Review of integrated energy system optimization considering new energy uncertainty

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Abstract. As one of the ways of low-carbon development, integrated energy system enables users to have stable and reliable energy to use through efficient and safe use of energy. However, it should be pointed out that improving IES is a very difficult task, because of the uncertainties in every link from production to use of energy. Firstly, introducing IES and describes the impact of uncertainty on system optimization in the energy industry. Secondly, random optimization, robust optimization and interval optimization are analyzed to identify the advantages and disadvantages of each method. Finally, the future research direction of IES optimization operation was prospected.

Keywords: Integrated energy system; uncertainty; Chance Constraint Programming; Interval Optimization Method; Robust optimization.

1. Introduction

The depletion of oil, coal and other traditional energy sources as well as the increasing environmental pollution make the energy problem an urgent problem to be solved for sustainable development. Integrated energy system [1] (IES) makes social energy supply reliable and secure through rational planning of energy use and satisfying users' requirements for electricity, heat, gas and other energy sources [2] It has great advantages in energy utilization and has become an important field of exploration in industry and academia.

In fact, due to the influence of uncertain factors such as the loads, the construction and analysis of system related models are more complicated, which makes the planning and operation of IES more difficult. For uncertainty mechanism, commonly used modeling methods mainly include probabilistic scenario method [2], chance constrained programming [3], point estimation method, robust optimization method and interval optimization theory. These methods have their own characteristics, but they all have weaknesses. Therefore, how to adopt appropriate methods to optimize the uncertainty of new energy output in IES has been paid attention by experts and scholars. It has become the focus of theoretical research and project practice. Although a lot of research has been done on this system worldwide, it is tough to find the way to solve the uncertainty of the energy output.

Therefore, this paper talks the research results of the uncertainty in the process of energy use, hoping to provide guidance on the improvement of energy industry operation. Firstly, this paper introduces what IES is and clarifies the influence of uncertainty on system optimization. Secondly, three main methods to solve this problem at home and abroad, namely stochastic optimization, robust optimization, interval optimization, and how to use these methods to respond to the output uncertainty of integrated energy system in relevant literature are reviewed, and the feasibility and limitations of each method are pointed out. Finally, the future research direction of IES optimization operation is prospected to provide guidance for future research in the energy industry.

2. Uncertainty optimization of IES

2.1. Concept of IES

IES is a very complex system. Through reasonable coordination and optimization of all links from production to use of energy, various energy management and scheduling can be realized, utilization efficiency can be improved, and environmental pollution can be alleviated. This system is the key to achieve energy coupling and layered use.

2.2. Characteristics of IES

In fact, compared with traditional energy systems, IES has the following basic characteristics:

Firstly, IES is safer and more reliable. The system has a variety of energy paths, among which there are many main parts that can be adjusted and manipulated, which can realize the cooperation between different systems, enhance the stability of energy output, and alleviate the problems about low safety and low self-healing ability of the traditional system.

Secondly, the comprehensive utilization rate of energy can be improved by the comprehensive energy system By taking advantage of the interaction between different systems, the system establishes a cooperative utilization mechanism among various energy sources in view of the phenomenon of staggered load demand, which make the problems of low flow density, strong dispersion and obvious intermittency of renewable energy can be reduced to enhance the utilization rate of infrastructure in the process of energy supply and promote sustainable development.

Thirdly, there are barriers between the different systems. Different energy networks have different analysis methods, different dynamic processes and different physical characteristics. In addition, different management entities are responsible for different network modes, leading to the existence of industry barriers such as information privacy, operation differences, and goal differences among the entities, which can vary the time it takes the components of the system to reach a specified operating state.

2.3. The influence of uncertainty on system optimization

It is worth noting that IES is becoming an important development object of every country in the energy field. At present, the most common way to study IES optimization operation is to manage the operation characteristics of multiple systems through coordinated control and optimization, but there are uncertainties in each link. For example, photovoltaic and other new energy sources are affected by light intensity, terminal load demand, energy price and other factors. Their randomness and intermittency characteristics make their power generation output uncertain, which will affect all aspects of energy from production to consumption.

Therefore, reducing how energy output uncertainty affects project optimization is of great significance for promoting sustainable energy supply and building a reliable comprehensive energy system. Aiming at the uncertainty in energy use, this paper introduces three aspects: chance constrained programming, robust optimization and interval optimization theory.

3. Integrated energy system optimization method

3.1. Chance Constraint Programming

Charnes and Cooper proposed opportunity-constrained programming (CCP). It is a very common and specific method of stochastic optimization theory, which can be applied to analyze the optimization problems with uncertain factors under a given confidence. Using this method, it should be noted that even if a certain range of errors are allowed, the given confidence should not be greater than the probability that the constraints are true [4].

In the existing research methods, researchers usually have two methods to solve the chance constrained programming model: one is to convert it into a deterministic model before solving it [4,6-8,10-12]; the other is to process the chance constrained conditions [3,5,9] through random simulation technology, and use the genetic algorithm to eliminate the fittest. If the chance constraint involves few random variables, the probability distribution function and its inverse function are easy to solve, which can be solved directly by the traditional programming method.

However, due to the existence of constraints that do not consider scenarios, these scenario-based results may not meet the constraints and not be robust at the same time, and can not get the best results in extreme cases. Generally speaking, there will be problems of low accuracy and long time.

Table 1 shows the existing research results on opportunity constraints sorted out in this paper.

Table 1. Comparison of opportunity constrained optimization models

Literature	Random variable	Solution method	Optimization objective
[3]	Wind power Natural gas load	Semi-invariant method Interior point method	Solve the optimal power flow
[4]	Solar radiation intensity Load prediction error	Particle swarm optimization algorithm	Optimal confidence level selection
[5]	Temperature	Transform to deterministic optimization question Monte Carlo simulation method	Rational power dispatching
[6]	Output of wind, electrical, photovoltaic	Converted to deterministic constraints	ICES coordinates with IB to optimize scheduling
[7]	User energy usage rule Temperature	Genetic algorithm Gurobipy solver	Reduce operating cost
[8]	Consumer water consumption	Genetic algorithm	Provide a zero tolerance scheme with good robustness
[9]	Output of wind, electrical, photovoltaic	Converted to deterministic constraints	Reduce operating cost
[10]	Output of wind, electrical	Particle swarm optimization	Reduce power fluctuation
[11]	Equipment power supply	Particle swarm optimization	Match total system output with planned output
[12]	Electricity price	Particle swarm optimization Monte Carlo simulation method	Profit maximization

3.2. Robust optimization

The robust optimization method adopts the method of uncertainty set. This method considers the poorest condition, describes the uncertainty in energy use, and is robust to the poorest case of uncertainty concentration. A key to solve this problem is to transform it into a convex optimization problem with certain computational complexity.

Through this method, one can find a result where the constraints are satisfied for all possible cases or an optimal decision in the worst case. Therefore, less uncertain parameter information is required, and only the interval range to which the parameter belongs needs to be obtained. However, due to the lack of information based on which part of easily available probability statistics information is not fully utilized, the control strategy obtained by the optimization model sometimes tends to be conservative, and the obtained scheme is not optimal [14].

The relevant researches on robust optimization model are shown in Table 2.

Table 2. Robust optimization model comparison

Literature	Random variable	Solution method	Optimization objective
[13]	Electricity price	Minimax robust optimization	Reduce operating cost
[14]	Integrated demand response load	Two-stage robustness	Static safety correction control
[15]	Mine gushing Photovoltaic power generation	Two-stage stochastic robustness	Improve energy recovery efficiency
[16]	Demand and renewable production forecasts	Affinely Adjustable Robust Formulation	Stable system operation
[17]	Wind uncertainty	Distributed robust optimization	manage the gas mixture
[18]	Temperature Power generation	Adaptive robustness	Reduced operating costs
[19]	Wind power output	Distributed robust optimization	Reduce rescheduling cost Obtain better scheduling solution
[20]	The load is uncertain Wind output	Two-stage robustness	Increase the wind power consumption‘function
[21]	Electricity price Wind power output	Minimax robust optimization	Consider the bias of an uncertain source
[22]	Gas storage effect	Distributed robust optimization	Promote the uptake of renewable energy

3.3. Interval Optimization Method

Interval optimization is a deterministic global optimization method in which interval variables replace point variables without accurate probability distribution information. Moore was the first to introduce this method [23].

When using this method, even if the statistical law is unknown, as long as the boundary conditions of the given parameters are clear, the interval variables can be expressed by the interval number, and can be transformed into two definite conventional optimization problems [24]. This method not only reduces the amount of information, but also provides a variety of feasible schemes for system operation, which is more suitable for dealing with uncertain information or unknown distribution function.

The relevant researches on interval optimization theory are shown in Table 3.

Table 3. Interval optimization model comparison

Literature	Random variable	Solution method	Optimization objective
[2]	Load forecasting energy price fluctuation	Particle swarm optimization algorithm CPLEX solver	Improve energy efficiency Curb earnings volatility
[23]	Load condition Electricity price	epsilon-constrained	Optimal Pareto solutions
[24]	Node load power	Two-stage solution	Reduce daily operating costs
[25]	Electric power requirement Competitor's offer	Convert into the equivalent linear programming	Maximum profit from electricity sales
[26]	Wind turbine output Photovoltaic output	Two-stage solution	Obtaine the generation power prediction interval
[27]	Photovoltaic output	Strengthen interval linear programming	Reduce operating cost
[28]	Wind power output	Transformed into deterministic optimization model Jaya algorithm	Smooth wind power output fluctuation
[29]	The node load is uncertain	Alternating direction multiplier method (ADMM)	The range information of interval programming variable is obtained

4. Future prospects of IES optimization

IES is a worth expecting energy system composed of multiple systems, which has become the focus of research around the world. Using this system can not only make energy more fully used, but also effectively promote energy saving. However, it should be noted that the optimization of energy systems also faces many challenges. In particular, the output and load prediction of renewable energy are highly uncertain, which greatly hinders the research process.

As for the uncertainty mechanism, the above-mentioned chance constrained programming, robust optimization method and interval optimization theory have their own characteristics as common methods to solve this problem, but they all have shortcomings in some aspects.

The chance constraint is solved by the given confidence degree. Its advantage is that the constraint conditions are allowed to be unsatisfied under certain probability, while the disadvantage is that the results have large deviations. This is because probability values are difficult to calculate precisely and there is no guarantee that the problem is convex. A typical problem in applying this approach is the newsboy problem.

Based on the worst-case optimization, robust optimization obtains a solution that must satisfy the constraints. However, due to the failure to make full use of probability statistics information, the optimization model tends to be rigid and conservative, and the optimal solution cannot be obtained. This method mainly solves the problem of small perturbation of parameters.

Interval optimization transforms the interval planning problem into two definite conventional optimization problems, reduces the amount of information, provides a variety of feasible schemes for system operation, and is more suitable for dealing with uncertain information or unknown distribution function.

In practical programming problems, the prediction of renewable energy output and load is uncertain, so getting a perfect probability density function is tough, but it is easy to get the value range of variables [27].

In terms of optimization methods, stochastic optimization can establish an accurate optimization model by obtaining the probability density function of uncertain variables, with high solving accuracy. But the usable price date and probability density function of distributed power are difficultly obtained as a matter of fact [7]. However, interval optimization is more suitable to deal with uncertain information or unknown distribution function. Therefore, when uncertainty is considered, interval optimization method can be selected to study IES scheduling problem, which can highlight the influence of uncertain parameters [29].

From the international research status, even though a large number of studies have been conducted on IES, there is still no complete research system for dealing with this problem, and according to the existing research, it is impossible to obtain an optimization algorithm which has the rapidity and stability to enhance the uncertainty in energy output.

As for those problems of low utilization rate, low safety and poor flexibility caused by uncertainties in all links of IES, relevant mechanisms suitable for the operation of integrated energy supply system should be gradually established in the future, and the low utilization rate of equipment should not be caused by independent design and construction of peak load. In addition, according to the actual situation of different regions, the supply network of all kinds of energy should be unified coordination and planning, weaken the problems caused by system barriers, continue to play the role of the system to reduce its dispersion, so as to obtain a variety of energy inputs and meet the needs of users, realize the optimization of energy efficiency and reduce various costs.

5. Conclusion

In the future, IES is the typical organizational form of energy interconnection systems in the future. This project provides an effective way for low-carbon development of the energy sector.

Aiming at the scientific problem of new energy output uncertainty, this paper reviews the main methods at home and abroad to solve this problem, and how relevant literature uses these methods to respond to the output uncertainty of IES, so as to obtain an effective optimization scheme for this problem. At the same time, based on the existing research results, the limitations of the use of these methods are sorted out, and the application scope and significance of these methods in the technical research level are clarified.

Internationally, although researchers have conducted numerous studies on IES, it remains unclear how to settle the mistakes caused by the uncertainty in the new energy output. In other words, how to design a set of optimization algorithms with accuracy and stability for IES remains to be studied. In addition, according to existing research, there are many uncertainties in the process of developing industrial uncertainty analysis models for industry. It should be noted that during the analysis, researchers aim to simulate the normal operation of the integrated energy system, leading to overly idealized research data, resulting in errors in the results and affecting the practicability.

The follow-up study can carry out the model study of the IES by considering the above problems, give full play to the characteristics of the IES such as reliability and scalability, and give full play to its greatest advantages in economy, energy and environmental protection.

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