels, also known as "PV panels", to generate electricity that may be used to power electrical equipment. Solar panels can be used for a wide variety of other things in addition to producing electricity for residential and commercial solar electric systems, including remote power systems for cabins, telecommunications equipment, remote sensing, and more.

Energy Storage System (ESS): To sustain power supply and avoid energy shortages, new power systems are frequently fitted with ESS. However, ESSs have expensive installation fees and limited lifespans because they are frequently charged and discharged. In general, low market prices are anticipated for ESS and high market prices for release.

3. Review of research on optimal network planning

3.1. Basic planning model

Optimal planning is the process of selecting the best scheme or combination of schemes from all system designs or equipment parameters (including installation quantity and location) using mathematical optimization and comprehensive evaluation while keeping various resource constraints, the environment, and system operation in mind. It strives to provide maximum system support by meeting all system operating conditions. It is the primary issue to be addressed during the system planning stage. Fig. 2 depicts the essential planned contents of new power systems. The planning themes primarily involve the design of voltage categorization, source-load-storage zoning, and network architecture at the system level, as well as the setup of DG, energy storage, and EV charging stations at the equipment level. Because the issue of planning covers all aspects of source-network-storage-load, optimal planning of new power systems is a multi-dimensional and multi-stage complicated task.

When modeling, these planning problems must be abstracted into mathematical formation. The general form of the optimization model is presented in Eqs. (1)–(4), where the variables include discrete variable x^{dis} (e.g., in or out of the equipment, 0–1 variable) and continuous variable x^{con}. (e.g. equipment capacity).

$$min \sum_{i} \sum_{t} OBJ\left(x_{i,t}^{dis}, x_{i,t}^{con}\right) \tag{1}$$

s.t.

$$BOU\left(x_{i,t}^{dis}, x_{i,t}^{con}\right) \leq 0, \forall i \in \{1, N\} \tag{2}$$

$$OPE\left(x_{i,t}^{dis}, x_{i,t}^{con}\right) \leq ED, \forall t \in \{1, T\} \tag{3}$$

$$REL\left(x_{i,t}^{dis}, x_{i,t}^{con}\right) \leq EENS \tag{4}$$

The objective function $OBJ\left(x_{i,t}^{dis}, x_{i,t}^{con}\right)$ in Eq. (1) is set to minimize the overall cost of investment, construction, and operation. In constraints (2), $BOU\left(x_{i,t}^{dis}, x_{i,t}^{con}\right)$ reflect configuration boundary conditions such as equipment capacity and service life, network topology, investment scale, and renewable energy permeability limits. In constraints (3), $OPE\left(x_{i,t}^{dis}, x_{i,t}^{con}\right)$ displays the system operation constraints, primarily the power flow equation and safe boundary. It is more complicated because of the usage of converter equipment because converter constraints such as the range of port control parameters change (droop control coefficient, modulation degree, etc.) and control mode switching restrictions must also be considered. Reliability constraints are denoted by $REL\left(x_{i,t}^{dis}, x_{i,t}^{con}\right)$ in constraints (4). The requirements of the planned scheme for connectivity in the event of failure or partial power deficit are primarily described by reliability restrictions. The upper limit of energy demand is known as *ED*, while the upper limit of inadequate energy supply is known as *EENS*. The projected time and the equipment's serial number are represented by the variables t and i respectively. N is the entire amount of equipment and T is the overall planning time. It is quite challenging to unify the modeling since there are so many planning factors, as illustrated in Fig. 2, and each variable has different phases and levels. As a result, the majority of recent research only pays attention to one of the planning contents in Fig. 2. Formula (1)–(4) are established with decision variables, objectives, and restrictions during the modeling process for specific system planning subjects.

The source-load-storage and flexible networking capabilities of new power systems can be fully utilized to enhance the dispatching functionality of the system. The modeling of the link between the source, network, load, and storage must therefore be considered during the planning phase. However, the distribution patterns in time and space of distributed renewable energy have complicated effects on the electrical grid. When modeling, data

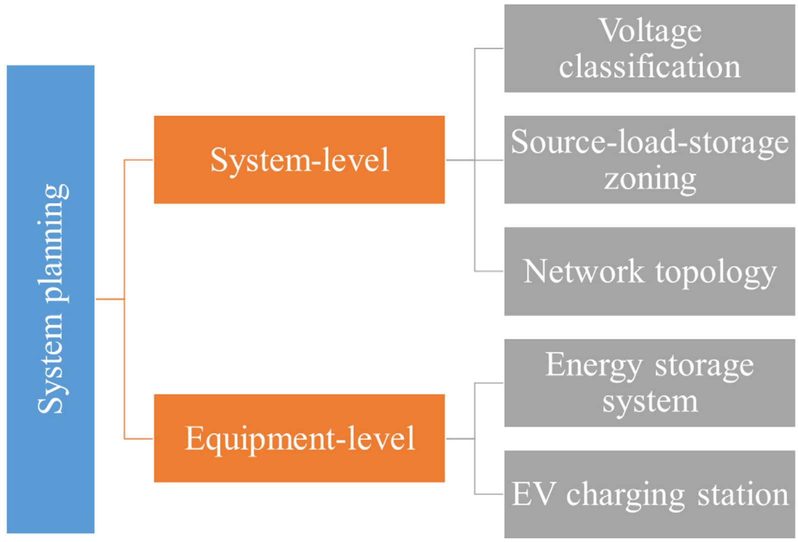

Fig. 2. Planning contents in new power systems.

from many ranges and time scales both inside and outside the system must be considered. The planning model must also meet the requirements for free and redundant connections between buses as well as the availability of renewable energy. Creating a model employing holistic, unified, and undifferentiated analysis techniques for decision-making and optimizing complex systems is challenging. Even though some researchers have looked into the source-load-temporal storage's coupling properties and the network's and generation's joint planning, the transmission system is where most of these topics are applied. The issue of collaborative modeling still has to be resolved because there is still a dearth of studies on the distribution system's characteristics and the relationships between its subsystems that complement one another.

3.2. Review and scope of current work

3.2.1. Control strategy

To maintain the stable operation of the power network and enhance the economics of network operation, it is especially crucial to select an acceptable control architecture in a new power system where distributed power sources are connected on a wide scale. New power systems' control structures typically fall into three categories: local control, centralized control, or distributed control.

Local control: Local control, also decentralized control, is the local regulation of an operable unit's output power using only its local electrical data. The sole requirement for communication between controllable units in local control is a local controller at each unit since it does not require a control center or coordinate the control of many controllable units. Each controllable unit can react fast based on local information and maintain the power balance of the distribution network in real-time because there is no communication channel. To ensure the stable operation of the distribution network, the local controller in local control collects the voltage and frequency data of the nearby distributed power sources in real-time and regulates their output active and reactive power. Control reliability is significantly increased, and communication costs are decreased because the DGs use their local electrical information and do not need to interact. Due to the lack of coordination between the various types of adjustable resources, the control method cannot achieve optimal control of the entire network when too many distributed power sources are connected to the distribution network. Additionally, because there is no communication system, the speed at which voltage and frequency recover after disrupting new power systems are slow, making system stability challenges.

Centralized control: In contrast to local control, centralized control involves creating a cluster control center in new power systems. This center will gather and process data from all resources that can be controlled within the network and will send control signals to all units that can be controlled in order to achieve coordinated control over the entire new power system. Following this control architecture, the central controller gathers and analyzes the voltage and power data from each distributed power source in new power systems, then produces control information provided to each power source (Reneses et al., 2006). Compared to local control, centralized control can achieve optimal control of the entire network, encourage the use of renewable energy in new power systems, reduce system network loss, and realize the economic operation of the entire network (Li et al., 2021a). This control architecture is equivalent to adding a second control layer to local control. The local controllers of each distributed power source receive the control signals from the centralized controller and modify the power of each distributed power source accordingly to respond to the centralized control signals.

Distributed control: Distributed control is built based on local control and centralized control. Distributed control generally divides new power systems into multiple sub-regions according to specific rules and achieves optimal operation of the entire network through autonomous control within each sub-region and coordinated control among sub-regions. Distributed control is free from the dependence on the central controller, and each controllable resource does not need to send information to or receive control signals from the central controller but only needs to interact with neighboring units to achieve optimal global control, which significantly reduces the communication and computation pressure and improves the operational reliability and practicality of new power systems. Distributed control combines the advantages of local control and centralized control, reduces data communication while achieving optimal control of the whole network, and has been widely used for coordinated control of new power systems with the support of multi-agent technology (Cao et al., 2021). Currently, distributed control of new power systems can be divided into two types according to the presence or absence of a centralized controller: distributed control strategy with a centralized controller and a fully distributed control strategy. In distributed control with a centralized controller, each controllable unit communicates with its neighboring units and transmits information to its regional centralized controller to achieve global optimization. In contrast, in fully distributed control, each controllable unit only communicates with its neighboring units and achieves global optimization through a consistency algorithm.

3.2.2. Power flow calculation

Optimal planning is based on power flow analysis. The steady-state analysis model, which is an algebraic equation satisfying Kirchhoff's law and adhering to the corresponding physical characteristics of the power system, is typically used in the power flow calculation for planning as the time scale taken into account in the planning stage is large enough to neglect the transient process. The novel power system, which differs from conventional power systems in that its power flow is controllable, necessitates the addition of control equations to the system steady-state model equation to create a non-linear power flow calculation equation group. Power flow analysis, a well-established field in electric transmission networks, aims to determine the voltage at each system bus and the power flowing in the network lines. A steady-state solution is offered by the power flow model in response to a particular set of loads, generation, and network parameters. AC power flow is the precise model that describes the non-linear and non-convex relationship between voltage and nodal power injection. However, the power flow equations can be approximated by a set of linear equations known as the DC power flow model after adopting some simplifying assumptions.

AC power flow model: Through a series of non-linear and non-convex equations, the AC power flow model defines the relationship between injected power, voltage magnitude, and voltage angle at each bus (Mei et al., 2014). The problem for non-linear term in AC power flows can be iteratively solved by employing the Gauss–Seidel, Newton–Raphson, or fast decoupling techniques. The AC Optimal Power Flow (ACOPF) framework can be used to determine the best overall solution by transforming the problem into a convex semi-definite program and applying convex relaxation techniques. Ref. Cao et al. (2019) employed a second-order conic program formulation to precisely express the ACOPF in operational circumstances. To test the proposed method and prove its scalability in Cao et al. (2019), a more complex microgrids structure based on IEEE 69-bus power system with the photovoltaic panels, micro turbines, and battery banks is adopted.

DC power flow model: To significantly improve the computational efficiency of complex optimization problems, linearization methods are often used for the power flow equations. Therefore, a linearized version, also known as DC optimum power flow (DCOPF), is often employed in practical applications. To create the DCOPF model, the following simplification assumptions are introduced (Zhao et al., 2019): (1) Each line has negligible shunt conductance and series resistance. Only the lines' series reactance is taken into account. (2) The voltage magnitudes are uniform and equal to one per unit. (3) A slight voltage angle variation is expected between the nodes that make up a line, nodes i and j. The DCOPF approach was used in Refs. Odetayo et al. (2018) and Li et al. (2018) to represent power flow in a power system and the modified IEEE 24-bussystem and the IEEE two-area RTS-96 system were adopted to test the proposed approaches.

3.2.3. Uncertainty handling

The new power systems establish mature infrastructural conditions for users to participate in system energy management and energy trading actively. With the maturation of the market mechanism for energy and service trading, the number of players in system energy management and market trading will gradually expand. Participants with diverse market participation patterns and habits will make different decisions as energy prices fluctuate, causing energy production and consumption unpredictability. This, together with the intermittent, fluctuating high proportion of renewable energy and the EV charging power, is a source of uncertainty. There are two main methods to deal with uncertainty in planning: stochastic programming and robust programming, which describe uncertainties through the scenario and uncertainty sets.

Stochastic programming: The stochastic technique uses a set of pertinent scenarios based on a well-known probability distribution to explain uncertainty. Thus, the planning is done so that all operating scenarios are expected to succeed with the aid of a look-ahead strategy. As a result, the objective function seeks to reduce the so-called expected system operation costs, which are the sum of the investment expenses incurred during the planning stage and the anticipated costs incurred during the operation stage (Li et al., 2020). Numerous publications have already been written about the stochastic planning of power systems. Ref. Reneses et al. (2006) used a stochastic model for generation planning that explicitly considers uncertainty and adopted in a system with two generation companies to illustrate the methodologies. Ref. Pourahmadi and Kazempour (2021) created a general two-stage stochastic programming model to plan the EV charging infrastructure inside an EV parking lot. Stochastic scenarios are utilized in Ref. Cao et al. (2019) to represent unpredictability. A joint chance constraint is included to control operational risks brought on by the uncertain nature of renewable energy generation and load variation, and contingent islanding brought on by external disturbances.

Robust programming: Robust programming: A uncertainty set, which may be created using knowledge of the lower and upper ranges of the stochastic parameters, is utilized to describe uncertainty. An uncertainty budget can be added to regulate the degree of conservatism. In this method, problems with an uncertain probability distribution and computational intractability brought on by the scale of the problem are resolved. In order to ensure that the dispatching solution is workable throughout the whole uncertainty set, the robust approach involves optimizing the system for the worst-case situation. On the other hand, robust planning optimization has a min–max–min structure that needs to be solved since robust optimization can result in overly cautious solutions. Numerous studies have already been written about the reliable planning of power systems. For instance, Ref. Mei et al. (2014) provided a solid optimization for power system static reserve planning with extensive wind power integration to guarantee the sufficiency of the producing capacity. A reliable generation expansion planning model was created in Ref. Pourahmadi and Kazempour (2021), considering a family of alternative probability distributions of wind forecast error uncertainty.

3.2.4. Network planning

Planning for networks is a crucial part of designing a power system. The two main objectives are the optimal power network structure for load development in the planning stage and a power planning strategy that can accommodate the need for affordable and dependable energy transmission. A significant characteristics of uncertainty and stochastic behavior has developed in power sources, which is the result of the connections between stochastic elements, such as energy storage and weather-sensitive loads, and renewable energy sources (large-scale wind and solar energy). Electricity is often provided by a large-scale generation unit and transferred and delivered to residential, commercial, and industrial consumers via a network in a centralized power-producing system (Shao et al., 2021). Rising renewable DG penetration has been viewed as one of the most critical issues for new power systems in recent years. Due to their commercial goods and distribution system supply potential, wind turbine and solar plant generations have drawn attention to renewable DGs. Before they may be widely distributed in future power system planners, however, a few obstacles must be removed (Fan et al., 2020).

Power system planners have successfully used network planning in the modern era. Conventional power network planning's primary goal is to determine the most cost-effective way to expand the system's assets to accommodate growing load demand and additional loads while still meeting security and quality standards (Yao et al., 2014). However, conventional power networks are evolving into new power systems with the widespread increase in DG penetration, mostly brought on by policy-making for renewable energy and its significant operational and planning benefits (Li et al., 2018). The economy and technology face significant hurdles due to this change. The technologies can offer essential answers to accomplish system stability, reliability, and sustainability as a system with adjustable mechanisms and variable energies. Applications involving wind and solar electricity can successfully utilize this strategy (Hu and Li, 2010). On the other hand, it has been demonstrated that key network management strategies, including demand side management, wind, solar, and continuous reactive power compensation, can reduce operating costs and obviate irrational investments in new power system design. There are numerous publications out there that discuss network planning. For instance, Ref. Cao et al. (2019) developed a stochastic conic program model with chance constraints for networked microgrid planning. A novel multi-stage model to ascertain the best sub-transmission system expansion planning was proposed in Ref. Jalali et al. (2014). To address the issue of optimal planning in integrated power distribution and EV charging systems, Ref. Yao et al. (2014) presents a multi-objective collaborative planning technique.

3.2.5. Equipment planning

The issue of equipment planning in new power systems mainly involves determining the capacity and location of EV charging stations and energy storage systems.

Generation: Power-generating facility operations have traditionally been organized hierarchically. Depending on their influence horizon, planning decisions are categorized as long-, medium-, or short-term (Pourahmadi and Kazempour, 2021). A long-term decision often takes more than three years to make, a medium-term one takes a few months to two years, and a short-term one takes place the next week. As the time horizon of interest lengthens, less information is available about the power system and time intervals (Mi et al., 2021). Longer-term decision levels must take into account the resource allocation requirements they will generate (Odetayo et al., 2018). Coordination between decision levels is especially important to guarantee that specific operational factors that may arise in the medium term (such as hydrothermal coordination, annual or monthly take-or-pay contracts with minimum fuel consumption requirements, annual emission allowances, etc.) are explicitly taken into account (Zhang et al., 2013). There are numerous articles available that discuss generation planning in power systems. For instance, Ref. Reneses et al. (2006) examined the synchronization between the short-term functioning of a power generation in a power system and medium-term generation planning. The ideal sub-transmission system expansion planning considers deploying dispersed generation over the planning periods described in Ref. Jalali et al. (2014). Models for generation expansion planning used the specific operation limitations from Ref. Li et al. (2020).

EV Charging Station: Using a stated objective function and subject to associated constraints, the EV Charging Station Optimal Planning Problem seeks to determine the locations and capacities of new charging stations to be built (Fan et al., 2020). It is generally believed that a single business coordinates the development of EV charging stations with the main objective of satisfying the demand for charging based on EV driving habits and battery capacity. Additionally, power system efficiency and dependability, as well as limiting power system losses brought on by EV charging power flows, are considered (Yao et al., 2014). Because of this, the main objective of the EV charging station planning problem typically consists of two parts. Two parts of the power network are reduced power losses and node voltage changes. The other is to increase the time each charging station is used, as measured by the total amount of EV traffic flowing along the EV travel routes in the traffic network. Numerous articles are available that describe the planning of EV charging stations in power systems. For instance, Ref. Chen et al. (2019) looked into the problem of designing a charging facility for an investor in EV charging stations who wanted to serve EV users with unpredictable requirements and behaviors while incurring lower economic costs for both the charging facilities and actual operation. According to Ref. Li et al. (2021a), Cournot competition game model is employed to optimize the competitive resource allocation strategy for charger planning in a market-based system. To solve this model, a multi-relation graph convolutional network-based encoder–decoder deep architecture is utilized in this method to estimate the EV charging demand. A method of coordinated planning for power distribution networks and EV charging stations, considering on-site batteries, is suggested in Ref. Shao et al. (2021). The Ref. Duan et al. (2020) suggests a strategy for PEV fast-charging station cost reduction planning that considers the effects of queue and driving time.

Energy Storage System: By storing energy during periods of low load and releasing it during periods of high load, an efficient energy storage system can help to lessen the unpredictability of renewable energy sources like wind and solar power. It is acknowledged that energy storage is a crucial part of the current power grid. Additionally, it is currently financially viable. How to determine the long-term system value of battery energy storage in systems with significant and rising wind and solar penetration has been studied. Since millions of users are already served by energy storage or will be in the future, optimizing expansion planning in this industry is crucial. Optimizing expansion planning for energy storage is crucial because it will impact millions of consumers whose load demand is already being fulfilled or will be in the future by new power systems. The energy storage expansion planning problem has been addressed using various mathematical optimization techniques, including linear programming, non-linear programming, mixed-integer linear programming, and heuristic optimization techniques, like the genetic algorithm. However, different real-world factors add more and more ambiguity to the scenario, making it harder and harder to find the best growth strategies. Numerous articles are available that describe the planning of energy storage systems in power systems. As an illustration, Ref. Oderinwale et al. (2019) examined how energy storage affects power investment planning. To reduce the investment cost of integrating additional natural gas-fired generators and storage necessary to provide desired confidence levels of fulfilling future stochastic power and natural gas demands, Ref. Odetayo et al. (2018) offered a chance-constrained programming technique.

3.3. Summary

The rapid growth of DGs and the emergence of V2G technologies pose new problems for future power systems. Integration and synergistic planning of new power systems have garnered increased attention as a viable technique to increase flexibility and promote RES penetration. The design of new power systems at various levels, according to the most recent literature, offers significant advantages in terms of overall planning costs, support for renewable power generation, and dependability. This study examines the problem of optimal design of new power systems from all angles, including a complete description of the many physical properties and feasible optimization methodologies. Table 1 covers the most significant literature on new power system planning.

Following is a summary of the review's key findings:

(1) Choosing an acceptable control structure is critical. Control structures for new power systems are usually divided into three categories depending on the system structure: local control, centralized control, or distributed control. Each control method has its characteristics regarding mathematical models and solution methods. Most of the methods adopted at exiting papers are centralized control. However, due to its high computational efficiency and fast convergence, the distributed method will become the mainstream method of new power system planning in the future.

(2) The optimal power flow is divided into ACOPF and DCOPF. When considering DCOPF, the sub-power is not considered, and the default voltage of all nodes is one p.u. When considering ACOPF, the sub-power and the voltages of different nodes are also considered. DCOPF is a linear convex function, easy to solve. ACOPF is non-linear and non-convex, difficult to solve.

(3) Since changing renewable generation and charging loads are mirrored in the power network, new power systems must predict the uncertainties associated with these factors. Analysis of the benefits and drawbacks of various methods for dealing with uncertainty leads to identifying robust optimization as a suitable strategy for system design.

(4) Network planning technologies can offer important answers for achieving the objective of system stability, reliability, and sustainability since they are a system with controllable mechanisms and universal energies.

(5) EV charging station planning can maximize the advantage of geographic space. Energy storage planning can design the address and capacity of energy storage systems from the planning stage, thus helping new power systems to consume new energy better.

4. Prospects of research on key technologies and future directions

4.1. Prospects of research on key technologies

Given the technical difficulties in the existing research, the planning of new power systems should have the following technical characteristics:

(1) As the source-network-load-storage characteristics become more tightly related, the collaborative complementary optimum allocation should be given more thought. The relationship between generating and network planning is increasingly clear. As a result, greater emphasis should be placed on the complimentary correlation features of source, load, and storage and the coordination of source-network planning.

(2) The market framework should prioritize user-side flexible resource planning. The unique features of new power systems enable consumers to actively participate in energy trade and system energy management. As a series of user-side schedulable flexible resources play an increasingly important role in system configuration, changes in user energy strategy under the market framework and the game among many stakeholders should be considered in configuration optimization.

(3) The technical and economic impact of the high proportion of renewable energy should be thoroughly considered in generation and network planning. The old planning method undervalues the technical and economic impact of large proportion penetration of renewable energy, resulting in a lack of scientific capacity calculation. Furthermore, the great controllability of a DC system for distributed generation and the ability to perform the rapid spatial transfer of regional energy make generation capacity and access mode (centralized/decentralized) more flexible in planning. Varying access mechanisms and generation capabilities correspond to different operating expenses.

4.2. Future direction

4.2.1. System interdependence

As EV adoption rises, it will be easier to see the system-wide interconnection between transportation and power distribution infrastructures. The synergy of power and transportation systems will bring many new challenges to the future synergistic planning of power systems and transportation systems. For example, more planning binary variables will cause the problem to be more difficult to solve. The mobility characteristics of EV users would also be considered in the future based on the UE model (Nesterov, 2000). Therefore, the future collaborative planning of power and transportation systems will become a research hotspot.

4.2.2. Various EV charging response

Utilizing the demand response capabilities of individual electric vehicles and electric buses appears to offer a very promising way to enhance system operating conditions. Please remember that driving styles for private vehicles, buses, and metro trains differ because buses cannot change their routes, and metro trains do not encounter traffic congestion. Electric buses and metro trains are effective demand response providers because a transportation authority regularly schedules them. Private EVs and rapid charging facilities are expected to take part in demand response programs in the future if optimal incentive decisions are made.

4.2.3. System resilience

It is critical to investigate the resilience of such infrastructures in the face of harsh weather and natural disasters, to activate immediate plans for system restoration and repair and emergency evacuation. In a catastrophic power outage, EVs and energy storage can provide valuable backup electric energy. Furthermore, inconsistency in one system can spread to the other. It is also critical to investigate how power flows are affected by a disaster to identify weak components that require upgrading or expansion.

4.2.4. Planning evaluation

A comprehensive evaluation of the planning scheme New evaluation indicators should be developed to account for the new characteristics of new power systems in energy efficiency and coordination. It is vital to establish moderate weights and design the index system while keeping the goals of economics, dependability, renewable energy utilization, and environmental compatibility in mind. The evaluation method that best matches the index system should be used to thoroughly analyze the optimized planned configuration and provide the best decision assistance.

5. Conclusions

This paper first analyzes the physical characteristics of new power systems in terms of system structure and describes the main elements of new power systems, i.e., distributed generation (DG) and electric vehicle (EV) charging load. Integrating DGs and EV charging loads makes new power systems flexible in flexible networking, rich operation control modes, and tight

Table 1
Selected relevant references reported in the literature. (SP: stochastic programming. RO: robust optimization. EVCS: EV charging station. ESS: energy storage system.)

Reference	Control strategy			Model	Uncertainties	Network planning	Equipment planning			Year	Sample size
	Local	Centralized	Distributed				Generation	EVCS	ESS		
Reneses et al. (2006)	–	Yes	–	–	Yes(SP)	–	Yes	–	–	2006	A system with two generation companies
Li et al. (2021a)	–	Yes	–	–	–	–	–	Yes	–	2021	Real data set from Sydney, Australia
Mei et al. (2014)	–	Yes	–	ACOPF	Yes(RO)	–	Yes	–	–	2014	IEEE RTS test system
Cao et al. (2019)	–	Yes	–	ACOPF	Yes(SP)	Yes	–	–	–	2019	IEEE 69-bus power system with the photovoltaic panels, micro turbines, and battery banks
Odetayo et al. (2018)	–	Yes	–	DCOPF	Yes(SP)	–	Yes	–	Yes	2018	20 years integrated expansion plan based on a ieee 30 bus test system
Li et al. (2018)	–	Yes	–	DCOPF	Yes(SP)	Yes	–	–	–	2018	Modified IEEE 24-bussystem and the IEEE two-area RTS-96 system
Li et al. (2020)	–	Yes	–	–	Yes(SP)	–	Yes	–	–	2020	Actual power grid in one province of China
Chen et al. (2019)	–	Yes	–	–	Yes(SP)	–	–	Yes	–	2019	Three EV charging stations with 100 parking spaces at residential areas, workplaces and other places, respectively.
Pourahmadi and Kazempour (2021)	–	Yes	–	ACOPF	Yes(RO)	–	Yes	–	–	2021	Modified IEEE 118-node test system
Shao et al. (2021)	–	Yes	–	DCOPF	–	Yes	–	Yes	–	2021	A transportation system modified from Xi'an City in China with 39 intersections and 132 main road arcs and a modified IEEE-14 distribution network.
Fan et al. (2020)	–	Yes	–	ACOPF	Yes(SP)	Yes	–	Yes	–	2020	54-node distribution network intertwined with a 25-node transportation system
Yao et al. (2014)	–	Yes	–	ACOPF	–	Yes	–	Yes	–	2014	23-Node Distribution and 20-Node Transportation System
Hu and Li (2010)	–	Yes	–	ACOPF	–	Yes	–	–	–	2010	IEEE 30-bus benchmark system
Jalali et al. (2014)	–	Yes	–	ACOPF	–	Yes	Yes	–	–	2014	5 existing and 17 candidate substations that feed 62 load points
Mi et al. (2021)	–	Yes	–	DCOPF	Yes(SP)	–	Yes	–	–	2021	A provincial power grid covering 2020 to 2026
Zhang et al. (2013)	–	Yes	–	–	–	–	Yes	–	–	2013	The test system with 17,000 MW generations as total installed capacity and the planning horizon assumed to be 5 years
Duan et al. (2020)	–	Yes	–	–	–	–	–	Yes	–	2020	Real trajectory data in Beijing urban area
Oderinwale et al. (2019)	–	Yes	–	–	–	–	Yes	–	Yes	2019	A strategic generation company

source-network-load-storage coupling. Given these new features, based on the summary of the basic system planning models, this paper summarizes and concludes the existing literature on the planning of power systems from five perspectives, i.e., control methods, power flow calculation, uncertainty handling, network planning, and equipment planning. In addition, the key issues of new power systems are summarized, and future research directions are also proposed, including system interdependence, various EV charging response, system resilience, and planning evaluation.

CRediT authorship contribution statement

Zhichun Yang: Conceptualization. **Fan Yang:** Methodology. **Huaidong Min:** Validation. **Hao Tian:** Supervision. **Wei Hu:** Data curation. **Jian Liu:** Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

This research was funded by State Grid Hubei Electric Power Co., Ltd. Major Science and Technology Project: Research on key technologies for active distribution network structure optimization and operation coordination adapting to the friendly interaction of microgrid clusters (project code: 521532220008).

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